Note: this is an early draft. It’s known to be incomplet and incorrekt, and it has lots of bad formatting.
Contents

Foreword x

Introduction xi

1 Scope 1

2 Normative references 2

3 Terms and definitions 3

4 General principles 10
   4.1 Implementation compliance 10
   4.2 Structure of this document 12
   4.3 Syntax notation 12

5 Lexical conventions 13
   5.1 Separate translation 13
   5.2 Phases of translation 13
   5.3 Character sets 14
   5.4 Preprocessing tokens 17
   5.5 Alternative tokens 18
   5.6 Tokens 18
   5.7 Comments 18
   5.8 Header names 19
   5.9 Preprocessing numbers 19
   5.10 Identifiers 19
   5.11 Keywords 20
   5.12 Operators and punctuators 20
   5.13 Literals 21

6 Basics 32
   6.1 Preamble 32
   6.2 Declarations and definitions 33
   6.3 One-definition rule 34
   6.4 Scope 39
   6.5 Name lookup 45
   6.6 Program and linkage 58
   6.7 Memory and objects 62
   6.8 Types 76
   6.9 Program execution 84

7 Expressions 97
   7.1 Preamble 97
   7.2 Properties of expressions 98
   7.3 Standard conversions 101
   7.4 Usual arithmetic conversions 106
   7.5 Primary expressions 106
   7.6 Compound expressions 125
   7.7 Constant expressions 158

8 Statements 167
   8.1 Preamble 167
   8.2 Label 168
   8.3 Expression statement 168
8.4 Compound statement or block .................................................. 168
8.5 Selection statements ............................................................. 168
8.6 Iteration statements .............................................................. 171
8.7 Jump statements ................................................................. 174
8.8 Declaration statement .......................................................... 175
8.9 Ambiguity resolution ............................................................. 176

9 Declarations 179
9.1 Preamble ................................................................. 179
9.2 Specifiers ................................................................. 182
9.3 Declarators ................................................................. 199
9.4 Initializers ................................................................. 217
9.5 Function definitions .......................................................... 234
9.6 Structured binding declarations ............................................... 240
9.7 Enumerations ............................................................... 241
9.8 Namespaces ................................................................. 245
9.9 The using declaration ......................................................... 249
9.10 The asm declaration .......................................................... 254
9.11 Linkage specifications .......................................................... 255
9.12 Attributes ................................................................. 257

10 Modules 266
10.1 Module units and purviews .................................................... 266
10.2 Export declaration ............................................................ 267
10.3 Import declaration ............................................................ 270
10.4 Global module fragment ....................................................... 271
10.5 Private module fragment ...................................................... 273
10.6 Instantiation context .......................................................... 274
10.7 Reachability ................................................................. 275

11 Classes 277
11.1 Preamble ................................................................. 277
11.2 Properties of classes .......................................................... 278
11.3 Class names ................................................................. 279
11.4 Class members ............................................................. 281
11.5 Unions ................................................................. 303
11.6 Local class declarations ....................................................... 305
11.7 Derived classes ............................................................. 306
11.8 Member access control ....................................................... 314
11.9 Initialization ............................................................... 324
11.10 Comparisons ............................................................... 336

12 Overloading 339
12.1 Preamble ................................................................. 339
12.2 Overload resolution .......................................................... 339
12.3 Address of an overload set .................................................. 366
12.4 Overloaded operators ......................................................... 368
12.5 Built-in operators ............................................................ 371
12.6 User-defined literals .......................................................... 373

13 Templates 375
13.1 Preamble ................................................................. 375
13.2 Template parameters .......................................................... 376
13.3 Names of template specializations ........................................ 380
13.4 Template arguments .......................................................... 383
13.5 Template constraints .......................................................... 389
13.6 Type equivalence ............................................................. 395
13.7 Template declarations .......................................................... 396
13.8 Name resolution ............................................................. 417
13.9 Template instantiation and specialization .............................................. 431
13.10 Function template specializations ...................................................... 443

14 Exception handling ................................................................................. 464
  14.1 Preamble .............................................................................................. 464
  14.2 Throwing an exception ......................................................................... 465
  14.3 Constructors and destructors ............................................................... 466
  14.4 Handling an exception ......................................................................... 467
  14.5 Exception specifications ...................................................................... 469
  14.6 Special functions ................................................................................. 471

15 Preprocessing directives ........................................................................... 473
  15.1 Preamble .............................................................................................. 473
  15.2 Conditional inclusion .......................................................................... 475
  15.3 Source file inclusion ............................................................................ 477
  15.4 Module directive .................................................................................. 478
  15.5 Header unit inclusion .......................................................................... 479
  15.6 Macro replacement .............................................................................. 480
  15.7 Line control .......................................................................................... 486
  15.8 Diagnostic directives ........................................................................... 486
  15.9Pragma directive .................................................................................. 486
  15.10 Null directive ..................................................................................... 487
  15.11 Predefined macro names ................................................................... 487
  15.12 Pragma operator ................................................................................ 490

16 Library introduction ................................................................................. 491
  16.1 General ................................................................................................ 491
  16.2 The C standard library ........................................................................ 492
  16.3 Method of description ......................................................................... 492
  16.4 Library-wide requirements .................................................................. 499

17 Language support library ........................................................................ 522
  17.1 General ................................................................................................ 522
  17.2 Common definitions ........................................................................... 522
  17.3 Implementation properties .................................................................. 526
  17.4 Arithmetic types .................................................................................. 538
  17.5 Startup and termination ..................................................................... 540
  17.6 Dynamic memory management ............................................................ 541
  17.7 Type identification .............................................................................. 548
  17.8 Source location .................................................................................... 549
  17.9 Exception handling ............................................................................. 552
  17.10 Initializer lists ..................................................................................... 556
  17.11 Comparisons ....................................................................................... 557
  17.12 Coroutines .......................................................................................... 565
  17.13 Other runtime support ....................................................................... 570
  17.14 C headers ............................................................................................ 571

18 Concepts library ....................................................................................... 574
  18.1 General ................................................................................................ 574
  18.2 Equality preservation .......................................................................... 574
  18.3 Header <concepts> synopsis ................................................................. 575
  18.4 Language-related concepts .................................................................. 577
  18.5 Comparison concepts .......................................................................... 582
  18.6 Object concepts .................................................................................... 585
  18.7 Callable concepts ................................................................................. 585

19 Diagnostics library .................................................................................... 587
  19.1 General ................................................................................................ 587
  19.2 Exception classes ................................................................................ 587
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.3</td>
<td>Assertions</td>
<td>590</td>
</tr>
<tr>
<td>19.4</td>
<td>Error numbers</td>
<td>591</td>
</tr>
<tr>
<td>19.5</td>
<td>System error support</td>
<td>592</td>
</tr>
<tr>
<td>19.6</td>
<td>Stacktrace</td>
<td>600</td>
</tr>
<tr>
<td>20</td>
<td>Memory management library</td>
<td>607</td>
</tr>
<tr>
<td>20.1</td>
<td>General</td>
<td>607</td>
</tr>
<tr>
<td>20.2</td>
<td>Memory</td>
<td>607</td>
</tr>
<tr>
<td>20.3</td>
<td>Smart pointers</td>
<td>625</td>
</tr>
<tr>
<td>20.4</td>
<td>Memory resources</td>
<td>653</td>
</tr>
<tr>
<td>20.5</td>
<td>Class template <code>scoped_allocator_adaptor</code></td>
<td>662</td>
</tr>
<tr>
<td>21</td>
<td>Metaprogramming library</td>
<td>667</td>
</tr>
<tr>
<td>21.1</td>
<td>General</td>
<td>667</td>
</tr>
<tr>
<td>21.2</td>
<td>Compile-time integer sequences</td>
<td>667</td>
</tr>
<tr>
<td>21.3</td>
<td>Metaprogramming and type traits</td>
<td>667</td>
</tr>
<tr>
<td>21.4</td>
<td>Compile-time rational arithmetic</td>
<td>695</td>
</tr>
<tr>
<td>22</td>
<td>General utilities library</td>
<td>699</td>
</tr>
<tr>
<td>22.1</td>
<td>General</td>
<td>699</td>
</tr>
<tr>
<td>22.2</td>
<td>Utility components</td>
<td>699</td>
</tr>
<tr>
<td>22.3</td>
<td>Pairs</td>
<td>706</td>
</tr>
<tr>
<td>22.4</td>
<td>Tuples</td>
<td>712</td>
</tr>
<tr>
<td>22.5</td>
<td>Optional objects</td>
<td>726</td>
</tr>
<tr>
<td>22.6</td>
<td>Variants</td>
<td>739</td>
</tr>
<tr>
<td>22.7</td>
<td>Storage for any type</td>
<td>751</td>
</tr>
<tr>
<td>22.8</td>
<td>Expected objects</td>
<td>756</td>
</tr>
<tr>
<td>22.9</td>
<td>Bitsets</td>
<td>777</td>
</tr>
<tr>
<td>22.10</td>
<td>Function objects</td>
<td>783</td>
</tr>
<tr>
<td>22.11</td>
<td>Class <code>type_index</code></td>
<td>818</td>
</tr>
<tr>
<td>22.12</td>
<td>Execution policies</td>
<td>820</td>
</tr>
<tr>
<td>22.13</td>
<td>Primitive numeric conversions</td>
<td>822</td>
</tr>
<tr>
<td>22.14</td>
<td>Formatting</td>
<td>824</td>
</tr>
<tr>
<td>22.15</td>
<td>Bit manipulation</td>
<td>852</td>
</tr>
<tr>
<td>22.16</td>
<td>Debugging</td>
<td>855</td>
</tr>
<tr>
<td>23</td>
<td>Strings library</td>
<td>857</td>
</tr>
<tr>
<td>23.1</td>
<td>General</td>
<td>857</td>
</tr>
<tr>
<td>23.2</td>
<td>Character traits</td>
<td>857</td>
</tr>
<tr>
<td>23.3</td>
<td>String view classes</td>
<td>862</td>
</tr>
<tr>
<td>23.4</td>
<td>String classes</td>
<td>872</td>
</tr>
<tr>
<td>23.5</td>
<td>Null-terminated sequence utilities</td>
<td>900</td>
</tr>
<tr>
<td>24</td>
<td>Containers library</td>
<td>906</td>
</tr>
<tr>
<td>24.1</td>
<td>General</td>
<td>906</td>
</tr>
<tr>
<td>24.2</td>
<td>Requirements</td>
<td>906</td>
</tr>
<tr>
<td>24.3</td>
<td>Sequence containers</td>
<td>941</td>
</tr>
<tr>
<td>24.4</td>
<td>Associative containers</td>
<td>978</td>
</tr>
<tr>
<td>24.5</td>
<td>Unordered associative containers</td>
<td>998</td>
</tr>
<tr>
<td>24.6</td>
<td>Container adaptors</td>
<td>1024</td>
</tr>
<tr>
<td>24.7</td>
<td>Views</td>
<td>1071</td>
</tr>
<tr>
<td>25</td>
<td>Iterators library</td>
<td>1119</td>
</tr>
<tr>
<td>25.1</td>
<td>General</td>
<td>1119</td>
</tr>
<tr>
<td>25.2</td>
<td>Header <code>&lt;iterator&gt;</code> synopsis</td>
<td>1119</td>
</tr>
<tr>
<td>25.3</td>
<td>Iterator requirements</td>
<td>1127</td>
</tr>
<tr>
<td>25.4</td>
<td>Iterator primitives</td>
<td>1148</td>
</tr>
<tr>
<td>25.5</td>
<td>Iterator adaptors</td>
<td>1151</td>
</tr>
<tr>
<td>25.6</td>
<td>Stream iterators</td>
<td>1178</td>
</tr>
</tbody>
</table>

Contents ©ISO/IEC
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.4</td>
<td>Standard locale categories</td>
<td>1709</td>
</tr>
<tr>
<td>30.5</td>
<td>C library locales</td>
<td>1740</td>
</tr>
<tr>
<td>30.6</td>
<td>Text encodings identification</td>
<td>1741</td>
</tr>
<tr>
<td>31</td>
<td>Input/output library</td>
<td>1749</td>
</tr>
<tr>
<td>31.1</td>
<td>General</td>
<td>1749</td>
</tr>
<tr>
<td>31.2</td>
<td>Iostreams requirements</td>
<td>1749</td>
</tr>
<tr>
<td>31.3</td>
<td>Forward declarations</td>
<td>1750</td>
</tr>
<tr>
<td>31.4</td>
<td>Standard istream objects</td>
<td>1752</td>
</tr>
<tr>
<td>31.5</td>
<td>Iostreams base classes</td>
<td>1754</td>
</tr>
<tr>
<td>31.6</td>
<td>Stream buffers</td>
<td>1769</td>
</tr>
<tr>
<td>31.7</td>
<td>Formatting and manipulators</td>
<td>1777</td>
</tr>
<tr>
<td>31.8</td>
<td>String-based streams</td>
<td>1805</td>
</tr>
<tr>
<td>31.9</td>
<td>Span-based streams</td>
<td>1821</td>
</tr>
<tr>
<td>31.10</td>
<td>File-based streams</td>
<td>1828</td>
</tr>
<tr>
<td>31.11</td>
<td>Synchronized output streams</td>
<td>1841</td>
</tr>
<tr>
<td>31.12</td>
<td>File systems</td>
<td>1846</td>
</tr>
<tr>
<td>31.13</td>
<td>C library files</td>
<td>1893</td>
</tr>
<tr>
<td>32</td>
<td>Regular expressions library</td>
<td>1896</td>
</tr>
<tr>
<td>32.1</td>
<td>General</td>
<td>1896</td>
</tr>
<tr>
<td>32.2</td>
<td>Requirements</td>
<td>1896</td>
</tr>
<tr>
<td>32.3</td>
<td>Header &lt;regex&gt; synopsis</td>
<td>1898</td>
</tr>
<tr>
<td>32.4</td>
<td>Namespace std::regex_constants</td>
<td>1902</td>
</tr>
<tr>
<td>32.5</td>
<td>Class regex_error</td>
<td>1905</td>
</tr>
<tr>
<td>32.6</td>
<td>Class template regex_traits</td>
<td>1905</td>
</tr>
<tr>
<td>32.7</td>
<td>Class template basic_regex</td>
<td>1907</td>
</tr>
<tr>
<td>32.8</td>
<td>Class template sub_match</td>
<td>1911</td>
</tr>
<tr>
<td>32.9</td>
<td>Class template match_results</td>
<td>1914</td>
</tr>
<tr>
<td>32.10</td>
<td>Regular expression algorithms</td>
<td>1918</td>
</tr>
<tr>
<td>32.11</td>
<td>Regular expression iterators</td>
<td>1923</td>
</tr>
<tr>
<td>32.12</td>
<td>Modified ECMAScript regular expression grammar</td>
<td>1928</td>
</tr>
<tr>
<td>33</td>
<td>Concurrency support library</td>
<td>1931</td>
</tr>
<tr>
<td>33.1</td>
<td>General</td>
<td>1931</td>
</tr>
<tr>
<td>33.2</td>
<td>Requirements</td>
<td>1931</td>
</tr>
<tr>
<td>33.3</td>
<td>Stop tokens</td>
<td>1934</td>
</tr>
<tr>
<td>33.4</td>
<td>Threads</td>
<td>1939</td>
</tr>
<tr>
<td>33.5</td>
<td>Atomic operations</td>
<td>1947</td>
</tr>
<tr>
<td>33.6</td>
<td>Mutual exclusion</td>
<td>1982</td>
</tr>
<tr>
<td>33.7</td>
<td>Condition variables</td>
<td>2000</td>
</tr>
<tr>
<td>33.8</td>
<td>Semaphore</td>
<td>2007</td>
</tr>
<tr>
<td>33.9</td>
<td>Coordination types</td>
<td>2009</td>
</tr>
<tr>
<td>33.10</td>
<td>Futures</td>
<td>2012</td>
</tr>
<tr>
<td>33.11</td>
<td>Safe reclamation</td>
<td>2026</td>
</tr>
</tbody>
</table>

### Annex A Grammar summary

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1</td>
<td>General</td>
<td>2033</td>
</tr>
<tr>
<td>A.2</td>
<td>Keywords</td>
<td>2033</td>
</tr>
<tr>
<td>A.3</td>
<td>Lexical conventions</td>
<td>2033</td>
</tr>
<tr>
<td>A.4</td>
<td>Basics</td>
<td>2038</td>
</tr>
<tr>
<td>A.5</td>
<td>Expressions</td>
<td>2038</td>
</tr>
<tr>
<td>A.6</td>
<td>Statements</td>
<td>2042</td>
</tr>
<tr>
<td>A.7</td>
<td>Declarations</td>
<td>2044</td>
</tr>
<tr>
<td>A.8</td>
<td>Modules</td>
<td>2050</td>
</tr>
<tr>
<td>A.9</td>
<td>Classes</td>
<td>2050</td>
</tr>
<tr>
<td>A.10</td>
<td>Overloading</td>
<td>2052</td>
</tr>
<tr>
<td>A.11</td>
<td>Templates</td>
<td>2052</td>
</tr>
<tr>
<td>A.12</td>
<td>Exception handling</td>
<td>2053</td>
</tr>
</tbody>
</table>
Index of library names 2181
Index of library concepts 2268
Index of implementation-defined behavior 2273
Foreword

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Introduction

Clauses and subclauses in this document are annotated with a so-called stable name, presented in square brackets next to the (sub)clause heading (such as “[lex.token]” for 5.6, “Tokens”). Stable names aid in the discussion and evolution of this document by serving as stable references to subclauses across editions that are unaffected by changes of subclause numbering.

Aspects of the language syntax of C++ are distinguished typographically by the use of italic, sans-serif type or constant width type to avoid ambiguities; see 4.3.
1 Scope

This document specifies requirements for implementations of the C++ programming language. The first such requirement is that an implementation implements the language, so this document also defines C++. Other requirements and relaxations of the first requirement appear at various places within this document.

C++ is a general purpose programming language based on the C programming language as described in ISO/IEC 9899:2018. C++ provides many facilities beyond those provided by C, including additional data types, classes, templates, exceptions, namespaces, operator overloading, function name overloading, references, free store management operators, and additional library facilities.
2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

(1.1) — ISO/IEC 2382, Information technology — Vocabulary

(1.2) — ISO 8601-1:2019, Date and time — Representations for information interchange — Part 1: Basic rules

(1.3) — ISO/IEC 9899:2018, Information technology — Programming languages — C


(1.7) — ISO/IEC 60559:2020, Information technology — Microprocessor Systems — Floating-Point arithmetic

(1.8) — ISO 80000-2:2019, Quantities and units — Part 2: Mathematics


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3 Terms and definitions [intro.defs]

1 For the purposes of this document, the terms and definitions given in ISO/IEC 2382, ISO 80000-2:2019, and the following apply.

2 ISO and IEC maintain terminology databases for use in standardization at the following addresses:

(2.1) — ISO Online browsing platform: available at https://www.iso.org/obp

(2.2) — IEC Electropedia: available at https://www.electropedia.org/

3.1 [defns.access]
access
(execution-time action) read or modify the value of an object

[Note 1 to entry: Only values of scalar type can be used to access objects. Reads of scalar objects are described in 7.3.2 and modifications of scalar objects are described in 7.6.19, 7.6.1.6, and 7.6.2.3. Attempts to read or modify an object of class type typically invoke a constructor (11.4.5) or assignment operator (11.4.6); such invocations do not themselves constitute accesses, although they may involve accesses of scalar subobjects. — end note]

3.2 [defns.argument]
argument
(function call expression) expression in the comma-separated list bounded by the parentheses

3.3 [defns.argument.macro]
argument
(function-like macro) sequence of preprocessing tokens in the comma-separated list bounded by the parentheses

3.4 [defns.argument.throw]
argument
(throw expression) operand of throw

3.5 [defns.argument.templ]
argument
(template instantiation) constant-expression, type-id, or id-expression in the comma-separated list bounded by the angle brackets

3.6 [defns.block]
block
(execution) wait for some condition (other than for the implementation to execute the execution steps of the thread of execution) to be satisfied before continuing execution past the blocking operation

3.7 [defns.block.stmt]
block
(statement) compound statement

3.8 [defns.c.lib]
C standard library
library described in ISO/IEC 9899:2018, Clause 7

[Note 1 to entry: With the qualifications noted in Clause 17 through Clause 33 and in C.8, the C standard library is a subset of the C++ standard library. — end note]

3.9 [defns.character]
character
(library) object which, when treated sequentially, can represent text

[Note 1 to entry: The term does not mean only char, char8_t, char16_t, char32_t, and wchar_t objects (6.8.2), but any value that can be represented by a type that provides the definitions specified in Clause 23, Clause 30, Clause 31, or Clause 32. — end note]
3.10 \([\text{defs.character.container}]\)
character container type
(library) class or a type used to represent a character (3.9)

[Note 1 to entry: It is used for one of the template parameters of \texttt{char_traits} and the class templates which use that, such as the string, iostream, and regular expression class templates. — end note]

3.11 \([\text{defs.regex.collating.element}]\)
collating element
sequence of one or more characters (3.9) within the current locale that collate as if they were a single character

3.12 \([\text{defs.component}]\)
component
(library) group of library entities directly related as members, \texttt{parameters} (3.37), or return types

[Note 1 to entry: For example, the class template \texttt{basic_string} and the non-member function templates that operate on strings are referred to as the string component. — end note]

3.13 \([\text{defs.cond.supp}]\)
conditionally-supported
program construct that an implementation is not required to support

[Note 1 to entry: Each implementation documents all conditionally-supported constructs that it does not support. — end note]

3.14 \([\text{defs.const.subexpr}]\)
constant subexpression
expression whose evaluation as subexpression of a \texttt{conditional-expression} \texttt{CE} would not prevent \texttt{CE} from being a core constant expression

3.15 \([\text{defs.deadlock}]\)
deadlock
(library) situation wherein one or more threads are unable to continue execution because each is \textit{blocked} (3.6) waiting for one or more of the others to satisfy some condition

3.16 \([\text{defs.default.behavior.impl}]\)
default behavior
(library implementation) specific behavior provided by the implementation, within the scope of the \textit{required behavior} (3.47)

3.17 \([\text{defs.diagnostic}]\)
diagnostic message
message belonging to an implementation-defined subset of the implementation’s output messages

3.18 \([\text{defs.dynamic.type}]\)
dynamic type
(glvalue) type of the most derived object to which the glvalue refers

[Example 1: If a pointer (9.3.4.2) \texttt{p} whose static type is “pointer to class B” is pointing to an object of class \texttt{D}, derived from \texttt{B} (11.7), the dynamic type of the expression \texttt{*p} is “D”. References (9.3.4.3) are treated similarly. — end example]

3.19 \([\text{defs.dynamic.type.prvalue}]\)
dynamic type
(prvalue) \textit{static type} (3.59) of the prvalue expression

3.20 \([\text{defs.erroneous}]\)
erroneous behavior
well-defined behavior that the implementation is recommended to diagnose

[Note 1 to entry: Erroneous behavior is always the consequence of incorrect program code. Implementations are allowed, but not required, to diagnose it (4.1.1). Evaluation of a constant expression (7.7) never exhibits behavior specified as erroneous in Clause 4 through Clause 15. — end note]
3.21 expression-equivalent
(library) expressions that all have the same effects, either are all potentially-throwing or are all not potentially-throwing, and either are all constant subexpressions (3.14) or are all not constant subexpressions

[Example 1: For a value \(x\) of type int and a function \(f\) that accepts integer arguments, the expressions \(f(x + 2)\), \(f(2 + x)\), and \(f(1 + x + 1)\) are expression-equivalent. — end example]

3.22 finite state machine
(regular expression) unspecified data structure that is used to represent a regular expression (3.45), and which permits efficient matches against the regular expression to be obtained

3.23 format specifier
(regular expression) sequence of one or more characters (3.9) that is expected to be replaced with some part of a regular expression (3.45) match

3.24 handler function
(library) non-reserved function whose definition may be provided by a C++ program

[Note 1 to entry: A C++ program may designate a handler function at various points in its execution by supplying a pointer to the function when calling any of the library functions that install handler functions (see Clause 17). — end note]

3.25 ill-formed program
program that is not well-formed (3.66)

3.26 implementation-defined behavior
behavior, for a well-formed program (3.66) construct and correct data, that depends on the implementation and that each implementation documents

3.27 implementation-defined strict total order over pointers
(library) implementation-defined strict total ordering over all pointer values such that the ordering is consistent with the partial order imposed by the built-in operators <, >, <=, >=, and <=>

3.28 implementation limit
restriction imposed upon programs by the implementation

3.29 locale-specific behavior
behavior that depends on local conventions of nationality, culture, and language that each implementation documents

3.30 matched
(regular expression) condition when a sequence of zero or more characters (3.9) correspond to a sequence of characters defined by the pattern

3.31 modifier function
(library) class member function other than a constructor, assignment operator, or destructor that alters the state of an object of the class

3.32 move assignment
(library) assignment of an rvalue of some object type to a modifiable lvalue of the same type
move construction
(library) direct-initialization of an object of some type with an rvalue of the same type

non-constant library call
invocation of a library function that, as part of evaluating any expression E, prevents E from being a core constant expression

NTCTS
(library) sequence of values that have character (3.9) type that precede the terminating null character type value charT()

observer function
(library) class member function that accesses the state of an object of the class but does not alter that state
[Note 1 to entry: Observer functions are specified as const member functions. —end note]

parameter
(function or catch clause) object or reference declared as part of a function declaration or definition or in the catch clause of an exception handler that acquires a value on entry to the function or handler

parameter
(function-like macro) identifier from the comma-separated list bounded by the parentheses immediately following the macro name

parameter
(template) member of a template-parameter-list

primary equivalence class
(regular expression) set of one or more characters (3.9) which share the same primary sort key: that is the sort key weighting that depends only upon character shape, and not accents, case, or locale specific tailorings

program-defined specialization
(library) explicit template specialization or partial specialization that is not part of the C++ standard library and not defined by the implementation

program-defined type
(library) non-closure class type or enumeration type that is not part of the C++ standard library and not defined by the implementation, or a closure type of a non-implementation-provided lambda expression, or an instantiation of a program-defined specialization (3.41)
[Note 1 to entry: Types defined by the implementation include extensions (4.1) and internal types used by the library. —end note]

projection
(library) transformation that an algorithm applies before inspecting the values of elements
[Example 1:
```cpp
std::pair<int, std::string_view> pairs[] = {{2, "foo"}, {1, "bar"}, {0, "baz"}};
std::ranges::sort(pairs, std::ranges::less{}, [](auto const& p) { return p.first; });
```
sorts the pairs in increasing order of their first members:
```
{{0, "baz"}, {1, "bar"}, {2, "foo"}}
```
3.44
referenceable type
[defs.referenceable]
type that is either an object type, a function type that does not have cv-qualifiers or a ref-qualifier, or a reference type

[Note 1 to entry: The term describes a type to which a reference can be created, including reference types. — end note]

3.45
regular expression
[defs.regex.regular.expression]
pattern that selects specific strings from a set of character (3.9) strings

3.46
replacement function
[defs.replacement]
(library) non-reserved function whose definition is provided by a C++ program

[Note 1 to entry: Only one definition for such a function is in effect for the duration of the program’s execution, as the result of creating the program (5.2) and resolving the definitions of all translation units (6.6). — end note]

3.47
required behavior
[defs.required.behavior]
(library) description of replacement function (3.46) and handler function (3.24) semantics applicable to both the behavior provided by the implementation and the behavior of any such function definition in the program

[Note 1 to entry: If such a function defined in a C++ program fails to meet the required behavior when it executes, the behavior is undefined. — end note]

3.48
reserved function
[defs.reserved.function]
(library) function, specified as part of the C++ standard library, that is defined by the implementation

[Note 1 to entry: If a C++ program provides a definition for any reserved function, the results are undefined. — end note]

3.49
signature
[defs.signature]
(library) name, parameter-type-list, and enclosing namespace

[Note 1 to entry: Signatures are used as a basis for name mangling and linking. — end note]

3.50
signature
[defs.signature.friend]
(non-template friend function with trailing requires-clause) name, parameter-type-list, enclosing class, and trailing requires-clause

3.51
signature
[defs.signature.templ]
(function template) name, parameter-type-list, enclosing namespace, return type, signature (3.57) of the template-head, and trailing requires-clause (if any)

3.52
signature
[defs.signature.templ.friend]
(friend function template with constraint involving enclosing template parameters) name, parameter-type-list, return type, enclosing class, signature (3.57) of the template-head, and trailing requires-clause (if any)

3.53
signature
[defs.signature.spec]
(function template specialization) signature (3.51) of the template of which it is a specialization and its template arguments (3.5) (whether explicitly specified or deduced)
3.54 signature
(class member function) name, parameter-type-list, class of which the function is a member, cv-qualifiers (if any), ref-qualifier (if any), and trailing requires-clause (if any)

3.55 signature
(class member function template) name, parameter-type-list, class of which the function is a member, cv-qualifiers (if any), ref-qualifier (if any), return type (if any), signature (3.57) of the template-head, and trailing requires-clause (if any)

3.56 signature
(class member function template specialization) signature (3.55) of the member function template of which it is a specialization and its template arguments (whether explicitly specified or deduced)

3.57 signature
(template-head) template parameter (3.39) list, excluding template parameter names and default arguments (3.5), and requires-clause (if any)

3.58 stable algorithm
(library) algorithm that preserves, as appropriate to the particular algorithm, the order of elements

[Note 1 to entry: Requirements for stable algorithms are given in 16.4.6.8. — end note]

3.59 static type
type of an expression resulting from analysis of the program without considering execution semantics

[Note 1 to entry: The static type of an expression depends only on the form of the program in which the expression appears, and does not change while the program is executing. — end note]

3.60 sub-expression
(regular expression) subset of a regular expression (3.45) that has been marked by parentheses

3.61 traits class
(library) class that encapsulates a set of types and functions necessary for class templates and function templates to manipulate objects of types for which they are instantiated

3.62 unblock
satisfy a condition that one or more blocked (3.6) threads of execution are waiting for

3.63 undefined behavior
behavior for which this document imposes no requirements

[Note 1 to entry: Undefined behavior may be expected when this document omits any explicit definition of behavior or when a program uses an incorrect construct or invalid data. Permissible undefined behavior ranges from ignoring the situation completely with unpredictable results, to behaving during translation or program execution in a documented manner characteristic of the environment (with or without the issuance of a diagnostic message (3.17)), to terminating a translation or execution (with the issuance of a diagnostic message). Many incorrect program constructs do not engender undefined behavior; they are required to be diagnosed. Evaluation of a constant expression (7.7) never exhibits behavior explicitly specified as undefined in Clause 4 through Clause 15. — end note]

3.64 unspecified behavior
behavior, for a well-formed program (3.66) construct and correct data, that depends on the implementation

[Note 1 to entry: The implementation is not required to document which behavior occurs. The range of possible behaviors is usually delineated by this document. — end note]
3.65 [defns.valid]
valid but unspecified state
(library) value of an object that is not specified except that the object’s invariants are met and operations on
the object behave as specified for its type

[Example 1: If an object x of type std::vector<int> is in a valid but unspecified state, x.empty() can be called
unconditionally, and x.front() can be called only if x.empty() returns false. — end example]

3.66 [defns.well-formed]
well-formed program
C++ program constructed according to the syntax and semantic rules
4 General principles

4.1 Implementation compliance

4.1.1 General

1 The set of diagnosable rules consists of all syntactic and semantic rules in this document except for those rules containing an explicit notation that “no diagnostic is required” or which are described as resulting in “undefined behavior”.

2 Although this document states only requirements on C++ implementations, those requirements are often easier to understand if they are phrased as requirements on programs, parts of programs, or execution of programs. Such requirements have the following meaning:

(2.1) — If a program contains no violations of the rules in Clause 5 through Clause 33 as well as those specified in Annex D, a conforming implementation shall accept and correctly execute\(^3\) that program, except when the implementation’s limitations (see below) are exceeded.

(2.2) — If a program contains a violation of a rule for which no diagnostic is required, this document places no requirement on implementations with respect to that program.

(2.3) — Otherwise, if a program contains

\((2.3.1)\) a violation of any diagnosable rule,
\((2.3.2)\) a preprocessing translation unit with a \#warning preprocessing directive (15.8), or
\((2.3.3)\) an occurrence of a construct described in this document as “conditionally-supported” when the implementation does not support that construct,

a conforming implementation shall issue at least one diagnostic message.

\[\text{[Note 1: During template argument deduction and substitution, certain constructs that in other contexts require a diagnostic are treated differently; see 13.10.3. — end note]}\]

Furthermore, a conforming implementation shall not accept

\((2.4)\) — a preprocessing translation unit containing a \#error preprocessing directive (15.8) or
\((2.5)\) — a translation unit with a static_assert-declaration that fails (9.1).

3 For classes and class templates, the library Clauses specify partial definitions. Private members (11.8) are not specified, but each implementation shall supply them to complete the definitions according to the description in the library Clauses.

4 For functions, function templates, objects, and values, the library Clauses specify declarations. Implementations shall supply definitions consistent with the descriptions in the library Clauses.

5 A C++ translation unit (5.2) obtains access to the names defined in the library by including the appropriate standard library header or importing the appropriate standard library named header unit (16.4.3.2).

6 The templates, classes, functions, and objects in the library have external linkage (6.6). The implementation provides definitions for standard library entities, as necessary, while combining translation units to form a complete C++ program (5.2).

7 Two kinds of implementations are defined: a hosted implementation and a freestanding implementation. A freestanding implementation is one in which execution may take place without the benefit of an operating system. A hosted implementation supports all the facilities described in this document, while a freestanding implementation supports the entire C++ language described in Clause 5 through Clause 15 and the subset of the library facilities described in 16.4.2.5.

8 An implementation is encouraged to document its limitations in the size or complexity of the programs it can successfully process, if possible and where known. Annex B lists some quantities that can be subject to limitations and a potential minimum supported value for each quantity.

\[^3\) “Correct execution” can include undefined behavior and erroneous behavior, depending on the data being processed; see Clause 3 and 6.9.1.\]
A conforming implementation may have extensions (including additional library functions), provided they
do not alter the behavior of any well-formed program. Implementations are required to diagnose programs
that use such extensions that are ill-formed according to this document. Having done so, however, they can
compile and execute such programs.

Each implementation shall include documentation that identifies all conditionally-supported constructs that
it does not support and defines all locale-specific characteristics.  

4.1.2 Abstract machine

The semantic descriptions in this document define a parameterized nondeterministic abstract machine. This
document places no requirement on the structure of conforming implementations. In particular, they need
not copy or emulate the structure of the abstract machine. Rather, conforming implementations are required
to emulate (only) the observable behavior of the abstract machine as explained below.

Certain aspects and operations of the abstract machine are described in this document as implementation-
defined behavior (for example, `sizeof(int)`). These constitute the parameters of the abstract machine. Each
implementation shall include documentation describing its characteristics and behavior in these respects.

Certain other aspects and operations of the abstract machine are described in this document as unspecified
behavior (for example, order of evaluation of arguments in a function call (7.6.1.3)). Where possible, this
document defines a set of allowable behaviors. These define the nondeterministic aspects of the abstract
machine. An instance of the abstract machine can thus have more than one possible execution for a given
program and a given input.

Certain other operations are described in this document as undefined behavior (for example, the effect of
attempting to modify a const object).

[Note 1: This document imposes no requirements on the behavior of programs that contain undefined behavior.
—end note]

A conforming implementation executing a well-formed program shall produce the same observable behavior as
one of the possible executions of the corresponding instance of the abstract machine with the same program
and the same input. However, if any such execution contains an undefined operation, this document places
no requirement on the implementation executing that program with that input (not even with regard to
operations preceding the first undefined operation). If the execution contains an operation specified as having
erroneous behavior, the implementation is permitted to issue a diagnostic and is permitted to terminate the
execution at an unspecified time after that operation.

Recommended practice: An implementation should issue a diagnostic when such an operation is executed.

[Note 2: An implementation can issue a diagnostic if it can determine that erroneous behavior is reachable under an
implementation-specific set of assumptions about the program behavior, which can result in false positives.
—end note]

The least requirements on a conforming implementation are:

(7.1) —Accesses through volatile glvalues are evaluated strictly according to the rules of the abstract machine.

(7.2) —At program termination, all data written into files shall be identical to one of the possible results that
execution of the program according to the abstract semantics would have produced.

(7.3) —The input and output dynamics of interactive devices shall take place in such a fashion that prompting
output is actually delivered before a program waits for input. What constitutes an interactive device is
implementation-defined.

These collectively are referred to as the observable behavior of the program.

[Note 3: More stringent correspondences between abstract and actual semantics can be defined by each implementation.
—end note]
4.2 Structure of this document

Clause 5 through Clause 15 describe the C++ programming language. That description includes detailed syntactic specifications in a form described in 4.3. For convenience, Annex A repeats all such syntactic specifications.

Clause 17 through Clause 33 and Annex D (the library clauses) describe the C++ standard library. That description includes detailed descriptions of the entities and macros that constitute the library, in a form described in Clause 16.

Annex B recommends lower bounds on the capacity of conforming implementations.

Annex C summarizes the evolution of C++ since its first published description, and explains in detail the differences between C++ and C. Certain features of C++ exist solely for compatibility purposes; Annex D describes those features.

4.3 Syntax notation

In the syntax notation used in this document, syntactic categories are indicated by italic, sans-serif type, and literal words and characters in constant width type. Alternatives are listed on separate lines except in a few cases where a long set of alternatives is marked by the phrase “one of”. If the text of an alternative is too long to fit on a line, the text is continued on subsequent lines indented from the first one. An optional terminal or non-terminal symbol is indicated by the subscript “opt”, so

```
{ expression_opt }
```

indicates an optional expression enclosed in braces.

Names for syntactic categories have generally been chosen according to the following rules:

1. X-name is a use of an identifier in a context that determines its meaning (e.g., class-name, typedef-name).
2. X-id is an identifier with no context-dependent meaning (e.g., qualified-id).
3. X-seq is one or more X’s without intervening delimiters (e.g., declaration-seq is a sequence of declarations).
4. X-list is one or more X’s separated by intervening commas (e.g., identifier-list is a sequence of identifiers separated by commas).
5 Lexical conventions

5.1 Separate translation

The text of the program is kept in units called source files in this document. A source file together with all the headers (16.4.2.3) and source files included (15.3) via the preprocessing directive `#include`, less any source lines skipped by any of the conditional inclusion (15.2) preprocessing directives, as modified by the implementation-defined behavior of any conditionally-supported-directives (15.1) and pragmas (15.9), if any, is called a preprocessing translation unit.

[Note 1: A C++ program need not all be translated at the same time. — end note]

2 [Note 2: Previously translated translation units and instantiation units can be preserved individually or in libraries. The separate translation units of a program communicate (6.6) by (for example) calls to functions whose identifiers have external or module linkage, manipulation of objects whose identifiers have external or module linkage, or manipulation of data files. Translation units can be separately translated and then later linked to produce an executable program (6.6). — end note]

5.2 Phases of translation

The precedence among the syntax rules of translation is specified by the following phases.7

1. An implementation shall support input files that are a sequence of UTF-8 code units (UTF-8 files). It may also support an implementation-defined set of other kinds of input files, and, if so, the kind of an input file is determined in an implementation-defined manner that includes a means of designating input files as UTF-8 files, independent of their content.

[Note 1: In other words, recognizing the u+feff byte order mark is not sufficient. — end note]

If an input file is determined to be a UTF-8 file, then it shall be a well-formed UTF-8 code unit sequence and it is decoded to produce a sequence of Unicode scalar values. A sequence of translation character set elements is then formed by mapping each Unicode scalar value to the corresponding translation character set element. In the resulting sequence, each pair of characters in the input sequence consisting of U+000D carriage return followed by U+000A line feed, as well as each U+000D carriage return not immediately followed by a U+000A line feed, is replaced by a single new-line character.

For any other kind of input file supported by the implementation, characters are mapped, in an implementation-defined manner, to a sequence of translation character set elements (5.3), representing end-of-line indicators as new-line characters.

2. If the first translation character is U+FEFF byte order mark, it is deleted. Each sequence of a backslash character (\) immediately followed by zero or more whitespace characters other than new-line followed by a new-line character is deleted, splicing physical source lines to form logical source lines. Only the last backslash on any physical source line shall be eligible for being part of such a splice.

[Note 2: Line splicing can form a universal-character-name (5.3). — end note]

A source file that is not empty and that (after splicing) does not end in a new-line character shall be processed as if an additional new-line character were appended to the file.

3. The source file is decomposed into preprocessing tokens (5.4) and sequences of whitespace characters (including comments). A source file shall not end in a partial preprocessing token or in a partial comment.9 Each comment is replaced by one space character. New-line characters are retained. Whether each nonempty sequence of whitespace characters other than new-line is retained or replaced by one space character is unspecified. As characters from the source file are consumed to form the next preprocessing token (i.e., not being consumed as part of a comment or other forms of whitespace), except when matching a c-char-sequence, s-char-sequence, r-char-sequence, h-char-sequence, or q-char-sequence, universal-character-names are recognized and replaced by the designated element of the

7) Implementations behave as if these separate phases occur, although in practice different phases can be folded together.
8) Unicode® is a registered trademark of Unicode, Inc. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO or IEC of this product.
9) A partial preprocessing token would arise from a source file ending in the first portion of a multi-character token that requires a terminating sequence of characters, such as a header-name that is missing the closing * or >. A partial comment would arise from a source file ending with an unclosed /* comment.
translation character set. The process of dividing a source file’s characters into preprocessing tokens is context-dependent.

[Example 1: See the handling of < within a #include preprocessing directive (15.3). — end example]

4. Preprocessing directives are executed, macro invocations are expanded, and _Pragma unary operator expressions are executed. A #include preprocessing directive causes the named header or source file to be processed from phase 1 through phase 4, recursively. All preprocessing directives are then deleted.

5. For a sequence of two or more adjacent string-literal tokens, a common encoding-prefix is determined as specified in 5.13.5. Each such string-literal token is then considered to have that common encoding-prefix.

6. Adjacent string-literal tokens are concatenated (5.13.5).

7. Whitespace characters separating tokens are no longer significant. Each preprocessing token is converted into a token (5.6). The resulting tokens constitute a translation unit and are syntactically and semantically analyzed and translated.

[Note 3: The process of analyzing and translating the tokens can occasionally result in one token being replaced by a sequence of other tokens (13.3). — end note]

It is implementation-defined whether the sources for module units and header units on which the current translation unit has an interface dependency (10.1, 10.3) are required to be available.

[Note 4: Source files, translation units and translated translation units need not necessarily be stored as files, nor need there be any one-to-one correspondence between these entities and any external representation. The description is conceptual only, and does not specify any particular implementation. — end note]

8. Translated translation units and instantiation units are combined as follows:

[Note 5: Some or all of these can be supplied from a library. — end note]

Each translated translation unit is examined to produce a list of required instantiations.

[Note 6: This can include instantiations which have been explicitly requested (13.9.3). — end note]

The definitions of the required templates are located. It is implementation-defined whether the source of the translation units containing these definitions is required to be available.

[Note 7: An implementation can choose to encode sufficient information into the translated translation unit so as to ensure the source is not required here. — end note]

All the required instantiations are performed to produce instantiation units.

[Note 8: These are similar to translated translation units, but contain no references to uninstantiated templates and no template definitions. — end note]

The program is ill-formed if any instantiation fails.

9. All external entity references are resolved. Library components are linked to satisfy external references to entities not defined in the current translation. All such translator output is collected into a program image which contains information needed for execution in its execution environment.

5.3 Character sets

1 The translation character set consists of the following elements:

(1.1) each abstract character assigned a code point in the Unicode codespace as specified in the Unicode Standard, and

(1.2) a distinct character for each Unicode scalar value not assigned to an abstract character.

[Note 1: Unicode code points are integers in the range [0, 10FFFF] (hexadecimal). A surrogate code point is a value in the range [D800, DFFF] (hexadecimal). A Unicode scalar value is any code point that is not a surrogate code point. — end note]

2 The basic character set is a subset of the translation character set, consisting of 99 characters as specified in Table 1.

[Note 2: Unicode short names are given only as a means to identifying the character; the numerical value has no other meaning in this context. — end note]

3 The universal-character-name construct provides a way to name other characters.

 n-char: one of

any member of the translation character set except the U+007D RIGHT CURLY BRACKET or new-line character
Table 1 — Basic character set  

<table>
<thead>
<tr>
<th>character</th>
<th>glyph</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+0009</td>
<td>CHARACTER TABULATION</td>
</tr>
<tr>
<td>U+000B</td>
<td>LINE TABULATION</td>
</tr>
<tr>
<td>U+000C</td>
<td>FORM FEED</td>
</tr>
<tr>
<td>U+0020</td>
<td>SPACE</td>
</tr>
<tr>
<td>U+000A</td>
<td>LINE FEED</td>
</tr>
<tr>
<td>U+0021</td>
<td>EXCLAMATION MARK</td>
</tr>
<tr>
<td>U+0022</td>
<td>QUOTATION MARK</td>
</tr>
<tr>
<td>U+0023</td>
<td>NUMBER SIGN</td>
</tr>
<tr>
<td>U+0024</td>
<td>DOLLAR SIGN</td>
</tr>
<tr>
<td>U+0025</td>
<td>PERCENT SIGN</td>
</tr>
<tr>
<td>U+0026</td>
<td>AMPERSAND</td>
</tr>
<tr>
<td>U+0027</td>
<td>APOSTROPHE</td>
</tr>
<tr>
<td>U+0028</td>
<td>LEFT PARENTHESIS</td>
</tr>
<tr>
<td>U+0029</td>
<td>RIGHT PARENTHESES</td>
</tr>
<tr>
<td>U+002A</td>
<td>ASTERISK</td>
</tr>
<tr>
<td>U+002B</td>
<td>PLUS SIGN</td>
</tr>
<tr>
<td>U+002C</td>
<td>COMMA</td>
</tr>
<tr>
<td>U+002D</td>
<td>HYPHEN-MINUS</td>
</tr>
<tr>
<td>U+002E</td>
<td>FULL STOP</td>
</tr>
<tr>
<td>U+002F</td>
<td>SOLIDUS</td>
</tr>
<tr>
<td>U+0030 .. U+0039</td>
<td>DIGIT ZERO .. NINE</td>
</tr>
<tr>
<td>U+003A</td>
<td>COLON</td>
</tr>
<tr>
<td>U+003B</td>
<td>SEMICOLON</td>
</tr>
<tr>
<td>U+003C</td>
<td>LESS-THAN SIGN</td>
</tr>
<tr>
<td>U+003D</td>
<td>_EQUALS SIGN</td>
</tr>
<tr>
<td>U+003E</td>
<td>GREATER-THEAN SIGN</td>
</tr>
<tr>
<td>U+003F</td>
<td>QUESTION MARK</td>
</tr>
<tr>
<td>U+0040</td>
<td>COMMERCIAL AT</td>
</tr>
<tr>
<td>U+0041 .. U+005A</td>
<td>LATIN CAPITAL LETTER A .. Z</td>
</tr>
<tr>
<td>U+005B</td>
<td>LEFT SQUARE BRACKET</td>
</tr>
<tr>
<td>U+005C</td>
<td>REVERSE SOLIDUS</td>
</tr>
<tr>
<td>U+005D</td>
<td>RIGHT SQUARE BRACKET</td>
</tr>
<tr>
<td>U+005E</td>
<td>CIRCUMFLEX ACCENT</td>
</tr>
<tr>
<td>U+005F</td>
<td>LOW LINE</td>
</tr>
<tr>
<td>U+0060</td>
<td>GRAVE ACCENT</td>
</tr>
<tr>
<td>U+0061 .. U+007A</td>
<td>LATIN SMALL LETTER A .. Z</td>
</tr>
<tr>
<td>U+007B</td>
<td>LEFT CURLY BRACKET</td>
</tr>
<tr>
<td>U+007C</td>
<td>VERTICAL LINE</td>
</tr>
<tr>
<td>U+007D</td>
<td>RIGHT CURLY BRACKET</td>
</tr>
<tr>
<td>U+007E</td>
<td>TILDE</td>
</tr>
</tbody>
</table>
A universal-character-name of the form \u hex-quad, \U hex-quad hex-quad, or \u{simple-hexadecimal-digit-sequence} designates the character in the translation character set whose Unicode scalar value is the hexadecimal number represented by the sequence of hexadecimal-digits in the universal-character-name. The program is ill-formed if that number is not a Unicode scalar value.

If a universal-character-name outside the c-char-sequence, s-char-sequence, or r-char-sequence of a character-literal or string-literal (in either case, including within a user-defined-literal) corresponds to a control character or to a character in the basic character set, the program is ill-formed.

Table 2 — Additional control characters in the basic literal character set

<table>
<thead>
<tr>
<th>character</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+0000   NULL</td>
<td>0</td>
</tr>
<tr>
<td>U+0007   ALERT</td>
<td>7</td>
</tr>
<tr>
<td>U+0008   BACKSPACE</td>
<td>8</td>
</tr>
<tr>
<td>U+000D   CARRIAGE RETURN</td>
<td>13</td>
</tr>
</tbody>
</table>

A code unit is an integer value of character type (6.8.2). Characters in a character-literal other than a multicharacter or non-encodable character literal or in a string-literal are encoded as a sequence of one or more code units, as determined by the encoding-prefix (5.13.3, 5.13.5); this is termed the respective literal encoding. The ordinary literal encoding is the encoding applied to an ordinary character or string literal. The wide literal encoding is the encoding applied to a wide character or string literal.

A literal encoding or a locale-specific encoding of one of the execution character sets (16.3.3.3.4) encodes each element of the basic literal character set as a single code unit with non-negative value, distinct from the code unit for any other such element.

The U+0000 NULL character is encoded as the value 0. No other element of the translation character set is encoded with a code unit of value 0. The code unit value of each decimal digit character after the digit 0 (U+0030) shall be one greater than the value of the previous. The ordinary and wide literal encodings are otherwise implementation-defined. For a UTF-8, UTF-16, or UTF-32 literal, the implementation shall encode
the Unicode scalar value corresponding to each character of the translation character set as specified in the Unicode Standard for the respective Unicode encoding form.

5.4 Preprocessing tokens

preprocessing-token:
  header-name
  import-keyword
  module-keyword
  export-keyword
  identifier
  pp-number
  character-literal
  user-defined-character-literal
  string-literal
  user-defined-string-literal
  preprocessing-op-or-punc

1 Each preprocessing token that is converted to a token (5.6) shall have the lexical form of a keyword, an identifier, a literal, or an operator or punctuator.

2 A preprocessing token is the minimal lexical element of the language in translation phases 3 through 6. In this document, glyphs are used to identify elements of the basic character set (5.3). The categories of preprocessing token are: header names, placeholder tokens produced by preprocessing import and module directives (import-keyword, module-keyword, and export-keyword), identifiers, preprocessing numbers, character literals (including user-defined character literals), string literals (including user-defined string literals), preprocessing operators and punctuators, and single non-whitespace characters that do not lexically match the other preprocessing token categories. If a U+0027 APOSTROPHE or a U+0022 QUOTATION MARK character matches the last category, the program is ill-formed. If any character not in the basic character set matches the last category, the program is ill-formed. Preprocessing tokens can be separated by whitespace; this consists of comments (5.7), or whitespace characters (U+0020 SPACE, U+0009 CHARACTER TABULATION, new-line, U+000C FORM FEED, and U+000D FORM FEED), or both. As described in Clause 15, in certain circumstances during translation phase 4, whitespace (or the absence thereof) serves as more than preprocessing token separation. Whitespace can appear within a preprocessing token only as part of a header name or between the quotation characters in a character literal or string literal.

3 If the input stream has been parsed into preprocessing tokens up to a given character:

(3.1) — If the next character begins a sequence of characters that could be the prefix and initial double quote of a raw string literal, such as R", the next preprocessing token shall be a raw string literal. Between the initial and final double quote characters of the raw string, any transformations performed in phase 2 (line splicing) are reverted; this reversion shall apply before any d-char, r-char, or delimiting parenthesis is identified. The raw string literal is defined as the shortest sequence of characters that matches the raw-string pattern

\[
\text{encoding-prefix}_\text{opt} \text{ R} \text{ raw-string}
\]

(3.2) — Otherwise, if the next three characters are <:: and the subsequent character is neither : nor >, the < is treated as a preprocessing token by itself and not as the first character of the alternative token <:.

(3.3) — Otherwise, the next preprocessing token is the longest sequence of characters that could constitute a preprocessing token, even if that would cause further lexical analysis to fail, except that a header-name (5.8) is only formed

(3.3.1) — after the include or import preprocessing token in an #include (15.3) or import (15.5) directive, or

(3.3.2) — within a has-include-expression.

[Example 1:

\[
\#define R "x"
\text{const char* s = R"y";} \quad \text{// ill-formed raw string, not "x" "y"}
\]

— end example]
The import-keyword is produced by processing an import directive (15.5), the module-keyword is produced by preprocessing a module directive (15.4), and the export-keyword is produced by preprocessing either of the previous two directives.

[Note 1: None has any observable spelling. — end note]

[Example 2: The program fragment 0xe+foo is parsed as a preprocessing number token (one that is not a valid integer-literal or floating-point-literal token), even though a parse as three preprocessing tokens 0xe, +, and foo can produce a valid expression (for example, if foo is a macro defined as 1). Similarly, the program fragment 1E1 is parsed as a preprocessing number (one that is a valid floating-point-literal token), whether or not E is a macro name. — end example]

[Example 3: The program fragment x+++++y is parsed as x ++ ++ + y, which, if x and y have integral types, violates a constraint on increment operators, even though the parse x ++ + ++ y can yield a correct expression. — end example]

5.5 Alternative tokens

Alternative token representations are provided for some operators and punctuators.10

In all respects of the language, each alternative token behaves the same, respectively, as its primary token, except for its spelling.11 The set of alternative tokens is defined in Table 3.

Table 3 — Alternative tokens

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Primary</th>
<th>Alternative</th>
<th>Primary</th>
<th>Alternative</th>
<th>Primary</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;% {</td>
<td>and</td>
<td>and_eq</td>
<td></td>
<td>&amp;=</td>
<td></td>
</tr>
<tr>
<td>%&gt; }</td>
<td>bitor</td>
<td>or_eq</td>
<td></td>
<td></td>
<td>=</td>
</tr>
<tr>
<td>&lt;: [</td>
<td>or</td>
<td>xor_eq</td>
<td></td>
<td>^=</td>
<td></td>
</tr>
<tr>
<td>&lt;: ]</td>
<td>xor</td>
<td>not</td>
<td></td>
<td>!=</td>
<td></td>
</tr>
<tr>
<td>%: #</td>
<td>compl</td>
<td>not_eq</td>
<td></td>
<td>!=</td>
<td></td>
</tr>
<tr>
<td>%: %: #</td>
<td>bitand</td>
<td>&amp;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.6 Tokens

token:

identifier
keyword
literal
operator-or-punctuator

There are five kinds of tokens: identifiers, keywords, literals,12 operators, and other separators. Blanks, horizontal and vertical tabs, newlines, formfeeds, and comments (collectively, “whitespace”), as described below, are ignored except as they serve to separate tokens.

[Note 1: Whitespace can separate otherwise adjacent identifiers, keywords, numeric literals, and alternative tokens containing alphabetic characters. — end note]

5.7 Comments

The characters /* start a comment, which terminates with the characters */. These comments do not nest. The characters // start a comment, which terminates immediately before the next new-line character. If there is a form-feed or a vertical-tab character in such a comment, only whitespace characters shall appear between it and the new-line that terminates the comment; no diagnostic is required.

[Note 1: The comment characters //, /*, and */ have no special meaning within a // comment and are treated just like other characters. Similarly, the comment characters // and /* have no special meaning within a /* comment. — end note]

10) These include “digraphs” and additional reserved words. The term “digraph” (token consisting of two characters) is not perfectly descriptive, since one of the alternative preprocessing-tokens is %:%: and of course several primary tokens contain two characters. Nonetheless, those alternative tokens that aren’t lexical keywords are colloquially known as “digraphs”.

11) Thus the “stringized” values (15.6.3) of [ and <: will be different, maintaining the source spelling, but the tokens can otherwise be freely interchanged.

12) Literals include strings and character and numeric literals.
5.8 **Header names**

header-name:
  < h-char-sequence >
  " q-char-sequence "

h-char-sequence:
  h-char
  h-char-sequence h-char

h-char:
  any member of the translation character set except new-line and U+003E GREATER-THE- SIGN

q-char-sequence:
  q-char
  q-char-sequence q-char

q-char:
  any member of the translation character set except new-line and U+0022 QUOTATION MARK

1 [Note 1: Header name preprocessing tokens only appear within a `#include` preprocessing directive, a `__has_include` preprocessing expression, or after certain occurrences of an `import` token (see 5.4). — end note]

The sequences in both forms of header-names are mapped in an implementation-defined manner to headers or to external source file names as specified in 15.3.

2 The appearance of either of the characters `*` or `/` or of either of the character sequences `*/` or `//` in a q-char-sequence or an h-char-sequence is conditionally-supported with implementation-defined semantics, as is the appearance of the character " in an h-char-sequence.13

5.9 **Preprocessing numbers**

pp-number:
  digit
  . digit
  pp-number identifier-continue
  pp-number + digit
  pp-number - digit
  pp-number e sign
  pp-number E sign
  pp-number p sign
  pp-number P sign
  pp-number .

1 Preprocessing number tokens lexically include all integer-literal tokens (5.13.2) and all floating-point-literal tokens (5.13.4).

2 A preprocessing number does not have a type or a value; it acquires both after a successful conversion to an integer-literal token or a floating-point-literal token.

5.10 **Identifiers**

identifier:
  identifier-start
  identifier identifier-continue

identifier-start:
  nondigit
  an element of the translation character set with the Unicode property XID_Start

identifier-continue:
  digit
  nondigit
  an element of the translation character set with the Unicode property XID_Continue

nondigit: one of
  a b c d e f g h i j k l m
  n o p q r s t u v w x y z
  A B C D E F G H I J K L M
  N O P Q R S T U V W X Y Z

13) Thus, a sequence of characters that resembles an escape sequence can result in an error, be interpreted as the character corresponding to the escape sequence, or have a completely different meaning, depending on the implementation.
The program is ill-formed if an identifier does not conform to Normalization Form C as specified in the Unicode Standard.

Note 2: Identifiers are case-sensitive. — end note

Note 3: Annex E compares the requirements of UAX #31 of the Unicode Standard with the C++ rules for identifiers. — end note

Note 4: In translation phase 4, identifier also includes those preprocessing-tokens (5.4) differentiated as keywords (5.11) in the later translation phase 7 (5.6). — end note

The identifiers in Table 4 have a special meaning when appearing in a certain context. When referred to in the grammar, these identifiers are used explicitly rather than using the identifier grammar production. Unless otherwise specified, any ambiguity as to whether a given identifier has a special meaning is resolved to interpret the token as a regular identifier.

Table 4 — Identifiers with special meaning [tab:lex.name.special]

<table>
<thead>
<tr>
<th>final</th>
<th>import</th>
<th>module</th>
<th>override</th>
</tr>
</thead>
</table>

In addition, some identifiers appearing as a token or preprocessing-token are reserved for use by C++ implementations and shall not be used otherwise; no diagnostic is required.

(3.1) Each identifier that contains a double underscore __ or begins with an underscore followed by an uppercase letter, other than those specified in this document (for example, __cplusplus (15.11)), is reserved to the implementation for any use.

(3.2) Each identifier that begins with an underscore is reserved to the implementation for use as a name in the global namespace.

Keywords [lex.key]

keyword:

| import-keyword | module-keyword | export-keyword |

The identifiers shown in Table 5 are reserved for use as keywords (that is, they are unconditionally treated as keywords in phase 7) except in an attribute-token (9.12.1).

Note 1: The register keyword is unused but is reserved for future use. — end note

Furthermore, the alternative representations shown in Table 6 for certain operators and punctuators (5.5) are reserved and shall not be used otherwise.

Operators and punctuators [lex.operators]

The lexical representation of C++ programs includes a number of preprocessing tokens that are used in the syntax of the preprocessor or are converted into tokens for operators and punctuators:

preprocessing-op-or-punct:

| preprocessing-operator | operator-or-punctuator |

# \# % %:

On systems in which linkers cannot accept extended characters, an encoding of the universal-character-name can be used in forming valid external identifiers. For example, some otherwise unused character or sequence of characters can be used to encode the \a in a universal-character-name. Extended characters can produce a long external identifier, but C++ does not place a translation limit on significant characters for external identifiers.
Table 5 — Keywords  [tab:lex.key]

<table>
<thead>
<tr>
<th>alignas</th>
<th>constinit</th>
<th>false</th>
<th>public</th>
<th>true</th>
</tr>
</thead>
<tbody>
<tr>
<td>alignof</td>
<td>const_cast</td>
<td>float</td>
<td>register</td>
<td>try</td>
</tr>
<tr>
<td>asm</td>
<td>continue</td>
<td>for</td>
<td>reinterpret_cast</td>
<td>typedef</td>
</tr>
<tr>
<td>auto</td>
<td>co_await</td>
<td>friend</td>
<td>requires</td>
<td>typeid</td>
</tr>
<tr>
<td>bool</td>
<td>co_return</td>
<td>goto</td>
<td>return</td>
<td>typename</td>
</tr>
<tr>
<td>break</td>
<td>co_yield</td>
<td>if</td>
<td>short</td>
<td>union</td>
</tr>
<tr>
<td>case</td>
<td>decftype</td>
<td>inline</td>
<td>signed</td>
<td>unsigned</td>
</tr>
<tr>
<td>catch</td>
<td>default</td>
<td>int</td>
<td>sizeof</td>
<td>using</td>
</tr>
<tr>
<td>char</td>
<td>delete</td>
<td>long</td>
<td>static</td>
<td>virtual</td>
</tr>
<tr>
<td>char8_t</td>
<td>do</td>
<td>mutable</td>
<td>static_assert</td>
<td>void</td>
</tr>
<tr>
<td>char16_t</td>
<td>double</td>
<td>namespace</td>
<td>static_cast</td>
<td>volatile</td>
</tr>
<tr>
<td>char32_t</td>
<td>dynamic_cast</td>
<td>new</td>
<td>struct</td>
<td>wchar_t</td>
</tr>
<tr>
<td>class</td>
<td>else</td>
<td>noexcept</td>
<td>switch</td>
<td>while</td>
</tr>
<tr>
<td>concept</td>
<td>enum</td>
<td>nullptr</td>
<td>template</td>
<td></td>
</tr>
<tr>
<td>const</td>
<td>explicit</td>
<td>operator</td>
<td>this</td>
<td></td>
</tr>
<tr>
<td>constexpr</td>
<td>export</td>
<td>private</td>
<td>thread_local</td>
<td></td>
</tr>
<tr>
<td>constexpr</td>
<td>extern</td>
<td>protected</td>
<td>throw</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 — Alternative representations  [tab:lex.key.digraph]

<table>
<thead>
<tr>
<th>operator-or-punctuator: one of</th>
</tr>
</thead>
<tbody>
<tr>
<td>{   }</td>
</tr>
<tr>
<td>&lt;:</td>
</tr>
<tr>
<td>?:</td>
</tr>
<tr>
<td>!=</td>
</tr>
<tr>
<td>==</td>
</tr>
<tr>
<td>==</td>
</tr>
<tr>
<td>&lt;&lt;=</td>
</tr>
<tr>
<td>and</td>
</tr>
<tr>
<td>and_eq</td>
</tr>
</tbody>
</table>

Each operator-or-punctuator is converted to a single token in translation phase 7 (5.2).

§ 5.13 Literals [lex.literal]

5.13.1 Kinds of literals [lex.literal.kinds]

There are several kinds of literals.15

 literal:
  integer-literal
  character-literal
  floating-point-literal
  string-literal
  boolean-literal
  pointer-literal
  user-defined-literal

[Note 1: When appearing as an expression, a literal has a type and a value category (7.5.2). — end note]

5.13.2 Integer literals [lex.icon]

1) The term “literal” generally designates, in this document, those tokens that are called “constants” in C.
integer-literal:
  binary-literal integer-suffix_{opt}
  octal-literal integer-suffix_{opt}
  decimal-literal integer-suffix_{opt}
  hexadecimal-literal integer-suffix_{opt}

binary-literal:
  0b binary-digit
  0B binary-digit
  binary-literal '_{opt} binary-digit

octal-literal:
  0
  octal-literal '_{opt} octal-digit

decimal-literal:
  nonzero-digit
  decimal-literal '_{opt} digit

hexadecimal-literal:
  hexadecimal-prefix hexadecimal-digit-sequence

binary-digit: one of
  0 1

octal-digit: one of
  0 1 2 3 4 5 6 7

nonzero-digit: one of
  1 2 3 4 5 6 7 8 9

hexadecimal-prefix: one of
  0x 0X

hexadecimal-digit-sequence:
  hexadecimal-digit
  hexadecimal-digit-sequence '_{opt} hexadecimal-digit

hexadecimal-digit: one of
  0 1 2 3 4 5 6 7 8 9
  a b c d e f
  A B C D E F

integer-suffix:
  unsigned-suffix long-suffix_{opt}
  unsigned-suffix long-long-suffix_{opt}
  unsigned-suffix size-suffix_{opt}
  long-suffix unsigned-suffix_{opt}
  long-long-suffix unsigned-suffix_{opt}
  size-suffix unsigned-suffix_{opt}

unsigned-suffix: one of
  u U

long-suffix: one of
  l L

long-long-suffix: one of
  ll LL

size-suffix: one of
  z Z

1 In an integer-literal, the sequence of binary-digits, octal-digits, digits, or hexadecimal-digits is interpreted as a base \(N\) integer as shown in table Table 7; the lexically first digit of the sequence of digits is the most significant.

[Note 1: The prefix and any optional separating single quotes are ignored when determining the value. — end note]

2 The hexadecimal-digits a through f and A through F have decimal values ten through fifteen.

[Example 1: The number twelve can be written 12, 014, 0XC, or 0b1100. The integer-literals 1048576, 1'048'576, 0X100000, 0x10'0000, and 0’004’000’000 all have the same value. — end example]
### Table 7 — Base of integer-literals

<table>
<thead>
<tr>
<th>Kind of integer-literal</th>
<th>base N</th>
</tr>
</thead>
<tbody>
<tr>
<td>binary-literal</td>
<td>2</td>
</tr>
<tr>
<td>octal-literal</td>
<td>8</td>
</tr>
<tr>
<td>decimal-literal</td>
<td>10</td>
</tr>
<tr>
<td>hexadecimal-literal</td>
<td>16</td>
</tr>
</tbody>
</table>

3 The type of an *integer-literal* is the first type in the list in Table 8 corresponding to its optional *integer-suffix* in which its value can be represented.

### Table 8 — Types of integer-literals

<table>
<thead>
<tr>
<th>integer-suffix</th>
<th>decimal-literal</th>
<th>integer-literal other than decimal-literal</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>int</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>long int</td>
<td>unsigned int</td>
</tr>
<tr>
<td></td>
<td>long long int</td>
<td>long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long long int</td>
</tr>
<tr>
<td>u or U</td>
<td>unsigned int</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>unsigned long int</td>
<td></td>
</tr>
<tr>
<td></td>
<td>unsigned long long int</td>
<td></td>
</tr>
<tr>
<td>l or L</td>
<td>long int</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>long long int</td>
<td>unsigned int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long long int</td>
</tr>
<tr>
<td>Both u or U and 1 or L</td>
<td>unsigned long int</td>
<td>int</td>
</tr>
<tr>
<td>Both u or U and l or LL</td>
<td>unsigned long long int</td>
<td>int</td>
</tr>
<tr>
<td>11 or LL</td>
<td>long long int</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long long int</td>
</tr>
<tr>
<td>z or Z</td>
<td>the signed integer type corresponding to std::size_t (17.2.4)</td>
<td>the signed integer type corresponding to std::size_t</td>
</tr>
<tr>
<td></td>
<td></td>
<td>std::size_t</td>
</tr>
<tr>
<td>Both u or U and z or Z</td>
<td>std::size_t</td>
<td>std::size_t</td>
</tr>
</tbody>
</table>

4 Except for *integer-literals* containing a *size-suffix*, if the value of an *integer-literal* cannot be represented by any type in its list and an extended integer type (6.8.2) can represent its value, it may have that extended integer type. If all of the types in the list for the *integer-literal* are signed, the extended integer type is signed. If all of the types in the list for the *integer-literal* are unsigned, the extended integer type is unsigned. If the list contains both signed and unsigned types, the extended integer type may be signed or unsigned. If an *integer-literal* cannot be represented by any of the allowed types, the program is ill-formed.

[Note 2: An *integer-literal* with a *z* or *Z* suffix is ill-formed if it cannot be represented by std::size_t. — end note]

#### 5.13.3 Character literals

character-literal:

  encoding-prefix\opt ' c-char-sequence '

encoding-prefix: one of

  u8  u  U  L

c-char-sequence:

  c-char

  c-char-sequence c-char
c-char:
  basic-c-char
  escape-sequence
  universal-character-name

basic-c-char:
  any member of the translation character set except the U+0027 APOSTROPHE,
  U+005C REVERSE SOLIDUS, or new-line character

escape-sequence:
  simple-escape-sequence
  numeric-escape-sequence
  conditional-escape-sequence

simple-escape-sequence:
  \ simple-escape-sequence-char

simple-escape-sequence-char: one of
  ' " ? \ a b f n r t v

numeric-escape-sequence:
  octal-escape-sequence
  hexadecimal-escape-sequence

simple-octal-digit-sequence:
  octal-digit
  simple-octal-digit-sequence octal-digit

octal-escape-sequence:
  \ octal-digit
  \ octal-digit octal-digit
  \ octal-digit octal-digit octal-digit
  \o{ simple-octal-digit-sequence }

hexadecimal-escape-sequence:
  \x simple-hexadecimal-digit-sequence
  \x{ simple-hexadecimal-digit-sequence }

conditional-escape-sequence:
  \ conditional-escape-sequence-char

conditional-escape-sequence-char:
  any member of the basic character set that is not an octal-digit, a simple-escape-sequence-char, or the
  characters N, o, u, U, or x

1 A multicharacter literal is a character-literal whose c-char-sequence consists of more than one c-char. A
multicharacter literal shall not have an encoding-prefix. If a multicharacter literal contains a c-char that is
not encodable as a single code unit in the ordinary literal encoding, the program is ill-formed. Multicharacter
literals are conditionally-supported.

2 The kind of a character-literal, its type, and its associated character encoding (5.3) are determined by its
encoding-prefix and its c-char-sequence as defined by Table 9.

Table 9 — Character literals  [tab:lex.ccon.literal]

<table>
<thead>
<tr>
<th>Encoding prefix</th>
<th>Kind</th>
<th>Type</th>
<th>Associated character encoding</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>ordinary character literal</td>
<td>char</td>
<td>ordinary literal encoding</td>
<td>'v'</td>
</tr>
<tr>
<td>L</td>
<td>wide character literal</td>
<td>wchar_t</td>
<td>wide literal encoding</td>
<td>L'w'</td>
</tr>
<tr>
<td>u8</td>
<td>UTF-8 character literal</td>
<td>char8_t</td>
<td>UTF-8</td>
<td>u8'x'</td>
</tr>
<tr>
<td>u</td>
<td>UTF-16 character literal</td>
<td>char16_t</td>
<td>UTF-16</td>
<td>u'y'</td>
</tr>
<tr>
<td>U</td>
<td>UTF-32 character literal</td>
<td>char32_t</td>
<td>UTF-32</td>
<td>U'z'</td>
</tr>
</tbody>
</table>
In translation phase 4, the value of a character-literal is determined using the range of representable values of the character-literal’s type in translation phase 7. A multicharacter literal has an implementation-defined value. The value of any other kind of character-literal is determined as follows:

(3.1) — A character-literal with a c-char-sequence consisting of a single basic-c-char, simple-escape-sequence, or universal-character-name is the code unit value of the specified character as encoded in the literal’s associated character encoding. If the specified character lacks representation in the literal’s associated character encoding or if it cannot be encoded as a single code unit, then the program is ill-formed.

(3.2) — A character-literal with a c-char-sequence consisting of a single numeric-escape-sequence has a value as follows:

(3.2.1) — Let \( v \) be the integer value represented by the octal number comprising the sequence of octal-digits in an octal-escape-sequence or by the hexadecimal number comprising the sequence of hexadecimal-digits in a hexadecimal-escape-sequence.

(3.2.2) — If \( v \) does not exceed the range of representable values of the character-literal’s type, then the value is \( v \).

(3.2.3) — Otherwise, if the character-literal’s encoding-prefix is absent or \( L \), and \( v \) does not exceed the range of representable values of the corresponding unsigned type for the underlying type of the character-literal’s type \( T \) that is congruent to \( v \) modulo \( 2^N \), where \( N \) is the width of \( T \).

(3.2.4) — Otherwise, the program is ill-formed.

(3.3) — A character-literal with a c-char-sequence consisting of a single conditional-escape-sequence is conditionally-supported and has an implementation-defined value.

The character specified by a simple-escape-sequence is specified in Table 10.

[Note 1: Using an escape sequence for a question mark is supported for compatibility with C++ 2014 and C. — end note]

<table>
<thead>
<tr>
<th>character</th>
<th>simple-escape-sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+000A</td>
<td>LINE FEED</td>
</tr>
<tr>
<td>U+0009</td>
<td>CHARACTER TABULATION</td>
</tr>
<tr>
<td>U+000B</td>
<td>LINE TABULATION</td>
</tr>
<tr>
<td>U+0008</td>
<td>BACKSPACE</td>
</tr>
<tr>
<td>U+000D</td>
<td>CARRIAGE RETURN</td>
</tr>
<tr>
<td>U+000C</td>
<td>FORM FEED</td>
</tr>
<tr>
<td>U+0007</td>
<td>ALERT</td>
</tr>
<tr>
<td>U+005C</td>
<td>REVERSE SOLIDUS</td>
</tr>
<tr>
<td>U+003F</td>
<td>QUESTION MARK</td>
</tr>
<tr>
<td>U+0027</td>
<td>APOSTROPHE</td>
</tr>
<tr>
<td>U+0022</td>
<td>QUOTATION MARK</td>
</tr>
</tbody>
</table>

5.13.4 Floating-point literals

floating-point-literal:
  decimal-floating-point-literal
  hexadecimal-floating-point-literal
decimal-floating-point-literal:
  fractional-constant exponent-part_{opt} floating-point-suffix_{opt}
  digit-sequence exponent-part floating-point-suffix_{opt}
hexadecimal-floating-point-literal:
  hexadecimal-prefix hexadecimal-fractional-constant binary-exponent-part floating-point-suffix_{opt}
  hexadecimal-prefix hexadecimal-digit-sequence binary-exponent-part floating-point-suffix_{opt}
fractional-constant:
  digit-sequence_{opt} . digit-sequence
  digit-sequence
hexadecimal-fractional-constant:
  hexadecimal-digit-sequence<opt>.hexadecimal-digit-sequence

exponent-part:
  e sign<opt> digit-sequence
  E sign<opt> digit-sequence

binary-exponent-part:
  p sign<opt> digit-sequence
  P sign<opt> digit-sequence

sign: one of
  + -

digit-sequence:
  digit
  digit-sequence ',opt' digit

floating-point-suffix: one of
  f 1 f16 f32 f64 f128 bf16 F L F16 F32 F64 F128 BF16

1 The type of a floating-point-literal (6.8.2, 6.8.3) is determined by its floating-point-suffix as specified in Table 11.
[Note 1: The floating-point suffixes f16, f32, f64, f128, bf16, F16, F32, F64, F128, and BF16 are conditionally-supported. See 6.8.3. — end note]

Table 11 — Types of floating-point-literals [tab:lex.fcon.type]

<table>
<thead>
<tr>
<th>floating-point-suffix</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>double</td>
</tr>
<tr>
<td>f or F</td>
<td>float</td>
</tr>
<tr>
<td>l or L</td>
<td>long double</td>
</tr>
<tr>
<td>f16 or F16</td>
<td>std::float16_t</td>
</tr>
<tr>
<td>f32 or F32</td>
<td>std::float32_t</td>
</tr>
<tr>
<td>f64 or F64</td>
<td>std::float64_t</td>
</tr>
<tr>
<td>f128 or F128</td>
<td>std::float128_t</td>
</tr>
<tr>
<td>bf16 or BF16</td>
<td>std::bfloat16_t</td>
</tr>
</tbody>
</table>

2 The significand of a floating-point-literal is the fractional-constant or digit-sequence of a decimal-floating-point-literal or the hexadecimal-fractional-constant or hexadecimal-digit-sequence of a hexadecimal-floating-point-literal. In the significand, the sequence of digits or hexadecimal-digits and optional period are interpreted as a base N real number s, where N is 10 for a decimal-floating-point-literal and 16 for a hexadecimal-floating-point-literal.
[Note 2: Any optional separating single quotes are ignored when determining the value. — end note]
If an exponent-part or binary-exponent-part is present, the exponent e of the floating-point-literal is the result of interpreting the sequence of an optional sign and the digits as a base 10 integer. Otherwise, the exponent e is 0. The scaled value of the literal is \( s \times 10^e \) for a decimal-floating-point-literal and \( s \times 2^e \) for a hexadecimal-floating-point-literal.
[Example 1: The floating-point-literals 49.625 and 0xC.68p+2 have the same value. The floating-point-literals 1.602’176’565e-19 and 1.602176565e-19 have the same value. — end example]

3 If the scaled value is not in the range of representable values for its type, the program is ill-formed. Otherwise, the value of a floating-point-literal is the scaled value if representable, else the larger or smaller representable value nearest the scaled value, chosen in an implementation-defined manner.

5.13.5 String literals [lex.string]

string-literal:
  encoding-prefix<opt> " s-char-sequence<opt> "
  encoding-prefix<opt> R raw-string

s-char-sequence:
  s-char
  s-char-sequence s-char
s-char:
  basic-s-char
  escape-sequence
  universal-character-name

basic-s-char:
  any member of the translation character set except the U+0022 QUOTATION MARK,
  U+005C REVERSE SOLIDUS, or new-line character

raw-string:
  " d-char-sequence Opt ( r-char-sequence Opt ) d-char-sequence Opt "

r-char-sequence:
  r-char
  r-char-sequence r-char

r-char:
  any member of the translation character set, except a U+0029 RIGHT PARENTHESIS followed by
  the initial d-char-sequence (which may be empty) followed by a U+0022 QUOTATION MARK

d-char-sequence:
  d-char
  d-char-sequence d-char

d-char:
  any member of the basic character set except:
    U+0020 SPACE, U+0028 LEFT PARENTHESIS, U+0029 RIGHT PARENTHESIS, U+005C REVERSE SOLIDUS,
    U+0009 CHARACTER TABULATION, U+000B LINE TABULATION, U+000C FORM FEED, and new-line

1 The kind of a string-literal, its type, and its associated character encoding (5.3) are determined by its encoding
prefix and sequence of s-chars or r-chars as defined by Table 12 where n is the number of encoded code units
as described below.

Table 12 — String literals  [tab:lex.string.literal]
<table>
<thead>
<tr>
<th>Encoding prefix</th>
<th>Kind</th>
<th>Type</th>
<th>Associated character encoding</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>ordinary string literal</td>
<td>array of n</td>
<td>ordinary literal encoding</td>
<td>&quot;ordinary string&quot;</td>
</tr>
<tr>
<td>L</td>
<td>wide string literal</td>
<td>const char</td>
<td>encoding</td>
<td>R&quot;(ordinary raw string)&quot;</td>
</tr>
<tr>
<td>u8</td>
<td>UTF-8 string literal</td>
<td>const wchar_t</td>
<td>encoding</td>
<td>L&quot;wide string&quot;</td>
</tr>
<tr>
<td>u</td>
<td>UTF-16 string literal</td>
<td>const char8_t</td>
<td>UTF-8</td>
<td>u8&quot;UTF-8 string&quot;</td>
</tr>
<tr>
<td>U</td>
<td>UTF-32 string literal</td>
<td>const char16_t</td>
<td>UTF-16</td>
<td>u8R&quot;x(UTF-8 raw string)x&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>const char32_t</td>
<td>UTF-32</td>
<td>u8R&quot;y(UTF-16 raw string)y&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UR&quot;z(UTF-32 raw string)z&quot;</td>
</tr>
</tbody>
</table>

2 A string-literal that has an R in the prefix is a raw string literal. The d-char-sequence serves as a delimiter. The
terminating d-char-sequence of a raw-string is the same sequence of characters as the initial d-char-sequence.
A d-char-sequence shall consist of at most 16 characters.

3 [Note 1: The characters ‘(‘ and ‘)’ can appear in a raw-string. Thus, R"delimiter((a|b))delimiter" is equivalent
to "(a|b)". — end note]

4 [Note 2: A source-file new-line in a raw string literal results in a new-line in the resulting execution string literal.
Assuming no whitespace at the beginning of lines in the following example, the assert will succeed:

```c
const char* p = R"(a\n b c)";
assert(strcmp(p, "a\n\nb\nc") == 0);
— end note]

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27
Example 1: The raw string

R"a(
)\a"

is equivalent to "\nna\n". The raw string

R"(x = "y")"

is equivalent to "x = "y". — end example]

Example 2:

"\xA" "B"

represents the code unit \xA and the character B after concatenation (and not the single code unit \xAB). Similarly,

R"(u00)" "41"

represents six characters, starting with a backslash and ending with the digit 1 (and not the single character A specified by a universal-character-name).

Table 13 has some examples of valid concatenations. — end example]

Table 13 — String literal concatenations [tab:lex.string.concat]

<table>
<thead>
<tr>
<th>Source</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>u&quot;a&quot;</td>
<td>u&quot;b&quot;</td>
</tr>
<tr>
<td>U&quot;a&quot;</td>
<td>U&quot;b&quot;</td>
</tr>
<tr>
<td>L&quot;a&quot;</td>
<td>L&quot;b&quot;</td>
</tr>
</tbody>
</table>

Evaluating a string-literal results in a string literal object with static storage duration (6.7.5).

Note 4: String literal objects are potentially non-unique (6.7.2). Whether successive evaluations of a string-literal yield the same or a different object is unspecified. — end note

Note 5: The effect of attempting to modify a string literal object is undefined. — end note

String literal objects are initialized with the sequence of code unit values corresponding to the string-literal’s sequence of s-chars (originally from non-raw string literals) and r-chars (originally from raw string literals), plus a terminating U+0000 NULL character, in order as follows:

1. The sequence of characters denoted by each contiguous sequence of basic-s-chars, r-chars, simple-escape-sequences (5.13.3), and universal-character-names (5.3) is encoded to a code unit sequence using the string-literal’s associated character encoding. If a character lacks representation in the associated character encoding, then the program is ill-formed.

Note 6: No character lacks representation in any Unicode encoding form. — end note

When encoding a stateful character encoding, implementations should encode the first such sequence beginning with the initial encoding state and encode subsequent sequences beginning with the final encoding state of the prior sequence.

Note 7: The encoded code unit sequence can differ from the sequence of code units that would be obtained by encoding each character independently. — end note

Each numeric-escape-sequence (5.13.3) contributes a single code unit with a value as follows:

Let v be the integer value represented by the octal number comprising the sequence of octal-digits in an octal-escape-sequence or by the hexadecimal number comprising the sequence of hexadecimal-digits in a hexadecimal-escape-sequence.
— If \( v \) does not exceed the range of representable values of the string-literal’s array element type, then the value is \( v \).

— Otherwise, if the string-literal’s encoding-prefix is absent or \( \text{L} \), and \( v \) does not exceed the range of representable values of the corresponding unsigned type for the underlying type of the string-literal’s array element type, then the value is the unique value of the string-literal’s array element type \( T \) that is congruent to \( v \) modulo \( 2^N \), where \( N \) is the width of \( T \).

— Otherwise, the program is ill-formed.

When encoding a stateful character encoding, these sequences should have no effect on encoding state.

— Each conditional-escape-sequence (5.13.3) contributes an implementation-defined code unit sequence. When encoding a stateful character encoding, it is implementation-defined what effect these sequences have on encoding state.

5.13.6 Unevaluated strings

\[ \text{unevaluated-string:} \]

\[ \text{string-literal} \]

1 An unevaluated-string shall have no encoding-prefix.

2 Each universal-character-name and each simple-escape-sequence in an unevaluated-string is replaced by the member of the translation character set it denotes. An unevaluated-string that contains a numeric-escape-sequence or a conditional-escape-sequence is ill-formed.

3 An unevaluated-string is never evaluated and its interpretation depends on the context in which it appears.

5.13.7 Boolean literals

\[ \text{boolean-literal:} \]

\[ \text{false} \]

\[ \text{true} \]

1 The Boolean literals are the keywords \text{false} and \text{true}. Such literals have type \text{bool}.

5.13.8 Pointer literals

\[ \text{pointer-literal:} \]

\[ \text{nullptr} \]

1 The pointer literal is the keyword \text{nullptr}. It has type \text{std::nullptr_t}.

[Note 1: \text{std::nullptr_t} is a distinct type that is neither a pointer type nor a pointer-to-member type; rather, a prvalue of this type is a null pointer constant and can be converted to a null pointer value or null member pointer value. See 7.3.12 and 7.3.13. — end note]

5.13.9 User-defined literals

\[ \text{user-defined-literal:} \]

\[ \text{user-defined-integer-literal} \]

\[ \text{user-defined-floating-point-literal} \]

\[ \text{user-defined-string-literal} \]

\[ \text{user-defined-character-literal} \]

\[ \text{user-defined-integer-literal:} \]

\[ \text{decimal-literal ud-suffix} \]

\[ \text{octal-literal ud-suffix} \]

\[ \text{hexadecimal-literal ud-suffix} \]

\[ \text{binary-literal ud-suffix} \]

\[ \text{user-defined-floating-point-literal:} \]

\[ \text{fractional-constant exponent-part opt ud-suffix} \]

\[ \text{digit-sequence exponent-part ud-suffix} \]

\[ \text{hexadecimal-prefix hexadecimal-fractional-constant binary-exponent-part ud-suffix} \]

\[ \text{hexadecimal-prefix hexadecimal-digit-sequence binary-exponent-part ud-suffix} \]

\[ \text{user-defined-string-literal:} \]

\[ \text{string-literal ud-suffix} \]

\[ \text{user-defined-character-literal:} \]

\[ \text{character-literal ud-suffix} \]
If a token matches both user-defined-literal and another literal kind, it is treated as the latter.

Example 1: 123_km is a user-defined-literal, but 12LL is an integer-literal. — end example

The syntactic non-terminal preceding the ud-suffix in a user-defined-literal is taken to be the longest sequence of characters that could match that non-terminal.

A user-defined-literal is treated as a call to a literal operator or literal operator template (12.6). To determine the form of this call for a given user-defined-literal \( L \) with ud-suffix \( X \), first let \( S \) be the set of declarations found by unqualified lookup for the literal-operator-id whose literal suffix identifier is \( X \) (6.5.3). \( S \) shall not be empty.

If \( L \) is a user-defined-integer-literal, let \( n \) be the literal without its ud-suffix. If \( S \) contains a literal operator with parameter type unsigned long long, the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"(n\text{ULL})
\]

Otherwise, \( S \) shall contain a raw literal operator or a numeric literal operator template (12.6) but not both. If \( S \) contains a raw literal operator, the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"("n")
\]

where \( n \) is the source character sequence \( c_1c_2...c_k \).

Note 1: The sequence \( c_1c_2...c_k \) can only contain characters from the basic character set. — end note

If \( L \) is a user-defined-floating-point-literal, let \( f \) be the literal without its ud-suffix. If \( S \) contains a literal operator with parameter type long double, the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"(fL)
\]

Otherwise, \( S \) shall contain a raw literal operator or a numeric literal operator template (12.6) but not both. If \( S \) contains a raw literal operator, the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"("f")
\]

where \( f \) is the source character sequence \( c_1c_2...c_k \).

Note 2: The sequence \( c_1c_2...c_k \) can only contain characters from the basic character set. — end note

If \( L \) is a user-defined-string-literal, let \( str \) be the literal without its ud-suffix and let \( len \) be the number of code units in \( str \) (i.e., its length excluding the terminating null character). If \( S \) contains a literal operator template with a non-type template parameter for which \( str \) is a well-formed template-argument, the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"<str>()
\]

Otherwise, the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"(str, len)
\]

If \( L \) is a user-defined-character-literal, let \( ch \) be the literal without its ud-suffix. \( S \) shall contain a literal operator (12.6) whose only parameter has the type of \( ch \) and the literal \( L \) is treated as a call of the form

\[
\operatorname{operator} "X"(ch)
\]

Example 2:

\[
\begin{align*}
\text{long double operator } & "._w(long double); \\
\text{std::string operator } & "._w(const char16_t*}, std::size_t); \\
\text{unsigned operator } & "._w(const char*); \\
\end{align*}
\]

int main() {
  1.2_w; // calls operator "._w(1.2L)
  u"one"_w; // calls operator "._w(u"one", 3)
  12_w; // calls operator "._w("12")
  "two"_w; // error: no applicable literal operator
}
In translation phase 6 (5.2), adjacent string-literals are concatenated and user-defined-string-literals are considered string-literals for that purpose. During concatenation, ud-suffixes are removed and ignored and the concatenation process occurs as described in 5.13.5. At the end of phase 6, if a string-literal is the result of a concatenation involving at least one user-defined-string-literal, all the participating user-defined-string-literals shall have the same ud-suffix and that suffix is applied to the result of the concatenation.

Example 3:

```c
int main() {
    L"A" "B" "C"_x; // OK, same as L"ABC"_x
    "P"_x "Q" "R"_y; // error: two different ud-suffixes
}
```

— end example]
6 Basics

6.1 Preamble

[Note 1: This Clause presents the basic concepts of the C++ language. It explains the difference between an object and a name and how they relate to the value categories for expressions. It introduces the concepts of a declaration and a definition and presents C++'s notion of type, scope, linkage, and storage duration. The mechanisms for starting and terminating a program are discussed. Finally, this Clause presents the fundamental types of the language and lists the ways of constructing compound types from these. — end note]

[Note 2: This Clause does not cover concepts that affect only a single part of the language. Such concepts are discussed in the relevant Clauses. — end note]

An entity is a value, object, reference, structured binding, function, enumerator, type, class member, bit-field, template, template specialization, namespace, or pack.

A name is an identifier (5.10), operator-function-id (12.4), literal-operator-id (12.6), or conversion-function-id (11.4.8.3).

Every name is introduced by a declaration, which is a

(5.1) name-declaration, block-declaration, or member-declaration (9.1, 11.4),
(5.2) init-declarator (9.3),
(5.3) identifier in a structured binding declaration (9.6),
(5.4) init-capture (7.5.6.3),
(5.5) condition with a declarator (8.1),
(5.6) member-declarator (11.4),
(5.7) using-declarator (9.9),
(5.8) parameter-declaration (9.3.4.6),
(5.9) type-parameter (13.2),
(5.10) elaborated-type-specifier that introduces a name (9.2.9.5),
(5.11) class-specifier (11.1),
(5.12) enum-specifier or enumerator-definition (9.7.1),
(5.13) exception-declaration (14.1), or
(5.14) implicit declaration of an injected-class-name (11.1).

[Note 3: The interpretation of a for-range-declaration produces one or more of the above (8.6.5). — end note]

An entity E is denoted by the name (if any) that is introduced by a declaration of E or by a typedef-name introduced by a declaration specifying E.

A variable is introduced by the declaration of a reference other than a non-static data member or of an object. The variable’s name, if any, denotes the reference or object.

A local entity is a variable with automatic storage duration (6.7.5.4), a structured binding (9.6) whose corresponding variable is such an entity, or the *this object (7.5.3).

Some names denote types or templates. In general, whenever a name is encountered it is necessary to determine whether that name denotes one of these entities before continuing to parse the program that contains it. The process that determines this is called name lookup (6.5).

Two names are the same if

(9.1) they are identifiers composed of the same character sequence, or
(9.2) they are operator-function-ids formed with the same operator, or
(9.3) they are conversion-function-ids formed with equivalent (13.7.7.2) types, or
(9.4) they are literal-operator-ids (12.6) formed with the same literal suffix identifier.
A name used in more than one translation unit can potentially refer to the same entity in these translation units depending on the linkage (6.6) of the name specified in each translation unit.

6.2 Declarations and definitions [basic.def]

A declaration (Clause 9) may (re)introduce one or more names and/or entities into a translation unit. If so, the declaration specifies the interpretation and semantic properties of these names. A declaration of an entity or typedef-name \( X \) is a redeclaration of \( X \) if another declaration of \( X \) is reachable from it (10.7). A declaration may also have effects including:

1. a static assertion (9.1),
2. controlling template instantiation (13.9.3),
3. guiding template argument deduction for constructors (13.7.2.3),
4. use of attributes (9.12), and
5. nothing (in the case of an empty-declaration).

Each entity declared by a declaration is also defined by that declaration unless:

1. it declares a function without specifying the function’s body (9.5),
2. it contains the extern specifier (9.2.2) or a linkage-specification\(^{16}\) (9.11) and neither an initializer nor a function-body,
3. it declares a non-inline static data member in a class definition (11.4, 11.4.9),
4. it declares a static data member outside a class definition and the variable was defined within the class with the constexpr specifier (11.4.9.3) (this usage is deprecated; see D.5),
5. it is an elaborated-type-specifier (11.3),
6. it is an opaque-enum-declaration (9.7.1),
7. it is a template-parameter (13.2),
8. it is a parameter-declaration (9.3.4.6) in a function declarator that is not the declarator of a function-definition,
9. it is a typedef declaration (9.2.4),
10. it is an alias-declaration (9.2.4),
11. it is a using-declaration (9.9),
12. it is a deduction-guide (13.7.2.3),
13. it is a static_assert-declaration (9.1),
14. it is an attribute-declaration (9.1),
15. it is an empty-declaration (9.1),
16. it is a using-directive (9.8.4),
17. it is a using-enum-declaration (9.7.2),
18. it is a template-declaration (13.1) whose template-head is not followed by either a concept-definition or a declaration that defines a function, a class, a variable, or a static data member,
19. it is an explicit instantiation declaration (13.9.3), or
20. it is an explicit specialization (13.9.4) whose declaration is not a definition.

A declaration is said to be a definition of each entity that it defines.

[Example 1: All but one of the following are definitions:

```c
int a;               // defines a
extern const int c = 1; // defines c
int f(int x) { return x+a; } // defines f and defines x
struct S { int a; int b; }; // defines S, S::a, and S::b
struct X {
    int x;          // defines X
}                // defines non-static data member x
```

\(^{16}\) Appearing inside the brace-enclosed declaration-seq in a linkage-specification does not affect whether a declaration is a definition.
static int y; // declares static data member y
X(): x(0) { } // defines a constructor of X
};
int X::y = 1; // defines X::y
enum { up, down }; // defines up and down
namespace N { int d; } // defines N and N::d
namespace N1 = N; // defines N1
X anX; // defines anX

whereas these are just declarations:
extern int a; // declares a
extern const int c; // declares c
int f(int); // declares f
struct S; // declares S
typedef int Int; // declares Int
extern X anotherX; // declares anotherX
using N::d; // declares d

—end example]

3 [Note 1: In some circumstances, C++ implementations implicitly define the default constructor (11.4.5.2), copy constructor, move constructor (11.4.5.3), copy assignment operator, move assignment operator (11.4.6), or destructor (11.4.7) member functions. —end note]

[Example 2: Given
#include <string>

struct C {
  std::string s; // std::string is the standard library class (23.4)
};

int main() {
  C a;
  C b = a;
  b = a;
}
the implementation will implicitly define functions to make the definition of C equivalent to

struct C {
  std::string s;
  C(): s() { }
  C(const C& x): s(x.s) { }
  C(C&& x): s(static_cast<std::string&&>(x.s)) { }
    // : s(std::move(x.s)) { }
  C& operator=(const C& x) { s = x.s; return *this; }
  C& operator=(C&& x) { s = static_cast<std::string&&>(x.s); return *this; }
    // { s = std::move(x.s); return *this; }
  ~C() { }
};
—end example]

4 [Note 2: A class name can also be implicitly declared by an elaborated-type-specifier (9.2.9.5). —end note]

5 In the definition of an object, the type of that object shall not be an incomplete type (6.8.1), an abstract class type (11.7.4), or a (possibly multidimensional) array thereof.

6.3 One-definition rule [basic.def.odr]

1 Each of the following is termed a definable item:
(1.1) — a class type (Clause 11),
(1.2) — an enumeration type (9.7.1),
(1.3) — a function (9.3.4.6),
(1.4) — a variable (6.1),
(1.5) — a templated entity (13.1),

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34
2 No translation unit shall contain more than one definition of any definable item.

3 An expression or conversion is potentially evaluated unless it is an unevaluated operand (7.2.3), a subexpression thereof, or a conversion in an initialization or conversion sequence in such a context. The set of potential results of an expression $E$ is defined as follows:

- If $E$ is an id-expression (7.5.5), the set contains only $E$.
- If $E$ is a subscripting operation (7.6.1.2) with an array operand, the set contains the potential results of that operand.
- If $E$ is a class member access expression (7.6.1.5) of the form $E_1 \cdot \text{template}_{\text{opt}} E_2$ naming a non-static data member, the set contains the potential results of $E_1$.
- If $E$ is a class member access expression naming a static data member, the set contains the id-expression designating the data member.
- If $E$ is a pointer-to-member expression (7.6.4) of the form $E_1 \cdot*$ $E_2$, the set contains the potential results of $E_1$.
- If $E$ has the form $(E_1)$, the set contains the potential results of $E_1$.
- If $E$ is a glvalue conditional expression (7.6.16), the set is the union of the sets of potential results of the second and third operands.
- If $E$ is a comma expression (7.6.20), the set contains the potential results of the right operand.
- Otherwise, the set is empty.

[Note 1: This set is a (possibly-empty) set of id-expressions, each of which is either $E$ or a subexpression of $E$.]

[Example 1: In the following example, the set of potential results of the initializer of $n$ contains the first $S::x$ subexpression, but not the second $S::x$ subexpression.]

```c
struct S { static const int x = 0; };
const int &f(const int &r);
int n = b ? (1, S::x) ; // $S::x$ is not odr-used here
 : f(S::x); // $S::x$ is odr-used here, so a definition is required
```

[end example]

[end note]

4 A function is named by an expression or conversion as follows:

- A function is named by an expression or conversion if it is the selected member of an overload set (6.5, 12.2, 12.3) in an overload resolution performed as part of forming that expression or conversion, unless it is a pure virtual function and either the expression is not an id-expression naming the function with an explicitly qualified name or the expression forms a pointer to member (7.6.2.2).

[Note 2: This covers taking the address of functions (7.3.4, 7.6.2.2), calls to named functions (7.6.1.3), operator overloading (Clause 12), user-defined conversions (11.4.8.3), allocation functions for new-expressions (7.6.2.8), as well as non-default initialization (9.4). A constructor selected to copy or move an object of class type is considered to be named by an expression or conversion even if the call is actually elided by the implementation (11.9.6).]

[end note]

5 A variable is named by an expression if the expression is an id-expression that denotes it. A variable $x$ that is named by a potentially-evaluated expression $E$ is odr-used by $E$ unless

- $x$ is a reference that is usable in constant expressions (7.7), or
- $x$ is a variable of non-reference type that is usable in constant expressions and has no mutable subobjects, and $E$ is an element of the set of potential results of an expression of non-volatile-qualified non-class type to which the lvalue-to-rvalue conversion (7.3.2) is applied, or
— $x$ is a variable of non-reference type, and $E$ is an element of the set of potential results of a discarded-value expression (7.2.3) to which the lvalue-to-rvalue conversion is not applied.

6 A structured binding is odr-used if it appears as a potentially-evaluated expression.

7 *this is odr-used if this appears as a potentially-evaluated expression (including as the result of any implicit transformation to a class member access expression (7.5.5.1)).

8 A virtual member function is odr-used if it is not pure. A function is odr-used if it is named by a potentially-evaluated expression or conversion. A non-placement allocation or deallocation function for a class is odr-used by the definition of a constructor of that class. A non-placement deallocation function for a class is odr-used by the definition of the destructor of that class, or by being selected by the lookup at the point of definition of a virtual destructor (11.4.7).\footnote{An implementation is not required to call allocation and deallocation functions from constructors or destructors; however, this is a permissible implementation technique.}

9 An assignment operator function in a class is odr-used by an implicitly-defined copy assignment or move assignment function for another class as specified in 11.4.6. A constructor for a class is odr-used as specified in 9.4. A destructor for a class is odr-used if it is potentially invoked (11.4.7).

10 A local entity (6.1) is odr-usable in a scope (6.4.1) if

\begin{enumerate}
\item either the local entity is not *this, or an enclosing class or non-lambda function parameter scope exists and, if the innermost such scope is a function parameter scope, it corresponds to a non-static member function, and

\item for each intervening scope (6.4.1) between the point at which the entity is introduced and the scope (where *this is considered to be introduced within the innermost enclosing class or non-lambda function definition scope), either:
\begin{enumerate}
\item the intervening scope is a block scope, or
\item the intervening scope is the function parameter scope of a lambda-expression, or
\item the intervening scope is the lambda scope of a lambda-expression that has a simple-capture naming the entity or has a capture-default, and the block scope of the lambda-expression is also an intervening scope.
\end{enumerate}
\end{enumerate}

If a local entity is odr-used in a scope in which it is not odr-usable, the program is ill-formed.

[Example 2):

```c++
void f(int n) {  
    [] { n = 1; };  // error: n is not odr-usable due to intervening lambda-expression

    struct A {  
        void f() { n = 2; }  // error: n is not odr-usable due to intervening function definition scope
    };

    void g(int = n);
    [=](int k = n) {};
    [&] { [n]{ return n; }; };  // OK

    -- end example ]
```

11 [Example 3]:

```c++
void g() {
    constexpr int x = 1;
    auto lambda = [] <typename T, int = ((T)x, 0)> {}  // OK
    lambda.operator()<int, 1>();  // OK, does not consider x at all
    lambda.operator()<int>();  // OK, does not odr-use x
    lambda.operator()<const int&>();  // error: odr-uses x from a context where x is not odr-usable
}
```

```c++
void h() {
    constexpr int x = 1;
    auto lambda = [] <typename T> { (T)x; };  // OK
    lambda.operator()<int>();  // OK, does not odr-use x
    lambda.operator()<void>();  // OK, does not odr-use x
```
Every program shall contain at least one definition of every function or variable that is odr-used in that program outside of a discarded statement (8.5.2); no diagnostic required. The definition can appear explicitly in the program, it can be found in the standard or a user-defined library, or (when appropriate) it is implicitly defined (see 11.4.5.2, 11.4.5.3, 11.4.7, and 11.4.6).

Example 4:

```c
auto f() {
    struct A {};
    return A{};
}
```

decltype(f()) g();
auto x = g();

A program containing this translation unit is ill-formed because g is odr-used but not defined, and cannot be defined in any other translation unit because the local class A cannot be named outside this translation unit. —end example

A definition domain is a private-module-fragment or the portion of a translation unit excluding its private-module-fragment (if any). A definition of an inline function or variable shall be reachable from the end of every definition domain in which it is odr-used outside of a discarded statement.

A definition of a class shall be reachable in every context in which the class is used in a way that requires the class type to be complete.

Example 5: The following complete translation unit is well-formed, even though it never defines X:

```
struct X;          // declare X as a struct type
struct X* x1;     // use X in pointer formation
X* x2;            // use X in pointer formation
```

—end example

Note 3: The rules for declarations and expressions describe in which contexts complete class types are required. A class type T must be complete if

1. an object of type T is defined (6.2), or
2. a non-static class data member of type T is declared (11.4), or
3. T is used as the allocated type or array element type in a new-expression (7.6.2.8), or
4. an lvalue-to-rvalue conversion is applied to a glvalue referring to an object of type T (7.3.2), or
5. an expression is converted (either implicitly or explicitly) to type T (7.3, 7.6.1.4, 7.6.1.7, 7.6.1.9, 7.6.3), or
6. an expression that is not a null pointer constant, and has type other than cv void*, is converted to the type pointer to T or reference to T using a standard conversion (7.3), a dynamic_cast (7.6.1.7) or a static_cast (7.6.1.9), or
7. a class member access operator is applied to an expression of type T (7.6.1.5), or
8. the typeid operator (7.6.1.8) or the sizeof operator (7.6.2.5) is applied to an operand of type T, or
9. a function with a return type or argument type of type T is defined (6.2) or called (7.6.1.3), or
10. a class with a base class of type T is defined (11.7), or
11. an lvalue of type T is assigned to (7.6.19), or
12. the type T is the subject of an alignof expression (7.6.2.6), or
13. an exception-declaration has type T, reference to T, or pointer to T (14.4).

—end note

For any definable item D with definitions in multiple translation units,

1. if D is a non-inline non-templated function or variable, or
2. if the definitions in different translation units do not satisfy the following requirements, the program is ill-formed; a diagnostic is required only if the definable item is attached to a named module and a prior definition is reachable at the point where a later definition occurs. Given such an item, for all definitions of D, or, if D is an unnamed enumeration, for all definitions of D that are reachable at any given program point, the following requirements shall be satisfied.
Each such definition shall not be attached to a named module (10.1).

Each such definition shall consist of the same sequence of tokens, where the definition of a closure type is considered to consist of the sequence of tokens of the corresponding lambda-expression.

In each such definition, corresponding names, looked up according to 6.5, shall refer to the same entity, after overload resolution (12.2) and after matching of partial template specialization (13.10.4), except that a name can refer to

1. a non-volatile const object with internal or no linkage if the object
   - has the same literal type in all definitions of D,
   - is initialized with a constant expression (7.7),
   - is not odr-used in any definition of D, and
   - has the same value in all definitions of D,

or

2. a reference with internal or no linkage initialized with a constant expression such that the reference refers to the same entity in all definitions of D.

In each such definition, except within the default arguments and default template arguments of D, corresponding lambda-expressions shall have the same closure type (see below).

In each such definition, corresponding entities shall have the same language linkage.

In each such definition, const objects with static or thread storage duration shall be constant-initialized if the object is constant-initialized in any such definition.

In each such definition, corresponding manifestly constant-evaluated expressions that are not value-dependent shall have the same value (7.7, 13.8.3.4).

In each such definition, the overloaded operators referred to, the implicit calls to conversion functions, constructors, operator new functions and operator delete functions, shall refer to the same function.

In each such definition, a default argument used by an (implicit or explicit) function call or a default template argument used by an (implicit or explicit) template-id or simple-template-id is treated as if its token sequence were present in the definition of D; that is, the default argument or default template argument is subject to the requirements described in this paragraph (recursively).

For the purposes of the preceding requirements:

1. If D is a class with an implicitly-declared constructor (11.4.5.2, 11.4.5.3), it is as if the constructor was implicitly defined in every translation unit where it is odr-used, and the implicit definition in every translation unit shall call the same constructor for a subobject of D.

**Example 6:**

```cpp
// translation unit 1:
struct X {
    X(int, int);
    X(int, int, int);
};
X::X(int, int = 0) { }
class D {
    X x = 0;
};
D d1; // X(int, int) called by D()
```

```cpp
// translation unit 2:
struct X {
    X(int, int);
    X(int, int, int);
};
X::X(int, int = 0, int = 0) { }
class D {
    X x = 0;
};
D d2; // X(int, int, int) called by D();
```

D()’s implicit definition violates the ODR
— end example]

(16.2) — If D is a class with a defaulted three-way comparison operator function (11.10.3), it is as if the operator was implicitly defined in every translation unit where it is odr-used, and the implicit definition in every translation unit shall call the same comparison operators for each subobject of D.

(16.3) — If D is a template and is defined in more than one translation unit, the requirements apply both to names from the template’s enclosing scope used in the template definition, and also to dependent names at the point of instantiation (13.8.3).

If D is a template and is defined in more than one translation unit, the requirements apply both to names from the template’s enclosing scope used in the template definition, and also to dependent names at the point of instantiation (13.8.3).

These requirements also apply to corresponding entities defined within each definition of D (including the closure types of lambda-expressions, but excluding entities defined within default arguments or default template arguments of either D or an entity not defined within D). For each such entity and for D itself, the behavior is as if there is a single entity with a single definition, including in the application of these requirements to other entities.

[Note 4: The entity is still declared in multiple translation units, and 6.6 still applies to these declarations. In particular, lambda-expressions (7.5.6) appearing in the type of D can result in the different declarations having distinct types, and lambda-expressions appearing in a default argument of D might still denote different types in different translation units. — end note]

Example 7:

```cpp
inline void f(bool cond, void (*p)()) {
    if (cond) f(false, []{});
}
inline void g(bool cond, void (*p)() = []{})) {
    if (cond) g(false);
}
struct X {
    void h(bool cond, void (*p)() = []{})) {
        if (cond) h(false);
    }
};
```

If the definition of f appears in multiple translation units, the behavior of the program is as if there is only one definition of f. If the definition of g appears in multiple translation units, the program is ill-formed (no diagnostic required) because each such definition uses a default argument that refers to a distinct lambda-expression closure type. The definition of X can appear in multiple translation units of a valid program; the lambda-expressions defined within the default argument of X::h within the definition of X denote the same closure type in each translation unit. — end example]

If, at any point in the program, there is more than one reachable unnamed enumeration definition in the same scope that have the same first enumerator name and do not have typedef names for linkage purposes (9.7.1), those unnamed enumeration types shall be the same; no diagnostic required.

## 6.4 Scope

### 6.4.1 General

The declarations in a program appear in a number of scopes that are in general discontinuous. The global scope contains the entire program; every other scope S is introduced by a declaration, parameter-declaration-clause, statement, or handler (as described in the following subclauses of 6.4) appearing in another scope which thereby contains S. An enclosing scope at a program point is any scope that contains it; the smallest such scope is said to be the immediate scope at that point. A scope intervenes between a program point P and a scope S (that does not contain P) if it is or contains S but does not contain P.

Unless otherwise specified:

(2.1) — The smallest scope that contains a scope S is the parent scope of S.

(2.2) — No two declarations (re)introduce the same entity.

(2.3) — A declaration inhabits the immediate scope at its locus (6.4.2).

(2.4) — A declaration’s target scope is the scope it inhabits.

(2.5) — Any names (re)introduced by a declaration are bound to it in its target scope.

An entity belongs to a scope S if S is the target scope of a declaration of the entity.
Note 1: Special cases include that:

(2.6) — Template parameter scopes are parents only to other template parameter scopes (6.4.9).
(2.7) — Corresponding declarations with appropriate linkage declare the same entity (6.6).
(2.8) — The declaration in a template-declaration inhabits the same scope as the template-declaration.
(2.9) — Friend declarations and declarations of qualified names and template specializations do not bind names (9.3.4); those with qualified names target a specified scope, and other friend declarations and certain elaborated-type-specifiers (9.2.9.5) target a larger enclosing scope.
(2.10) — Block-scope extern declarations target a larger enclosing scope but bind a name in their immediate scope.
(2.11) — The names of unscoped enumerators are bound in the two innermost enclosing scopes (9.7.1).
(2.12) — A class’s name is also bound in its own scope (11.1).
(2.13) — The names of the members of an anonymous union are bound in the union’s parent scope (11.5.2).

— end note

3 Two non-static member functions have corresponding object parameters if
(3.1) — exactly one is an implicit object member function with no ref-qualifier and the types of their object parameters (9.3.4.6), after removing top-level references, are the same, or
(3.2) — their object parameters have the same type.
Two non-static member function templates have corresponding object parameters if
(3.3) — exactly one is an implicit object member function with no ref-qualifier and the types of their object parameters, after removing any references, are equivalent, or
(3.4) — the types of their object parameters are equivalent.
Two function templates have corresponding signatures if their template-parameter-lists have the same length, their corresponding template-parameters are equivalent, they have equivalent non-object-parameter-type-lists and return types (if any), and, if both are non-static members, they have corresponding object parameters.

4 Two declarations correspond if they (re)introduce the same name, both declare constructors, or both declare destructors, unless
(4.1) — either is a using-declarator, or
(4.2) — one declares a type (not a typedef-name) and the other declares a variable, non-static data member other than of an anonymous union (11.5.2), enumerator, function, or function template, or
(4.3) — each declares a function or function template and they do not declare corresponding overloads.
Two function or function template declarations declare corresponding overloads if
(4.4) — both declare functions with the same non-object-parameter-type-list,18 equivalent (13.7.7.2) trailing requires-clauses (if any, except as specified in 13.7.5), and, if both are non-static members, they have corresponding object parameters, or
(4.5) — both declare function templates with corresponding signatures and equivalent template-heads and trailing requires-clauses (if any).

[Note 2: Declarations can correspond even if neither binds a name.

Example 1:

```c
struct A {
  friend void f(); // #1
};
struct B {
  friend void f() {} // corresponds to, and defines, #1
};
```

— end example

— end note

Example 2:

```c
typedef int Int;
enum E : int { a };
```

18) An implicit object parameter (12.2.2) is not part of the parameter-type-list.
A declaration is name-independent if its name is \( U+005F \) LOW LINE and it declares

(5.1) — a variable with automatic storage duration,

(5.2) — a structured binding with no storage-class-specifier and not inhabiting a namespace scope,

(5.3) — the variable introduced by an init-capture, or

(5.4) — a non-static data member of other than an anonymous union.

Recommended practice: Implementations should not emit a warning that a name-independent declaration is used or unused.

Two declarations potentially conflict if they correspond and cause their shared name to denote different entities (6.6). The program is ill-formed if, in any scope, a name is bound to two declarations \( A \) and \( B \) that potentially conflict and \( A \) precedes \( B \) (6.5), unless \( B \) is name-independent.

[Note 3: An id-expression that names a unique name-independent declaration is usable until an additional declaration of the same name is introduced in the same scope (6.5.1). — end note]

[Note 4: Overload resolution can consider potentially conflicting declarations found in multiple scopes (e.g., via using-directives or for operator functions), in which case it is often ambiguous. — end note]

[Example 3:

```c
void f() {
    int x,y;
    void x(); // error: different entity for x
    int y;   // error: redefinition
}
enum { f }; // error: different entity for ::f
namespace A {}
namespace B = A; // OK, no effect
namespace B = A; // OK, no effect
namespace A = B; // OK, no effect
namespace B {}    // error: different entity for B

void g() {
    int _;
    _ = 0;   // OK
    int _;   // OK, name-independent declaration
    _ = 0;   // error: two non-function declarations in the lookup set
}
void h () {
    int _;    // #1
    _ ++;    // OK
    static int _; // error: conflicts with #1 because static variables are not name-independent
}
```
A declaration is nominable in a class, class template, or namespace $E$ at a point $P$ if it precedes $P$, it does not inhabit a block scope, and its target scope is the scope associated with $E$ or, if $E$ is a namespace, any element of the inline namespace set of $E$ (9.8.2).

[Example 4:
```cpp
define namespace A {
    void f() {void g();}
    inline namespace B {
        struct S {
            friend void h();
            static int i;
        };
    }
}
```
At the end of this example, the declarations of $f$, $B$, $S$, and $h$ are nominable in $A$, but those of $g$ and $i$ are not. — end example]

When instantiating a templated entity (13.1), any scope $S$ introduced by any part of the template definition is considered to be introduced by the instantiated entity and to contain the instantiations of any declarations that inhabit $S$.

### 6.4.2 Point of declaration

The locus of a declaration (6.1) that is a declarator is immediately after the complete declarator (9.3).

[Example 1:
```cpp
unsigned char x = 12;
{ unsigned char x = x; }
```
Here, the initialization of the second $x$ has undefined behavior, because the initializer accesses the second $x$ outside its lifetime (6.7.3). — end example]

[Note 1: A name from an outer scope remains visible up to the locus of the declaration that hides it.

[Example 2:
```cpp
const int i = 2;
{ int i[1]; }
```
declares a block-scope array of two integers. — end example]

— end note]

3 The locus of a class-specifier is immediately after the identifier or simple-template-id (if any) in its class-head (11.1). The locus of an enum-specifier is immediately after its enum-head; the locus of an opaque-enum-declaration is immediately after it (9.7.1). The locus of an alias-declaration is immediately after it.

4 The locus of a using-declarator that does not name a constructor is immediately after the using-declarator (9.9).

5 The locus of an enumerator-definition is immediately after it.

[Example 3:
```cpp
const int x = 12;
{ enum { x = x }; }
```
Here, the enumerator $x$ is initialized with the value of the constant $x$, namely 12. — end example]

[Note 2: After the declaration of a class member, the member name can be found in the scope of its class even if the class is an incomplete class.

[Example 4:
```cpp
struct X {
    enum E { z = 16 };
    int b[X::z];  // OK
};
```
— end example]

— end note]
The locus of an elaborated-type-specifier that is a declaration (9.2.9.5) is immediately after it.

The locus of an injected-class-name declaration (11.1) is immediately following the opening brace of the class definition.

The locus of the implicit declaration of a function-local predefined variable (9.5.1) is immediately before the function-body of its function’s definition.

The locus of the declaration of a structured binding (9.6) is immediately after the identifier-list of the structured binding declaration.

The locus of a for-range-declaration of a range-based for statement (8.6.5) is immediately after the for-range-initializer.

The locus of a template-parameter is immediately after it.

[Example 5:]

typedef unsigned char T;
template<class T

    = T
        // lookup finds the typedef-name
    , T
        // lookup finds the template parameter

    N = 0> struct A { };

— end example]

The locus of a concept-definition is immediately after its concept-name (13.7.9).

[Note 3: The constraint-expression cannot use the concept-name. — end note]

The locus of a namespace-definition with an identifier is immediately after the identifier.

[Note 4: An identifier is invented for an unnamed-namespace-definition (9.8.2.2). — end note]

[Note 5: Friend declarations can introduce functions or classes that belong to the nearest enclosing namespace or block scope, but they do not bind names anywhere (11.8.4). Function declarations at block scope and variable declarations with the extern specifier at block scope declare entities that belong to the nearest enclosing namespace, but they do not bind names in it. — end note]

[Note 6: For point of instantiation of a template, see 13.8.4.1. — end note]

6.4.3 Block scope

[basic.scope.block] Each

(1.1) — selection or iteration statement (8.5, 8.6),
(1.2) — substatement of such a statement,
(1.3) — handler (14.1), or
(1.4) — compound statement (8.4) that is not the compound-statement of a handler introduces a block scope that includes that statement or handler.

[Note 1: A substatement that is also a block has only one scope. — end note]

A variable that belongs to a block scope is a block variable.

[Example 1:]

    int i = 42;
    int a[10];

    for (int i = 0; i < 10; i++)
        a[i] = i;

    int j = i;  // j = 42

— end example]

If a declaration that is not a name-independent declaration and that binds a name in the block scope S of a

(2.1) — compound-statement of a lambda-expression, function-body, or function-try-block,
(2.2) — substatement of a selection or iteration statement that is not itself a selection or iteration statement, or
(2.3) — handler of a function-try-block

potentially conflicts with a declaration whose target scope is the parent scope of S, the program is ill-formed.
Example 2:

```c
if (int x = f()) {
    int x;     // error: redeclaration of x
}
else {
    int x;     // error: redeclaration of x
}
— end example
```

6.4.4 Function parameter scope

A parameter-declaration-clause \( P \) introduces a function parameter scope that includes \( P \).

[Note 1: A function parameter cannot be used for its value within the parameter-declaration-clause (9.3.4.7). — end note]

(1.1) — If \( P \) is associated with a declarator and is preceded by a (possibly-parenthesized) nopt-declarator of the form declarator-id attribute-specifier-seq_opt, its scope extends to the end of the nearest enclosing init-declarator, member-declarator, declarator of a parameter-declaration or a nodeclspec-function-declaration, or function-definition, but does not include the locus of the associated declarator.

[Note 2: In this case, \( P \) declares the parameters of a function (or a function or template parameter declared with function type). A member function’s parameter scope is nested within its class’s scope. — end note]

(1.2) — If \( P \) is associated with a lambda-declarator, its scope extends to the end of the compound-statement in the lambda-expression.

(1.3) — If \( P \) is associated with a requirement-parameter-list, its scope extends to the end of the requirement-body of the requires-expression.

(1.4) — If \( P \) is associated with a deduction-guide, its scope extends to the end of the deduction-guide.

6.4.5 Lambda scope

A lambda-expression \( E \) introduces a lambda scope that starts immediately after the lambda-introducer of \( E \) and extends to the end of the compound-statement of \( E \).

6.4.6 Namespace scope

Any namespace-definition for a namespace \( N \) introduces a namespace scope that includes the namespace-body for every namespace-definition for \( N \). For each non-friend redeclaration or specialization whose target scope is or is contained by the scope, the portion after the declarator-id, class-head-name, or enum-head-name is also included in the scope. The global scope is the namespace scope of the global namespace (9.8).

[Example 1:

```c
namespace Q {
    namespace V { void f(); }
    void V::f() { // in the scope of V
        void h(); // declares Q::V::h
    }
}
— end example]
```

6.4.7 Class scope

Any declaration of a class or class template \( C \) introduces a class scope that includes the member-specification of the class-specifier for \( C \) (if any). For each non-friend redeclaration or specialization whose target scope is or is contained by the scope, the portion after the declarator-id, class-head-name, or enum-head-name is also included in the scope.

[Note 1: Lookup from a program point before the class-specifier of a class will find no bindings in the class scope.

[Example 1:

```c
template<class D>
struct B {
    D::type x;     // #1
};
```
struct A { using type = int; }
struct C : A, B<C> {}; // error at #1: C::type not found
— end example]
— end note]

6.4.8 Enumeration scope

Any declaration of an enumeration E introduces an enumeration scope that includes the enumerator-list of the enum-specifier for E (if any).

6.4.9 Template parameter scope

Each template template-parameter introduces a template parameter scope that includes the template-head of the template-parameter.

Each template-declaration D introduces a template parameter scope that extends from the beginning of its template-parameter-list to the end of the template-declaration. Any declaration outside the template-parameter-list that would inhabit that scope instead inhabits the same scope as D. The parent scope of any scope S that is not a template parameter scope is the smallest scope that contains S and is not a template parameter scope.

[Note 1: Therefore, only template parameters belong to a template parameter scope, and only template parameter scopes have a template parameter scope as a parent scope. — end note]

6.5 Name lookup

6.5.1 General

The name lookup rules apply uniformly to all names (including typedef-names (9.2.4), namespace-names (9.8), and class-names (11.3)) wherever the grammar allows such names in the context discussed by a particular rule. Name lookup associates the use of a name with a set of declarations (6.2) of that name. Unless otherwise specified, the program is ill-formed if no declarations are found. If the declarations found by name lookup all denote functions or function templates, the declarations are said to form an overload set. Otherwise, if the declarations found by name lookup do not all denote the same entity, they are ambiguous and the program is ill-formed. Overload resolution (12.2, 12.3) takes place after name lookup has succeeded. The access rules (11.8) are considered only once name lookup and function overload resolution (if applicable) have succeeded. Only after name lookup, function overload resolution (if applicable) and access checking have succeeded are the semantic properties introduced by the declarations used in further processing.

A program point P is said to follow any declaration in the same translation unit whose locus (6.4.2) is before P.

[Note 1: The declaration might appear in a scope that does not contain P. — end note]

A declaration X precedes a program point P in a translation unit L if P follows X, X inhabits a class scope and is reachable from P, or else X appears in a translation unit D and

(2.1) — P follows a module-import-declaration or module-declaration that imports D (directly or indirectly), and
(2.2) — X appears after the module-declaration in D (if any) and before the private-module-fragment in D (if any), and
(2.3) — either X is exported or else D and L are part of the same module and X does not inhabit a namespace with internal linkage or declare a name with internal linkage.

[Note 2: Names declared by a using-declaration have no linkage. — end note]

[Note 3: A module-import-declaration imports both the named translation unit(s) and any modules named by exported module-import-declarations within them, recursively.

[Example 1:

Translation unit #1:

    export module Q;
    export int sq(int i) { return i*i; }

Translation unit #2:

    export module R;
    export import Q;
Translation unit #3:

```c
import R;
int main() { return sq(9); } // OK, sq from module Q
— end example]
— end note]
```

3 A single search in a scope \( S \) for a name \( N \) from a program point \( P \) finds all declarations that precede \( P \) to which any name that is the same as \( N \) (6.1) is bound in \( S \). If any such declaration is a using-declarator whose terminal name (7.5.5.2) is not dependent (13.8.3.2), it is replaced by the declarations named by the using-declarator (9.9).

4 In certain contexts, only certain kinds of declarations are included. After any such restriction, any declarations of classes or enumerations are discarded if any other declarations are found.

[Note 4: A type (but not a typedef-name or template) is therefore hidden by any other entity in its scope. — end note]

However, if a lookup is type-only, only declarations of types and templates whose specializations are types are considered: furthermore, if declarations of a typedef-name and of the type to which it refers are found, the declaration of the typedef-name is discarded instead of the type declaration.

### 6.5.2 Member name lookup

1 A search in a scope \( X \) for a name \( M \) from a program point \( P \) is a single search in \( X \) for \( M \) from \( P \) unless \( X \) is the scope of a class or class template \( T \), in which case the following steps define the result of the search.

[Note 1: The result differs only if \( M \) is a conversion-function-id or if the single search would find nothing. — end note]

2 The lookup set for a name \( N \) in a class or class template \( C \), called \( S(N,C) \), consists of two component sets: the declaration set, a set of members named \( N \); and the subobject set, a set of subobjects where declarations of these members were found (possibly via using-declarations). In the declaration set, type declarations (including injected-class-names) are replaced by the types they designate. \( S(N,C) \) is calculated as follows:

3 The declaration set is the result of a single search in the scope of \( C \) for \( N \) from immediately after the class-specifier of \( C \) if \( P \) is in a complete-class context of \( C \) or from \( P \) otherwise. If the resulting declaration set is not empty, the subobject set contains \( C \) itself, and calculation is complete.

4 Otherwise (i.e., \( C \) does not contain a declaration of \( N \) or the resulting declaration set is empty), \( S(N,C) \) is initially empty. Calculate the lookup set for \( N \) in each direct non-dependent (13.8.3.2) base class subobject \( B_i \), and merge each such lookup set \( S(N,B_i) \) in turn into \( S(N,C) \).

[Note 2: If \( C \) is incomplete, only base classes whose base-specifier appears before \( P \) are considered. If \( C \) is an instantiatted class, its base classes are not dependent. — end note]

5 The following steps define the result of merging lookup set \( S(N,B_i) \) into the intermediate \( S(N,C) \):

- If each of the subobject members of \( S(N,B_i) \) is a base class subobject of at least one of the subobject members of \( S(N,C) \), or if \( S(N,B_i) \) is empty, \( S(N,C) \) is unchanged and the merge is complete. Conversely, if each of the subobject members of \( S(N,C) \) is a base class subobject of at least one of the subobject members of \( S(N,B_i) \), or if \( S(N,C) \) is empty, the new \( S(N,C) \) is a copy of \( S(N,B_i) \).

- Otherwise, if the declaration sets of \( S(N,B_i) \) and \( S(N,C) \) differ, the merge is ambiguous: the new \( S(N,C) \) is a lookup set with an invalid declaration set and the union of the subobject sets. In subsequent merges, an invalid declaration set is considered different from any other.

- Otherwise, the new \( S(N,C) \) is a lookup set with the shared set of declarations and the union of the subobject sets.

6 The result of the search is the declaration set of \( S(M,T) \). If it is an invalid set, the program is ill-formed. If it differs from the result of a search in \( T \) for \( M \) in a complete-class context (11.4) of \( T \), the program is ill-formed, no diagnostic required.

**[Example 1]**

```c
generic template T

struct A { int x; };  // S(x,A) = \{ \{ A::x \}, \{ A \} \}
struct B { float x; };  // S(x,B) = \{ \{ B::x \}, \{ B \} \}
struct C: public A, public B { };  // S(x,C) = \{ invalid, \{ A in C, B in C \} \}
struct D: public virtual C { };  // S(x,D) = S(x,C)
struct E: public virtual C { char x; };  // S(x,E) = \{ \{ E::x \}, \{ E \} \}
struct F: public D, public E { };  // S(x,F) = S(x,E)
generic template T
```
```c
int main() {
    F f;
    f.x = 0; // OK, lookup finds E::x
}
```

*S(x,F)* is unambiguous because the A and B base class subobjects of D are also base class subobjects of E, so *S(x,D)* is discarded in the first merge step. — end example]

7 If *M* is a non-dependent conversion-function-id, conversion function templates that are members of *T* are considered. For each such template *F*, the lookup set *S(t,T)* is constructed, considering a function template declaration to have the name *t* only if it corresponds to a declaration of *F* (6.4.1). The members of the declaration set of each such lookup set, which shall not be an invalid set, are included in the result.

[Note 3: Overload resolution will discard those that cannot convert to the type specified by *M* (13.10.4). — end note]

8 [Note 4: A static member, a nested type or an enumerator defined in a base class *T* can unambiguously be found even if an object has more than one base class subobject of type *T*. Two base class subobjects share the non-static member subobjects of their common virtual base classes. — end note]

[Example 2:
```
struct V {
    int v;
};
struct A {
    int a;
    static int s;
    enum { e };
};
struct B : A, virtual V {}; 
struct C : A, virtual V {}; 
struct D : B, C { }; 

void f(D* pd) {
    pd->v++; // OK, only one v (virtual)
    pd->s++; // OK, only one s (static)
    int i = pd->e; // OK, only one e (enumerator)
    pd->a++; // error: ambiguous: two a's in D
}
```
— end example]

9 [Note 5: When virtual base classes are used, a hidden declaration can be reached along a path through the subobject lattice that does not pass through the hiding declaration. This is not an ambiguity. The identical use with non-virtual base classes is an ambiguity; in that case there is no unique instance of the name that hides all the others. — end note]

[Example 3:
```
struct V { int f(); int x; }; 
struct W { int g(); int y; }; 
struct B : virtual V, W { 
    int f(); int x;
    int g(); int y;
}; 
struct C : virtual V, W {}; 
struct D : B, C { void glorp(); }; 
```

```
```

![Figure 1 — Name lookup](fig:class.lookup)
As illustrated in Figure 1, the names declared in V and the left-hand instance of W are hidden by those in B, but the names declared in the right-hand instance of W are not hidden at all.

```cpp
void D::glorp() {
  x++;          // OK, B::x hides V::x
  f();          // OK, B::f() hides V::f()
  y++;          // error: B::y and C's W::y
  g();          // error: B::g() and C's W::g()
}
—end example]
```

An explicit or implicit conversion from a pointer to or an expression designating an object of a derived class to a pointer or reference to one of its base classes shall unambiguously refer to a unique object representing the base class.

[Example 4:
```
struct V { }
struct A { }
struct B : A, virtual V { }
struct C : A, virtual V { }
struct D : B, C { }

void g() {
  D d;
  B* pb = &d;
  A* pa = &d;   // error: ambiguous: C's A or B's A?
  V* pv = &d;  // OK, only one V subobject
}
—end example]
```

[Note 6: Even if the result of name lookup is unambiguous, use of a name found in multiple subobjects might still be ambiguous (7.3.13, 7.6.1.5, 11.8.3). — end note]

[Example 5:
```
struct B1 {
  void f();
  static void f(int);
  int i;
};
struct B2 {
  void f(double);
};
struct I1 : B1 { }
struct I2 : B1 { }
struct D : I1, I2, B2 {
  using B1::f;
  using B2::f;
  void g() {
    f();                 // Ambiguous conversion of this
    f(0);               // Unambiguous (static)
    f(0.0);             // Unambiguous (only one B2)
    int B1::* mpB1 = &D::i; // Unambiguous
    int D::* mpD = &D::i; // Ambiguous conversion
  }
};
—end example]
```

6.5.3 Unqualified name lookup

A *using-directive* is active in a scope S at a program point P if it precedes P and inhabits either S or the scope of a namespace nominated by a *using-directive* that is active in S at P.

An *unqualified search* in a scope S from a program point P includes the results of searches from P in — S, and

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— for any scope $U$ that contains $P$ and is or is contained by $S$, each namespace contained by $S$ that is nominated by a using-directive that is active in $U$ at $P$.

If no declarations are found, the results of the unqualified search are the results of an unqualified search in the parent scope of $S$, if any, from $P$.

Note 1: When a class scope is searched, the scopes of its base classes are also searched (6.5.2). If it inherits from a single base, it is as if the scope of the base immediately contains the scope of the derived class. Template parameter scopes that are associated with one scope in the chain of parents are also considered (13.8.2). — end note

Unqualified name lookup from a program point performs an unqualified search in its immediate scope.

An unqualified name is a name that does not immediately follow a nested-name-specifier or the . or -> in a class member access expression (7.6.1.5), possibly after a template keyword or ~. Unless otherwise specified, such a name undergoes unqualified name lookup from the point where it appears.

An unqualified name that is a component name (7.5.5.2) of a type-specifier or ptr-operator of a conversion-type-id is looked up in the same fashion as the conversion-function-id in which it appears. If that lookup finds nothing, it undergoes unqualified name lookup; in each case, only names that denote types or templates whose specializations are types are considered.

Example 1:

```c
struct T1 { struct U { int i; }; };  
struct T2 {};  
struct U1 {};  
struct U2 {};  

struct B {  
    using T = T1;  
    using U = U1;  
    operator U1 T1::*();  
    operator U1 T2::*();  
    operator U2 T1::*();  
    operator U2 T2::*();  
};

template<class X, class T>  
int g() {  
    using U = U2;  
    X().operator U T::*();  // #1, searches for T in the scope of X first  
    X().operator U decltype(T())::*();  // #2  
    return 0;  
}  
int x = g<B, T2>();  // #1 calls B::operator U1 T1::*  
// #2 calls B::operator U1 T2::*

— end example
```

6 In a friend declaration declarator whose declarator-id is a qualified-id whose lookup context (6.5.5) is a class or namespace $S$, lookup for an unqualified name that appears after the declarator-id performs a search in the scope associated with $S$. If that lookup finds nothing, it undergoes unqualified name lookup.

Example 2:

```c
using I = int;  
using D = double;  
namespace A {  
    inline namespace N {using C = char; }  
    using F = float;  
    void f(I);  
    void f(D);  
    void f(C);  
    void f(F);  
}  
struct X0 {using F = float; };  
struct W {  
    using D = void;
```
struct X : X0 {
    void g(I);
    void g(D);
    void g(F);
};
}

namespace B {
    typedef short I, F;
    class Y {
        friend void A::f(I);
        // error: no void A::f(short)
        friend void A::f(D);
        // OK
        friend void A::f(C);
        // error: A::N::C not found
        friend void A::f(F);
        // OK
        friend void W::X::g(I);
        // error: no void X::g(short)
        friend void W::X::g(D);
        // OK
        friend void W::X::g(F);
        // OK
    };
}

@end example

6.5.4 Argument-dependent name lookup [basic.lookup.argdep]

When the postfix-expression in a function call (7.6.1.3) is an unqualified-id, and unqualified lookup (6.5.3) for
the name in the unqualified-id does not find any

(1.1) — declaration of a class member, or
(1.2) — function declaration inhabiting a block scope, or
(1.3) — declaration not of a function or function template

then lookup for the name also includes the result of argument-dependent lookup in a set of associated
namespaces that depends on the types of the arguments (and for template template arguments, the namespace
of the template argument), as specified below.

[Example 1:]

namespace N {
    struct S { }
    void f(S);
}

void g() {
    N::S s;
    f(s);       // OK, calls N::f
    (f)(s);     // error: N::f not considered; parentheses prevent argument-dependent lookup
}

@end example

Note 1: For purposes of determining (during parsing) whether an expression is a postfix-expression for a function call,
the usual name lookup rules apply. In some cases a name followed by < is treated as a template-name even though
name lookup did not find a template-name (see 13.3). For example,

    int h;
    void g();
    namespace N {
        struct A { }
        template <class T> int f(T);
        template <class T> int g(T);
        template <class T> int h(T);
    }

    int x = f<N::A>(N::A());      // OK, lookup of f finds nothing, f treated as template name
    int y = g<N::A>(N::A());      // OK, lookup of g finds a function, g treated as template name
    int z = h<N::A>(N::A());      // error: h does not begin a template-id

The rules have no effect on the syntactic interpretation of an expression. For example,

typedef int f;
namespace N {
struct A {
friend void f(A &);
operator int();
void g(A a) {
    int i = f(a);
    // f is the typedef, not the friend function: equivalent to int(a)
}
};
}

Because the expression is not a function call, argument-dependent name lookup does not apply and the friend function f is not found. — end note]

For each argument type T in the function call, there is a set of zero or more associated entities to be considered. The set of entities is determined entirely by the types of the function arguments (and any template argument templates). Any typedef-names and using-declarations used to specify the types do not contribute to this set. The set of entities is determined in the following way:

(3.1) — If T is a fundamental type, its associated set of entities is empty.

(3.2) — If T is a class type (including unions), its associated entities are: the class itself; the class of which it is a member, if any; and, if it is a complete type, its direct and indirect base classes. Furthermore, if T is a class template specialization, its associated entities also include: the entities associated with the types of the template arguments provided for template type parameters; the templates used as template template arguments; and the classes of which any member templates used as template template arguments are members.

[Note 2: Non-type template arguments do not contribute to the set of associated entities. — end note]

(3.3) — If T is an enumeration type, its associated entities are T and, if it is a class member, the member’s class.

(3.4) — If T is a pointer to U or an array of U, its associated entities are those associated with U.

(3.5) — If T is a function type, its associated entities are those associated with the function parameter types and those associated with the return type.

(3.6) — If T is a pointer to a member function of a class X, its associated entities are those associated with the function parameter types and return type, together with those associated with X.

(3.7) — If T is a pointer to a data member of class X, its associated entities are those associated with the member type together with those associated with X.

In addition, if the argument is an overload set or the address of such a set, its associated entities are the union of those associated with each of the members of the set, i.e., the entities associated with its parameter types and return type. Additionally, if the aforementioned overload set is named with a template-id, its associated entities also include its template template-arguments and those associated with its type template-arguments.

The associated namespaces for a call are the innermost enclosing non-inline namespaces for its associated entities as well as every element of the inline namespace set (9.8.2) of those namespaces. Argument-dependent lookup finds all declarations of functions and function templates that

(4.1) — are found by a search of any associated namespace, or

(4.2) — are declared as a friend (11.8.4) of any class with a reachable definition in the set of associated entities, or

(4.3) — are exported, are attached to a named module M (10.2), do not appear in the translation unit containing the point of the lookup, and have the same innermost enclosing non-inline namespace scope as a declaration of an associated entity attached to M (6.6).

If the lookup is for a dependent name (13.8.3, 13.8.4.2), the above lookup is also performed from each point in the instantiation context (10.6) of the lookup, additionally ignoring any declaration that appears in another translation unit, is attached to the global module, and is either discarded (10.4) or has internal linkage.

[Example 2:

Translation unit #1:

```cpp
export module M;
namespace R {
    export struct X {};
}
```
export void f(X);
} namespace S {
    export void f(R::X, R::X);
}

Translation unit #2:

export module N;
import M;
export R::X make();
namespace R { static int g(X); }
export template<typename T, typename U> void apply(T t, U u) {
    f(t, u);
    g(t);
}

Translation unit #3:

module Q;
import N;
namespace S {
    struct Z { template<typename T> operator T(); }
}

void test() {
    auto x = make();  // OK, decltype(x) is R::X in module M
    R::f(x);          // error: R and R::f are not visible here
    f(x);
    f(x, S::Z());     // error: S::f in module M not considered
                      // even though S is an associated namespace
    apply(x, S::Z()); // error: S::f is visible in instantiation context, but
                      // R::g has internal linkage and cannot be used outside TU #2

    —end example] 6

[Note 3: The associated namespace can include namespaces already considered by ordinary unqualified lookup. — end note]

[Example 3:

namespace NS {
    class T {
    public:
        static int n;
    };
    void f(T);
    void g(T, int);
}
NS::T parm;
void g(NS::T, float);
int main() {
    f(parm);       // OK, calls NS::f
    external void g(NS::T, float);
    g(parm, 1);    // OK, calls g(NS::T, float)

    —end example]

6.5.5 Qualified name lookup [basic.lookup.qual]
6.5.5.1 General [basic.lookup.qual.general]

1 Lookup of an identifier followed by a :: scope resolution operator considers only namespaces, types, and templates whose specializations are types. If a name, template-id, or computed-type-specifier is followed by a ::, it shall designate a namespace, class, enumeration, or dependent type, and the :: is never interpreted as a complete nested-name-specifier.

[Example 1:

    class A {
    public:
        static int n;
    };

§ 6.5.5.1 ©ISO/IEC 52
int main() {
    int A;
    A::n = 42; // OK
    A b; // error: A does not name a type
}

template<int> struct B : A {};
namespace N {
    template<int> void B();
    int f() {
        return B<0>::n; // error: N::B<0> is not a type
    }
}

— end example —

A member-qualified name is the (unique) component name (7.5.5.2), if any, of

(2.1) an unqualified-id or
(2.2) a nested-name-specifier of the form type-name :: or namespace-name :: in the id-expression of a class member access expression (7.6.1.5). A qualified name is

(2.3) a member-qualified name or
(2.4) the terminal name of
    (2.4.1) a qualified-id,
    (2.4.2) a using-declarator,
    (2.4.3) a typename-specifier,
    (2.4.4) a qualified-namespace-specifier, or
    (2.4.5) a nested-name-specifier, elaborated-type-specifier, or class-or-decltype that has a nested-name-specifier (7.5.5.3).

The lookup context of a member-qualified name is the type of its associated object expression (considered dependent if the object expression is type-dependent). The lookup context of any other qualified name is the type, template, or namespace nominated by the preceding nested-name-specifier.

[Note 1: When parsing a class member access, the name following the -> or . is a qualified name even though it is not yet known of which kind. — end note]

[Example 2: In

N::C::m::Base::f()]

Base is a member-qualified name; the other qualified names are C, m, and f. — end example —

Qualified name lookup in a class, namespace, or enumeration performs a search of the scope associated with it (6.5.2) except as specified below. Unless otherwise specified, a qualified name undergoes qualified name lookup in its lookup context from the point where it appears unless the lookup context either is dependent and is not the current instantiation (13.8.3.2) or is not a class or class template. If nothing is found by qualified lookup for a member-qualified name that is the terminal name (7.5.5.2) of a nested-name-specifier and is not dependent, it undergoes unqualified lookup.

[Note 2: During lookup for a template specialization, no names are dependent. — end note]

[Example 3:]

int f();
struct A {
    int B, C;
    template<int> using D = void;
    using T = void;
    void f();
};
    using B = A;
    template<int> using C = A;
    template<int> using D = A;
    template<int> using X = A;
template<
class T>
void g(T *p) { // as instantiated for g<A>:
  p->X<0>::f(); // error: A::X not found in ((p->X) < 0) > ::f()
  p->template X<0>::f(); // OK, ::X found in definition context
  p->B::f(); // OK, non-type A::B ignored
  p->template C<0>::f(); // error: A::C is not a template
  p->template D<0>::f(); // error: A::D<0> is not a class type
  p->T::f(); // error: A::T is not a class type
}
template void g(A*);
—end example]  

If a qualified name Q follows a ~:

(4.1) — If Q is a member-qualified name, it undergoes unqualified lookup as well as qualified lookup.

(4.2) — Otherwise, its nested-name-specifier N shall nominate a type. If N has another nested-name-specifier S, Q is looked up as if its lookup context were that nominated by S.

(4.3) — Otherwise, if the terminal name of N is a member-qualified name M, Q is looked up as if ~Q appeared in place of M (as above).

(4.4) — Otherwise, Q undergoes unqualified lookup.

(4.5) — Each lookup for Q considers only types (if Q is not followed by a <) and templates whose specializations are types. If it finds nothing or is ambiguous, it is discarded.

(4.6) — The type-name that is or contains Q shall refer to its (original) lookup context (ignoring cv-qualification) under the interpretation established by at least one (successful) lookup performed.

[Example 4:]
structure C {
  typedef int I;
};
typeid int I1, I2;
extern int* p;
extern int* q;
void f() {
p->C::I::~I(); // I is looked up in the scope of C
q->I1::~I2(); // I2 is found by unqualified lookup
}
structure A {
  ~A();
};
typeid A AB;
int main() {
  AB* p;
p->AB::~AB(); // explicitly calls the destructor for A
}
—end example]

6.5.5.2 Class members [class.qual]

1 In a lookup for a qualified name N whose lookup context is a class C in which function names are not ignored,19

(1.1) — if the search finds the injected-class-name of C (11.1), or

(1.2) — if N is dependent and is the terminal name of a using-declarator (9.9) that names a constructor,

N is instead considered to name the constructor of class C. Such a constructor name shall be used only in the declarator-id of a (friend) declaration of a constructor or in a using-declaration.

[Example 1:]
structure A { A(); };
structure B: public A { B(); };

19) Lookups in which function names are ignored include names appearing in a nested-name-specifier, an elaborated-type-specifier, or a base-specifier.
6.5.5.3 Namespace members

Qualified name lookup in a namespace \(N\) additionally searches every element of the inline namespace set of \(N\) (9.8.2). If nothing is found, the results of the lookup are the results of qualified name lookup in each namespace nominated by a using-directive that precedes the point of the lookup and inhabits \(N\) or an element of \(N\)'s inline namespace set.

[Note 1: If a using-directive refers to a namespace that has already been considered, it does not affect the result. — end note]

[Example 1:

```cpp
int x;
namespace Y {
    void f(float);
    void h(int);
}

namespace Z {
    void h(double);
}

namespace A {
    using namespace Y;
    void f(int);
    void g(int);
    int i;
}

namespace B {
    using namespace Z;
    void f(char);
    int i;
}

namespace AB {
    using namespace A;
    using namespace B;
    void g();
}

void h()
{
    AB::g(); // g is declared directly in AB, therefore \(S\) is \{AB::g()\} and AB::g() is chosen
    AB::f(1); // f is not declared directly in AB so the rules are applied recursively to A and B;
               // namespace Y is not searched and Y::f(float) is not considered;
               // \(S\) is \{A::f(int), B::f(char)\} and overload resolution chooses A::f(int)
    AB::f('c'); // as above but resolution chooses B::f(char)
    AB::x++; // x is not declared directly in AB, and is not declared in A or B, so the rules
              // are applied recursively to Y and Z, \(S\) is {} so the program is ill-formed
    AB::i++; // i is not declared directly in AB so the rules are applied recursively to A and B,
              // \(S\) is \{A::i, B::i\} so the use is ambiguous and the program is ill-formed
}```]
AB::h(16.8);  // h is not declared directly in AB and not declared directly in A or B so the rules
  // are applied recursively to Y and Z, S is \{Y::h(int), Z::h(double)\} and
  // overload resolution chooses Z::h(double)
}
— end example]

² [Note 2: The same declaration found more than once is not an ambiguity (because it is still a unique declaration).

Example 2:
namespace A {
  int a;
}
namespace B {
  using namespace A;
}
namespace C {
  using namespace A;
}
namespace BC {
  using namespace B;
  using namespace C;
}
void f()
{
  BC::a++;
  // OK, S is \{A::a, A::a\}
}
namespace D {
  using A::a;
}
namespace BD {
  using namespace B;
  using namespace D;
}
void g()
{
  BD::a++;
  // OK, S is \{A::a, A::a\}
— end example]
— end note]
B::a++;  // OK, both A and B searched (once), S is {A::a}
A::b++;  // OK, both A and B searched (once), S is {B::b}
B::b++;  // OK, b declared directly in B, S is {B::b}

— end example]

4 [Note 3: Class and enumeration declarations are not discarded because of other declarations found in other searches. — end note]

[Example 4:

```c
namespace A {
    struct x { };  int x;
    int y;
}

namespace B {
    struct y { }
}

namespace C {
    using namespace A;
    using namespace B;
    int i = C::x;  // OK, A::x (of type int)
    int j = C::y;  // ambiguous, A::y or B::y
}

— end example]

6.5.6 Elaborated type specifiers  [basic.lookup.elab]

1 If the class-key or enum keyword in an elaborated-type-specifier is followed by an identifier that is not followed by ::, lookup for the identifier is type-only (6.5.1).

[Note 1: In general, the recognition of an elaborated-type-specifier depends on the following tokens. If the identifier is followed by ::, see 6.5.5. — end note]

2 If the terminal name of the elaborated-type-specifier is a qualified name, lookup for it is type-only. If the name lookup does not find a previously declared type-name, the elaborated-type-specifier is ill-formed.

3 [Example 1:

```c
struct Node {
    struct Node* Next;  // OK, refers to injected-class-name Node
    struct Data* Data;  // OK, declares type Data at global scope and member Data
}

struct Data {
    struct Node* Node;  // OK, refers to Node at global scope
    friend struct ::Glob;  // error: Glob is not declared, cannot introduce a qualified type (9.2.9.5)
    friend struct Glob;  // OK, refers to (as yet) undeclared Glob at global scope.
    /* ... */
}

struct Base {
    struct Data;  // OK, declares nested Data
    struct ::Data* thatData;  // OK, refers to ::Data
    struct Base::Data* thisData;  // OK, refers to nested Data
    friend class ::Data;  // OK, global Data is a friend
    friend class Data;  // OK, nested Data is a friend
    struct Data { /* ... */ };  // Defines nested Data
};

struct Data;  // OK, redeclares Data at global scope
struct ::Data;  // error: cannot introduce a qualified type (9.2.9.5)
struct Base::Data;  // error: cannot introduce a qualified type (9.2.9.5)
struct Base::Datum;  // error: Datum undefined
struct Base::Data* pBase;  // OK, refers to nested Data
```
6.5.7 Using-directives and namespace aliases

In a using-directive or namespace-alias-definition, during the lookup for a namespace-name or for a name in a nested-name-specifier only namespace names are considered.

6.6 Program and linkage

A program consists of one or more translation units (5.1) linked together. A translation unit consists of a sequence of declarations.

translation-unit:
  declaration-seq_opt
global-module-fragment_opt module-declaration declaration-seq_opt private-module-fragment_opt

A name can have external linkage, module linkage, internal linkage, or no linkage, as determined by the rules below.

[Note 1: All declarations of an entity with a name with internal linkage appear in the same translation unit. All declarations of an entity with module linkage are attached to the same module. — end note]

The name of an entity that belongs to a namespace scope (6.4.6) has internal linkage if it is the name of

- a variable, variable template, function, or function template that is explicitly declared static; or
- a non-template variable of non-volatile const-qualified type, unless
  - it is declared in the purview of a module interface unit (outside the private-module-fragment, if any) or module partition, or
  - it is explicitly declared extern, or
  - it is inline, or
  - it was previously declared and the prior declaration did not have internal linkage; or
- a data member of an anonymous union.

[Note 2: An instantiated variable template that has const-qualified type can have external or module linkage, even if not declared extern. — end note]

An unnamed namespace or a namespace declared directly or indirectly within an unnamed namespace has internal linkage. All other namespaces have external linkage. The name of an entity that belongs to a namespace scope that has not been given internal linkage above and that is the name of

- a variable; or
- a function; or
- a named class (11.1), or an unnamed class defined in a typedef declaration in which the class has the typedef name for linkage purposes (9.2.4); or
- a named enumeration (9.7.1), or an unnamed enumeration defined in a typedef declaration in which the enumeration has the typedef name for linkage purposes (9.2.4); or
- an unnamed enumeration that has an enumerator as a name for linkage purposes (9.7.1); or
- a template

has its linkage determined as follows:

- if the entity is a function or function template first declared in a friend declaration and that declaration is a definition and the enclosing class is defined within an export-declaration, the name has the same linkage, if any, as the name of the enclosing class (11.8.4);
- otherwise, if the entity is a function or function template declared in a friend declaration and a corresponding non-friend declaration is reachable, the name has the linkage determined from that prior declaration,
- otherwise, if the enclosing namespace has internal linkage, the name has internal linkage;
- otherwise, if the declaration of the name is attached to a named module (10.1) and is not exported (10.2), the name has module linkage;
- otherwise, the name has external linkage.
In addition, a member function, a static data member, a named class or enumeration that inhabits a class scope, or an unnamed class or enumeration defined in a typedef declaration that inhabits a class scope such that the class or enumeration has the typedef name for linkage purposes (9.2.4), has the same linkage, if any, as the name of the class of which it is a member.

[Example 1:

```cpp
static void f();
extern "C" void h();
static int i = 0;  // #1

void q() {
extern void f();  // internal linkage
extern void g();  // ::g, external linkage
eextern void h();  // C language linkage
int i;  // #2: i has no linkage
{
eextern void f();  // internal linkage
extern int i;  // #3: internal linkage
}
}
```

Even though the declaration at line #2 hides the declaration at line #1, the declaration at line #3 still redeclares #1 and receives internal linkage. — end example]

Names not covered by these rules have no linkage. Moreover, except as noted, a name declared at block scope (6.4.3) has no linkage.

Two declarations of entities declare the same entity if, considering declarations of unnamed types to introduce their names for linkage purposes, if any (9.2.4, 9.7.1), they correspond (6.4.1), have the same target scope that is not a function or template parameter scope, neither is a name-independent declaration, and either

(8.1) — they appear in the same translation unit, or
(8.2) — they both declare names with module linkage and are attached to the same module, or
(8.3) — they both declare names with external linkage.

[Note 3: There are other circumstances in which declarations declare the same entity (9.11, 13.6, 13.7.6). — end note]

If a declaration $H$ that declares a name with internal linkage precedes a declaration $D$ in another translation unit $U$ and would declare the same entity as $D$ if it appeared in $U$, the program is ill-formed.

[Note 4: Such an $H$ can appear only in a header unit. — end note]

If two declarations of an entity are attached to different modules, the program is ill-formed; no diagnostic is required if neither is reachable from the other.

[Example 2:

```cpp
"decls.h":

int f(); // #1, attached to the global module
int g(); // #2, attached to the global module

Module interface of M:

#include "decls.h"
export module M;
export using ::f; // OK, does not declare an entity, exports #1
int g(); // error: matches #2, but attached to M
export int h(); // #3
export int k(); // #4

Other translation unit:

import M;
static int h(); // error: matches #3
int k(); // error: matches #4

— end example]

As a consequence of these rules, all declarations of an entity are attached to the same module; the entity is said to be attached to that module.
For any two declarations of an entity $E$:

- If one declares $E$ to be a variable or function, the other shall declare $E$ as one of the same type.

- If one declares $E$ to be an enumerator, the other shall do so.

- If one declares $E$ to be a namespace, the other shall do so.

- If one declares $E$ to be a type, the other shall declare $E$ to be a type of the same kind (9.2.9.5).

- If one declares $E$ to be a class template, the other shall do so with the same kind and an equivalent template-head (13.7.7.2).

[Note 5: The declarations can supply different default template arguments. — end note]

- If one declares $E$ to be a function template or a (partial specialization of a) variable template, the other shall declare $E$ to be one with an equivalent template-head and type.

- If one declares $E$ to be an alias template, the other shall declare $E$ to be one with an equivalent template-head and defining-type-id.

- If one declares $E$ to be a concept, the other shall do so.

Types are compared after all adjustments of types (during which typedefs (9.2.4) are replaced by their definitions); declarations for an array object can specify array types that differ by the presence or absence of a major array bound (9.3.4.5). No diagnostic is required if neither declaration is reachable from the other.

**Example 3:**

```cpp
int f(int x, int x);  // error: different entities for x
void g();            // #1
void g(int);         // OK, different entity from #1
int g();             // error: same entity as #1 with different type
void h();            // #2
namespace h {}       // error: same entity as #2, but not a function
```

[Note 6: Linkage to non-C++ declarations can be achieved using a linkage-specification (9.11). — end note]

A declaration $D$ names an entity $E$ if

- $D$ contains a lambda-expression whose closure type is $E$,

- $E$ is not a function or function template and $D$ contains an id-expression, type-specifier, nested-name-specifier, template-name, or concept-name denoting $E$, or

- $E$ is a function or function template and $D$ contains an expression that names $E$ (6.3) or an id-expression that refers to a set of overloads that contains $E$.

[Note 7: Non-dependent names in an instantiated declaration do not refer to a set of overloads (13.8). — end note]

A declaration is an exposure if it either names a TU-local entity (defined below), ignoring

- the function-body for a non-inline function or function template (but not the deduced return type for a (possibly instantiated) definition of a function with a declared return type that uses a placeholder type (9.2.9.7)),

- the initializer for a variable or variable template (but not the variable’s type),

- friend declarations in a class definition, and

- any reference to a non-volatile const object or reference with internal or no linkage initialized with a constant expression that is not an odr-use (6.3),

or defines a constexpr variable initialized to a TU-local value (defined below).

[Note 8: An inline function template can be an exposure even though certain explicit specializations of it would be usable in other translation units. — end note]

An entity is **TU-local** if it is

- a type, function, variable, or template that

  - has a name with internal linkage, or

  - does not have a name with linkage and is declared, or introduced by a lambda-expression, within the definition of a TU-local entity,
— a type with no name that is defined outside a class-specifier, function body, or initializer or is introduced by a defining-type-specifier that is used to declare only TU-local entities,

— a specialization of a TU-local template,

— a specialization of a template with any TU-local template argument, or

— a specialization of a template whose (possibly instantiated) declaration is an exposure.

[Note 9: A specialization can be produced by implicit or explicit instantiation. — end note]

A value or object is TU-local if either

— it is, or is a pointer to, a TU-local function or the object associated with a TU-local variable, or

— it is an object of class or array type and any of its subobjects or any of the objects or functions to which its non-static data members of reference type refer is TU-local and is usable in constant expressions.

If a (possibly instantiated) declaration of, or a deduction guide for, a non-TU-local entity in a module interface unit (outside the private-module-fragment, if any) or module partition (10.1) is an exposure, the program is ill-formed. Such a declaration in any other context is deprecated (D.6).

If a declaration that appears in one translation unit names a TU-local entity declared in another translation unit that is not a header unit, the program is ill-formed. A declaration instantiated for a template specialization (13.9) appears at the point of instantiation of the specialization (13.8.4.1).

[Example 4:

Translation unit #1:

export module A;
static void f() {}
inline void it() { f(); } // error: is an exposure of f
static inline void its() { f(); } // OK
template<int> void g() { its(); } // OK
template void g<0>();
decltype(f) *fp; // error: f (though not its type) is TU-local
auto &fr = f; // OK
constexpr auto &fr2 = fr; // error: is an exposure of f
constexpr static auto fp2 = fr; // OK
struct S { void (&ref)(); } s{f}; // OK, value is TU-local
constexpr extern struct W { S &s; } wrap{s}; // OK, value is not TU-local
static auto x = []{f();}; // OK
auto x2 = x; // error: the closure type is TU-local
int y = ([](f());),0); // error: the closure type is not TU-local
int y2 = (x,0); // OK
namespace N {
    struct A {};
    void adl(A);
    static void adl(int);
}
void adl(double);
inline void h(auto x) { adl(x); } // OK, but certain specializations are exposures

Translation unit #2:

module A;
void other() {
    g<0>()(); // OK, specialization is explicitly instantiated
    g<1>()(); // error: instantiation uses TU-local its
    h(N::A{}); // error: overload set contains TU-local N::adl(int)
    h(0); // OK, calls adl(double)
    adl(N::A{}); // OK; N::adl(int) not found, calls N::adl(N::A)
    fr(); // OK, calls f

§ 6.6 ©ISO/IEC 61
6.7 Memory and objects

6.7.1 Memory model

The fundamental storage unit in the C++ memory model is the byte. A byte is at least large enough to contain the ordinary literal encoding of any element of the basic literal character set (5.3) and the eight-bit code units of the Unicode UTF-8 encoding form and is composed of a contiguous sequence of bits, the number of which is implementation-defined. The least significant bit is called the low-order bit; the most significant bit is called the high-order bit. The memory available to a C++ program consists of one or more sequences of contiguous bytes. Every byte has a unique address.

A memory location is either an object of scalar type that is not a bit-field or a maximal sequence of adjacent bit-fields all having nonzero width.

Two or more threads of execution can access separate memory locations without interfering with each other.

[Example 1: A class declared as

```cpp
struct {
    char a;
    int b:5,
    c:11,
    :0,
    d:8;
    struct {int ee:8;} e;
};
```

contains four separate memory locations: The member a and bit-fields d and e.ee are each separate memory locations, and can be modified concurrently without interfering with each other. The bit-fields b and c together constitute the fourth memory location. The bit-fields b and c cannot be concurrently modified, but b and a, for example, can be.

---

6.7.2 Object model

The constructs in a C++ program create, destroy, refer to, access, and manipulate objects. An object is created by a definition (6.2), by a new-expression (7.6.2.8), by an operation that implicitly creates objects (see below), when implicitly changing the active member of a union (11.5), or when a temporary object is created (7.3.5, 6.7.7). An object occupies a region of storage in its period of construction (11.9.5), throughout its lifetime (6.7.3), and in its period of destruction (11.9.5).

[Note 1: A function is not an object, regardless of whether or not it occupies storage in the way that objects do.]

The properties of an object are determined when the object is created. An object can have a name (6.1). An object has a storage duration (6.7.5) which influences its lifetime (6.7.3). An object has a type (6.8).

[Note 2: Some objects are polymorphic (11.7.3); the implementation generates information associated with each such object that makes it possible to determine that object’s type during program execution.]

Objects can contain other objects, called subobjects. A subobject can be a member subobject (11.4), a base class subobject (11.7), or an array element. An object that is not a subobject of any other object is called a complete object. If an object is created in storage associated with a member subobject or array element e (which may or may not be within its lifetime), the created object is a subobject of e’s containing object if

---

20) The number of bits in a byte is reported by the macro `CHAR_BIT` in the header `<climits>` (17.3.6).
— the lifetime of \(e\)'s containing object has begun and not ended, and

— the storage for the new object exactly overlays the storage location associated with \(e\), and

— the new object is of the same type as \(e\) (ignoring cv-qualification).

If a complete object is created (7.6.2.8) in storage associated with another object \(e\) of type “array of \(N\) unsigned char” or of type “array of \(N\) std::byte” (17.2.1), that array provides storage for the created object if

— the lifetime of \(e\) has begun and not ended, and

— the storage for the new object fits entirely within \(e\), and

— there is no array object that satisfies these constraints nested within \(e\).

[Note 3: If that portion of the array previously provided storage for another object, the lifetime of that object ends because its storage was reused (6.7.3). — end note]

[Example 1:

```cpp
// assumes that sizeof(int) is equal to 4

template<typename ...T>
struct AlignedUnion {
  alignas(T...) unsigned char data[max(sizeof(T)...)];
};

int f() {
  AlignedUnion<int, char> au;
  int *p = new (au.data) int;  // OK, au.data provides storage
  char *c = new (au.data) char();  // OK, ends lifetime of *p
  char *d = new (au.data + 1) char();
  return *c + *d;  // OK
}

struct A { unsigned char a[32];
};
struct B { unsigned char b[16];
};
alignas(int) A a;
B *b = new (a.a + 8) B;
int *p = new (b->b + 4) int;
  // a.a provides storage for *b
  // b->b provides storage for *p
  // a.a does not provide storage for *p (directly),
  // but *p is nested within a (see below)

  — end example]

An object \(a\) is nested within another object \(b\) if

— \(a\) is a subobject of \(b\), or

— \(b\) provides storage for \(a\), or

— there exists an object \(c\) where \(a\) is nested within \(c\), and \(c\) is nested within \(b\).

For every object \(x\), there is some object called the complete object of \(x\), determined as follows:

— If \(x\) is a complete object, then the complete object of \(x\) is itself.

— Otherwise, the complete object of \(x\) is the complete object of the (unique) object that contains \(x\).

If a complete object, a member subobject, or an array element is of class type, its type is considered the most derived class, to distinguish it from the class type of any base class subobject; an object of a most derived class type or of a non-class type is called a most derived object.

A potentially-overlapping subobject is either:

— a base class subobject, or

— a non-static data member declared with the no_unique_address attribute (9.12.12).

An object has nonzero size if it

— is not a potentially-overlapping subobject, or

— is of class type, or

— is of a class type with virtual member functions or virtual base classes, or

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63
— has subobjects of nonzero size or unnamed bit-fields of nonzero length.
Otherwise, if the object is a base class subobject of a standard-layout class type with no non-static data
members, it has zero size. Otherwise, the circumstances under which the object has zero size are implementa-
tion-defined. Unless it is a bit-field (11.4.10), an object with nonzero size shall occupy one or more bytes of
storage, including every byte that is occupied in full or in part by any of its subobjects. An object of trivially
copyable or standard-layout type (6.8.1) shall occupy contiguous bytes of storage.

An object is a potentially non-unique object if it is a string literal object (5.13.5), the backing array of an
initializer list (9.4.4), or a subobject thereof.

Unless an object is a bit-field or a subobject of zero size, the address of that object is the address of the first
byte it occupies. Two objects with overlapping lifetimes that are not bit-fields may have the same address if
— one is nested within the other,
— at least one is a subobject of zero size and they are not of similar types (7.3.6), or
— they are both potentially non-unique objects;
otherwise, they have distinct addresses and occupy disjoint bytes of storage.\(^{21}\)

\[\text{Example 2:}\]
\begin{verbatim}
static const char test1 = 'x';
static const char test2 = 'x';
const bool b = &test1 != &test2;  // always true

static const char (&r)[] = "x";
static const char *s = "x";
static std::initializer_list<char> il = { 'x' };
const bool b2 = r != il.begin();  // unspecified result
const bool b3 = r != s;          // unspecified result
const bool b4 = il.begin() != &test1;  // always true
const bool b5 = r != &test1;      // always true
\end{verbatim}
\[\text{— end example}\]

The address of a non-bit-field subobject of zero size is the address of an unspecified byte of storage occupied
by the complete object of that subobject.

Some operations are described as implicitly creating objects within a specified region of storage. For each
operation that is specified as implicitly creating objects, that operation implicitly creates and starts the
lifetime of zero or more objects of implicit-lifetime types (6.8.1) in its specified region of storage if doing
so would result in the program having defined behavior. If no such set of objects would give the program
defined behavior, the behavior of the program is undefined. If multiple such sets of objects would give the
program defined behavior, it is unspecified which such set of objects is created.

\[\text{[Note 4: Such operations do not start the lifetimes of subobjects of such objects that are not themselves of implicit-
lifetime types. — end note]}\]

Further, after implicitly creating objects within a specified region of storage, some operations are described as
producing a pointer to a suitable created object. These operations select one of the implicitly-created objects
whose address is the address of the start of the region of storage, and produce a pointer value that points
to that object, if that value would result in the program having defined behavior. If no such pointer value
would give the program defined behavior, the behavior of the program is undefined. If multiple such pointer
values would give the program defined behavior, it is unspecified which such pointer value is produced.

\[\text{[Example 3:}\]
\begin{verbatim}
#include <cstdlib>
struct X { int a, b; };
X *make_x() {
    // The call to std::malloc implicitly creates an object of type X
    // and its subobjects a and b, and returns a pointer to that X object
    // (or an object that is pointer-interconvertible (6.8.4) with it),
    // in order to give the subsequent class member access operations
    // defined behavior.
    X *p = (X*)std::malloc(sizeof(struct X));
\end{verbatim}
\[\text{21) Under the “as-if” rule an implementation is allowed to store two objects at the same machine address or not store an object
at all if the program cannot observe the difference (6.9.1).}\]
```
p->a = 1;
p->b = 2;
return p;
}
— end example
```

Except during constant evaluation, an operation that begins the lifetime of an array of `unsigned char` or `std::byte` implicitly creates objects within the region of storage occupied by the array.

[Note 5: The array object provides storage for these objects. — end note]

Except during constant evaluation, any implicit or explicit invocation of a function named `operator new` or `operator new[]` implicitly creates objects in the returned region of storage and returns a pointer to a suitable created object.

[Note 6: Some functions in the C++ standard library implicitly create objects (20.2.6, 20.2.12, 20.4.2.2, 22.15.3, 23.5.3). — end note]

### 6.7.3 Lifetime

The lifetime of an object or reference is a runtime property of the object or reference. A variable is said to have *vacuous initialization* if it is default-initialized, no other initialization is performed, and, if it is of class type or a (possibly multidimensional) array thereof, a trivial constructor of that class type is selected for the default-initialization. The lifetime of an object of type `T` begins when:

1. Storage with the proper alignment and size for type `T` is obtained, and
2. Its initialization (if any) is complete (including vacuous initialization) (9.4), except that if the object is a union member or subobject thereof, its lifetime only begins if that union member is the initialized member in the union (9.4.2, 11.9.3), or as described in 11.5, 11.4.5.3, and 11.4.6, and except as described in 20.2.10.2. The lifetime of an object `o` of type `T` ends when:
   1. If `T` is a non-class type, the object is destroyed, or
   2. If `T` is a class type, the destructor call starts, or
   3. The storage which the object occupies is released, or is reused by an object that is not nested within `o` (6.7.2).

When evaluating a `new-expression`, storage is considered reused after it is returned from the allocation function, but before the evaluation of the `new-initializer` (7.6.2.8).

```
Example 1:
struct S {
  int m;
};
void f() {
  S x{1};
  new(&x) S(x.m);  // undefined behavior
}
— end example
```

The lifetime of a reference begins when its initialization is complete. The lifetime of a reference ends as if it were a scalar object requiring storage.

[Note 1: 11.9.3 describes the lifetime of base and member subobjects. — end note]

The properties ascribed to objects and references throughout this document apply for a given object or reference only during its lifetime.

[Note 2: In particular, before the lifetime of an object starts and after its lifetime ends there are significant restrictions on the use of the object, as described below, in 11.9.3, and in 11.9.5. Also, the behavior of an object under construction and destruction can differ from the behavior of an object whose lifetime has started and not ended. 11.9.3 and 11.9.5 describe the behavior of an object during its periods of construction and destruction. — end note]

A program may end the lifetime of an object of class type without invoking the destructor, by reusing or releasing the storage as described above.

[Note 3: A `delete-expression` (7.6.2.9) invokes the destructor prior to releasing the storage. — end note]
In this case, the destructor is not implicitly invoked.

[Note 4: The correct behavior of a program often depends on the destructor being invoked for each object of class type. — end note]

Before the lifetime of an object has started but after the storage which the object will occupy has been allocated or, after the lifetime of an object has ended and before the storage which the object occupied is reused or released, any pointer that represents the address of the storage location where the object will be or was located may be used but only in limited ways. For an object under construction or destruction, see 11.9.5. Otherwise, such a pointer refers to allocated storage (6.7.5.5.2), and using the pointer as if the pointer were of type void* is well-defined. Indirection through such a pointer is permitted but the resulting lvalue may only be used in limited ways, as described below. The program has undefined behavior if

(6.1) — the pointer is used as the operand of a delete-expression,

(6.2) — the pointer is used to access a non-static data member or call a non-static member function of the object, or

(6.3) — the pointer is implicitly converted (7.3.12) to a pointer to a virtual base class, or

(6.4) — the pointer is used as the operand of a static_cast (7.6.1.9), except when the conversion is to pointer to cv void, or to pointer to cv void and subsequently to pointer to cv char, cv unsigned char, or cv std::byte (17.2.1), or

(6.5) — the pointer is used as the operand of a dynamic_cast (7.6.1.7).

[Example 2:
#include <cstdlib>

struct B {
    virtual void f();
    void mutate();
    virtual ~B();
};

struct D1 : B { void f(); };
struct D2 : B { void f(); };

void B::mutate() {
    new (this) D2;  // reuses storage — ends the lifetime of *this
    f();           // undefined behavior
    ... = this;    // OK, this points to valid memory
}

void g() {
    void* p = std::malloc(sizeof(D1) + sizeof(D2));
    B* pb = new (p) D1;
    pb->mutate();
    *pb;           // OK, pb points to valid memory
    void* q = pb;  // OK, pb points to valid memory
    pb->f();       // undefined behavior: lifetime of *pb has ended
}
—end example]

Similarly, before the lifetime of an object has started but after the storage which the object will occupy has been allocated or, after the lifetime of an object has ended and before the storage which the object occupied is reused or released, any glvalue that refers to the original object may be used but only in limited ways. For an object under construction or destruction, see 11.9.5. Otherwise, such a glvalue refers to allocated storage (6.7.5.5.2), and using the properties of the glvalue that do not depend on its value is well-defined. The program has undefined behavior if

(7.1) — the glvalue is used to access the object, or

(7.2) — the glvalue is used to call a non-static member function of the object, or

(7.3) — the glvalue is bound to a reference to a virtual base class (9.4.4), or

For example, before the dynamic initialization of an object with static storage duration (6.9.3.3).
the glvalue is used as the operand of a dynamic_cast (7.6.1.7) or as the operand of typeid.

An object \( o_1 \) is transparently replaceable by an object \( o_2 \) if

- the storage that \( o_2 \) occupies exactly overlays the storage that \( o_1 \) occupied, and
- \( o_1 \) and \( o_2 \) are of the same type (ignoring the top-level cv-qualifiers), and
- \( o_1 \) is not a const, complete object, and
- neither \( o_1 \) nor \( o_2 \) is a potentially-overlapping subobject (6.7.2), and
- either \( o_1 \) and \( o_2 \) are both complete objects, or \( o_1 \) and \( o_2 \) are direct subobjects of objects \( p_1 \) and \( p_2 \), respectively, and \( p_1 \) is transparently replaceable by \( p_2 \).

After the lifetime of an object has ended and before the storage which the object occupied is reused or released, if a new object is created at the storage location which the original object occupied and the original object was transparently replaceable by the new object, a pointer that pointed to the original object, a reference that referred to the original object, or the name of the original object will automatically refer to the new object and, once the lifetime of the new object has started, can be used to manipulate the new object.

[Example 3:]
```c
struct C {
    int i;
    void f();
    const C& operator=( const C& );
};

const C& C::operator=( const C& other) {
    if ( this != &other ) {
        this->~C();          // lifetime of *this ends
        new (this) C(other);  // new object of type C created
        f();                  // well-defined
    }
    return *this;
}
```

\( C c1; \)
\( C c2; \)
\( c1 = c2; \)  // well-defined
\( c1.f(); \)   // well-defined; \( c1 \) refers to a new object of type \( C \)

[Note 5: If these conditions are not met, a pointer to the new object can be obtained from a pointer that represents the address of its storage by calling std::launder (17.6.5). — end note]

If a program ends the lifetime of an object of type \( T \) with static (6.7.5.2), thread (6.7.5.3), or automatic (6.7.5.4) storage duration and if \( T \) has a non-trivial destructor, and another object of the original type does not occupy that same storage location when the implicit destructor call takes place, the behavior of the program is undefined. This is true even if the block is exited with an exception.

[Example 4:]
```c
class T { }; 
struct B { 
    ~B();
};

void h() {
    B b;
    new (&b) T;  // undefined behavior at block exit
}
```

23) That is, an object for which a destructor will be called implicitly—upon exit from the block for an object with automatic storage duration, upon exit from the thread for an object with thread storage duration, or upon exit from the program for an object with static storage duration.
Creating a new object within the storage that a const, complete object with static, thread, or automatic
storage duration occupies, or within the storage that such a const object used to occupy before its lifetime
ended, results in undefined behavior.

[Example 5:

```cpp
struct B {
    B();
    ~B();
};

const B b;

void h() {
    b.~B();
    new (const_cast<B*>(&b)) const B; // undefined behavior
}
```
—end example]

In this subclause, “before” and “after” refer to the “happens before” relation (6.9.2).

[Note 6: Therefore, undefined behavior results if an object that is being constructed in one thread is referenced from
another thread without adequate synchronization. —end note]

### 6.7.4 Indeterminate and erroneous values

[basic.indet]

When storage for an object with automatic or dynamic storage duration is obtained, the bytes comprising
the storage for the object have the following initial value:

1. If the object has dynamic storage duration, or is the object associated with a variable or function
   parameter whose first declaration is marked with the `[[indeterminate]]` attribute (9.12.7), the bytes
   have indeterminate values;
2. otherwise, the bytes have erroneous values, where each value is determined by the implementation
   independently of the state of the program.

If no initialization is performed for an object (including subobjects), such a byte retains its initial value until
that value is replaced (9.4.1, 7.6.19). If any bit in the value representation has an indeterminate value, the
object has an indeterminate value; otherwise, if any bit in the value representation has an erroneous value,
the object has an erroneous value (7.3.2).

[Note 1: Objects with static or thread storage duration are zero-initialized, see 6.9.3.2. —end note]

Except in the following cases, if an indeterminate value is produced by an evaluation, the behavior is undefined,
and if an erroneous value is produced by an evaluation, the behavior is erroneous and the result of the
evaluation is the value so produced but is not erroneous:

1. If an indeterminate or erroneous value of unsigned ordinary character type (6.8.2) or `std::byte`
type (17.2.1) is produced by the evaluation of:
   1.1. the second or third operand of a conditional expression (7.6.16),
   1.2. the right operand of a comma expression (7.6.20),
   1.3. the operand of a cast or conversion (7.3.9, 7.6.1.4, 7.6.1.9, 7.6.3) to an unsigned ordinary character
type or `std::byte` type (17.2.1), or
   1.4. a discarded-value expression (7.2.3),
   then the result of the operation is an indeterminate value or that erroneous value, respectively.
2. If an indeterminate or erroneous value of unsigned ordinary character type or `std::byte` type is
   produced by the evaluation of the right operand of a simple assignment operator (7.6.19) whose first
   operand is an lvalue of unsigned ordinary character type or `std::byte` type, an indeterminate value or
   that erroneous value, respectively, replaces the value of the object referred to by the left operand.
3. If an indeterminate or erroneous value of unsigned ordinary character type is produced by the evaluation
   of the initialization expression when initializing an object of unsigned ordinary character type, that
   object is initialized to an indeterminate value or that erroneous value, respectively.
If an indeterminate value of unsigned ordinary character type or std::byte type is produced by the evaluation of the initialization expression when initializing an object of std::byte type, that object is initialized to an indeterminate value or that erroneous value, respectively.

Converting an indeterminate or erroneous value of unsigned ordinary character type or std::byte type produces an indeterminate or erroneous value, respectively. In the latter case, the result of the conversion is the value of the converted operand.

[Example 1:

```cpp
int f(bool b) {
    unsigned char *c = new unsigned char;
    unsigned char d = *c; // OK, d has an indeterminate value
    int e = d; // undefined behavior
    return b ? d : 0; // undefined behavior if b is true
}

int g(bool b) {
    unsigned char c;
    unsigned char d = c; // no erroneous behavior, but d has an erroneous value
    assert(c == d); // holds, both integral promotions have erroneous behavior
    int e = d; // erroneous behavior
    return b ? d : 0; // erroneous behavior if b is true
}

void h() {
    int d1, d2;
    int e1 = d1; // erroneous behavior
    int e2 = d1; // erroneous behavior
    assert(e1 == e2); // holds
    assert(e1 == d1); // holds, erroneous behavior
    assert(e2 == d1); // holds, erroneous behavior
    std::memcpy(&d2, &d1, sizeof(int)); // no erroneous behavior, but d2 has an erroneous value
    assert(e1 == d2); // holds, erroneous behavior
    assert(e2 == d2); // holds, erroneous behavior
}
```

— end example]

6.7.5 Storage duration

6.7.5.1 General

1 The storage duration is the property of an object that defines the minimum potential lifetime of the storage containing the object. The storage duration is determined by the construct used to create the object and is one of the following:

1.1 static storage duration
1.2 thread storage duration
1.3 automatic storage duration
1.4 dynamic storage duration

[Note 1: After the duration of a region of storage has ended, the use of pointers to that region of storage is limited (6.8.4). — end note]

2 Static, thread, and automatic storage durations are associated with objects introduced by declarations (6.2) and with temporary objects (6.7.7). The dynamic storage duration is associated with objects created by a new-expression (7.6.2.8) or with implicitly created objects (6.7.2).

3 The storage duration categories apply to references as well.
6.7.5.2 Static storage duration

1 All variables which

(1.1) — do not have thread storage duration and
(1.2) — belong to a namespace scope (6.4.6) or are first declared with the static or extern keywords (9.2.2) have static storage duration. The storage for these entities lasts for the duration of the program (6.9.3.2, 6.9.3.4).

2 If a variable with static storage duration has initialization or a destructor with side effects, it shall not be eliminated even if it appears to be unused, except that a class object or its copy/move may be eliminated as specified in 11.9.6.

3 [Note 1: The keyword static can be used to declare a block variable (6.4.3) with static storage duration; 8.8 and 6.9.3.4 describe the initialization and destruction of such variables. The keyword static applied to a class data member in a class definition gives the data member static storage duration (11.4.9.3). — end note]

6.7.5.3 Thread storage duration

1 All variables declared with the thread_local keyword have thread storage duration. The storage for these entities lasts for the duration of the thread in which they are created. There is a distinct object or reference per thread, and use of the declared name refers to the entity associated with the current thread.

2 [Note 1: A variable with thread storage duration is initialized as specified in 6.9.3.2, 6.9.3.3, and 8.8 and, if constructed, is destroyed on thread exit (6.9.3.4). — end note]

6.7.5.4 Automatic storage duration

1 Variables that belong to a block scope and are not explicitly declared static, thread_local, or extern have automatic storage duration. The storage for such variables lasts until the block in which they are created exits.

[Note 1: These variables are initialized and destroyed as described in 8.8. — end note]

Variables that belong to a parameter scope also have automatic storage duration. The storage for a function parameter lasts until immediately after its destruction (7.6.1.3).

2 If a variable with automatic storage duration has initialization or a destructor with side effects, an implementation shall not destroy it before the end of its block nor eliminate it as an optimization, even if it appears to be unused, except that a class object or its copy/move may be eliminated as specified in 11.9.6.

6.7.5.5 Dynamic storage duration

6.7.5.5.1 General

1 Objects can be created dynamically during program execution (6.9.1), using new-expressions (7.6.2.8), and destroyed using delete-expressions (7.6.2.9). A C++ implementation provides access to, and management of, dynamic storage via the global allocation functions operator new and operator new[] and the global deallocation functions operator delete and operator delete[].

[Note 1: The non-allocating forms described in 17.6.3.4 do not perform allocation or deallocation. — end note]

2 The library provides default definitions for the global allocation and deallocation functions. Some global allocation and deallocation functions are replaceable (17.6.3); these are attached to the global module (10.1). A C++ program shall provide at most one definition of a replaceable allocation or deallocation function. Any such function definition replaces the default version provided in the library (16.4.5.6). The following allocation and deallocation functions (17.6) are implicitly declared in global scope in each translation unit of a program.

```cpp
[[nodiscard]] void* operator new(std::size_t);
[[nodiscard]] void* operator new(std::size_t, std::align_val_t);

void operator delete(void*) noexcept;
void operator delete(void*, std::size_t) noexcept;
void operator delete(void*, std::align_val_t) noexcept;
void operator delete(void*, std::size_t, std::align_val_t) noexcept;

[[nodiscard]] void* operator new[](std::size_t);
[[nodiscard]] void* operator new[](std::size_t, std::align_val_t);
```
void operator delete[](void*) noexcept;
void operator delete[](void*, std::size_t) noexcept;
void operator delete[](void*, std::align_val_t) noexcept;
void operator delete[](void*, std::size_t, std::align_val_t) noexcept;

These implicit declarations introduce only the function names `operator new`, `operator new[]`, `operator delete`, and `operator delete[]`.

[Note 2: The implicit declarations do not introduce the names `std`, `std::size_t`, `std::align_val_t`, or any other names that the library uses to declare these names. Thus, a `new-expression`, `delete-expression`, or function call that refers to one of these functions without importing or including the header `<new>` (17.6.2) or importing a C++ library module (16.4.2.4) is well-formed. However, referring to `std` or `std::size_t` or `std::align_val_t` is ill-formed unless a standard library declaration (17.2.1, 17.6.2, 16.4.2.4) of that name precedes (6.5.1) the use of that name. —end note]

Allocation and/or deallocation functions may also be declared and defined for any class (11.4.11).

3 If the behavior of an allocation or deallocation function does not satisfy the semantic constraints specified in 6.7.5.5.2 and 6.7.5.5.3, the behavior is undefined.

6.7.5.5.2 Allocation functions [basic.stc.dynamic.allocation]

An allocation function that is not a class member function shall belong to the global scope and not have a name with internal linkage. The return type shall be `void*`. The first parameter shall have type `std::size_t` (17.2). The first parameter shall not have an associated default argument (9.3.4.7). The value of the first parameter is interpreted as the requested size of the allocation. An allocation function can be a function template. Such a template shall declare its return type and first parameter as specified above (that is, template parameter types shall not be used in the return type and first parameter type). Allocation function templates shall have two or more parameters.

2 An allocation function attempts to allocate the requested amount of storage. If it is successful, it returns the address of the start of a block of storage whose length in bytes is at least as large as the requested size. The order, contiguity, and initial value of storage allocated by successive calls to an allocation function are unspecified. Even if the size of the space requested is zero, the request can fail. If the request succeeds, the value returned by a replaceable allocation function is a non-null pointer value (6.8.4) p0 different from any previously returned value p1, unless that value p1 was subsequently passed to a replaceable deallocation function. Furthermore, for the library allocation functions in 17.6.3.2 and 17.6.3.3, p0 represents the address of a block of storage disjoint from the storage for any other object accessible to the caller. The effect of indirecting through a pointer returned from a request for zero size is undefined.24

3 For an allocation function other than a reserved placement allocation function (17.6.3.4), the pointer returned on a successful call shall represent the address of storage that is aligned as follows:

(3.1) — If the allocation function takes an argument of type `std::align_val_t`, the storage will have the alignment specified by the value of this argument.

(3.2) — Otherwise, if the allocation function is named `operator new[]`, the storage is aligned for any object that does not have new-extended alignment (6.7.6) and is no larger than the requested size.

(3.3) — Otherwise, the storage is aligned for any object that does not have new-extended alignment and is of the requested size.

4 An allocation function that fails to allocate storage can invoke the currently installed new-handler function (17.6.4.3), if any.

[Note 1: A program-supplied allocation function can obtain the currently installed `new_handler` using the `std::get_new_handler` function (17.6.4.5). —end note]

An allocation function that has a non-throwing exception specification (14.5) indicates failure by returning a null pointer value. Any other allocation function never returns a null pointer value and indicates failure only by throwing an exception (14.2) of a type that would match a handler (14.4) of type `std::bad_alloc` (17.6.4.1).

5 A global allocation function is only called as the result of a new expression (7.6.2.8), or called directly using the function call syntax (7.6.1.3), or called indirectly to allocate storage for a coroutine state (9.5.4), or called indirectly through calls to the functions in the C++ standard library.

24) The intent is to have `operator new()` implementable by calling `std::malloc()` or `std::calloc()`, so the rules are substantially the same. C++ differs from C in requiring a zero request to return a non-null pointer.
[Note 2: In particular, a global allocation function is not called to allocate storage for objects with static storage duration (6.7.5.2), for objects or references with thread storage duration (6.7.5.3), for objects of type `std::type_info` (7.6.1.8), or for an exception object (14.2). — end note]

### 6.7.5.5.3 Deallocation functions [basic.stc.dynamic.deallocation]

1. A deallocation function that is not a class member function shall belong to the global scope and not have a name with internal linkage.

2. A deallocation function is a *destroying operator delete* if it has at least two parameters and its second parameter is of type `std::destroying_delete_t`. A destroying operator delete shall be a class member function named `operator delete`.

[Note 1: Array deletion cannot use a destroying operator delete. — end note]

3. Each deallocation function shall return `void`. If the function is a destroying operator delete declared in class type `C`, the type of its first parameter shall be `C*`; otherwise, the type of its first parameter shall be `void*`. A deallocation function may have more than one parameter. A *usual deallocation function* is a deallocation function whose parameters after the first are

   - optionally, a parameter of type `std::destroying_delete_t`, then
   - optionally, a parameter of type `std::size_t`, then
   - optionally, a parameter of type `std::align_val_t`.

   A destroying operator delete shall be a usual deallocation function. A deallocation function may be an instance of a function template. Neither the first parameter nor the return type shall depend on a template parameter. A deallocation function template shall have two or more function parameters. A template instance is never a usual deallocation function, regardless of its signature.

4. If a deallocation function terminates by throwing an exception, the behavior is undefined. The value of the first argument supplied to a deallocation function may be a null pointer value; if so, and if the deallocation function is one supplied in the standard library, the call has no effect.

5. If the argument given to a deallocation function in the standard library is a pointer that is not the null pointer value (6.8.4), the deallocation function shall deallocate the storage referenced by the pointer, ending the duration of the region of storage.

### 6.7.5.6 Duration of subobjects [basic.stc.inherit]

1. The storage duration of subobjects and reference members is that of their complete object (6.7.2).

### 6.7.6 Alignment [basic.align]

1. Object types have *alignment requirements* (6.8.2, 6.8.4) which place restrictions on the addresses at which an object of that type may be allocated. An *alignment* is an implementation-defined integer value representing the number of bytes between successive addresses at which a given object can be allocated. An object type imposes an alignment requirement on every object of that type; stricter alignment can be requested using the alignment specifier (9.12.2). Attempting to create an object (6.7.2) in storage that does not meet the alignment requirements of the object’s type is undefined behavior.

2. A *fundamental alignment* is represented by an alignment less than or equal to the greatest alignment supported by the implementation in all contexts, which is equal to `alignof(std::max_align_t)` (17.2). The alignment required for a type may be different when it is used as the type of a complete object and when it is used as the type of a subobject.

[Example 1:]

```cpp
struct B { long double d; }
struct D : virtual B { char c; }
```

When `D` is the type of a complete object, it will have a subobject of type `B`, so it must be aligned appropriately for a `long double`. If `D` appears as a subobject of another object that also has `B` as a virtual base class, the `B` subobject might be part of a different subobject, reducing the alignment requirements on the `D` subobject. — end example]
The result of the `alignof` operator reflects the alignment requirement of the type in the complete-object case.

An extended alignment is represented by an alignment greater than `alignof(std::max_align_t)`. It is implementation-defined whether any extended alignments are supported and the contexts in which they are supported (9.12.2). A type having an extended alignment requirement is an over-aligned type.

[Note 1: Every over-aligned type is or contains a class type to which extended alignment applies (possibly through a non-static data member). — end note]

A new-extended alignment is represented by an alignment greater than `__STDCPP_DEFAULT_NEW_ALIGNMENT__` (15.11).

Alignments are represented as values of the type `std::size_t`. Valid alignments include only those values returned by an `alignof` expression for the fundamental types plus an additional implementation-defined set of values, which may be empty. Every alignment value shall be a non-negative integral power of two.

Alignments have an order from weaker to stronger or stricter alignments. Stricter alignments have larger alignment values. An address that satisfies an alignment requirement also satisfies any weaker valid alignment requirement.

The alignment requirement of a complete type can be queried using an `alignof` expression (7.6.2.6). Furthermore, the narrow character types (6.8.2) shall have the weakest alignment requirement.

[Note 2: This enables the ordinary character types to be used as the underlying type for an aligned memory area (9.12.2). — end note]

Comparing alignments is meaningful and provides the obvious results:

1. Two alignments are equal when their numeric values are equal.
2. Two alignments are different when their numeric values are not equal.
3. When an alignment is larger than another it represents a stricter alignment.

[Note 3: The runtime pointer alignment function (20.2.5) can be used to obtain an aligned pointer within a buffer; an alignment-specifier (9.12.2) can be used to align storage explicitly. — end note]

If a request for a specific extended alignment in a specific context is not supported by an implementation, the program is ill-formed.

### 6.7.7 Temporary objects

Temporary objects are created when a prvalue is converted to an xvalue (7.3.5) and when needed by the implementation to pass or return an object of trivially copyable type (see below).

Even when the creation of the temporary object is unevaluated (7.2.3), all the semantic restrictions shall be respected as if the temporary object had been created and later destroyed.

[Note 1: This includes accessibility (11.8) and whether it is deleted, for the constructor selected and for the destructor. However, in the special case of the operand of a `decltype-specifier` (9.2.9.6), no temporary is introduced, so the foregoing does not apply to such a prvalue. — end note]

The materialization of a temporary object is generally delayed as long as possible in order to avoid creating unnecessary temporary objects.

[Note 2: Temporary objects are materialized:
1. when binding a reference to a prvalue (9.4.4, 7.6.1.4, 7.6.1.7, 7.6.1.9, 7.6.1.11, 7.6.3),
2. when performing certain member accesses on a class prvalue (7.6.1.5, 7.6.4),
3. when invoking an implicit object member function on a class prvalue (7.6.1.3),
4. when performing an array-to-pointer conversion or subscripting on an array prvalue (7.3.3, 7.6.1.2),
5. when initializing an object of type `std::initializer_list<T>` from a braced-init-list (9.4.5),
6. for certain unevaluated operands (7.6.1.8, 7.6.2.5), and
7. when a prvalue that has type other than `cv void` appears as a discarded-value expression (7.2.3).
— end note]

[Example 1: Consider the following code:
class X {
public:
  X(int);
  X(const X&);
  X& operator=(const X&);
  ~X();
};

class Y {
public:
  Y(int);
  Y(Y&&);
  ~Y();
};

X f(X);
Y g(Y);

void h() {
  X a(1);
  X b = f(X(2));
  Y c = g(Y(3));
  a = f(a);
}

X(2) is constructed in the space used to hold f()'s argument and Y(3) is constructed in the space used to hold g()'s argument. Likewise, f()'s result is constructed directly in b and g()'s result is constructed directly in c. On the other hand, the expression a = f(a) requires a temporary for the result of f(a), which is materialized so that the reference parameter of X::operator=(const X&) can bind to it. —end example

3 When an object of class type X is passed to or returned from a potentially-evaluated function call, if X has at least one eligible copy or move constructor (11.4.4), each such constructor is trivial, and the destructor of X is either trivial or deleted, implementations are permitted to create a temporary object to hold the function parameter or result object. The temporary object is constructed from the function argument or return value, respectively, and the function's parameter or return object is initialized as if by using the eligible trivial constructor to copy the temporary (even if that constructor is inaccessible or would not be selected by overload resolution to perform a copy or move of the object).

[Note 3: This latitude is granted to allow objects of class type to be passed to or returned from functions in registers. —end note]

4 Temporary objects are destroyed as the last step in evaluating the full-expression (6.9.1) that (lexically) contains the point where they were created. This is true even if that evaluation ends in throwing an exception. The value computations and side effects of destroying a temporary object are associated only with the full-expression, not with any specific subexpression.

5 There are five contexts in which temporaries are destroyed at a different point than the end of the full-expression. The first context is when a default constructor is called to initialize an element of an array with no corresponding initializer (9.4). The second context is when a copy constructor is called to copy an element of an array while the entire array is copied (7.5.6.3, 11.4.5.3). In either case, if the constructor has one or more default arguments, the destruction of every temporary created in a default argument is sequenced before the construction of the next array element, if any.

6 The third context is when a reference binds to a temporary object. The temporary object to which the reference is bound or the temporary object that is the complete object of a subobject to which the reference is bound persists for the lifetime of the reference if the gvalue to which the reference is bound was obtained through one of the following:

(6.1) — a temporary materialization conversion (7.3.5),
(6.2) — ( expression ), where expression is one of these expressions,
(6.3) — subscripting (7.6.1.2) of an array operand, where that operand is one of these expressions,
(6.4) — a class member access (7.6.1.5) using the . operator where the left operand is one of these expressions and the right operand designates a non-static data member of non-reference type,

26) The same rules apply to initialization of an initializer_list object (9.4.5) with its underlying temporary array.
— a pointer-to-member operation (7.6.4) using the \* operator where the left operand is one of these expressions and the right operand is a pointer to data member of non-reference type,

— a

(6.6.1) \texttt{const\_cast (7.6.1.11)},

(6.6.2) \texttt{static\_cast (7.6.1.9)},

(6.6.3) \texttt{dynamic\_cast (7.6.1.7)}, or

(6.6.4) \texttt{reinterpret\_cast (7.6.1.10)}

converting, without a user-defined conversion, a glvalue operand that is one of these expressions to a glvalue that refers to the object designated by the operand, or to its complete object or a subobject thereof,

(6.7) a conditional expression (7.6.16) that is a glvalue where the second or third operand is one of these expressions, or

(6.8) a comma expression (7.6.20) that is a glvalue where the right operand is one of these expressions.

\[\text{Example 2:}\]

\begin{verbatim}
template<typename T> using id = T;

int i = 1;
int&& a = id<int[3]>\{1, 2, 3\}[i]; // temporary array has same lifetime as a
const int& b = static_cast<const int&>(0); // temporary int has same lifetime as b
int&& c = cond ? id<int[3]>\{1, 2, 3\}[i] : static_cast<int&&>(0);
// exactly one of the two temporaries is lifetime-extended
\end{verbatim}

\[\text{—end example}\]

\[\text{Note 4:} \text{ An explicit type conversion (7.6.1.4, 7.6.3) is interpreted as a sequence of elementary casts, covered above.}\]

\[\text{Example 3:}\]

\begin{verbatim}
const int& x = (const int&)1; // temporary for value 1 has same lifetime as x
\end{verbatim}

\[\text{—end example}\]

\[\text{—end note}\]

\[\text{Note 5:} \text{ If a temporary object has a reference member initialized by another temporary object, lifetime extension applies recursively to such a member’s initializer.}\]

\[\text{Example 4:}\]

\begin{verbatim}
struct S {
    const int& m;
};
const S& s = S\{1\}; // both S and int temporaries have lifetime of s
\end{verbatim}

\[\text{—end example}\]

\[\text{—end note}\]

The exceptions to this lifetime rule are:

(6.9) A temporary object bound to a reference parameter in a function call (7.6.1.3) persists until the completion of the full-expression containing the call.

(6.10) A temporary object bound to a reference element of an aggregate of class type initialized from a parenthesized expression-list (9.4) persists until the completion of the full-expression containing the expression-list.

(6.11) A temporary bound to a reference in a new-initializer (7.6.2.8) persists until the completion of the full-expression containing the new-initializer.

\[\text{Note 6:} \text{ This might introduce a dangling reference. — end note}\]

\[\text{Example 5:}\]

\begin{verbatim}
struct S { int mi; const std::pair<int, int>& mp; }; S a { int, \{2,3\} }; S* p = new S\{ 1, \{2,3\} \}; // creates dangling reference
\end{verbatim}

\[\text{—end example}\]
The fourth context is when a temporary object is created in the `for-range-initializer` of a range-based for statement. If such a temporary object would otherwise be destroyed at the end of the `for-range-initializer` full-expression, the object persists for the lifetime of the reference initialized by the `for-range-initializer`.

The fifth context is when a temporary object is created in a structured binding declaration (9.6). Any temporary objects introduced by the `initializers` for the variables with unique names are destroyed at the end of the structured binding declaration.

Let \( x \) and \( y \) each be either a temporary object whose lifetime is not extended, or a function parameter. If the lifetimes of \( x \) and \( y \) end at the end of the same full-expression, and \( x \) is initialized before \( y \), then the destruction of \( y \) is sequenced before that of \( x \). If the lifetime of two or more temporaries with lifetimes extending beyond the full-expressions in which they were created ends at the same point, these temporaries are destroyed at that point in the reverse order of the completion of their construction. In addition, the destruction of such temporaries shall take into account the ordering of destruction of objects with static, thread, or automatic storage duration (6.7.5.2, 6.7.5.3, 6.7.5.4); that is, if \( \text{obj1} \) is an object with the same storage duration as the temporary and created before the temporary is created, the temporary shall be destroyed before \( \text{obj1} \) is destroyed; if \( \text{obj2} \) is an object with the same storage duration as the temporary and created after the temporary is created, the temporary shall be destroyed after \( \text{obj2} \) is destroyed.

Example 6:

```cpp
template S
S();
S(int);
friend S operator+(const S&, const S&);
~S();
S obj1;
const S& cr = S(16)+S(23);
S obj2;
```

The expression \( S(16) + S(23) \) creates three temporaries: a first temporary \( T1 \) to hold the result of the expression \( S(16) \), a second temporary \( T2 \) to hold the result of the expression \( S(23) \), and a third temporary \( T3 \) to hold the result of the addition of these two expressions. The temporary \( T3 \) is then bound to the reference \( cr \). It is unspecified whether \( T1 \) or \( T2 \) is created first. On an implementation where \( T1 \) is created before \( T2 \), \( T2 \) shall be destroyed before \( T1 \). The temporaries \( T1 \) and \( T2 \) are bound to the reference parameters of `operator+`; these temporaries are destroyed at the end of the full-expression containing the call to `operator+`. The temporary \( T3 \) bound to the reference \( cr \) is destroyed at the end of \( cr \)'s lifetime, that is, at the end of the program. In addition, the order in which \( T3 \) is destroyed takes into account the destruction order of other objects with static storage duration. That is, because \( \text{obj1} \) is constructed before \( T3 \), and \( T3 \) is constructed before \( \text{obj2} \), \( \text{obj2} \) shall be destroyed before \( T3 \), and \( T3 \) shall be destroyed before \( \text{obj1} \).

6.8 Types [basic.types]

6.8.1 General [basic.types.general]

For any object (other than a potentially-overlapping subobject) of trivially copyable type \( T \), whether or not the object holds a valid value of type \( T \), the underlying bytes (6.7.1) making up the object can be copied into an array of `char`, `unsigned char`, or `std::byte` (17.2.1). If the content of that array is copied back into the object, the object shall subsequently hold its original value.

Example 1:

```cpp
costexpr std::size_t N = sizeof(T);
char buf[N];
T obj;
// obj initialized to its original value
std::memcpy(buf, &obj, N);
// between these two calls to std::memcpy, obj might be modified
std::memcpy(&obj, buf, N);
// at this point, each subobject of obj of scalar type holds its original value
```

Note 1: 6.8 and the subclauses thereof impose requirements on implementations regarding the representation of types. There are two kinds of types: fundamental types and compound types. Types describe objects (6.7.2), references (9.3.4.3), or functions (9.3.4.6). — end note

27) By using, for example, the library functions (16.4.2.3) `std::memcpy` or `std::memmove`. 

§ 6.8.1 ©ISO/IEC 76
For two distinct objects obj1 and obj2 of trivially copyable type T, where neither obj1 nor obj2 is a potentially-overlapping subobject, if the underlying bytes (6.7.1) making up obj1 are copied into obj2,\(^{28}\) obj2 shall subsequently hold the same value as obj1.

[Example 2:

```c
T* t1p;
T* t2p;
    // provided that t2p points to an initialized object ...
std::memcpy(t1p, t2p, sizeof(T));
    // at this point, every subobject of trivially copyable type in *t1p contains
    // the same value as the corresponding subobject in *t2p
```
— end example]

The object representation of a complete object type T is the sequence of \(N\) unsigned char objects taken up by a non-bit-field complete object of type T, where \(N\) equals `sizeof(T)`. The value representation of a type T is the set of bits in the object representation of T that participate in representing a value of type T. The object and value representation of a non-bit-field complete object of type T are the bytes and bits, respectively, of the object corresponding to the object and value representation of its type. The object representation of a bit-field object is the sequence of \(N\) bits taken up by the object, where \(N\) is the width of the bit-field (11.4.10). The value representation of a bit-field object is the set of bits in the object representation that participate in representing its value. Bits in the object representation of a type or object that are not part of the value representation are padding bits. For trivially copyable types, the value representation is a set of bits in the object representation that determines a value, which is one discrete element of an implementation-defined set of values.\(^{29}\)

A class that has been declared but not defined, an enumeration type in certain contexts (9.7.1), or an array of unknown bound or of incomplete element type, is an incompletely-defined object type.\(^{30}\) Incompletely-defined object types and `cv` `void` are incomplete types (6.8.2).

[Note 2: Objects cannot be defined to have an incomplete type (6.2). — end note]

A class type (such as “class X”) can be incomplete at one point in a translation unit and complete later on; the type “class X” is the same type at both points. The declared type of an array object can be an array of incomplete class type and therefore incomplete; if the class type is completed later on in the translation unit, the array type becomes complete; the array type at those two points is the same type. The declared type of an array object can be an array of unknown bound and therefore be incomplete at one point in a translation unit and complete later on; the array types at those two points (“array of unknown bound of T” and “array of N T”) are different types.

[Note 3: The type of a pointer or reference to array of unknown bound permanently points to or refers to an incomplete type. An array of unknown bound named by a `typedef` declaration permanently refers to an incomplete type. In either case, the array type cannot be completed. — end note]

[Example 3:

```c
class X; // X is an incomplete type
extern X* xp; // xp is a pointer to an incomplete type
typedef int arr[]; // the type of arr is incomplete
typedef int UNKA[]; // UNKA is an incomplete type
UNKA* arrp; // arrp is a pointer to an incomplete type
UNKA** arrpp;

void foo() {
    xp++; // error: X is incomplete
    arrp++; // error: incomplete type
    arrpp++; // OK; sizeof UNKA* is known
}

typedef struct X { int i; }; // now X is a complete type
int arr[10]; // now the type of arr is complete
```

\(^{28}\) By using, for example, the library functions (16.4.2.3) `std::memcpy` or `std::memmove`.

\(^{29}\) The intent is that the memory model of C++ is compatible with that of the C programming language.

\(^{30}\) The size and layout of an instance of an incompletely-defined object type is unknown.
X x;
void bar() {
    xp = &x;    // OK; type is "pointer to X"
    arrp = &arr; // OK; qualification conversion (7.3.6)
    xp++;
    // OK, X is complete
    arrp++;
    // error: UNK/ can't be completed
}
—end example]

[Note 4: The rules for declarations and expressions describe in which contexts incomplete types are prohibited. — end note]

An object type is a (possibly cv-qualified) type that is not a function type, not a reference type, and not cv void.

Arithmetic types (6.8.2), enumeration types, pointer types, pointer-to-member types (6.8.4), std::nullptr_t, and cv-qualified (6.8.5) versions of these types are collectively called scalar types. Scalar types, trivially copyable class types (11.2), arrays of such types, and cv-qualified versions of these types are collectively called trivially copyable types. Scalar types, trivial class types (11.2), arrays of such types, and cv-qualified versions of these types are collectively called trivial types. Scalar types, standard-layout class types (11.2), arrays of such types, and cv-qualified versions of these types are collectively called standard-layout types. Scalar types, implicit-lifetime class types (11.2), array types, and cv-qualified versions of these types are collectively called implicit-lifetime types.

A type is a literal type if it is:

- cv void; or
- a scalar type; or
- a reference type; or
- an array of literal type; or
- a possibly cv-qualified class type (Clause 11) that has all of the following properties:
  - it has a constexpr destructor (9.2.6),
  - all of its non-static non-variant data members and base classes are of non-volatile literal types, and
  - it
    - is a closure type (7.5.6.2),
    - is an aggregate union type that has either no variant members or at least one variant member
      of non-volatile literal type,
    - is a non-union aggregate type for which each of its anonymous union members satisfies the
      above requirements for an aggregate union type, or
    - has at least one constexpr constructor or constructor template (possibly inherited (9.9) from
      a base class) that is not a copy or move constructor.[Note 5: A literal type is one for which it might be possible to create an object within a constant expression. It is not a guarantee that it is possible to create such an object, nor is it a guarantee that any object of that type will be usable in a constant expression. — end note]

Two types cv1 T1 and cv2 T2 are layout-compatible types if T1 and T2 are the same type, layout-compatible enumerations (9.7.1), or layout-compatible standard-layout class types (11.4).

### 6.8.2 Fundamental types

There are five standard signed integer types: “signed char”, “short int”, “int”, “long int”, and “long long int”. In this list, each type provides at least as much storage as those preceding it in the list. There may also be implementation-defined extended signed integer types. The standard and extended signed integer types are collectively called signed integer types. The range of representable values for a signed integer type is \(-2^{N-1}\) to \(2^{N-1} - 1\) (inclusive), where \(N\) is called the width of the type.

[Note 1: Plain ints are intended to have the natural width suggested by the architecture of the execution environment; the other signed integer types are provided to meet special needs. — end note]

For each of the standard signed integer types, there exists a corresponding (but different) standard unsigned integer type: “unsigned char”, “unsigned short int”, “unsigned int”, “unsigned long int”, “unsigned long long int”.

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and "unsigned long long int". Likewise, for each of the extended signed integer types, there exists a corresponding extended unsigned integer type. The standard and extended unsigned integer types are collectively called unsigned integer types. An unsigned integer type has the same width $N$ as the corresponding signed integer type. The range of representable values for the unsigned type is $0$ to $2^N - 1$ (inclusive); arithmetic for the unsigned type is performed modulo $2^N$.

[Note 2: Unsigned arithmetic does not overflow. Overflow for signed arithmetic yields undefined behavior (7.1). — end note]

An unsigned integer type has the same object representation, value representation, and alignment requirements (6.7.6) as the corresponding signed integer type. For each value $x$ of a signed integer type, the value of the corresponding unsigned integer type congruent to $x$ modulo $2^N$ has the same value of corresponding bits in its value representation.\footnote{This is also known as two's complement representation.}

[Example 1: The value $-1$ of a signed integer type has the same representation as the largest value of the corresponding unsigned type. — end example]

### Table 14 — Minimum width

<table>
<thead>
<tr>
<th>Type</th>
<th>Minimum width $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signed char</td>
<td>8</td>
</tr>
<tr>
<td>short int</td>
<td>16</td>
</tr>
<tr>
<td>int</td>
<td>16</td>
</tr>
<tr>
<td>long int</td>
<td>32</td>
</tr>
<tr>
<td>long long int</td>
<td>64</td>
</tr>
</tbody>
</table>

The width of each standard signed integer type shall not be less than the values specified in Table 14. The value representation of a signed or unsigned integer type comprises $N$ bits, where $N$ is the respective width. Each set of values for any padding bits (6.8.1) in the object representation are alternative representations of the value specified by the value representation.

[Note 3: Padding bits have unspecified value, but cannot cause traps. In contrast, see ISO/IEC 9899:2018 6.2.6.2. — end note]

[Note 4: The signed and unsigned integer types satisfy the constraints given in ISO/IEC 9899:2018 5.2.4.2.1. — end note]

Except as specified above, the width of a signed or unsigned integer type is implementation-defined.

Each value $x$ of an unsigned integer type with width $N$ has a unique representation $x = x_0 2^0 + x_1 2^1 + \ldots + x_{N-1} 2^{N-1}$, where each coefficient $x_i$ is either 0 or 1; this is called the base-2 representation of $x$. The base-2 representation of a value of signed integer type is the base-2 representation of the congruent value of the corresponding unsigned integer type. The standard signed integer types and standard unsigned integer types are collectively called the standard integer types, and the extended signed integer types and extended unsigned integer types are collectively called the extended integer types.

A fundamental type specified to have a signed or unsigned integer type as its underlying type has the same object representation, value representation, alignment requirements (6.7.6), and range of representable values as the underlying type. Further, each value has the same representation in both types.

Type `char` is a distinct type that has an implementation-defined choice of “signed char” or “unsigned char” as its underlying type. The three types `char`, `signed char`, and `unsigned char` are collectively called ordinary character types. The ordinary character types and `char8_t` are collectively called narrow character types. For narrow character types, each possible bit pattern of the object representation represents a distinct value.

[Note 5: This requirement does not hold for other types. — end note]

[Note 6: A bit-field of narrow character type whose width is larger than the width of that type has padding bits; see 6.8.1. — end note]

Type `wchar_t` is a distinct type that has an implementation-defined signed or unsigned integer type as its underlying type.
Type `char8_t` denotes a distinct type whose underlying type is `unsigned char`. Types `char16_t` and `char32_t` denote distinct types whose underlying types are `uint_least16_t` and `uint_least32_t`, respectively, in `<cstdint>` (17.4.1).

Type `bool` is a distinct type that has the same object representation, value representation, and alignment requirements as an implementation-defined unsigned integer type. The values of type `bool` are `true` and `false`.

[Note 7: There are no `signed`, `unsigned`, `short`, or `long` `bool` types or values. — end note]

The types `char`, `wchar_t`, `char8_t`, `char16_t`, and `char32_t` are collectively called `character types`. The character types, `bool`, the signed and unsigned integer types, and cv-qualified versions (6.8.5) thereof, are collectively termed `integral types`. A synonym for integral type is `integer type`.

[Note 8: Enumerations (9.7.1) are not integral; however, unscoped enumerations can be promoted to integral types as specified in 7.3.7. — end note]

The three distinct types `float`, `double`, and `long double` can represent floating-point numbers. The type `double` provides at least as much precision as `float`, and the type `long double` provides at least as much precision as `double`. The set of values of the type `float` is a subset of the set of values of the type `double`; the set of values of the type `double` is a subset of the set of values of the type `long double`. The types `float`, `double`, and `long double`, and cv-qualified versions (6.8.5) thereof, are collectively termed `standard floating-point types`. An implementation may also provide additional types that represent floating-point values and define them (and cv-qualified versions thereof) to be `extended floating-point types`. The standard and extended floating-point types are collectively termed `floating-point types`.

[Note 9: Any additional implementation-specific types representing floating-point values that are not defined by the implementation to be extended floating-point types are not considered to be floating-point types, and this document imposes no requirements on them or their interactions with floating-point types. — end note]

Except as specified in 6.8.3, the object and value representations and accuracy of operations of floating-point types are implementation-defined.

The minimum range of representable values for a floating-point type is the most negative finite floating-point number representable in that type through the most positive finite floating-point number representable in that type. In addition, if negative infinity is representable in a type, the range of that type is extended to all negative real numbers; likewise, if positive infinity is representable in a type, the range of that type is extended to all positive real numbers.

[Note 10: Since negative and positive infinity are representable in ISO/IEC 60559 formats, all real numbers lie within the range of representable values of a floating-point type adhering to ISO/IEC 60559. — end note]

Integral and floating-point types are collectively termed `arithmetic types`.

[Note 11: Properties of the arithmetic types, such as their minimum and maximum representable value, can be queried using the facilities in the standard library headers `<limits>` (17.3.3), `<climits>` (17.3.6), and `<cfloat>` (17.3.7). — end note]

A type `cv void` is an incomplete type that cannot be completed; such a type has an empty set of values. It is used as the return type for functions that do not return a value. Any expression can be explicitly converted to type `cv void` (7.6.1.4, 7.6.1.9, 7.6.3). An expression of type `cv void` shall be used only as an expression statement (8.3), as an operand of a comma expression (7.6.20), as a second or third operand of `?:` (7.6.16), as the operand of `typeid`, `noexcept`, or `decltype`, as the expression in a `return` statement (8.7.4) for a function with the return type `cv void`, or as the operand of an explicit conversion to type `cv void`.

The types denoted by `cv std::nullptr_t` are distinct types. A value of type `std::nullptr_t` is a null pointer constant (7.3.12). Such values participate in the pointer and the pointer-to-member conversions (7.3.12, 7.3.13). `sizeof(std::nullptr_t)` shall be equal to `sizeof(void*)`.

The types described in this subclause are called `fundamental types`.

[Note 12: Even if the implementation defines two or more fundamental types to have the same value representation, they are nevertheless different types. — end note]

### 6.8.3 Optional extended floating-point types

If the implementation supports an extended floating-point type (6.8.2) whose properties are specified by the ISO/IEC 60559 floating-point interchange format binary16, then the `typedef-name std::float16_t` is defined in the header `<stdfloat>` (17.4.2) and names such a type, the macro `__STDCPP_FLOAT16_T__` is defined (15.11), and the floating-point literal suffixes `f16` and `F16` are supported (5.13.4).
If the implementation supports an extended floating-point type whose properties are specified by the ISO/IEC 60559 floating-point interchange format binary32, then the typedef-name std::float32_t is defined in the header <stdfloat> and names such a type, the macro __STDCPP_FLOAT32_T__ is defined, and the floating-point literal suffixes f32 and F32 are supported.

If the implementation supports an extended floating-point type whose properties are specified by the ISO/IEC 60559 floating-point interchange format binary64, then the typedef-name std::float64_t is defined in the header <stdfloat> and names such a type, the macro __STDCPP_FLOAT64_T__ is defined, and the floating-point literal suffixes f64 and F64 are supported.

If the implementation supports an extended floating-point type whose properties are specified by the ISO/IEC 60559 floating-point interchange format binary128, then the typedef-name std::float128_t is defined in the header <stdfloat> and names such a type, the macro __STDCPP_FLOAT128_T__ is defined, and the floating-point literal suffixes f128 and F128 are supported.

If the implementation supports an extended floating-point type with the properties, as specified by ISO/IEC 60559, of radix \( b \) of 2, storage width in bits \( k \) of 16, precision in bits \( p \) of 8, maximum exponent \( e_{\text{max}} \) of 127, and exponent field width in bits \( w \) of 8, then the typedef-name std::bfloat16_t is defined in the header <stdfloat> and names such a type, the macro __STDCPP_BFLOAT16_T__ is defined, and the floating-point literal suffixes bf16 and BF16 are supported.

[Note 1: A summary of the parameters for each type is given in Table 15. The precision \( p \) includes the implicit 1 bit at the beginning of the significand, so the storage used for the significand is \( p - 1 \) bits. ISO/IEC 60559 does not assign a name for a type having the parameters specified for std::bfloat16_t. — end note]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>float16_t</th>
<th>float32_t</th>
<th>float64_t</th>
<th>float128_t</th>
<th>bfloat16_t</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO/IEC 60559 name</td>
<td>binary16</td>
<td>binary32</td>
<td>binary64</td>
<td>binary128</td>
<td></td>
</tr>
<tr>
<td>( k ), storage width in bits</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>128</td>
<td>16</td>
</tr>
<tr>
<td>( p ), precision in bits</td>
<td>11</td>
<td>24</td>
<td>53</td>
<td>113</td>
<td>8</td>
</tr>
<tr>
<td>( e_{\text{max}} ), maximum exponent</td>
<td>15</td>
<td>127</td>
<td>1023</td>
<td>16383</td>
<td>127</td>
</tr>
<tr>
<td>( w ), exponent field width in bits</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Recommended practice: Any names that the implementation provides for the extended floating-point types described in this subsection that are in addition to the names defined in the <stdfloat> header should be chosen to increase compatibility and interoperability with the interchange types _Float16, _Float32, _Float64, and _Float128 defined in ISO/IEC TS 18661-3 and with future versions of ISO/IEC 9899.

### 6.8.4 Compound types

Compound types can be constructed in the following ways:

1. **arrays** of objects of a given type, 9.3.4.5;
2. **functions**, which have parameters of given types and return void or references or objects of a given type, 9.3.4.6;
3. **pointers** to cv void or objects or functions (including static members of classes) of a given type, 9.3.4.2;
4. **references** to objects or functions of a given type, 9.3.4.3. There are two types of references:
   1.4.1 **lvalue reference**
   1.4.2 **rvalue reference**
5. **classes** containing a sequence of objects of various types (Clause 11), a set of types, enumerations and functions for manipulating these objects (11.4.2), and a set of restrictions on the access to these entities (11.8);
6. **unions**, which are classes capable of containing objects of different types at different times, 11.5;
7. **enumerations**, which comprise a set of named constant values, 9.7.1;
(1.8) — *pointers to non-static class members*,\(^{32}\) which identify members of a given type within objects of a
given class, 9.3.4.4. Pointers to data members and pointers to member functions are collectively called
*pointer-to-member* types.

2 These methods of constructing types can be applied recursively; restrictions are mentioned in 9.3.4. Construct-
uring a type such that the number of bytes in its object representation exceeds the maximum value
representable in the type `std::size_t` (17.2) is ill-formed.

3 The type of a pointer to `cv void` or a pointer to an object type is called an *object pointer type*.

   [Note 1: A pointer to `void` does not have a pointer-to-object type, however, because `void` is not an object type.
— end note]

   The type of a pointer that can designate a function is called a *function pointer type*. A pointer to an object
   of type `T` is referred to as a “pointer to `T`”.

   [Example 1: A pointer to an object of type `int` is referred to as “pointer to `int`” and a pointer to an object of class `X`
is called a “pointer to `X`”. — end example]

Except for pointers to static members, text referring to “pointers” does not apply to pointers to members.
Pointers to incomplete types are allowed although there are restrictions on what can be done with them (6.8.1).
Every value of pointer type is one of the following:

1. a *pointer to an object or function* (the pointer is said to *point* to the object or function), or
2. a *pointer past the end of an object* (7.6.6), or
3. the *null pointer value* for that type, or
4. an *invalid pointer value*.

A value of a pointer type that is a pointer to or past the end of an object *represents the address* of the first
byte in memory (6.7.1) occupied by the object\(^{33}\) or the first byte in memory after the end of the storage
occupied by the object, respectively.

   [Note 2: A pointer past the end of an object (7.6.6) is not considered to point to an unrelated object of the object’s
type, even if the unrelated object is located at that address. — end note]

For purposes of pointer arithmetic (7.6.6) and comparison (7.6.9, 7.6.10), a pointer past the end of the
last element of an array `x` of `n` elements is considered to be equivalent to a pointer to a hypothetical array
element `n` of `x` and an object of type `T` that is not an array element is considered to belong to an array
with one element of type `T`. The value representation of pointer types is implementation-defined. Pointers to
layout-compatible types shall have the same value representation and alignment requirements (6.7.6).

   [Note 3: Pointers to over-aligned types (6.7.6) have no special representation, but their range of valid values is
restricted by the extended alignment requirement. — end note]

4 A pointer value `P` is *valid in the context* of an evaluation `E` if `P` is a null pointer value, or if it is a pointer
to or past the end of an object `O` and `E` happens before the end of the duration of the region of storage
for `O`. If a pointer value `P` is used in an evaluation `E` and `P` is not valid in the context of `E`, then the
behavior is undefined if `E` is an indirection (7.6.2.2) or an invocation of a deallocation function (6.7.5.5.3),
and implementation-defined otherwise.\(^{34}\)

   [Note 4: `P` can be valid in the context of `E` even if it points to a type unrelated to that of `O` or if `O` is not within its
lifetime, although further restrictions apply to such pointer values (6.7.3, 7.2.1, 7.6.6). — end note]

5 Two objects `a` and `b` are *pointer-interconvertible* if

    1. they are the same object, or
    2. one is a union object and the other is a non-static data member of that object (11.5), or
    3. one is a standard-layout class object and the other is the first non-static data member of that object
        or any base class subobject of that object (11.4), or
    4. there exists an object `c` such that `a` and `c` are pointer-interconvertible, and `c` and `b` are pointer-
        interconvertible.

If two objects are pointer-interconvertible, then they have the same address, and it is possible to obtain a
pointer to one from a pointer to the other via a `reinterpret_cast` (7.6.1.10).

---

\(^{32}\) Static class members are objects or functions, and pointers to them are ordinary pointers to objects or functions.

\(^{33}\) For an object that is not within its lifetime, this is the first byte in memory that it will occupy or used to occupy.

\(^{34}\) Some implementations might define that copying such a pointer value causes a system-generated runtime fault.
[Note 5: An array object and its first element are not pointer-interconvertible, even though they have the same address. — end note]

6 A byte of storage \( b \) is reachable through a pointer value that points to an object \( x \) if there is an object \( y \), pointer-interconvertible with \( x \), such that \( b \) is within the storage occupied by \( y \), or the immediately-enclosing array object if \( y \) is an array element.

7 A pointer to \( cv \ void \) can be used to point to objects of unknown type. Such a pointer shall be able to hold any object pointer. An object of type “pointer to \( cv \ void \)” shall have the same representation and alignment requirements as an object of type “pointer to \( cv \ char \)”.

### 6.8.5 CV-qualifiers [basic.type.qualifier]

1 Each type other than a function or reference type is part of a group of four distinct, but related, types: a \( cv \)-unqualified version, a \( const \)-qualified version, a \( volatile \)-qualified version, and a \( const \), \( volatile \)-qualified version. The types in each such group shall have the same representation and alignment requirements (6.7.6).\(^{35}\)

A function or reference type is always \( cv \)-unqualified.

(1.1) — A \( const \) object is an object of type \( const \ T \) or a non-mutable subobject of a \( const \) object.

(1.2) — A \( volatile \) object is an object of type \( volatile \ T \) or a subobject of a \( volatile \) object.

(1.3) — A \( const \), \( volatile \) object is an object of type \( const \ volatile \ T \), a non-mutable subobject of a \( const \) \( volatile \) object, a \( const \) subobject of a \( volatile \) object, or a non-mutable \( volatile \) subobject of a \( const \) object.

[Note 1: The type of an object (6.7.2) includes the \( cv \)-qualifiers specified in the decl-specifier-seq (9.2), declarator (9.3), type-id (9.3.2), or new-type-id (7.6.2.8) when the object is created. — end note]

2 Except for array types, a compound type (6.8.4) is not \( cv \)-qualified by the \( cv \)-qualifiers (if any) of the types from which it is compounded.

3 An array type whose elements are \( cv \)-qualified is also considered to have the same \( cv \)-qualifications as its elements.

[Note 2: \( cv \)-qualifiers applied to an array type attach to the underlying element type, so the notation “\( cv \ T \)” where \( T \) is an array type, refers to an array whose elements are so-qualified (9.3.4.5). — end note]

[Example 1:

typedef char CA[5];
typedef const char CC;
CC arr1[5] = { 0 };
const CA arr2 = { 0 };

The type of both \( arr1 \) and \( arr2 \) is “array of 5 \( const \ char \)”, and the array type is considered to be \( const \)-qualified. — end example]

4 [Note 3: See 9.3.4.6 and 12.2.2 regarding function types that have \( cv \)-qualifiers. — end note]

5 There is a partial ordering on \( cv \)-qualifiers, so that a type can be said to be more \( cv \)-qualified than another. Table 16 shows the relations that constitute this ordering.

#### Table 16 — Relations on \( const \) and \( volatile \) [tab:basic.type.qualifier.rel]

<table>
<thead>
<tr>
<th>no ( cv )-qualifier</th>
<th>( const )</th>
</tr>
</thead>
<tbody>
<tr>
<td>no ( cv )-qualifier</td>
<td>( volatile )</td>
</tr>
<tr>
<td>( const )</td>
<td>( const ), ( volatile )</td>
</tr>
<tr>
<td>( volatile )</td>
<td>( const ), ( volatile )</td>
</tr>
</tbody>
</table>

6 In this document, the notation \( cv \) (or \( cv1 \), \( cv2 \), etc.), used in the description of types, represents an arbitrary set of \( cv \)-qualifiers, i.e., one of \{\( const \}\}, \{\( volatile \}\}, \{\( const \), \( volatile \}\}, or the empty set. For a type \( cv \ T \), the top-level \( cv \)-qualifiers of that type are those denoted by \( cv \).

[Example 2: The type corresponding to the type-id \( const \ int \) \( * const \) has no top-level \( cv \)-qualifiers. The type corresponding to the type-id \( volatile \ int \) \( * const \) has the top-level \( cv \)-qualifier \( const \). For a class type \( C \), the type corresponding to the type-id \( void \) \( (C::*) volatile\)(int) \( const \) has the top-level \( cv \)-qualifier \( volatile \). — end example]

\(^{35}\) The same representation and alignment requirements are meant to imply interchangeability as arguments to functions, return values from functions, and non-static data members of unions.
6.8.6 Conversion ranks

1 Every integer type has an integer conversion rank defined as follows:

   (1.1) No two signed integer types other than char and signed char (if char is signed) have the same rank, even if they have the same representation.

   (1.2) The rank of a signed integer type is greater than the rank of any signed integer type with a smaller width.

   (1.3) The rank of long long int is greater than the rank of long int, which is greater than the rank of int, which is greater than the rank of short int, which is greater than the rank of signed char.

   (1.4) The rank of any unsigned integer type equals the rank of the corresponding signed integer type.

   (1.5) The rank of any standard integer type is greater than the rank of any extended integer type with the same width.

   (1.6) The rank of char equals the rank of signed char and unsigned char.

   (1.7) The rank of bool is less than the rank of all standard integer types.

   (1.8) The ranks of char8_t, char16_t, char32_t, and wchar_t equal the ranks of their underlying types (6.8.2).

   (1.9) The rank of any extended signed integer type relative to another extended signed integer type with the same width is implementation-defined, but still subject to the other rules for determining the integer conversion rank.

   (1.10) For all integer types T1, T2, and T3, if T1 has greater rank than T2 and T2 has greater rank than T3, then T1 has greater rank than T3.

[Note 1: The integer conversion rank is used in the definition of the integral promotions (7.3.7) and the usual arithmetic conversions (7.4). — end note]

2 Every floating-point type has a floating-point conversion rank defined as follows:

   (2.1) The rank of a floating point type T is greater than the rank of any floating-point type whose set of values is a proper subset of the set of values of T.

   (2.2) The rank of long double is greater than the rank of double, which is greater than the rank of float.

   (2.3) Two extended floating-point types with the same set of values have equal ranks.

   (2.4) An extended floating-point type with the same set of values as exactly one cv-unqualified standard floating-point type has a rank equal to the rank of that standard floating-point type.

   (2.5) An extended floating-point type with the same set of values as more than one cv-unqualified standard floating-point type has a rank equal to the rank of double.

[Note 2: The treatment of std::float64_t differs from that of the analogous _Float64 in C, for example on platforms where all of long double, double, and std::float64_t have the same set of values (see ISO/IEC 9899:2024 H.4.2). — end note]

[Note 3: The conversion ranks of floating-point types T1 and T2 are unordered if the set of values of T1 is neither a subset nor a superset of the set of values of T2. This can happen when one type has both a larger range and a lower precision than the other. — end note]

3 Floating-point types that have equal floating-point conversion ranks are ordered by floating-point conversion subrank. The subrank forms a total order among types with equal ranks. The types std::float16_t, std::float32_t, std::float64_t, and std::float128_t (17.4.2) have a greater conversion subrank than any standard floating-point type with equal conversion rank. Otherwise, the conversion subrank order is implementation-defined.

[Note 4: The floating-point conversion rank and subrank are used in the definition of the usual arithmetic conversions (7.4). — end note]

6.9 Program execution

6.9.1 Sequential execution

An instance of each object with automatic storage duration (6.7.5.4) is associated with each entry into its block. Such an object exists and retains its last-stored value during the execution of the block and while the block is suspended (by a call of a function, suspension of a coroutine (7.6.2.4), or receipt of a signal).
A constituent expression is defined as follows:

(2.1) The constituent expression of an expression is that expression.

(2.2) The constituent expression of a conversion is the corresponding implicit function call, if any, or the converted expression otherwise.

(2.3) The constituent expressions of a braced-init-list or of a (possibly parenthesized) expression-list are the constituent expressions of the elements of the respective list.

(2.4) The constituent expressions of a brace-or-equal-initializer of the form = initializer-clause are the constituent expressions of the initializer-clause.

Example 1:

```c
struct A { int x; }
struct B { int y; struct A a; }
B b = { 5, { 1+1 } };
```

The constituent expressions of the initializer used for the initialization of b are 5 and 1+1.

The immediate subexpressions of an expression E are

(3.1) the constituent expressions of E's operands (7.2),

(3.2) any function call that E implicitly invokes,

(3.3) if E is a lambda-expression (7.5.6), the initialization of the entities captured by copy and the constituent expressions of the initializer of the init-captures,

(3.4) if E is a function call (7.6.1.3) or implicitly invokes a function, the constituent expressions of each default argument (9.3.4.7) used in the call, or

(3.5) if E creates an aggregate object (9.4.2), the constituent expressions of each default member initializer (11.4) used in the initialization.

Note 1: Expressions appearing in the compound-statement of a lambda-expression are not subexpressions of the lambda-expression.

The potentially-evaluated subexpressions of an expression, conversion, or initializer E are

(4.1) the constituent expressions of E and

(4.2) the subexpressions thereof that are not subexpressions of a nested unevaluated operand (7.2.3).

A full-expression is

(5.1) an unevaluated operand (7.2.3),

(5.2) a constant-expression (7.7),

(5.3) an immediate invocation (7.7),

(5.4) an init-declarator (9.3) (including such introduced by a structured binding (9.6)) or a mem-initializer (11.9.3), including the constituent expressions of the initializer,

(5.5) an invocation of a destructor generated at the end of the lifetime of an object other than a temporary object (6.7.7) whose lifetime has not been extended, or

(5.6) an expression that is not a subexpression of another expression and that is not otherwise part of a full-expression.

If a language construct is defined to produce an implicit call of a function, a use of the language construct is considered to be an expression for the purposes of this definition. Conversions applied to the result of an expression in order to satisfy the requirements of the language construct in which the expression appears are also considered to be part of the full-expression. For an initializer, performing the initialization of the entity (including evaluating default member initializers of an aggregate) is also considered part of the full-expression.

Example 2:

```c
struct S { 
    S(int i): I(i) { } // full-expression is initialization of I
    int& v() { return I; } 
    ~S() noexcept(false) { } 
} 
```
private:
    int I;
};

S s1(1);  // full-expression comprises call of S::S(int)
void f() {
    S s2 = 2;  // full-expression comprises call of S::S(int)
    if (S(3).v())  // full-expression includes lvalue-to-rvalue and int to bool conversions,
        // performed before temporary is deleted at end of full-expression
    {
    }
    bool b = noexcept(S(4));  // exception specification of destructor of S considered for noexcept
    // full-expression is destruction of s2 at end of block
}

struct B {
    B(S = S(0));
};

B b[2] = { B(), B() };  // full-expression is the entire initialization
    // including the destruction of temporaries

— end example]  

6 [Note 8: The evaluation of a full-expression can include the evaluation of subexpressions that are not lexically part of the full-expression. For example, subexpressions involved in evaluating default arguments (9.3.4.7) are considered to be created in the expression that calls the function, not the expression that defines the default argument. — end note]

7 Reading an object designated by a volatile glvalue (7.2.1), modifying an object, calling a library I/O function, or calling a function that does any of those operations are all side effects, which are changes in the state of the execution environment. Evaluation of an expression (or a subexpression) in general includes both value computations (including determining the identity of an object for glvalue evaluation and fetching a value previously assigned to an object for prvalue evaluation) and initiation of side effects. When a call to a library I/O function returns or an access through a volatile glvalue is evaluated, the side effect is considered complete, even though some external actions implied by the call (such as the I/O itself) or by the volatile access may not have completed yet.

8 Sequenced before is an asymmetric, transitive, pair-wise relation between evaluations executed by a single thread (6.9.2), which induces a partial order among those evaluations. Given any two evaluations A and B, if A is sequenced before B (or, equivalently, B is sequenced after A), then the execution of A shall precede the execution of B. If A is not sequenced before B and B is not sequenced before A, then A and B are unsequenced.

[Note 3: The execution of unsequenced evaluations can overlap. — end note]

Evaluations A and B are indeterminately sequenced when either A is sequenced before B or B is sequenced before A, but it is unspecified which.

[Note 4: Indeterminately sequenced evaluations cannot overlap, but either can be executed first. — end note]

An expression X is said to be sequenced before an expression Y if every value computation and every side effect associated with the expression X is sequenced before every value computation and every side effect associated with the expression Y.

9 Every value computation and side effect associated with a full-expression is sequenced before every value computation and side effect associated with the next full-expression to be evaluated.56

10 Except where noted, evaluations of operands of individual operators and of subexpressions of individual expressions are unsequenced.

[Note 5: In an expression that is evaluated more than once during the execution of a program, unsequenced and indeterminately sequenced evaluations of its subexpressions need not be performed consistently in different evaluations. — end note]

The value computations of the operands of an operator are sequenced before the value computation of the result of the operator. If a side effect on a memory location (6.7.1) is unsequenced relative to either another side effect on the same memory location or a value computation using the value of any object in the same memory location, and they are not potentially concurrent (6.9.2), the behavior is undefined.

56) As specified in 6.7.7, after a full-expression is evaluated, a sequence of zero or more invocations of destructor functions for temporary objects takes place, usually in reverse order of the construction of each temporary object.

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[Note 6: The next subclause imposes similar, but more complex restrictions on potentially concurrent computations. —end note] 

[Example 3:]

```c
void g(int i) {
    i = 7, i++, i++; // i becomes 9
    i = i++ + 1; // the value of i is incremented
    i = i++ + i; // undefined behavior
    i = i + 1; // the value of i is incremented
}
—end example]
```

11 When invoking a function (whether or not the function is inline), every argument expression and the postfix expression designating the called function are sequenced before every expression or statement in the body of the called function. For each function invocation or evaluation of an `await-expression F`, each evaluation that does not occur within `F` but is evaluated on the same thread and as part of the same signal handler (if any) is either sequenced before all evaluations that occur within `F` or sequenced after all evaluations that occur within `F`\(^{37}\) if `F` invokes or resumes a coroutine (7.6.2.4), only evaluations subsequent to the previous suspension (if any) and prior to the next suspension (if any) are considered to occur within `F`.

Several contexts in C++ cause evaluation of a function call, even though no corresponding function call syntax appears in the translation unit.

[Example 4: Evaluation of a `new-expression` invokes one or more allocation and constructor functions; see 7.6.2.8. For another example, invocation of a conversion function (11.4.8.3) can arise in contexts in which no function call syntax appears. —end example]

The sequencing constraints on the execution of the called function (as described above) are features of the function calls as evaluated, regardless of the syntax of the expression that calls the function.

12 If a signal handler is executed as a result of a call to the `std::raise` function, then the execution of the handler is sequenced after the invocation of the `std::raise` function and before its return.

[Note 7: When a signal is received for another reason, the execution of the signal handler is usually unsequenced with respect to the rest of the program. —end note] 

### 6.9.2 Multi-threaded executions and data races

#### 6.9.2.1 General

A thread of execution (also known as a thread) is a single flow of control within a program, including the initial invocation of a specific top-level function, and recursively including every function invocation subsequently executed by the thread.

[Note 1: When one thread creates another, the initial call to the top-level function of the new thread is executed by the new thread, not by the creating thread. —end note]

Every thread in a program can potentially access every object and function in a program.\(^{38}\) Under a hosted implementation, a C++ program can have more than one thread running concurrently. The execution of each thread proceeds as defined by the remainder of this document. The execution of the entire program consists of an execution of all of its threads.

[Note 2: Usually the execution can be viewed as an interleaving of all its threads. However, some kinds of atomic operations, for example, allow executions inconsistent with a simple interleaving, as described below. —end note]

Under a freestanding implementation, it is implementation-defined whether a program can have more than one thread of execution.

For a signal handler that is not executed as a result of a call to the `std::raise` function, it is unspecified which thread of execution contains the signal handler invocation.

#### 6.9.2.2 Data races

The value of an object visible to a thread `T` at a particular point is the initial value of the object, a value assigned to the object by `T`, or a value assigned to the object by another thread, according to the rules below.

37) In other words, function executions do not interleave with each other.

38) An object with automatic or thread storage duration (6.7.5) is associated with one specific thread, and can be accessed by a different thread only indirectly through a pointer or reference (6.8.4).
[Note 1: In some cases, there might instead be undefined behavior. Much of this subclause is motivated by the desire to support atomic operations with explicit and detailed visibility constraints. However, it also implicitly supports a simpler view for more restricted programs. — end note]

2 Two expression evaluations conflict if one of them modifies a memory location (6.7.1) and the other one reads or modifies the same memory location.

3 The library defines a number of atomic operations (33.5) and operations on mutexes (Clause 33) that are specially identified as synchronization operations. These operations play a special role in making assignments in one thread visible to another. A synchronization operation on one or more memory locations is either a consume operation, an acquire operation, a release operation, or both an acquire and release operation. A synchronization operation without an associated memory location is a fence and can be either an acquire fence, a release fence, or both an acquire and release fence. In addition, there are relaxed atomic operations, which are not synchronization operations, and atomic read-modify-write operations, which have special characteristics.

[Note 2: For example, a call that acquires a mutex will perform an acquire operation on the locations comprising the mutex. Correspondingly, a call that releases the same mutex will perform a release operation on those same locations. Informally, performing a release operation on A forces prior side effects on other memory locations to become visible to other threads that later perform a consume or an acquire operation on A. “Relaxed” atomic operations are not synchronization operations even though, like synchronization operations, they cannot contribute to data races. — end note]

4 All modifications to a particular atomic object M occur in some particular total order, called the modification order of M.

[Note 3: There is a separate order for each atomic object. There is no requirement that these can be combined into a single total order for all objects. In general this will be impossible since different threads can observe modifications to different objects in inconsistent orders. — end note]

5 A release sequence headed by a release operation A on an atomic object M is a maximal contiguous subsequence of side effects in the modification order of M, where the first operation is A, and every subsequent operation is an atomic read-modify-write operation.

6 Certain library calls synchronize with other library calls performed by another thread. For example, an atomic store-release synchronizes with a load-acquire that takes its value from the store (33.5.4).

[Note 4: Except in the specified cases, reading a later value does not necessarily ensure visibility as described below. Such a requirement would sometimes interfere with efficient implementation. — end note]

[Note 5: The specifications of the synchronization operations define when one reads the value written by another. For atomic objects, the definition is clear. All operations on a given mutex occur in a single total order. Each mutex acquisition “reads the value written” by the last mutex release. — end note]

7 An evaluation A carries a dependency to an evaluation B if

(7.1) — the value of A is used as an operand of B, unless:

(7.1.1) — B is an invocation of any specialization of std::kill_dependency (33.5.4), or

(7.1.2) — A is the left operand of a built-in logical AND (&&, see 7.6.14) or logical OR (||, see 7.6.15) operator, or

(7.1.3) — A is the left operand of a conditional (?:, see 7.6.16) operator, or

(7.1.4) — A is the left operand of the built-in comma (,) operator (7.6.20); or

(7.2) — A writes a scalar object or bit-field M, B reads the value written by A from M, and A is sequenced before B, or

(7.3) — for some evaluation X, A carries a dependency to X, and X carries a dependency to B.

[Note 6: “Carries a dependency to” is a subset of “is sequenced before”, and is similarly strictly intra-thread. — end note]

8 An evaluation A is dependency-ordered before an evaluation B if

(8.1) — A performs a release operation on an atomic object M, and, in another thread, B performs a consume operation on M and reads the value written by A, or

(8.2) — for some evaluation X, A is dependency-ordered before X and X carries a dependency to B.
An evaluation \( A \) \textit{inter-thread happens before} an evaluation \( B \) if

\begin{enumerate}
\item[(9.1)] \( A \) synchronizes with \( B \), or
\item[(9.2)] \( A \) is dependency-ordered before \( B \), or
\item[(9.3)] for some evaluation \( X \)
\begin{enumerate}
\item[(9.3.1)] \( A \) synchronizes with \( X \) and \( X \) is sequenced before \( B \), or
\item[(9.3.2)] \( A \) is sequenced before \( X \) and \( X \) inter-thread happens before \( B \), or
\item[(9.3.3)] \( A \) inter-thread happens before \( X \) and \( X \) inter-thread happens before \( B \).
\end{enumerate}
\end{enumerate}

\[ \text{Note 8: The “inter-thread happens before” relation describes arbitrary concatenations of “sequenced before”, “synchronizes with” and “dependency-ordered before” relationships, with two exceptions. The first exception is that a concatenation never ends with “dependency-ordered before” followed by “sequenced before”. The reason for this limitation is that a consume operation participating in a “dependency-ordered before” relationship provides ordering only with respect to operations to which this consume operation actually carries a dependency. The reason that this limitation applies only to the end of such a concatenation is that any subsequent release operation will provide the required ordering for a prior consume operation. The second exception is that a concatenation never consist entirely of “sequenced before”. The reasons for this limitation are (1) to permit “inter-thread happens before” to be transitively closed and (2) the “happens before” relation, defined below, provides for relationships consisting entirely of “sequenced before”.} \] — end note

An evaluation \( A \) \textit{happens before} an evaluation \( B \) (or, equivalently, \( B \) \textit{happens after} \( A \)) if

\begin{enumerate}
\item[(10.1)] \( A \) is sequenced before \( B \), or
\item[(10.2)] \( A \) inter-thread happens before \( B \).
\end{enumerate}

The implementation shall ensure that no program execution demonstrates a cycle in the “happens before” relation.

\[ \text{Note 9: This cycle would otherwise be possible only through the use of consume operations.} \] — end note

An evaluation \( A \) \textit{simply happens before} an evaluation \( B \) if either

\begin{enumerate}
\item[(11.1)] \( A \) is sequenced before \( B \), or
\item[(11.2)] \( A \) synchronizes with \( B \), or
\item[(11.3)] \( A \) simply happens before \( X \) and \( X \) simply happens before \( B \).
\end{enumerate}

\[ \text{Note 10: In the absence of consume operations, the happens before and simply happens before relations are identical.} \] — end note

An evaluation \( A \) \textit{strongly happens before} an evaluation \( D \) if, either

\begin{enumerate}
\item[(12.1)] \( A \) is sequenced before \( D \), or
\item[(12.2)] \( A \) synchronizes with \( D \), and both \( A \) and \( D \) are sequentially consistent atomic operations (33.5.4), or
\item[(12.3)] there are evaluations \( B \) and \( C \) such that \( A \) is sequenced before \( B \), \( B \) simply happens before \( C \), and \( C \) is sequenced before \( D \), or
\item[(12.4)] there is an evaluation \( B \) such that \( A \) strongly happens before \( B \), and \( B \) strongly happens before \( D \).
\end{enumerate}

\[ \text{Note 11: Informally, if \( A \) strongly happens before \( B \), then \( A \) appears to be evaluated before \( B \) in all contexts. Strongly happens before excludes consume operations.} \] — end note

A \textit{visible side effect} \( A \) on a scalar object or bit-field \( M \) with respect to a value computation \( B \) of \( M \) satisfies the conditions:

\begin{enumerate}
\item[(13.1)] \( A \) happens before \( B \) and
\item[(13.2)] there is no other side effect \( X \) to \( M \) such that \( A \) happens before \( X \) and \( X \) happens before \( B \).
\end{enumerate}

The value of a non-atomic scalar object or bit-field \( M \), as determined by evaluation \( B \), is the value stored by the visible side effect \( A \).

\[ \text{Note 12: If there is ambiguity about which side effect to a non-atomic object or bit-field is visible, then the behavior is either unspecified or undefined.} \] — end note

\[ \text{§ 6.9.2.2} \]
The value of an atomic object $M$, as determined by evaluation $B$, is the value stored by some unspecified side effect $A$ that modifies $M$, where $B$ does not happen before $A$.

If an operation $A$ that modifies an atomic object $M$ happens before an operation $B$ that modifies $M$, then $A$ is earlier than $B$ in the modification order of $M$.

If a value computation $A$ of an atomic object $M$ happens before a value computation $B$ of $M$, and $A$ takes its value from a side effect $X$ on $M$, then the value computed by $B$ is either the value stored by $X$ or the value stored by a side effect $Y$ on $M$, where $Y$ follows $X$ in the modification order of $M$.

If a value computation $A$ of an atomic object $M$ happens before an operation $B$ that modifies $M$, then $A$ takes its value from a side effect $X$ on $M$, where $X$ precedes $B$ in the modification order of $M$.

If a side effect $X$ on an atomic object $M$ happens before a value computation $B$ of $M$, then the evaluation $B$ takes its value from $X$ or from a side effect $Y$ that follows $X$ in the modification order of $M$.

Two actions are potentially concurrent if

1. they are performed by different threads, or
2. they are unsequenced, at least one is performed by a signal handler, and they are not both performed by the same signal handler invocation.

The execution of a program contains a data race if it contains two potentially concurrent conflicting actions, at least one of which is not atomic, and neither happens before the other, except for the special case for signal handlers described below. Any such data race results in undefined behavior.

Two accesses to the same object of type `volatile std::sig_atomic_t` do not result in a data race if both occur in the same thread, even if one or more occurs in a signal handler. For each signal handler invocation, evaluations performed by the thread invoking a signal handler can be divided into two groups $A$ and $B$, such that no evaluations in $B$ happen before evaluations in $A$, and the evaluations of such `volatile std::sig_atomic_t` objects take values as though all evaluations in $A$ happened before the execution of the signal handler and the execution of the signal handler happened before all evaluations in $B$.

Compiler transformations that introduce assignments to a potentially shared memory location that would not be modified by the abstract machine are generally precluded by this document, since such an assignment might overwrite another assignment by a different thread in cases in which an abstract machine execution would not have encountered a data race. This includes implementations of data member assignment that overwrite adjacent members in separate memory locations. Reordering of atomic loads in cases in which the atomics in question might alias is also generally precluded, since this could violate the coherence rules.
Transformations that introduce a speculative read of a potentially shared memory location might not preserve the semantics of the C++ program as defined in this document, since they potentially introduce a data race. However, they are typically valid in the context of an optimizing compiler that targets a specific machine with well-defined semantics for data races. They would be invalid for a hypothetical machine that is not tolerant of races or provides hardware race detection. —end note

6.9.2.3 Forward progress

The implementation may assume that any thread will eventually do one of the following:

1. terminate,
2. invoke the function std::this_thread::yield (33.4.5),
3. make a call to a library I/O function,
4. perform an access through a volatile glvalue,
5. perform a synchronization operation or an atomic operation, or
6. continue execution of a trivial infinite loop (8.6.1).

[Note 1: This is intended to allow compiler transformations such as removal, merging, and reordering of empty loops, even when termination cannot be proven. An affordance is made for trivial infinite loops, which cannot be removed nor reordered. —end note]

Executions of atomic functions that are either defined to be lock-free (33.5.10) or indicated as lock-free (33.5.5) are lock-free executions.

1. If there is only one thread that is not blocked (3.6) in a standard library function, a lock-free execution in that thread shall complete.

   [Note 2: Concurrently executing threads might prevent progress of a lock-free execution. For example, this situation can occur with load-locked store-conditional implementations. This property is sometimes termed obstruction-free. —end note]

2. When one or more lock-free executions run concurrently, at least one should complete.

   [Note 3: It is difficult for some implementations to provide absolute guarantees to this effect, since repeated and particularly inopportune interference from other threads could prevent forward progress, e.g., by repeatedly stealing a cache line for unrelated purposes between load-locked and store-conditional instructions. For implementations that follow this recommendation and ensure that such effects cannot indefinitely delay progress under expected operating conditions, such anomalies can therefore safely be ignored by programmers. Outside this document, this property is sometimes termed lock-free. —end note]

During the execution of a thread of execution, each of the following is termed an execution step:

1. termination of the thread of execution,
2. performing an access through a volatile glvalue, or
3. completion of a call to a library I/O function, a synchronization operation, or an atomic operation.

An invocation of a standard library function that blocks (3.6) is considered to continuously execute execution steps while waiting for the condition that it blocks on to be satisfied.

[Example 1: A library I/O function that blocks until the I/O operation is complete can be considered to continuously check whether the operation is complete. Each such check consists of one or more execution steps, for example using observable behavior of the abstract machine. —end example]

[Note 4: Because of this and the preceding requirement regarding what threads of execution have to perform eventually, it follows that no thread of execution can execute forever without an execution step occurring. —end note]

A thread of execution makes progress when an execution step occurs or a lock-free execution does not complete because there are other concurrent threads that are not blocked in a standard library function (see above).

For a thread of execution providing concurrent forward progress guarantees, the implementation ensures that the thread will eventually make progress for as long as it has not terminated.

[Note 5: This applies regardless of whether or not other threads of execution (if any) have been or are making progress. To eventually fulfill this requirement means that this will happen in an unspecified but finite amount of time. —end note]

It is implementation-defined whether the implementation-created thread of execution that executes main (6.9.3.1) and the threads of execution created by std::thread (33.4.3) or std::jthread (33.4.4) provide concurrent forward progress guarantees. General-purpose implementations should provide these guarantees.
For a thread of execution providing parallel forward progress guarantees, the implementation is not required to ensure that the thread will eventually make progress if it has not yet executed any execution step; once this thread has executed a step, it provides concurrent forward progress guarantees.

[Note 6: This does not specify a requirement for when to start this thread of execution, which will typically be specified by the entity that creates this thread of execution. For example, a thread of execution that provides concurrent forward progress guarantees and executes tasks from a set of tasks in an arbitrary order, one after the other, satisfies the requirements of parallel forward progress for these tasks. —end note]

For a thread of execution providing weakly parallel forward progress guarantees, the implementation does not ensure that the thread will eventually make progress.

[Note 7: Threads of execution providing weakly parallel forward progress guarantees cannot be expected to make progress regardless of whether other threads make progress or not; however, blocking with forward progress guarantee delegation, as defined below, can be used to ensure that such threads of execution make progress eventually. —end note]

Concurrent forward progress guarantees are stronger than parallel forward progress guarantees, which in turn are stronger than weakly parallel forward progress guarantees.

[Note 8: For example, some kinds of synchronization between threads of execution might only make progress if the respective threads of execution provide parallel forward progress guarantees, but will fail to make progress under weakly parallel guarantees. —end note]

When a thread of execution \( P \) is specified to block with forward progress guarantee delegation on the completion of a set \( S \) of threads of execution, then throughout the whole time of \( P \) being blocked on \( S \), the implementation shall ensure that the forward progress guarantees provided by at least one thread of execution in \( S \) is at least as strong as \( P \)'s forward progress guarantees.

[Note 9: It is unspecified which thread or threads of execution in \( S \) are chosen and for which number of execution steps. The strengthening is not permanent and not necessarily in place for the rest of the lifetime of the affected thread of execution. As long as \( P \) is blocked, the implementation has to eventually select and potentially strengthen a thread of execution in \( S \). —end note]

Once a thread of execution in \( S \) terminates, it is removed from \( S \). Once \( S \) is empty, \( P \) is unblocked.

[Note 10: A thread of execution \( B \) thus can temporarily provide an effectively stronger forward progress guarantee for a certain amount of time, due to a second thread of execution \( A \) being blocked on it with forward progress guarantee delegation. In turn, if \( B \) then blocks with forward progress guarantee delegation on \( C \), this can also temporarily provide a stronger forward progress guarantee to \( C \). —end note]

[Note 11: If all threads of execution in \( S \) finish executing (e.g., they terminate and do not use blocking synchronization incorrectly), then \( P \)'s execution of the operation that blocks with forward progress guarantee delegation will not result in \( P \)'s progress guarantee being effectively weakened. —end note]

[Note 12: This does not remove any constraints regarding blocking synchronization for threads of execution providing parallel or weakly parallel forward progress guarantees because the implementation is not required to strengthen a particular thread of execution whose too-weak progress guarantee is preventing overall progress. —end note]

An implementation should ensure that the last value (in modification order) assigned by an atomic or synchronization operation will become visible to all other threads in a finite period of time.

### 6.9.3 Start and termination

#### [basic.start]

##### 6.9.3.1 main function

A program shall contain exactly one function called `main` that belongs to the global scope. Executing a program starts a main thread of execution (6.9.2, 33.4) in which the `main` function is invoked. It is implementation-defined whether a program in a freestanding environment is required to define a `main` function.

[Note 1: In a freestanding environment, startup and termination is implementation-defined; startup contains the execution of constructors for non-local objects with static storage duration; termination contains the execution of destructors for objects with static storage duration. —end note]

An implementation shall not redefine the `main` function. Its type shall have C++ language linkage and it shall have a declared return type of type `int`, but otherwise its type is implementation-defined. An implementation shall allow both

1. a function of `()` returning `int` and
2. a function of `(int, pointer to pointer to char)` returning `int`
as the type of `main` (9.3.4.6). In the latter form, for purposes of exposition, the first function parameter is called `argv` and the second function parameter is called `argc`, where `argc` shall be the number of arguments passed to the program from the environment in which the program is run. If `argc` is nonzero these arguments shall be supplied in `argv[0]` through `argv[argc-1]` as pointers to the initial characters of null-terminated multibyte strings (NTMBS) (16.3.3.4.3) and `argv[0]` shall be the pointer to the initial character of an NTMBS that represents the name used to invoke the program or "". The value of `argc` shall be non-negative. The value of `argv[argc]` shall be 0.

**Recommended practice:** Any further (optional) parameters should be added after `argv`.

3 The function `main` shall not be named by an expression. The linkage (6.6) of `main` is implementation-defined. A program that defines `main` as deleted or that declares `main` to be `inline, static, constexpr, or consteval` is ill-formed. The function `main` shall not be a coroutine (9.5.4). The `main` function shall not be declared with a `linkage-specification` (9.11). A program that declares

(3.1) — a variable `main` that belongs to the global scope, or
(3.2) — a function `main` that belongs to the global scope and is attached to a named module, or
(3.3) — a function template `main` that belongs to the global scope, or
(3.4) — an entity named `main` with C language linkage (in any namespace)

is ill-formed. The name `main` is not otherwise reserved.

*[Example 1: Member functions, classes, and enumerations can be called `main`, as can entities in other namespaces. — end example]*

4 Terminating the program without leaving the current block (e.g., by calling the function `std::exit(int)` (17.5)) does not destroy any objects with automatic storage duration (11.4.7). If `std::exit` is invoked during the destruction of an object with static or thread storage duration, the program has undefined behavior.

5 A `return` statement (8.7.4) in `main` has the effect of leaving the main function (destroying any objects with automatic storage duration) and calling `std::exit` with the return value as the argument. If control flows off the end of the `compound-statement` of `main`, the effect is equivalent to a `return` with operand 0 (see also 14.4).

### 6.9.3.2 Static initialization

Variables with static storage duration are initialized as a consequence of program initiation. Variables with thread storage duration are initialized as a consequence of thread execution. Within each of these phases of initiation, initialization occurs as follows.

2 **Constant initialization** is performed if a variable or temporary object with static or thread storage duration is constant-initialized (7.7). If constant initialization is not performed, a variable with static storage duration (6.7.5.2) or thread storage duration (6.7.5.3) is zero-initialized (9.4). Together, zero-initialization and constant initialization are called **static initialization**; all other initialization is **dynamic initialization**. All static initialization strongly happens before (6.9.2.2) any dynamic initialization.

*[Note 1: The dynamic initialization of non-block variables is described in 6.9.3.3; that of static block variables is described in 8.8. — end note]*

3 An implementation is permitted to perform the initialization of a variable with static or thread storage duration as a static initialization even if such initialization is not required to be done statically, provided that

(3.1) — the dynamic version of the initialization does not change the value of any other object of static or thread storage duration prior to its initialization, and
(3.2) — the static version of the initialization produces the same value in the initialized variable as would be produced by the dynamic initialization if all variables not required to be initialized statically were initialized dynamically.

*[Note 2: As a consequence, if the initialization of an object `obj1` refers to an object `obj2` potentially requiring dynamic initialization and defined later in the same translation unit, it is unspecified whether the value of `obj2` used will be the value of the fully initialized `obj2` (because `obj2` was statically initialized) or will be the value of `obj2` merely zero-initialized. For example,

```c
inline double fd() { return 1.0; }
extern double d1;
double d2 = d1; // unspecified:
```*
Dynamic initialization of a non-block variable with static storage duration is unordered if the variable is an implicitly or explicitly instantiated specialization, is partially-ordered if the variable is an inline variable that is not an implicitly or explicitly instantiated specialization, and otherwise is ordered.

[Note 1: A non-inline explicit specialization of a templated variable has ordered initialization. — end note]

A declaration D is appearance-ordered before a declaration E if

1. D appears in the same translation unit as E, or
2. the translation unit containing E has an interface dependency on the translation unit containing D, in either case prior to E.

Dynamic initialization of non-block variables V and W with static storage duration are ordered as follows:

1. If V and W have ordered initialization and the definition of V is appearance-ordered before the definition of W, or if V has partially-ordered initialization, W does not have unordered initialization, and for every definition E of W there exists a definition D of V such that D is appearance-ordered before E, then
2. if the program does not start a thread (6.9.2) other than the main thread (6.9.3.1) or V and W have ordered initialization and they are defined in the same translation unit, the initialization of V is sequenced before the initialization of W;
3. otherwise, the initialization of V strongly happens before the initialization of W.

Otherwise, if the program starts a thread other than the main thread before either V or W is initialized, it is unspecified in which threads the initializations of V and W occur; the initializations are unsequenced if they occur in the same thread.

[Note 2: This definition permits initialization of a sequence of ordered variables concurrently with another sequence. — end note]

A non-initialization odr-use is an odr-use (6.3) not caused directly or indirectly by the initialization of a non-block static or thread storage duration variable.

It is implementation-defined whether the dynamic initialization of a non-block non-inline variable with static storage duration is sequenced before the first statement of main or is deferred. If it is deferred, it strongly happens before any non-initialization odr-use of any non-inline function or non-inline variable defined in the same translation unit as the variable to be initialized. It is implementation-defined in which threads and at which points in the program such deferred dynamic initialization occurs.

Recommended practice: An implementation should choose such points in a way that allows the programmer to avoid deadlocks.

[Example 1]

```c
#include "a.h"
#include "b.h"
B b;
A::A() {
    b.Use();
}
```

39 A non-block variable with static storage duration having initialization with side effects is initialized in this case, even if it is not itself odr-used (6.3, 6.7.5.2).
It is implementation-defined whether either \texttt{a} or \texttt{b} is initialized before \texttt{main} is entered or whether the initializations are delayed until \texttt{a} is first odr-used in \texttt{main}. In particular, if \texttt{a} is initialized before \texttt{main} is entered, it is not guaranteed that \texttt{b} will be initialized before it is odr-used by the initialization of \texttt{a}, that is, before \texttt{A::A} is called. If, however, \texttt{a} is initialized at some point after the first statement of \texttt{main}, \texttt{b} will be initialized prior to its use in \texttt{A::A}. — end example]

It is implementation-defined whether the dynamic initialization of a non-block inline variable with static storage duration is sequenced before the first statement of \texttt{main} or is deferred. If it is deferred, it strongly happens before any non-initialization odr-use of that variable. It is implementation-defined in which threads and at which points in the program such deferred dynamic initialization occurs.

It is implementation-defined whether the dynamic initialization of a non-block non-inline variable with thread storage duration is sequenced before the first statement of the initial function of a thread or is deferred. If it is deferred, the initialization associated with the entity for thread \texttt{t} is sequenced before the first non-initialization odr-use by \texttt{t} of any non-inline variable with thread storage duration defined in the same translation unit as the variable to be initialized. It is implementation-defined in which threads and at which points in the program such deferred dynamic initialization occurs.

If the initialization of a non-block variable with static or thread storage duration exits via an exception, the function \texttt{std::terminate} is called (14.6.2).

6.9.3.4 Termination

1 Constructed objects (9.4) with static storage duration are destroyed and functions registered with \texttt{std::atexit} are called as part of a call to \texttt{std::exit} (17.5). The call to \texttt{std::exit} is sequenced before the destructors and the registered functions.

[Note 1: Returning from \texttt{main} invokes \texttt{std::exit} (6.9.3.1). — end note]

2 Constructed objects with thread storage duration within a given thread are destroyed as a result of returning from the initial function of that thread and as a result of that thread calling \texttt{std::exit}. The destruction of all constructed objects with thread storage duration within that thread strongly happens before destroying any object with static storage duration.

3 If the completion of the constructor or dynamic initialization of an object with static storage duration strongly happens before that of another, the completion of the destructor of the second is sequenced before the initiation of the destructor of the first. If the completion of the constructor or dynamic initialization of an object with thread storage duration is sequenced before that of another, the completion of the destructor of the second is sequenced before the initiation of the destructor of the first. If an object is initialized statically, the object is destroyed in the same order as if the object was dynamically initialized. For an object of array or class type, all subobjects of that object are destroyed before any block variable with static storage duration initialized during the construction of the subobjects is destroyed. If the destruction of an object with static or thread storage duration exits via an exception, the function \texttt{std::terminate} is called (14.6.2).

4 If a function contains a block variable of static or thread storage duration that has been destroyed and the function is called during the destruction of an object with static or thread storage duration, the program has undefined behavior if the flow of control passes through the definition of the previously destroyed block variable.

[Note 2: Likewise, the behavior is undefined if the block variable is used indirectly (e.g., through a pointer) after its destruction. — end note]

5 If the completion of the initialization of an object with static storage duration strongly happens before a call to \texttt{std::atexit} (see <cstdlib>, 17.5), the call to the function passed to \texttt{std::atexit} is sequenced before the call to the destructor for the object. If a call to \texttt{std::atexit} strongly happens before the completion of the initialization of an object with static storage duration, the call to the destructor for the object is sequenced before the call to the function passed to \texttt{std::atexit}. If a call to \texttt{std::atexit} strongly happens before

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another call to `std::atexit`, the call to the function passed to the second `std::atexit` call is sequenced before the call to the function passed to the first `std::atexit` call.

6 If there is a use of a standard library object or function not permitted within signal handlers (17.13) that does not happen before (6.9.2) completion of destruction of objects with static storage duration and execution of `std::atexit` registered functions (17.5), the program has undefined behavior.

[Note 3: If there is a use of an object with static storage duration that does not happen before the object’s destruction, the program has undefined behavior. Terminating every thread before a call to `std::exit` or the exit from `main` is sufficient, but not necessary, to satisfy these requirements. These requirements permit thread managers as static-storage-duration objects. — end note]

7 Calling the function `std::abort()` declared in `<cstdlib>` (17.2.2) terminates the program without executing any destructors and without calling the functions passed to `std::atexit()` or `std::at_quick_exit()`.
7 Expressions

7.1 Preamble

[Note 1: Clause 7 defines the syntax, order of evaluation, and meaning of expressions. An expression is a sequence of operators and operands that specifies a computation. An expression can result in a value and can cause side effects. — end note]

[Note 2: Operators can be overloaded, that is, given meaning when applied to expressions of class type (Clause 11) or enumeration type (9.7.1). Uses of overloaded operators are transformed into function calls as described in 12.4. Overloaded operators obey the rules for syntax and evaluation order specified in 7.6, but the requirements of operand type and value category are replaced by the rules for function call. Relations between operators, such as \(a++\) meaning \(a*=1\), are not guaranteed for overloaded operators (12.4). — end note]

Subclause 7.6 defines the effects of operators when applied to types for which they have not been overloaded. Operator overloading shall not modify the rules for the built-in operators, that is, for operators applied to types for which they are defined by this Standard. However, these built-in operators participate in overload resolution, and as part of that process user-defined conversions will be considered where necessary to convert the operands to types appropriate for the built-in operator. If a built-in operator is selected, such conversions will be applied to the operands before the operation is considered further according to the rules in 7.6; see 12.2.2.3, 12.5.

If during the evaluation of an expression, the result is not mathematically defined or not in the range of representable values for its type, the behavior is undefined.

[Note 3: Treatment of division by zero, forming a remainder using a zero divisor, and all floating-point exceptions varies among machines, and is sometimes adjustable by a library function. — end note]

[Note 4: The implementation can regroup operators according to the usual mathematical rules only where the operators really are associative or commutative. For example, in the following fragment

int a, b;
/* ... */
a = a + 32760 + b + 5;

the expression statement behaves exactly the same as

\[a = (((a + 32760) + b) + 5)\];

due to the associativity and precedence of these operators. Thus, the result of the sum \((a + 32760)\) is next added to \(b\), and that result is then added to 5 which results in the value assigned to \(a\). On a machine in which overflows produce an exception and in which the range of values representable by an \texttt{int} is \([-32768, +32767]\), the implementation cannot rewrite this expression as

\[a = ((a + b) + 32765)\];

since if the values for \(a\) and \(b\) were, respectively, \(-32754\) and \(-15\), the sum \(a + b\) would produce an exception while the original expression would not; nor can the expression be rewritten as either

\[a = ((a + 32765) + b)\];
or

\[a = (a + (b + 32765))\];

since the values for \(a\) and \(b\) might have been, respectively, 4 and \(-8\) or \(-17\) and 12. However on a machine in which overflows do not produce an exception and in which the results of overflows are reversible, the above expression statement can be rewritten by the implementation in any of the above ways because the same result will occur. — end note]

The values of the floating-point operands and the results of floating-point expressions may be represented in greater precision and range than that required by the type; the types are not changed thereby.]

---

40) The precedence of operators is not directly specified, but it can be derived from the syntax.
41) Overloaded operators are never assumed to be associative or commutative.
42) The cast and assignment operators must still perform their specific conversions as described in 7.6.1.4, 7.6.3, 7.6.1.9 and 7.6.19.
7.2 Properties of expressions

7.2.1 Value category

Expressions are categorized according to the taxonomy in Figure 2.

Figure 2 — Expression category taxonomy

(1.1) A glvalue is an expression whose evaluation determines the identity of an object or function.

(1.2) A prvalue is an expression whose evaluation initializes an object or computes the value of an operand of an operator, as specified by the context in which it appears, or an expression that has type cv void.

(1.3) An xvalue is a glvalue that denotes an object whose resources can be reused (usually because it is near the end of its lifetime).

(1.4) An lvalue is a glvalue that is not an xvalue.

(1.5) An rvalue is a prvalue or an xvalue.

Every expression belongs to exactly one of the fundamental categories in this taxonomy: lvalue, xvalue, or prvalue. This property of an expression is called its value category.

[Note 1: The discussion of each built-in operator in 7.6 indicates the category of the value it yields and the value categories of the operands it expects. For example, the built-in assignment operators expect that the left operand is an lvalue and that the right operand is a prvalue and yield an lvalue as the result. User-defined operators are functions, and the categories of values they expect and yield are determined by their parameter and return types. — end note]

[Note 2: Historically, lvalues and rvalues were so-called because they could appear on the left- and right-hand side of an assignment (although this is no longer generally true); glvalues are “generalized” lvalues; prvalues are “pure” rvalues, and xvalues are “eXpiring” lvalues. Despite their names, these terms apply to expressions, not values. — end note]

[Note 3: An expression is an xvalue if it is:

- a move-eligible id-expression (7.5.5.2),
- the result of calling a function, whether implicitly or explicitly, whose return type is an rvalue reference to object type (7.6.1.3),
- a cast to an rvalue reference to object type (7.6.1.4, 7.6.1.7, 7.6.1.9, 7.6.1.10, 7.6.1.11, 7.6.3),
- a subscripting operation with an xvalue array operand (7.6.1.2),
- a class member access expression designating a non-static data member of non-reference type in which the object expression is an xvalue (7.6.1.5), or
- a .* pointer-to-member expression in which the first operand is an xvalue and the second operand is a pointer to data member (7.6.4).

In general, the effect of this rule is that named rvalue references are treated as lvalues and unnamed rvalue references to objects are treated as xvalues; rvalue references to functions are treated as lvalues whether named or not. — end note]

Example 1:

```
struct A {
    int m;
};
A& operator+(A, A);
A& f();

A a;
A& ar = static_cast<A&>(a);
```

The expressions f(), f().m, static_cast<A&>(a), and a + a are xvalues. The expression ar is an lvalue. — end example]
The result of a glvalue is the entity denoted by the expression. The result of a prvalue is the value that the expression stores into its context; a prvalue that has type cv void has no result. A prvalue whose result is the value \( V \) is sometimes said to have or name the value \( V \). The result object of a prvalue is the object initialized by the prvalue; a non-discarded prvalue that is used to compute the value of an operand of a built-in operator or a prvalue that has type cv void has no result object.

[Note 4: Except when the prvalue is the operand of a decltype-specifier, a prvalue of class or array type always has a result object. For a discarded prvalue that has type other than cv void, a temporary object is materialized; see 7.2.3. — end note]

Whenever a glvalue appears as an operand of an operator that requires a prvalue for that operand, the value-to-rvalue (7.3.2), array-to-pointer (7.3.3), or function-to-pointer (7.3.4) standard conversions are applied to convert the expression to a prvalue.

[Note 5: An attempt to bind an rvalue reference to an lvalue is not such a context; see 9.4.4. — end note]

[Note 6: Because cv-qualifiers are removed from the type of an expression of non-class type when the expression is converted to a prvalue, an lvalue of type const int can, for example, be used where a prvalue of type int is required. — end note]

[Note 7: There are no prvalue bit-fields; if a bit-field is converted to a prvalue (7.3.2), a prvalue of the type of the bit-field is created, which might then be promoted (7.3.7). — end note]

Whenever a prvalue appears as an operand of an operator that expects a glvalue for that operand, the temporary materialization conversion (7.3.5) is applied to convert the expression to an xvalue.

[Note 8: The discussion of reference initialization in 9.4.4 and of temporaries in 6.7.7 indicates the behavior of lvalues and rvalues in other significant contexts. — end note]

Unless otherwise indicated (9.2.9.6), a prvalue shall always have complete type or the void type; if it has a class type or (possibly multidimensional) array of class type, that class shall not be an abstract class (11.7.4). A glvalue shall not have type cv void.

[Note 9: A glvalue can have complete or incomplete non-void type. Class and array prvalues can have cv-qualified types; other prvalues always have cv-unqualified types. See 7.2.2. — end note]

An lvalue is modifiable unless its type is const-qualified or is a function type.

[Note 10: A program that attempts to modify an object through a nonmodifiable lvalue or through an rvalue is ill-formed (7.6.19, 7.6.1.6, 7.6.2.3). — end note]

An object of dynamic type \( T_{\text{obj}} \) is type-accessible through a glvalue of type \( T_{\text{ref}} \) if \( T_{\text{ref}} \) is similar (7.3.6) to:

1. \( T_{\text{obj}} \)
2. a type that is the signed or unsigned type corresponding to \( T_{\text{obj}} \), or
3. a char, unsigned char, or std::byte type.

If a program attempts to access (3.1) the stored value of an object through a glvalue through which it is not type-accessible, the behavior is undefined. 43 If a program invokes a defaulted copy/move constructor or copy/move assignment operator for a union of type \( U \) with a glvalue argument that does not denote an object of type cv \( U \) within its lifetime, the behavior is undefined.

[Note 11: In C, an entire object of structure type can be accessed, e.g., using assignment. By contrast, C++ has no notion of accessing an object of class type through an lvalue of class type. — end note]

### 7.2.2 Type [expr.type]

If an expression initially has the type “reference to \( T \)” (9.3.4.3, 9.4.4), the type is adjusted to \( T \) prior to any further analysis. The expression designates the object or function denoted by the reference, and the expression is an lvalue or an xvalue, depending on the expression.

[Note 1: Before the lifetime of the reference has started or after it has ended, the behavior is undefined (see 6.7.3). — end note]

If a prvalue initially has the type “cv \( T \)”, where \( T \) is a cv-unqualified non-class, non-array type, the type of the expression is adjusted to \( T \) prior to any further analysis.

The composite pointer type of two operands \( p1 \) and \( p2 \) having types \( T1 \) and \( T2 \), respectively, where at least one is a pointer or pointer-to-member type or std::nullptr_t, is:

1. if both \( p1 \) and \( p2 \) are null pointer constants, std::nullptr_t;
— if either \( p_1 \) or \( p_2 \) is a null pointer constant, \( T_2 \) or \( T_1 \), respectively;

— if \( T_1 \) or \( T_2 \) is “pointer to cv1 void” and the other type is “pointer to cv2 T”, where \( T \) is an object type or \( \text{void} \), “pointer to cv12 void”, where \( cv12 \) is the union of \( cv1 \) and \( cv2 \);

— if \( T_1 \) or \( T_2 \) is “pointer to noexcept function” and the other type is “pointer to function”, where the function types are otherwise the same, “pointer to function”;

— if \( T_1 \) or \( T_2 \) is “pointer to member of \( C_1 \) of type function”, the other type is “pointer to member of \( C_2 \) of type noexcept function”, and \( C_1 \) is reference-related to \( C_2 \) or \( C_2 \) is reference-related to \( C_1 \) (9.4.4), where the function types are otherwise the same, “pointer to member of \( C_2 \) of type function” or “pointer to member of \( C_1 \) of type function”, respectively;

— if \( T_1 \) is “pointer to member of \( C_1 \) of type \( cv1 U \)” and \( T_2 \) is “pointer to member of \( C_2 \) of type \( cv2 U \)”, for some non-function type \( U \), where \( C_1 \) is reference-related to \( C_2 \) or \( C_2 \) is reference-related to \( C_1 \) (9.4.4), the qualification-combined type of \( T_1 \) and \( T_2 \) or the qualification-combined type of \( T_2 \) and \( T_1 \), respectively;

— if \( T_1 \) and \( T_2 \) are similar types (7.3.6), the qualification-combined type of \( T_1 \) and \( T_2 \);

— otherwise, a program that necessitates the determination of a composite pointer type is ill-formed.

\[\text{Example 1:}\]

```c
typedef void *p;
typedef const int *q;
typedef int **pi;
typedef const int **pci;
```

The composite pointer type of \( p \) and \( q \) is “pointer to const void”; the composite pointer type of \( pi \) and \( pci \) is “pointer to const pointer to const int”. — end example]

### 7.2.3 Context dependence

In some contexts, unevaluated operands appear (7.5.8, 7.6.1.8, 7.6.2.5, 7.6.2.7, 9.2.9.6, 13.1, 13.7.9). An unevaluated operand is not evaluated.

\[\text{Note 1:}\] In an unevaluated operand, a non-static class member can be named (7.5.5) and naming of objects or functions does not, by itself, require that a definition be provided (6.3). An unevaluated operand is considered a full-expression (6.9.1). — end note]

In some contexts, an expression only appears for its side effects. Such an expression is called a discarded-value expression. The array-to-pointer (7.3.3) and function-to-pointer (7.3.4) standard conversions are not applied. The lvalue-to-rvalue conversion (7.3.2) is applied if and only if the expression is a glvalue of volatile-qualified type and it is one of the following:

\[(2.1)\] ( expression ), where expression is one of these expressions,

\[(2.2)\] id-expression (7.5.5),

\[(2.3)\] subscripting (7.6.1.2),

\[(2.4)\] class member access (7.6.1.5),

\[(2.5)\] indirection (7.6.2.2),

\[(2.6)\] pointer-to-member operation (7.6.4),

\[(2.7)\] conditional expression (7.6.16) where both the second and the third operands are one of these expressions, or

\[(2.8)\] comma expression (7.6.20) where the right operand is one of these expressions.

\[\text{Note 2:}\] Using an overloaded operator causes a function call; the above covers only operators with built-in meaning. — end note]

The temporary materialization conversion (7.3.5) is applied if the (possibly converted) expression is a prvalue of object type.

\[\text{Note 3:}\] If the original expression is an lvalue of class type, it must have a volatile copy constructor to initialize the temporary object that is the result object of the temporary materialization conversion. — end note]

The expression is evaluated and its result (if any) is discarded.
7.3 Standard conversions

7.3.1 General

Standard conversions are implicit conversions with built-in meaning. 7.3 enumerates the full set of such conversions. A standard conversion sequence is a sequence of standard conversions in the following order:

1. Zero or one conversion from the following set: lvalue-to-rvalue conversion, array-to-pointer conversion, and function-to-pointer conversion.
2. Zero or one conversion from the following set: integral promotions, floating-point promotion, integral conversions, floating-point conversions, floating-integral conversions, pointer conversions, pointer-to-member conversions, and boolean conversions.
3. Zero or one function pointer conversion.
4. Zero or one qualification conversion.

[Note 1: A standard conversion sequence can be empty, i.e., it can consist of no conversions. — end note]

A standard conversion sequence will be applied to an expression if necessary to convert it to an expression having a required destination type and value category.

2 [Note 2: Expressions with a given type will be implicitly converted to other types in several contexts:

1. When used as operands of operators. The operator’s requirements for its operands dictate the destination type (7.6).
2. When used in the condition of an if statement (8.5.2) or iteration statement (8.6). The destination type is bool.
3. When used in the expression of a switch statement (8.5.3). The destination type is integral.
4. When used as the source expression for an initialization (which includes use as an argument in a function call and use as the expression in a return statement). The type of the entity being initialized is (generally) the destination type. See 9.4, 9.4.4.

— end note]

An expression E can be implicitly converted to a type T if and only if the declaration T t=E; is well-formed, for some invented temporary variable t (9.4).

3 Certain language constructs require that an expression be converted to a Boolean value. An expression E appearing in such a context is said to be contextually converted to bool and is well-formed if and only if the declaration bool t(E); is well-formed, for some invented temporary variable t (9.4).

4 Certain language constructs require conversion to a value having one of a specified set of types appropriate to the construct. An expression E of class type C appearing in such a context is said to be contextually implicitly converted to a specified type T and is well-formed if and only if E can be implicitly converted to a type T that is determined as follows: C is searched for non-explicit conversion functions whose return type is cv T or reference to cv T such that T is allowed by the context. There shall be exactly one such T.

5 The effect of any implicit conversion is the same as performing the corresponding declaration and initialization and then using the temporary variable as the result of the conversion. The result is an lvalue if T is an lvalue reference type or an rvalue reference to function type (9.3.4.3), an xvalue if T is an rvalue reference to object type, and a prvalue otherwise. The expression E is used as a glvalue if and only if the initialization uses it as a glvalue.

6 [Note 3: For class types, user-defined conversions are considered as well; see 11.4.8. In general, an implicit conversion sequence (12.2.4.2) consists of a standard conversion sequence followed by a user-defined conversion followed by another standard conversion sequence. — end note]

7 [Note 4: There are some contexts where certain conversions are suppressed. For example, the lvalue-to-rvalue conversion is not done on the operand of the unary & operator. Specific exceptions are given in the descriptions of those operators and contexts. — end note]

7.3.2 Lvalue-to-rvalue conversion

1 A glvalue (7.2.1) of a non-function, non-array type T can be converted to a prvalue. If T is an incomplete type, a program that necessitates this conversion is ill-formed. If T is a non-class type, the type of the prvalue

44) For historical reasons, this conversion is called the “lvalue-to-rvalue” conversion, even though that name does not accurately reflect the taxonomy of expressions described in 7.2.1.
is the cv-unqualified version of \( T \). Otherwise, the type of the prvalue is \( T \).\(^{45}\)

When an lvalue-to-rvalue conversion is applied to an expression \( E \), and either
\[ (2.1) \text{ E is not potentially evaluated, or} \]
\[ (2.2) \text{ the evaluation of E results in the evaluation of a member } E_x \text{ of the set of potential results of E, and } E_x \text{ names a variable } x \text{ that is not odr-used by } E_x \text{ (6.3),} \]

the value contained in the referenced object is not accessed.

\[ \text{Example 1:} \]
```cpp
struct S { int n; };
auto f() {
    S x { 1 };
    constexpr S y { 2 };
    return [&](bool b) { return (b ? y : x).n; }; }
auto g = f();
int m = g(false);    // undefined behavior: access of x.n outside its lifetime
int n = g(true);     // OK, does not access y.n
```

\[ \text{—end example} \]

The result of the conversion is determined according to the following rules:

\[ (3.1) \text{ If } T \text{ is } cv \text{ std::nullptr_t, the result is a null pointer constant (7.3.12).} \]

\[ \text{[Note 1]: Since the conversion does not access the object to which the glvalue refers, there is no side effect even if } T \text{ is volatile-qualified (6.9.1), and the glvalue can refer to an inactive member of a union (11.5). — end note]} \]

\[ (3.2) \text{ Otherwise, if } T \text{ has a class type, the conversion copy-initializes the result object from the glvalue.} \]

\[ (3.3) \text{ Otherwise, if the object to which the glvalue refers contains an invalid pointer value (6.7.5.5.3), the behavior is implementation-defined.} \]

\[ (3.4) \text{ Otherwise, the object indicated by the glvalue is read (3.1), and the value contained in the object is the prvalue result. If the result is an erroneous value (6.7.4) and the bits in the value representation are not valid for the object’s type, the behavior is undefined.} \]

\[ \text{[Note 2]: See also 7.2.1. — end note]} \]

\section*{7.3.3 Array-to-pointer conversion \[\text{[conv.array]}\]}

An lvalue or rvalue of type “array of N T” or “array of unknown bound of T” can be converted to a prvalue of type “pointer to T”. The temporary materialization conversion (7.3.5) is applied. The result is a pointer to the first element of the array.

\section*{7.3.4 Function-to-pointer conversion \[\text{[conv.func]}\]}

An lvalue of function type \( T \) can be converted to a prvalue of type “pointer to \( T \)”. The result is a pointer to the function.\(^{46}\)

\section*{7.3.5 Temporary materialization conversion \[\text{[conv.rval]}\]}

A prvalue of type \( T \) can be converted to an xvalue of type \( T \). This conversion initializes a temporary object (6.7.7) of type \( T \) from the prvalue by evaluating the prvalue with the temporary object as its result object, and produces an xvalue denoting the temporary object. \( T \) shall be a complete type.

\[ \text{[Note 1]: If } T \text{ is a class type (or array thereof), it must have an accessible and non-deleted destructor; see 11.4.7. — end note]} \]

\[ \text{[Example 1:} \]
```cpp
struct X { int n; };
int k = X().n;   // OK, X() prvalue is converted to xvalue
```

\[ \text{—end example} \]

\[ ^{45} \text{In C++ class and array prvalues can have cv-qualified types. This differs from C, in which non-lvalues never have cv-qualified types.} \]

\[ ^{46} \text{This conversion never applies to non-static member functions because an lvalue that refers to a non-static member function cannot be obtained.} \]
7.3.6 Qualification conversions

A qualification-decomposition of a type \( T \) is a sequence of \( cv_i \) and \( P_i \) such that \( T \) is

\[
\text{"cv}_0 \text{cv}_1 \text{cv}_2 \cdots \text{cv}_{n-1} \text{cv}_n \text{P}_n \cdots \text{P}_m \"}
\]

where each \( cv_i \) is a set of cv-qualifiers (6.8.5), and each \( P_i \) is “pointer to” (9.3.4.2), “pointer to member of class \( C_i \) of type” (9.3.4.4), “array of bound \( B_i \)”, or “array of unknown bound of” (9.3.4.5). If \( P_i \) designates an array, the cv-qualifiers \( cv_{i+1} \) on the element type are also taken as the cv-qualifiers \( cv_i \) of the array.

[Example 1: The type denoted by the type-id \( \text{const int **} \) has three qualification-decompositions, taking \( V \) as “int”, as “pointer to \( \text{int} \)”, and as “pointer to pointer to \( \text{int} \)”. — end example]

The \( n \)-tuple of cv-qualifiers after the first one in the longest qualification-decomposition of \( T \), that is, \( cv_1, cv_2, \ldots, cv_n \), is called the cv-qualification signature of \( T \).

Two types \( T_1 \) and \( T_2 \) are similar if they have qualification-decompositions with the same \( n \) such that the corresponding \( P_i \) components are either the same or one is “array of \( N_i \)”, and the other is “array of unknown bound of”, and the types denoted by \( V \) are the same.

The qualification-combined type of two types \( T_1 \) and \( T_2 \) is the type \( T_3 \) similar to \( T_1 \) whose qualification-decomposition is such that:

\begin{itemize}
  \item for every \( i > 0 \), \( cv_i \) is the union of \( cv_i^1 \) and \( cv_i^2 \),
  \item if either \( P_i^1 \) or \( P_i^2 \) is “array of unknown bound of”, \( P_i^3 \) is “array of unknown bound of”, otherwise it is \( P_i^1 \) and \( P_i^2 \),
  \item if the resulting \( cv_i^3 \) is different from \( cv_i^1 \) or \( cv_i^2 \), or the resulting \( P_i^3 \) is different from \( P_i^1 \) or \( P_i^2 \), then \( \text{const} \) is added to every \( cv_k^i \) for \( 0 < k < i \),
\end{itemize}

where \( cv_i^1 \) and \( P_i^1 \) are the components of the qualification-decomposition of \( T_j \). A prvalue of type \( T_1 \) can be converted to type \( T_2 \) if the qualification-combined type of \( T_1 \) and \( T_2 \) is \( T_2 \).

[Note 1: If a program could assign a pointer of type \( T** \) to a pointer of type \( \text{const T**} \) (that is, if line \#1 below were allowed), a program could inadvertently modify a const object (as it is done on line \#2). For example,

\begin{verbatim}
int main() {
  const char c = 'c';
  char* pc;
  const char** pcc = &pc;    // #1: not allowed
  *pcc = &c;
  *pc = 'C';                  // #2: modifies a const object
}
\end{verbatim}

— end note]

[Note 2: Given similar types \( T_1 \) and \( T_2 \), this construction ensures that both can be converted to the qualification-combined type of \( T_1 \) and \( T_2 \). — end note]

[Note 3: A prvalue of type “pointer to cv1 T” can be converted to a prvalue of type “pointer to cv2 T” if “cv2 T” is more cv-qualified than “cv1 T”. A prvalue of type “pointer to member of X of type cv1 T” can be converted to a prvalue of type “pointer to member of X of type cv2 T” if “cv2 T” is more cv-qualified than “cv1 T”. — end note]

[Note 4: Function types (including those used in pointer-to-member-function types) are never cv-qualified (9.3.4.6). — end note]

7.3.7 Integral promotions

For the purposes of 7.3.7, a converted bit-field is a prvalue that is the result of an lvalue-to-rvalue conversion (7.3.2) applied to a bit-field (11.4.10).

A prvalue that is not a converted bit-field and has an integer type other than \( \text{bool} \), \( \text{char8_t} \), \( \text{char16_t} \), \( \text{char32_t} \), or \( \text{wchar_t} \) whose integer conversion rank (6.8.6) is less than the rank of \( \text{int} \) can be converted to a prvalue of type \( \text{int} \) if \( \text{int} \) can represent all the values of the source type; otherwise, the source prvalue can be converted to a prvalue of type \( \text{unsigned int} \).

A prvalue of an unscoped enumeration type whose underlying type is not fixed can be converted to a prvalue of the first of the following types that can represent all the values of the enumeration (9.7.1): \( \text{int} \), \( \text{unsigned int} \), \( \text{long int} \), \( \text{unsigned long int} \), \( \text{long long int} \), or \( \text{unsigned long long int} \). If none of the types in that list can represent all the values of the enumeration, a prvalue of an unscoped enumeration type can be converted to a prvalue of the extended integer type with lowest integer conversion rank (6.8.6) greater than...
the rank of `long long` in which all the values of the enumeration can be represented. If there are two such extended types, the signed one is chosen.

A prvalue of an unscoped enumeration type whose underlying type is fixed (9.7.1) can be converted to a prvalue of its underlying type. Moreover, if integral promotion can be applied to its underlying type, a prvalue of an unscoped enumeration type whose underlying type is fixed can also be converted to a prvalue of the promoted underlying type.

[Note 1: A converted bit-field of enumeration type is treated as any other value of that type for promotion purposes. — end note]

A converted bit-field of integral type can be converted to a prvalue of type `int` if `int` can represent all the values of the bit-field; otherwise, it can be converted to `unsigned int` if `unsigned int` can represent all the values of the bit-field.

A prvalue of type `char8_t`, `char16_t`, `char32_t`, or `wchar_t` (6.8.2) (including a converted bit-field that was not already promoted to `int` or `unsigned int` according to the rules above) can be converted to a prvalue of the first of the following types that can represent all the values of its underlying type: `int`, `unsigned int`, `long int`, `unsigned long int`, `long long int`, `unsigned long long int`, or its underlying type.

A prvalue of type `bool` can be converted to a prvalue of type `int`, with `false` becoming zero and `true` becoming one.

These conversions are called `integral promotions`.

### 7.3.8 Floating-point promotion

A prvalue of type `float` can be converted to a prvalue of type `double`. The value is unchanged.

This conversion is called `floating-point promotion`.

### 7.3.9 Integral conversions

A prvalue of an integer type can be converted to a prvalue of another integer type. A prvalue of an unscoped enumeration type can be converted to a prvalue of an integer type.

If the destination type is `bool`, see 7.3.15. If the source type is `bool`, the value `false` is converted to zero and the value `true` is converted to one.

Otherwise, the result is the unique value of the destination type that is congruent to the source integer modulo $2^N$, where $N$ is the width of the destination type.

The conversions allowed as integral promotions are excluded from the set of integral conversions.

### 7.3.10 Floating-point conversions

A prvalue of floating-point type can be converted to a prvalue of another floating-point type with a greater or equal conversion rank (6.8.6). A prvalue of standard floating-point type can be converted to a prvalue of another standard floating-point type.

If the source value can be exactly represented in the destination type, the result of the conversion is that exact representation. If the source value is between two adjacent destination values, the result of the conversion is an implementation-defined choice of either of those values. Otherwise, the behavior is undefined.

The conversions allowed as floating-point promotions are excluded from the set of floating-point conversions.

### 7.3.11 Floating-integral conversions

A prvalue of a floating-point type can be converted to a prvalue of an integer type. The conversion truncates; that is, the fractional part is discarded. The behavior is undefined if the truncated value cannot be represented in the destination type.

[Note 1: If the destination type is `bool`, see 7.3.15. — end note]

A prvalue of an integer type or of an unscoped enumeration type can be converted to a prvalue of a floating-point type. The result is exact if possible. If the value being converted is in the range of values that can be represented but the value cannot be represented exactly, it is an implementation-defined choice of either the next lower or higher representable value.

[Note 2: Loss of precision occurs if the integral value cannot be represented exactly as a value of the floating-point type. — end note]
7.3.12 Pointer conversions [conv.ptr]

A null pointer constant is an integer literal (5.13.2) with value zero or a prvalue of type std::nullptr_t. A null pointer constant can be converted to a pointer type; the result is the null pointer value of that type (6.8.4) and is distinguishable from every other value of object pointer or function pointer type. Such a conversion is called a null pointer conversion. The conversion of a null pointer constant to a pointer to cv-qualified type is a single conversion, and not the sequence of a pointer conversion followed by a qualification conversion (7.3.6).

A null pointer constant of integral type can be converted to a prvalue of type std::nullptr_t.

[Note 1: The resulting prvalue is not a null pointer value. — end note]

A prvalue of type “pointer to cv T”, where T is an object type, can be converted to a prvalue of type “pointer to cv void”. The pointer value (6.8.4) is unchanged by this conversion.

A prvalue v of type “pointer to cv D”, where D is a complete class type, can be converted to a prvalue of type “pointer to cv B”, where B is a base class (11.7) of D. If B is an inaccessible (11.8) or ambiguous (6.5.2) base class of D, a program that necessitates this conversion is ill-formed. If v is a null pointer value, the result is a null pointer value. Otherwise, if B is a virtual base class of D and v does not point to an object whose type is a null pointer constant to a pointer to cv-qualified type is a single conversion, and not the sequence of a pointer-to-member conversion followed by a qualification conversion (7.3.6).

The null member pointer value is converted to the null member pointer value of the destination type.

7.3.13 Pointer-to-member conversions [conv.mem]

A null pointer constant (7.3.12) can be converted to a pointer-to-member type; the result is the null member pointer value of that type and is distinguishable from any pointer to member not created from a null pointer constant. Such a conversion is called a null member pointer conversion. The conversion of a null pointer constant to a pointer to member of cv-qualified type is a single conversion, and not the sequence of a pointer-to-member conversion followed by a qualification conversion (7.3.6).

A prvalue of type “pointer to member of B of type cv T”, where B is a class type, can be converted to a prvalue of type “pointer to member of D of type cv T”, where D is a complete class derived (11.7) from B. If B is an inaccessible (11.8), ambiguous (6.5.2), or virtual (11.7.2) base class of D, or a base class of a virtual base class of D, a program that necessitates this conversion is ill-formed. If class D does not contain the original member and is not a base class of the class containing the original member, the behavior is undefined. Otherwise, the result of the conversion refers to the same member as the pointer to member before the conversion took place, but it refers to the base class member as if it were a member of the derived class. The result refers to the member in D’s instance of B. Since the result has type “pointer to member of D of type cv T”, indirection through it with a D object is valid. The result is the same as if indirecting through the pointer to member of B with the B subobject of D. The null member pointer value is converted to the null member pointer value of the destination type.\(^{47}\)

7.3.14 Function pointer conversions [conv.fctptr]

A prvalue of type “pointer to noexcept function” can be converted to a prvalue of type “pointer to function”. The result is a pointer to the function. A prvalue of type “pointer to member of type noexcept function” can be converted to a prvalue of type “pointer to member of type function”. The result designates the member function.

Example 1:

```c
void (*p)();
void (**pp)() noexcept = &p;  // error: cannot convert to pointer to noexcept function

struct S { typedef void (*p)(); operator p(); };
void (*q)() noexcept = S();    // error: cannot convert to pointer to noexcept function

— end example
```

\(^{47}\) The rule for conversion of pointers to members (from pointer to member of base to pointer to member of derived) appears inverted compared to the rule for pointers to objects (from pointer to derived to pointer to base) (7.3.12, 11.7). This inversion is necessary to ensure type safety. Note that a pointer to member is not an object pointer or a function pointer and the rules for conversions of such pointers do not apply to pointers to members. In particular, a pointer to member cannot be converted to a void*.
7.3.15 Boolean conversions

A prvalue of arithmetic, unscoped enumeration, pointer, or pointer-to-member type can be converted to a prvalue of type bool. A zero value, null pointer value, or null member pointer value is converted to false; any other value is converted to true.

7.4 Usual arithmetic conversions

Many binary operators that expect operands of arithmetic or enumeration type cause conversions and yield result types in a similar way. The purpose is to yield a common type, which is also the type of the result. This pattern is called the usual arithmetic conversions, which are defined as follows:

1. The lvalue-to-rvalue conversion (7.3.2) is applied to each operand and the resulting prvalues are used in place of the original operands for the remainder of this section.
2. If either operand is of scoped enumeration type (9.7.1), no conversions are performed; if the other operand does not have the same type, the expression is ill-formed.
3. Otherwise, if one operand is of enumeration type and the other operand is of a different enumeration type or a floating-point type, the expression is ill-formed.
4. Otherwise, if either operand is of floating-point type, the following rules are applied:
   - If both operands have the same type, no further conversion is performed.
   - Otherwise, if one of the operands is of a non-floating-point type, that operand is converted to the type of the operand with the floating-point type.
   - Otherwise, if the floating-point conversion ranks (6.8.6) of the types of the operands are ordered but not equal, then the operand of the type with the lesser floating-point conversion rank is converted to the type of the other operand.
   - Otherwise, if the floating-point conversion ranks of the types of the operands are equal, then the operand with the lesser floating-point conversion subrank (6.8.6) is converted to the type of the other operand.
   - Otherwise, the expression is ill-formed.
5. Otherwise, each operand is converted to a common type C. The integral promotion rules (7.3.7) are used to determine a type T1 and type T2 for each operand. Then the following rules are applied to determine C:
   - If T1 and T2 are the same type, C is that type.
   - Otherwise, if T1 and T2 are both signed integer types or are both unsigned integer types, C is the type with greater rank.
   - Otherwise, let U be the unsigned integer type and S be the signed integer type.
     - If U has rank greater than or equal to the rank of S, C is U.
     - Otherwise, if S can represent all of the values of U, C is S.
     - Otherwise, C is the unsigned integer type corresponding to S.

7.5 Primary expressions

7.5.1 Grammar

primary-expression:
  literal
  this
  ( expression )
  id-expression
  lambda-expression
  fold-expression
  requires-expression

As a consequence, operands of type bool, char8_t, char16_t, char32_t, wchar_t, or of enumeration type are converted to some integral type.
7.5.2 Literals

The type of a literal is determined based on its form as specified in 5.13. A string-literal is an lvalue designating a corresponding string literal object (5.13.5), a user-defined-literal has the same value category as the corresponding operator call expression described in 5.13.9, and any other literal is a prvalue.

7.5.3 This

The keyword this names a pointer to the object for which an implicit object member function (11.4.3) is invoked or a non-static data member’s initializer (11.4) is evaluated.

1 The current class at a program point is the class associated with the innermost class scope containing that point.

[Note 1: A lambda-expression does not introduce a class scope. — end note]

3 If a declaration declares a member function or member function template of a class X, the expression this is a prvalue of type “pointer to cv-qualifier-seq X” wherever X is the current class between the optional cv-qualifier-seq and the end of the function-definition, member-declarator, or declarator. It shall not appear within the declaration of a static or explicit object member function of the current class (although its type and value category are defined within such member functions as they are within an implicit object member function).

[Note 2: This is because declaration matching does not occur until the complete declarator is known. — end note]

[Note 3: In a trailing-return-type, the class being defined is not required to be complete for purposes of class member access (7.6.1.5). Class members declared later are not visible.]

[Example 1:]

```cpp
struct A {
    char g();
    template<class T> auto f(T t) -> decltype(t + g())
        { return t + g(); }  // error: not inside a member function
    template auto A::f(int t) -> decltype(t + g());
};
```

—end example

4 Otherwise, if a member-declarator declares a non-static data member (11.4) of a class X, the expression this is a prvalue of type “pointer to X” wherever X is the current class within the optional default member initializer (11.4).

5 The expression this shall not appear in any other context.

[Example 2:]

```cpp
class Outer {
    int a[sizeof(*this)];  // error: not inside a member function
    unsigned int sz = sizeof(*this);  // OK, in default member initializer
    
    void f() {
        int b[sizeof(*this)];  // OK
        
        struct Inner {
            int c[sizeof(*this)];  // error: not inside a member function of Inner
        }
    }
};
```

—end example

7.5.4 Parentheses

A parenthesized expression (E) is a primary expression whose type, result, and value category are identical to those of E. The parenthesized expression can be used in exactly the same contexts as those where E can be used, and with the same meaning, except as otherwise indicated.

7.5.5 Names

7.5.5.1 General
An \textit{id-expression} is a restricted form of a \textit{primary-expression}.

\begin{itemize}
\item \[\text{Note 1: An id-expression can appear after . and \texttt{-\texttt{\textarrow}} operators (7.6.1.5). \text{end note}}\]
\end{itemize}

If an \textit{id-expression} $E$ denotes a non-static non-type member of some class $C$ at a point where the current class (7.5.3) is $X$ and

\begin{itemize}
\item (2.1) $E$ is potentially evaluated or $C$ is $X$ or a base class of $X$, and
\item (2.2) $E$ is not the \textit{id-expression} of a class member access expression (7.6.1.5), and
\item (2.3) if $E$ is a \textit{qualified-id}, $E$ is not the un-parenthesized operand of the unary \texttt{&} operator (7.6.2.2),
\end{itemize}

the \textit{id-expression} is transformed into a class member access expression using (\texttt{*this}) as the object expression.

\begin{itemize}
\item \[\text{Note 2: If C is not X or a base class of X, the class member access expression is ill-formed. Also, if the id-expression occurs within a static or explicit object member function, the class member access is ill-formed. \text{end note}}\]
\end{itemize}

This transformation does not apply in the template definition context (13.8.3.2).

If an \textit{id-expression} $E$ denotes a member $M$ of an anonymous union (11.5.2) $U$:

\begin{itemize}
\item (3.1) If $U$ is a non-static data member, $E$ refers to $M$ as a member of the lookup context of the terminal name of $E$ (after any implicit transformation to a class member access expression).
\item (3.2) Otherwise, $E$ is interpreted as a class member access (7.6.1.5) that designates the member subobject $M$ of the anonymous union variable for $U$.
\end{itemize}

\begin{itemize}
\item \[\text{Note 3: Under this interpretation, E no longer denotes a non-static data member. \text{end note}}\]
\end{itemize}

\begin{itemize}
\item \[\text{Example 2: N::x is interpreted as N::u.x, where u names the anonymous union variable. \text{end example}}\]
\end{itemize}

An \textit{id-expression} that denotes a non-static data member or implicit object member function of a class can only be used:

\begin{itemize}
\item (4.1) as part of a class member access (after any implicit transformation (see above)) in which the object expression refers to the member’s class or a class derived from that class, or
\item (4.2) to form a pointer to member (7.6.2.2), or
\item (4.3) if that \textit{id-expression} denotes a non-static data member and it appears in an unevaluated operand.
\end{itemize}

\begin{itemize}
\item \[\text{Example 3:}\]
\end{itemize}

\begin{itemize}
\item \[\text{struct S {\}}\]
\item \[\text{int m;}\]
\item \[\text{int i = sizeof(S::m);} \quad \text{\texttt{\textbackslash / OK}}\]
\item \[\text{int j = sizeof(S::m + 42);} \quad \text{\texttt{\textbackslash / OK}}\]
\end{itemize}

\begin{itemize}
\item \[\text{end example}\]
\end{itemize}

For an \textit{id-expression} that denotes an overload set, overload resolution is performed to select a unique function (12.2, 12.3).

\begin{itemize}
\item \[\text{Note 4: A program cannot refer to a function with a trailing requires-clause whose constraint-expression is not satisfied, because such functions are never selected by overload resolution.}\]
\end{itemize}

\begin{itemize}
\item \[\text{Example 4:}\]
\end{itemize}

\begin{itemize}
\item \[\text{template<typename T> struct A {\}}\]
\item \[\text{static void f(int) requires false;}\]
\end{itemize}

\begin{itemize}
\item \[\text{void g()} \{\}
\item \[\text{A<int>::f(0);} \quad \text{\texttt{\textbackslash / error: cannot call f}}\]
\item \[\text{void (*p1)(int) = A<int>::f;} \quad \text{\texttt{\textbackslash / error: cannot take the address of f}}\]
\item \[\text{decltype(A<int>::f)* p2 = nullptr;} \quad \text{\texttt{\textbackslash / error: the type decltype(A<int>::f) is invalid}}\]
\end{itemize}

\begin{itemize}
\item \[\text{}}\]
\end{itemize}
In each case, the constraints of \( f \) are not satisfied. In the declaration of \( p2 \), those constraints need to be satisfied even though \( f \) is an unevaluated operand (7.2.3). — end example

— end note

7.5.5.2 Unqualified names

Unqualified-id:

- identifier
- operator-function-id
- conversion-function-id
- literal-operator-id
- ~ type-name
- ~ computed-type-specifier
- template-id

1 An identifier is only an id-expression if it has been suitably declared (Clause 9) or if it appears as part of a declarator-id (9.3). An identifier that names a coroutine parameter refers to the copy of the parameter (9.5.4).

[Note 1: For operator-function-ids, see 12.4; for conversion-function-ids, see 11.4.8.3; for literal-operator-ids, see 12.6; for template-ids, see 13.3. A type-name or computed-type-specifier prefixed by ~ denotes the destructor of the type so named; see 7.5.5.5. — end note]

2 A component name of an unqualified-id \( U \) is

(2.1) \( U \) if it is a name or

(2.2) the component name of the template-id or type-name of \( U \), if any.

[Note 2: Other constructs that contain names to look up can have several component names (7.5.5.3, 9.2.9.3, 9.2.9.5, 9.3.4.4, 9.9, 13.2, 13.3, 13.8). — end note]

The terminal name of a construct is the component name of that construct that appears lexically last.

3 The result is the entity denoted by the unqualified-id (6.5.3). If the unqualified-id appears in a lambda-expression at program point \( P \) and the entity is a local entity (6.1) or a variable declared by an init-capture (7.5.6.3), then let \( S \) be the compound-statement of the innermost enclosing lambda-expression of \( P \). If naming the entity from outside of an unevaluated operand within \( S \) would refer to an entity captured by copy in some intervening lambda-expression, then let \( E \) be the innermost such lambda-expression.

(3.1) If there is such a lambda-expression and if \( P \) is in \( E \)'s function parameter scope but not its parameter-declaration-clause, then the type of the expression is the type of a class member access expression (7.6.1.5) naming the non-static data member that would be declared for such a capture in the object parameter (9.3.4.6) of the function call operator of \( E \).

[Note 3: If \( E \) is not declared mutable, the type of such an identifier will typically be const qualified. — end note]

(3.2) Otherwise (if there is no such lambda-expression or if \( P \) either precedes \( E \)'s function parameter scope or is in \( E \)'s parameter-declaration-clause), the type of the expression is the type of the result.

If the entity is a template parameter object for a template parameter of type \( T \) (13.2), the type of the expression is const \( T \). In all other cases, the type of the expression is the type of the entity.

[Note 4: The type will be adjusted as described in 7.2.2 if it is cv-qualified or is a reference type. — end note]

The expression is an xvalue if it is move-eligible (see below); an lvalue if the entity is a function, variable, structured binding (9.6), data member, or template parameter object; and a prvalue otherwise (7.2.1); it is a bit-field if the identifier designates a bit-field.

[Example 1:]

```c
void f() {
    float x, &r = x;
    [=]() -> decltype((x)) { // lambda returns float const because this lambda is not mutable and
        // x is an lvalue
        decltype(x) y1; // y1 has type float
        decltype((x)) y2 = y1; // y2 has type float const
        decltype(r) r1 = y1; // r1 has type float
        decltype((r)) r2 = y2; // r2 has type float const
        return y2;
    };
}
```

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An implicitly movable entity is a variable of automatic storage duration that is either a non-volatile object or an rvalue reference to a non-volatile object type. In the following contexts, an id-expression is move-eligible:

1. If the id-expression (possibly parenthesized) is the operand of a return (8.7.4) or co_return (8.7.5) statement, and names an implicitly movable entity declared in the body or parameter-declaration-clause of the innermost enclosing function or lambda-expression, or

2. If the id-expression (possibly parenthesized) is the operand of a throw-expression (7.6.18), and names an implicitly movable entity that belongs to a scope that does not contain the compound-statement of the innermost lambda-expression, try-block, or function-try-block (if any) whose compound-statement or ctor-initializer contains the throw-expression.

7.5.5.3 Qualified names

qualified-id:
   nested-nameSpecifier template_opt unqualified-id

   nested-nameSpecifier:
   ::
      type-name ::
      namespace-name ::
      computed-typeSpecifier ::
      nested-nameSpecifier identifier ::
      nested-nameSpecifier template_opt simple-template-id ::

1. The component names of a qualified-id are those of its nested-nameSpecifier and unqualified-id. The component names of a nested-nameSpecifier are its identifier (if any) and those of its type-name, namespace-name, simple-template-id, and/or nested-nameSpecifier.

2. A nested-nameSpecifier is declarative if it is part of
   (2.1) a class-head-name,
   (2.2) an enum-head-name,
   (2.3) a qualified-id that is the id-expression of a declarator-id, or
   (2.4) a declarative nested-nameSpecifier.

A declarative nested-nameSpecifier shall not have a computed-typeSpecifier. A declaration that uses a declarative nested-nameSpecifier shall be a friend declaration or inhabit a scope that contains the entity being redeclared or specialized.

3. The nested-nameSpecifier :: nommates the global namespace. A nested-nameSpecifier with a computed-typeSpecifier nommates the type denoted by the computed-typeSpecifier, which shall be a class or enumeration type. If a nested-nameSpecifier N is declarative and has a simple-template-id with a template argument list A that involves a template parameter, let T be the template nominated by N without A. T shall be a class template.

   (3.1) If A is the template argument list (13.4) of the corresponding template-head H (13.7.3), N nommates the primary template of T; H shall be equivalent to the template-head of T (13.7.7.2).
   (3.2) Otherwise, N nommates the partial specialization (13.7.6) of T whose template argument list is equivalent to A (13.7.7.2); the program is ill-formed if no such partial specialization exists.

Any other nested-nameSpecifier nommates the entity denoted by its type-name, namespace-name, identifier, or simple-template-id. If the nested-nameSpecifier is not declarative, the entity shall not be a template.
A qualified-id shall not be of the form nested-name-specifier template opt - computed-type-specifier nor of the form computed-type-specifier :: ~ computed-type-specifier.

The result of a qualified-id Q is the entity it denotes (6.5.5). The type of the expression is the type of the result. The result is an lvalue if the member is

1. a function other than a non-static member function,
2. a non-static member function if Q is the operand of a unary & operator,
3. a variable,
4. a structured binding (9.6), or
5. a data member,

and a prvalue otherwise.

7.5.5.4 Pack indexing expression [expr.prim.pack.index]

pack-index-expression:
  id-expression ... [ constant-expression ]

1. The id-expression P in a pack-index-expression shall be an identifier that denotes a pack.
2. The constant-expression shall be a converted constant expression (7.7) of type std::size_t whose value V, termed the index, is such that 0 ≤ V < sizeof...(P).
3. A pack-index-expression is a pack expansion (13.7.4).
4. [Note 1: A pack-index-expression denotes the Vth element of the pack. — end note]

7.5.5.5 Destruction [expr.prim.id.dtor]

1. An id-expression that denotes the destructor of a type T names the destructor of T if T is a class type (11.4.7), otherwise the id-expression is said to name a pseudo-destructor.
2. If the id-expression names a pseudo-destructor, T shall be a scalar type and the id-expression shall appear as the right operand of a class member access (7.6.1.5) that forms the postfix-expression of a function call (7.6.1.3).
3. [Note 1: Such a call ends the lifetime of the object (7.6.1.3, 6.7.3). — end note]

[Example 1:

```cpp
struct C { }
void f() {
  C * pc = new C;
  using C2 = C;
  pc->C::~C2(); // OK, destroys pc
  C().C::~C(); // undefined behavior: temporary of type C destroyed twice
  using T = int;
  0 .T::~T(); // OK, no effect
  0 .T::~T(); // error: 0 .T is a user-defined-floating-point-literal (5.13.9)
}
```
— end example]

7.5.6 Lambda expressions [expr.prim.lambda]

7.5.6.1 General [expr.prim.lambda.general]

lambda-expression:
  lambda-introducer attribute-specifier-seq opt lambda-declarator compound-statement
  lambda-introducer < template-parameter-list > requires-clause opt attribute-specifier-seq opt lambda-declarator compound-statement

lambda-introducer:
  [ lambda-capture opt ]

lambda-declarator:
  lambda-specifier-seq noexceptSpecifier opt attribute-specifier-seq opt trailing-return-type opt
  noexceptSpecifier attribute-specifier-seq opt trailing-return-type opt
  trailing-return-type opt
  ( parameter-declaration-clause ) lambda-specifier-seq opt noexceptSpecifier opt attribute-specifier-seq opt
  trailing-return-type opt requires-clause opt
A `lambda-expression` provides a concise way to create a simple function object.

```cpp
#include <algorithm>
#include <cmath>
void abssort(float* x, unsigned N) {
  std::sort(x, x + N, [](float a, float b) { return std::abs(a) < std::abs(b); });
}
—end example
```

2 A `lambda-expression` is a prvalue whose result object is called the closure object.

[Note 1: A closure object behaves like a function object (22.10). — end note]

An ambiguity can arise because a `requires-clause` can end in an `attribute-specifier-seq`, which collides with the `attribute-specifier-seq` in `lambda-expression`. In such cases, any attributes are treated as `attribute-specifier-seq` in `lambda-expression`.

[Note 2: Such ambiguous cases cannot have valid semantics because the constraint expression would not have type `bool`. — end note]

A `lambda-specifier-seq` shall contain at most one of each `lambda-specifier` and shall not contain both `constexpr` and `consteval`. If the `lambda-declarator` contains an explicit object parameter (9.3.4.6), then no `lambda-specifier` in the `lambda-specifier-seq` shall be `mutable` or `static`. The `lambda-specifier-seq` shall not contain both `mutable` and `static`. If the `lambda-specifier-seq` contains `static`, there shall be no `lambda-capture`.

[Note 3: The trailing `requires-clause` is described in 9.3. — end note]

5 A `lambda-expression`’s parameter-declaration-clause is the parameter-declaration-clause of the `lambda-expression`’s `lambda-declarator`, if any, or empty otherwise. If the `lambda-declarator` does not include a `trailing-return-type`, it is considered to be `-> auto`.

[Note 4: In that case, the return type is deduced from `return` statements as described in 9.2.9.7. — end note]

```cpp
auto x1 = [](int i) { return i; }; // OK, return type is int
auto x2 = [](return { 1, 2 }); // error: deducing return type from braced-init-list
int j;
auto x3 = [k]()->auto&& { return j; }; // OK, return type is int&
—end example
```

7.5.6.2 Closure types

The type of a `lambda-expression` (which is also the type of the closure object) is a unique, unnamed non-union class type, called the closure type, whose properties are described below.
2 The closure type is declared in the smallest block scope, class scope, or namespace scope that contains the corresponding lambda-expression.

[Note 1: This determines the set of namespaces and classes associated with the closure type (6.5.4). The parameter types of a lambda-declarator do not affect these associated namespaces and classes. — end note]

3 The closure type is not an aggregate type (9.4.2); it is a structural type (13.2) if and only if the lambda has no lambda-capture. An implementation may define the closure type differently from what is described below provided this does not alter the observable behavior of the program other than by changing:

(1.1) — the size and/or alignment of the closure type,
(1.2) — whether the closure type is trivially copyable (11.2), or
(1.3) — whether the closure type is a standard-layout class (11.2).

An implementation shall not add members of rvalue reference type to the closure type.

4 The closure type for a lambda-expression has a public inline function call operator (for a non-generic lambda) or function call operator template (for a generic lambda) (12.4.4) whose parameters and return type are those of the lambda-expression’s parameter-declaration-clause and trailing-return-type respectively, and whose template-parameter-list consists of the specified template-parameter-list, if any. The requires-clause of the function call operator template is the requires-clause immediately following < template-parameter-list >, if any. The trailing requires-clause of the function call operator or operator template is the requires-clause of the lambda-declarator, if any.

[Note 2: The function call operator template for a generic lambda can be an abbreviated function template (9.3.4.6). — end note]

[Example 1:

auto glambda = [](auto a, auto&& b) { return a < b; };
bool b = glambda(3, 3.14); // OK

auto vglambda = [](auto printer) {
    return [=](auto&& ... ts) {
        printer(std::forward<decltype(ts)>(ts)...); // OK, ts is a function parameter pack
    }
    
    printer(ts ...);
};

auto p = vglambda( [](auto v1, auto v2, auto v3) {
    std::cout << v1 << v2 << v3; } );

auto q = p(1, 'a', 3.14); // OK, outputs 1a3.14
q(); // OK, outputs 1a3.14

auto fact = [](this auto self, int n) -> int {
    return (n <= 1) ? 1 : n * self(n-1);
};

std::cout << fact(5); // OK, outputs 120
— end example]

5 Given a lambda with a lambda-capture, the type of the explicit object parameter, if any, of the lambda’s function call operator (possibly instantiated from a function call operator template) shall be either:

(2.1) — the closure type,
(2.2) — a class type publicly and unambiguously derived from the closure type, or
(2.3) — a reference to a possibly cv-qualified such type.

[Example 2:

struct C {
    template <typename T>
    C(T); 
};

§ 7.5.6.2 ©ISO/IEC 113
The function call operator or operator template is a static member function or static member function template (11.4.9.2) if the lambda-expression’s parameter-declaration-clause is followed by static. Otherwise, it is a non-static member function or member function template (11.4.3) that is declared const (11.4.3) if and only if the lambda-expression’s parameter-declaration-clause is not followed by mutable and the lambda-declarator does not contain an explicit object parameter. It is neither virtual nor declared volatile. Any noexcept-specifier specified on a lambda-expression applies to the corresponding function call operator or operator template. An attribute-specifier-seq in a lambda-declarator appertains to the type of the corresponding function call operator or operator template. An attribute-specifier-seq in a lambda-expression preceding a lambda-declarator appertains to the corresponding function call operator or operator template. The function call operator or any given operator template specialization is a constexpr function if either the corresponding lambda-expression’s parameter-declaration-clause is followed by constexpr or consteval, or it is constexpr-suitable (9.2.6). It is an immediate function (9.2.6) if the corresponding lambda-expression’s parameter-declaration-clause is followed by consteval.

Example 3:

```cpp
auto ID = [](auto a) { return a; }; // OK
static_assert(ID(3) == 3);
struct NonLiteral {
    NonLiteral(int n) : n(n) { } // error
    int n;
};
static_assert(ID(NonLiteral{3}).n == 3);
```

Example 4:

```cpp
auto monoid = [](auto v) { return [=] { return v; }; }; // OK
auto add = [](auto m1) constexpr {
    auto ret = m1();
    return [=](auto m2) mutable {
        auto m1val = m1();
        auto plus = [=](auto m2val) mutable constexpr {
            return m1val += m2val;
        };
        ret = plus(m2());
        return monoid(ret);
    };
};
constexpr auto zero = monoid(0);
constexpr auto one = monoid(1);
static_assert(add(one)(zero)() == one()); // OK
// Since two below is not declared constexpr, an evaluation of its constexpr member function call operator cannot perform an lvalue-to-rvalue conversion on one of its subobjects (that represents its capture)
// in a constant expression.
auto two = monoid(2);
assert(two() == 2); // OK, not a constant expression.
static_assert(add(one)(one)() == two()); // error: two() is not a constant expression
static_assert(add(one)(one)() == monoid(2)()); // OK
```

Note 3: The function call operator or operator template can be constrained (13.5.3) by a type-constraint (13.2), a requires-clause (13.1), or a trailing requires-clause (9.3).

Example 5:

```cpp
template <typename T>
concept C1 = /* ... */;
template <std::size_t N>
concept C2 = /* ... */;
```
template <typename A, typename B> concept C3 = /* ... */;

auto f = []<typename T1, C1 T2> requires C2<sizeof(T1) + sizeof(T2)>
(T1 a1, T1 b1, T2 a2, auto a3, auto a4) requires C3<decltype(a4), T2> {
    // T2 is constrained by a type-constraint.
    // T1 and T2 are constrained by a requires-clause, and
    // T2 and the type of a4 are constrained by a trailing requires-clause.
};

—end example
—end note

The closure type for a non-generic lambda-expression with no lambda-capture and no explicit object parameter (9.3.4.6) whose constraints (if any) are satisfied has a conversion function to pointer to function with C++ language linkage (9.11) having the same parameter and return types as the closure type’s function call operator. The conversion is to “pointer to noexcept function” if the function call operator has a non-throwing exception specification. If the function call operator is a static member function, then the value returned by this conversion function is the address of the function call operator. Otherwise, the value returned by this conversion function is the address of a function F that, when invoked, has the same effect as invoking the closure type’s function call operator on a default-constructed instance of the closure type. F is a constexpr function if the function call operator is a constexpr function and is an immediate function if the function call operator is an immediate function.

For a generic lambda with no lambda-capture and no explicit object parameter (9.3.4.6), the closure type has a conversion function template to pointer to function. The conversion function template has the same invented template parameter list, and the pointer to function has the same parameter types, as the function call operator template. The return type of the pointer to function shall behave as if it were a decltype-specifier denoting the return type of the corresponding function call operator template specialization.

[Note 4: If the generic lambda has no trailing-return-type or the trailing-return-type contains a placeholder type, return type deduction of the corresponding function call operator template specialization has to be done. The corresponding specialization is that instantiation of the function call operator template with the same template arguments as those deduced for the conversion function template. Consider the following:]

auto glambda = []<auto a> { return a; };
int (*fp)(int) = glambda;

The behavior of the conversion function of glambda above is like that of the following conversion function:

struct Closure {
    template<class T> auto operator()(T t) const { /* ... */ }
    template<class T> static auto lambda_call_operator_invoker(T a) {
        // forwards execution to operator()(a) and therefore has
        /* ... */
    }
    template<class T> using fptr_t = decltype(lambda_call_operator_invoker(declval<T>()))(T);
    template<class T> operator fptr_t<T>() const
    { return &lambda_call_operator_invoker; }
};

—end note

[Example 6:]

void f1(int (*)(int)) { }  // #1
void f2(char (*)(int)) { }  // #2
void g(int (*)(int)) { }  // #3
void g(char (*)(char)) { }  // #4
void h(int (*)(int)) { }  // #5
void h(char (*)(int)) { }  // #6

auto glambda = []<auto a> { return a; };
f1(glambda);  // OK
f2(glamba); // error: ID is not convertible
g(glamba); // error: ambiguous
h(glamba); // OK, calls #3 since it is convertible from ID
int& (*fpi)(int*) = [] (auto* a) -> auto& { return *a; }; // OK

—end example

12 If the function call operator template is a static member function template, then the value returned by any given specialization of this conversion function template is the address of the corresponding function call operator template specialization. Otherwise, the value returned by any given specialization of this conversion function template is the address of a function F that, when invoked, has the same effect as invoking the generic lambda’s corresponding function call operator template specialization on a default-constructed instance of the closure type. F is a constexpr function if the corresponding specialization is a constexpr function and F is an immediate function if the function call operator template specialization is an immediate function.

[Note 5: This will result in the implicit instantiation of the generic lambda’s body. The instantiated generic lambda’s return type and parameter types need to match the return type and parameter types of the pointer to function.
—end note]

[Example 7:
  auto GL = [] (auto a) { std::cout << a; return a; };
  int (*GL_int)(int) = GL; // OK, through conversion function template
  GL_int(3); // OK, same as GL(3)
—end example]

13 The conversion function or conversion function template is public, constexpr, non-virtual, non-explicit, const, and has a non-throwing exception specification (14.5).

[Example 8:
  auto Fwd = [] (int (*fp)(int), auto a) { return fp(a); };
  auto C = [] (auto a) { return a; };

  static_assert(Fwd(C,3) == 3); // OK
  // No specialization of the function call operator template can be constexpr (due to the local static).
  auto NC = [] (auto a) { static int s; return a; };
  static_assert(Fwd(NC,3) == 3); // error
—end example]

14 The lambda-expression’s compound-statement yields the function-body (9.5) of the function call operator, but it is not within the scope of the closure type.

[Example 9:
  struct S1 {
    int x, y;
    int operator()(int);
    void f() {
      [=] ()->int {
        return operator()(this->x + y); // equivalent to S1::operator()(this->x + (*this).y)
        // this has type S1*
      };
    }
  };
—end example]

Further, a variable __func__ is implicitly defined at the beginning of the compound-statement of the lambda-expression, with semantics as described in 9.5.1.

15 The closure type associated with a lambda-expression has no default constructor if the lambda-expression has a lambda-capture, and a defaulted default constructor otherwise. It has a defaulted copy constructor and a defaulted move constructor (11.4.5.3). It has a deleted copy assignment operator if the lambda-expression has a lambda-capture and defaulted copy and move assignment operators otherwise (11.4.6).

[Note 6: These special member functions are implicitly defined as usual, which can result in them being defined as deleted. —end note]
The closure type associated with a \textit{lambda-expression} has an implicitly-declared destructor (11.4.7).

A member of a closure type shall not be explicitly instantiated (13.9.3), explicitly specialized (13.9.4), or named in a friend declaration (11.8.4).

1. The body of a \textit{lambda-expression} may refer to local entities of enclosing block scopes by capturing those entities, as described below.

2. If a \textit{lambda-capture} includes a \textit{capture-default} that is \&, no identifier in a \textit{simple-capture} of that \textit{lambda-capture} shall be preceded by \&. If a \textit{lambda-capture} includes a \textit{capture-default} that is \=, each \textit{simple-capture} of that \textit{lambda-capture} shall be of the form “\& \textit{identifier} \ldots \textit{opt}”, “\textit{this}”, or “\* \textit{this}”.

[\textit{Note 1}: The form [\&, \textit{this}] is redundant but accepted for compatibility with C++ 2014. — \textit{end note}]

Ignoring appearances in \textit{initializers} of \textit{init-captures}, an identifier or \textit{this} shall not appear more than once in a \textit{lambda-capture}.

\textbf{Example 1:}

\begin{verbatim}
struct S2 { void f(int i); }
void S2::f(int i) {
  [&, i]{};    // OK
  [&, this, i]{}; // OK, equivalent to [&, i]
  [&, &i]{};    // error: \textit{i} preceded by \& when \& is the default
  [=, &this]{}; // OK
  [=, this]{};  // OK, equivalent to [=]
  [i, i]{};     // error: \textit{i} repeated
  [this, &this]{}; // error: \textit{this} appears twice
}
\end{verbatim}

— \textit{end example}]

3. A \textit{lambda-expression} shall not have a \textit{capture-default} or \textit{simple-capture} in its \textit{lambda-introducer} unless its innermost enclosing scope is a block scope (6.4.3) or it appears within a default member initializer and its innermost enclosing scope is the corresponding class scope (6.4.7).

4. The \textit{identifier} in a \textit{simple-capture} shall denote a local entity (6.5.3, 6.1). The \textit{simple-captures} \textit{this} and \* \textit{this} denote the local entity \*\textit{this}. An entity that is designated by a \textit{simple-capture} is said to be \textit{explicitly captured}.

5. If an \textit{identifier} in a \textit{capture} appears as the \textit{declarator-id} of a parameter of the \textit{lambda-declarator}’s \textit{parameter-declaration-clause} or as the name of a template parameter of the \textit{lambda-expression}’s \textit{template-parameter-list}, the program is ill-formed.
An `init-capture` inhabits the lambda scope (6.4.5) of the lambda-expression. An `init-capture` without ellipsis behaves as if it declares and explicitly captures a variable of the form “auto init-capture ;”, except that:

- if the capture is by copy (see below), the non-static data member declared for the capture and the variable are treated as two different ways of referring to the same object, which has the lifetime of the non-static data member, and no additional copy and destruction is performed, and
- if the capture is by reference, the variable’s lifetime ends when the closure object’s lifetime ends.

---

**Example 3:**
```cpp
int x = 4;
auto y = [&r = x, x = x+1]()->int {
    r += 2;
    return x+2;
}(); // Updates \( \text{::x} \) to 6, and initializes \( \text{y} \) to 7.

auto z = [a = 42](int a) { return 1; }; // error: parameter and conceptual local variable have the same name
auto counter = [i=0] mutable -> decltype(i) {
    // OK, returns int
    return i++;  
};
```

---

For the purposes of lambda capture, an expression potentially references local entities as follows:

- An `id-expression` that names a local entity potentially references that entity; an `id-expression` that names one or more non-static class members and does not form a pointer to member (7.6.2.2) potentially references `*this`.
  
  **Note 3:** This occurs even if overload resolution selects a static member function for the `id-expression`. — end note

- A `this` expression potentially references `*this`.

- A lambda-expression potentially references the local entities named by its simple-captures.

  If an expression potentially references a local entity within a scope in which it is odr-usable (6.3), and the expression would be potentially evaluated if the effect of any enclosing `typeid` expressions (7.6.1.8) were ignored, the entity is said to be implicitly captured by each intervening lambda-expression with an associated `capture-default` that does not explicitly capture it. The implicit capture of `*this` is deprecated when the `capture-default` is `=`; see D.2.

---

**Example 4:**
```cpp
void f(int, const int (&)[2] = {}); // #1
void f(const int&, const int (&)[1]); // #2
void test() {
    const int x = 17;
    auto g = [](auto a) {
        f(x); // OK, calls #1, does not capture x
    };

    auto g1 = [=](auto a) {
        f(x); // OK, calls #1, captures x
    };
```
auto g2 = [=](auto a) {
  int selector[sizeof(a) == 1 ? 1 : 2]{};
  f(x, selector);                  // OK, captures x, can call #1 or #2
};

auto g3 = [=](auto a) {
  typeid(a + x);                   // captures x regardless of whether a + x is an unevaluated operand
};

Within g1, an implementation can optimize away the capture of x as it is not odr-used. —end example—

[Note 4: The set of captured entities is determined syntactically, and entities are implicitly captured even if the expression denoting a local entity is within a discarded statement (8.5.2).]

[Example 5:]

```cpp
template<bool B>
void f(int n) {
  [=](auto a) {
    if constexpr (B && sizeof(a) > 4) {
      (void)n;                  // captures n regardless of the value of B and sizeof(int)
    }
  }(0);
}
—end example
—end note
```

8 An entity is captured if it is captured explicitly or implicitly. An entity captured by a lambda-expression is odr-used (6.3) by the lambda-expression.

[Note 5: As a consequence, if a lambda-expression explicitly captures an entity that is not odr-usable, the program is ill-formed (6.3). —end note]

[Example 6:]

```cpp
void f1(int i) {
  int const N = 20;
  auto m1 = [=]{
    int const M = 30;
    auto m2 = [i]{
      int x[N][M];             // OK, N and M are not odr-used
      x[0][0] = i;             // OK, i is explicitly captured by m2 and implicitly captured by m1
    }
  };
}
struct s1 {
  int f;
  void work(int n) {
    int m = n*n;
    int j = 40;
    auto m3 = [this,m] {
      auto m4 = [k,j] {
        int x = n;
        x *= m;          // OK, m implicitly captured by m4 and explicitly captured by m3
        x *= i;
        x += f;          // OK, this captured implicitly by m4 and explicitly by m3
      }
    }
  }
};
struct s2 {
  double ohseven = .007;
  auto f() {
    return [this] {
      return [*this] {
```
return ohseven; // OK
}

auto g() {
    return [] {
        return [*this] { }; // error: *this not captured by outer lambda-expression
    }();
};

—end example] 9

[Note 6: Because local entities are not odr usable within a default argument (6.3), a lambda-expression appearing in a default argument cannot implicitly or explicitly capture any local entity. Such a lambda-expression can still have an init-capture if any full-expression in its initializer satisfies the constraints of an expression appearing in a default argument (9.3.4.7). —end note]

[Example 7:]
void f2() {
    int i = 1;
    void g1(int i = (i){ return i; })(); // error
    void g2(int i = (i){ return 0; })(); // error
    void g3(int i = (i){ return i; })(); // error
    void g4(int i = (i){ return 0; })(); // OK
    void g5(int i = (i){ return sizeof i; })(); // OK
    void g6(int i = (i=x=1){ return x; })(); // OK
    void g7(int i = (i=x=i){ return x; })(); // error
}

—end example]

10 An entity is captured by copy if
— it is implicitly captured, the capture-default is =, and the captured entity is not *this, or
10.2 — it is explicitly captured with a capture that is not of the form this, & identifier, or & identifier initializer.

For each entity captured by copy, an unnamed non-static data member is declared in the closure type. The declaration order of these members is unspecified. The type of such a data member is the referenced type if the entity is a reference to an object, an lvalue reference to the referenced function type if the entity is a reference to a function, or the type of the corresponding captured entity otherwise. A member of an anonymous union shall not be captured by copy.

11 Every id-expression within the compound-statement of a lambda-expression that is an odr-use (6.3) of an entity captured by copy is transformed into an access to the corresponding unnamed data member of the closure type.

[Note 7: An id-expression that is not an odr-use refers to the original entity, never to a member of the closure type. However, such an id-expression can still cause the implicit capture of the entity. —end note]

If *this is captured by copy, each expression that odr-uses *this is transformed to instead refer to the corresponding unnamed data member of the closure type.

[Example 8:]
void f(const int*);
void g() {
    const int N = 10;
    [N] {
        int arr[N]; // OK, not an odr-use, refers to automatic variable
        f(&N); // OK, causes N to be captured; &N points to
            // the corresponding member of the closure type
    };
}

—end example]

12 An entity is captured by reference if it is implicitly or explicitly captured but not captured by copy. It is unspecified whether additional unnamed non-static data members are declared in the closure type for entities captured by reference. If declared, such non-static data members shall be of literal type.
Example 9:

// The inner closure type must be a literal type regardless of how reference captures are represented.
static_assert([](int n) { return [&n] { return ++n; }(); }(3) == 4);

—end example

A bit-field or a member of an anonymous union shall not be captured by reference.

An id-expression within the compound-statement of a lambda-expression that is an odr-use of a reference captured by reference refers to the entity to which the captured reference is bound and not to the captured reference.

[Note 8: The validity of such captures is determined by the lifetime of the object to which the reference refers, not by the lifetime of the reference itself. — end note]

Example 10:

auto h(int &r) {
    return [&]
        { ++r; /* Valid after h returns if the lifetime of the
           // object to which r is bound has not ended */
    };
}

—end example

If a lambda-expression m2 captures an entity and that entity is captured by an immediately enclosing lambda-expression m1, then m2’s capture is transformed as follows:

(14.1) — If m1 captures the entity by copy, m2 captures the corresponding non-static data member of m1’s closure type; if m1 is not mutable, the non-static data member is considered to be const-qualified.

(14.2) — If m1 captures the entity by reference, m2 captures the same entity captured by m1.

Example 11: The nested lambda-expressions and invocations below will output 123234.

int a = 1, b = 1, c = 1;
auto m1 = [a, &b, &c]() mutable {
    auto m2 = [a, b, &c]() mutable {
        std::cout << a << b << c;
        a = 4; b = 4; c = 4;
    };
    a = 3; b = 3; c = 3;
    m2();
};
a = 2; b = 2; c = 2;
m1();
std::cout << a << b << c;

—end example

When the lambda-expression is evaluated, the entities that are captured by copy are used to direct-initialize each corresponding non-static data member of the resulting closure object, and the non-static data members corresponding to the init-captures are initialized as indicated by the corresponding initializer (which may be copy- or direct-initialization). (For array members, the array elements are direct-initialized in increasing subscript order.) These initializations are performed in the (unspecified) order in which the non-static data members are declared.

[Note 9: This ensures that the destructors will occur in the reverse order of the constructions. — end note]

[Note 10: If a non-reference entity is implicitly or explicitly captured by reference, invoking the function call operator of the corresponding lambda-expression after the lifetime of the entity has ended is likely to result in undefined behavior. — end note]

A simple-capture containing an ellipsis is a pack expansion (13.7.4). An init-capture containing an ellipsis is a pack expansion that declares an init-capture pack (13.7.4).

Example 12:

template<class... Args>
void f(Args... args) {
    auto lm = [&args...] { return g(args...); };
    lm();
}
auto lm2 = [...xs=std::move(args)] { return g(xs...); };  
  lm2(); 
}

—end example]

7.5.7 Fold expressions

A fold expression performs a fold of a pack (13.7.4) over a binary operator.

fold-expression:
  ( cast-expression fold-operator ... )
  ( ... fold-operator cast-expression )
  ( cast-expression fold-operator ... fold-operator cast-expression )
fold-operator: one of
  + - * / \ ^ & | << >> += -= *= /= %= ^= &= | = <<= >= =
  != < > <= >= && || , .* \-*

An expression of the form (... op e) where op is a fold-operator is called a unary left fold. An expression of the form (e op ...) where op is a fold-operator is called a unary right fold. Unary left folds and unary right folds are collectively called unary folds. In a unary fold, the cast-expression shall contain an unexpanded pack (13.7.4).

An expression of the form (e1 op1 ... op2 e2) where op1 and op2 are fold-operators is called a binary fold. In a binary fold, op1 and op2 shall be the same fold-operator, and either e1 shall contain an unexpanded pack or e2 shall contain an unexpanded pack, but not both. If e2 contains an unexpanded pack, the expression is called a binary left fold. If e1 contains an unexpanded pack, the expression is called a binary right fold.

[Example 1:
  template<typename ...Args>
  bool f(Args ...args) {
    return (true && ... && args); // OK
  }
  template<typename ...Args>
  bool f(Args ...args) {
    return (args + ... + args); // error: both operands contain unexpanded packs
  }
  —end example]

7.5.8 Requires expressions

7.5.8.1 General

A requires-expression provides a concise way to express requirements on template arguments that can be checked by name lookup (6.5) or by checking properties of types and expressions.

requires-expression:
  requires requirement-parameter-list_opt requirement-body
requirement-parameter-list:
  ( parameter-declaration-clause )
requirement-body:
  { requirement-seq }
requirement-seq:
  requirement
  requirement requirement-seq
requirement:
  simple-requirement
  type-requirement
  compound-requirement
  nested-requirement

A requires-expression is a prvalue of type bool whose value is described below. Expressions appearing within a requirement-body are unevaluated operands (7.2.3).
A common use of requires-expressions is to define requirements in concepts such as the one below:

```cpp
template<typename T>
concept R = requires (T i) {
    typename T::type;
    {*i} -> std::convertible_to<const typename T::type&>;
};
```

A requires-expression can also be used in a requires-clause (13.1) as a way of writing ad hoc constraints on template arguments such as the one below:

```cpp
template<typename T>
requires requires (T x) { x + x; }
T add(T a, T b) { return a + b; }
```

The first requires introduces the requires-clause, and the second introduces the requires-expression. — end example

A requires-expression may introduce local parameters using a parameter-declaration-clause. A local parameter of a requires-expression shall not have a default argument. The type of such a parameter is determined as specified for a function parameter in 9.3.4.6. These parameters have no linkage, storage, or lifetime; they are only used as notation for the purpose of defining requirements. The parameter-declaration-clause of a requirement-parameter-list shall not terminate with an ellipsis.

```cpp
template<typename T>
concept C = requires(T t, ...) { // error: terminates with an ellipsis
    t;
};
template<typename T>
concept C2 = requires(T p[2]) {
    (decltype(p))nullptr; // OK, p has type "pointer to T"
};
```

— end example

The substitution of template arguments into a requires-expression can result in the formation of invalid types or expressions in the immediate context of its requirements (13.10.3.1) or the violation of the semantic constraints of those requirements. In such cases, the requires-expression evaluates to false; it does not cause the program to be ill-formed. The substitution and semantic constraint checking proceeds in lexical order and stops when a condition that determines the result of the requires-expression is encountered. If substitution (if any) and semantic constraint checking succeed, the requires-expression evaluates to true.

Note 1: If a requires-expression contains invalid types or expressions in its requirements, and it does not appear within the declaration of a templated entity, then the program is ill-formed. — end note

If the substitution of template arguments into a requirement would always result in a substitution failure, the program is ill-formed; no diagnostic required.

```cpp
template<typename T> concept C =
requires {
    new decltype((void)T{}); // ill-formed, no diagnostic required
};
```

— end example

7.5.8.2 Simple requirements

A simple-requirement asserts the validity of an expression.

Note 1: The enclosing requires-expression will evaluate to false if substitution of template arguments into the expression fails. The expression is an unevaluated operand (7.2.3). — end note

```cpp
template<typename T> concept C =
requires (T a, T b) {
    a + b; // C<T> is true if a + b is a valid expression
};
```
2 A requirement that starts with a requires token is never interpreted as a simple-requirement. [Note 2: This simplifies distinguishing between a simple-requirement and a nested-requirement. — end note]

7.5.8.3 Type requirements

type-requirement:
  typename nested-name-specifier_opt type-name ;

1 A type-requirement asserts the validity of a type. The component names of a type-requirement are those of its nested-name-specifier (if any) and type-name.

[Note 1: The enclosing requires-expression will evaluate to false if substitution of template arguments fails. — end note]

[Example 1:
  template<typename T, typename T::type = 0> struct S;
  template<typename T> using Ref = T&;
  template<typename T> concept C = requires {
    typename T::inner; // required nested member name
    typename S<T>; // required valid (13.3) template-id;
    typename Ref<T>; // required alias template substitution, fails if T is void
  };
  — end example]

2 A type-requirement that names a class template specialization does not require that type to be complete (6.8.1).

7.5.8.4 Compound requirements

compound-requirement:
  { expression } noexcept_opt return-type-requirement_opt ;

return-type-requirement:
  -> type-constraint

1 A compound-requirement asserts properties of the expression E. Substitution of template arguments (if any) and verification of semantic properties proceed in the following order:

(1.1) — Substitution of template arguments (if any) into the expression is performed.

(1.2) — If the noexcept specifier is present, E shall not be a potentially-throwing expression (14.5).

(1.3) — If the return-type-requirement is present, then:

(1.3.1) — Substitution of template arguments (if any) into the return-type-requirement is performed.

(1.3.2) — The immediately-declared constraint (13.2) of the type-constraint for decltype((E)) shall be satisfied.

[Example 1: Given concepts C and D,
  requires {
    { E1 } -> C;
    { E2 } -> D<A_1, ..., A_n>;
  };
  is equivalent to
  requires {
    E1; requires C<decltype((E1))>;
    E2; requires D<decltype((E2)), A_1, ..., A_n>;
  };
  (including in the case where n is zero). — end example]

[Example 2:
  template<typename T> concept C1 = requires(T x) {
    {x++};
  };

§ 7.5.8.4 ©ISO/IEC
The \textit{compound-requirement} in C1 requires that \texttt{x++} is a valid expression. It is equivalent to the \textit{simple-requirement} \texttt{x++;}.

\begin{verbatim}
template<typename T> concept C2 = requires(T x) {
    {*x} -> std::same_as<typename T::inner>;
};
\end{verbatim}

The \textit{compound-requirement} in C2 requires that \texttt{!*x} is a valid expression, that \texttt{typename T::inner} is a valid type, and that \texttt{std::same_as<decltype(*x)>, typename T::inner> is satisfied.}

\begin{verbatim}
template<typename T> concept C3 =
    requires(T x) {
        requires(C<decltype (+t)>
    }
};
\end{verbatim}

D<T> is satisfied if \texttt{sizeof(decltype (+t)) == 1} (13.5.2.3). — end example]

\subsection{Compound expressions}
\subsubsection{Postfix expressions}
\paragraph{General}

\begin{verbatim}
postfix-expression:
    primary-expression
    postfix-expression [ expression-list_opt ]
    postfix-expression ( expression-list_opt )
    simple-type-specifier ( expression-list_opt )
    typename-specifier ( expression-list_opt )
    simple-type-specifier braced-init-list
    typename-specifier braced-init-list
    postfix-expression . template_opt id-expression
    postfix-expression -> template_opt id-expression
    postfix-expression ++
    postfix-expression --
    dynamic_cast < type-id > ( expression )
    static_cast < type-id > ( expression )
    reinterpret_cast < type-id > ( expression )
    const_cast < type-id > ( expression )
    typeid ( expression )
    typeid ( type-id )

expression-list:
    initializer-list
\end{verbatim}

\footnote{The \texttt{>} token following the \texttt{type-id} in a \texttt{dynamic_cast}, \texttt{static_cast}, \texttt{reinterpret_cast}, or \texttt{const_cast} can be the product of replacing a \texttt{>>} token by two consecutive \texttt{>} tokens (13.3). — end note]
A function call is a postfix expression followed by parentheses containing a possibly empty, comma-separated list of \texttt{initializer-clauses} that constitute the arguments to the function. The postfix-expression and the initialization of the object parameter of any applicable subscript operator function is sequenced before each expression in the \texttt{expression-list} and also before any default argument. The initialization of a non-object parameter of a subscript operator function $S$ (12.4.5), including every associated value computation and side effect, is indeterminately sequenced with respect to that of any other non-object parameter of $S$.

With the built-in subscript operator, an \texttt{expression-list} shall be present, consisting of a single \texttt{assignment-expression}. One of the expressions shall be a glvalue of type “array of $T$” or a prvalue of type “pointer to $T$” and the other shall be a prvalue of unscoped enumeration or integral type. The result is of type “$T$”. The type “$T$” shall be a completely-defined object type.\(^{49}\) The expression $E1[E2]$ is identical (by definition) to $*((E1)+(E2))$, except that in the case of an array operand, the result is an lvalue if that operand is an lvalue and an xvalue otherwise.

\[\text{Note 1:} \text{Despite its asymmetric appearance, subscripting is a commutative operation except for sequencing. See 7.6.2 and 7.6.6 for details of } \ast \text{ and } + \text{ and 9.3.4.5 for details of array types. } \text{— end note}\]

A function call is a postfix expression followed by parentheses containing a possibly empty, comma-separated list of \texttt{initializer-clauses} which constitute the arguments to the function.

\[\text{Note 1:} \text{If the postfix expression is a function or member function name, the appropriate function and the validity of the call are determined according to the rules in 12.2. } \text{— end note}\]

The postfix expression shall have function type or function pointer type. For a call to a non-member function or to a static member function, the postfix expression shall be either an lvalue that refers to a function (in which case the function-to-pointer standard conversion (7.3.4) is suppressed on the postfix expression), or a prvalue of function pointer type.

If the selected function is non-virtual, or if the \texttt{id-expression} in the class member access expression is a \texttt{qualified-id}, that function is called. Otherwise, its final overrider (11.7.3) in the dynamic type of the object expression is called; such a call is referred to as a \texttt{virtual function call}.

\[\text{Note 2:} \text{The dynamic type is the type of the object referred to by the current value of the object expression. 11.9.5 describes the behavior of virtual function calls when the object expression refers to an object under construction or destruction. } \text{— end note}\]

\[\text{Note 3:} \text{If a function or member function name is used, and name lookup (6.5) does not find a declaration of that name, the program is ill-formed. No function is implicitly declared by such a call. } \text{— end note}\]

If the postfix-expression names a destructor or pseudo Destructor (7.5.5.5), the type of the function call expression is \texttt{void}; otherwise, the type of the function call expression is the return type of the statically chosen function (i.e., ignoring the \texttt{virtual} keyword), even if the type of the function actually called is different. If the postfix-expression names a pseudo Destructor (in which case the postfix-expression is a possibly-parenthesized class member access), the function call destroys the object of scalar type denoted by the object expression of the class member access (7.6.1.5, 6.7.3).

\[\text{Note 4:} \text{This requirement allows the case when the expression has the type of a potentially-throwing function, but the called function has a non-throwing exception specification, and the function types are otherwise the same. } \text{— end note}\]

When a function is called, each parameter (9.3.4.6) is initialized (9.4, 11.4.5.3) with its corresponding argument. If the function is an explicit object member function and there is an implied object argument (12.2.2.2.2), the list of provided arguments is preceded by the implied object argument for the purposes of this correspondence. If there is no corresponding argument, the default argument for the parameter is used.

\[\text{Note 49:} \text{This is true even if the subscript operator is used in the following common idiom: } \texttt{xz[0]}.\]

\[\S 7.6.1.3 \text{© ISO/IEC 126}\]
Example 1:

```cpp
template<typename ...T> int f(int n = 0, T ...t);
int x = f<int>();  // error: no argument for second function parameter
```

If the function is an implicit object member function, the object expression of the class member access shall be a glvalue and the `this` parameter of the function (7.5.3) is initialized with a pointer to the object of the call, converted as if by an explicit type conversion (7.6.3).

[Note 5: There is no access or ambiguity checking on this conversion; the access checking and disambiguation are done as part of the (possibly implicit) class member access operator. See 6.5.2, 11.8.3, and 7.6.1.5. — end note]

When a function is called, the type of any parameter shall not be a class type that is either incomplete or abstract.

[Note 6: This still allows a parameter to be a pointer or reference to such a type. However, it prevents a passed-by-value parameter to have an incomplete or abstract class type. — end note]

It is implementation-defined whether a parameter is destroyed when the function in which it is defined exits (8.7.4, 14.3) or at the end of the enclosing full-expression; parameters are always destroyed in the reverse order of their construction. The initialization and destruction of each parameter occurs within the context of the full-expression (6.9.1) where the function call appears.

Example 2: The access (11.8.1) of the constructor, conversion functions, or destructor is checked at the point of call. If a constructor or destructor for a function parameter throws an exception, any function-try-block (14.1) of the called function with a handler that can handle the exception is not considered. — end example]

The postfix-expression is sequenced before each expression in the expression-list and any default argument. The initialization of a parameter, including every associated value computation and side effect, is indeterminately sequenced with respect to that of any other parameter.

[Note 7: All side effects of argument evaluations are sequenced before the function is entered (see 6.9.1). — end note]

Example 3:

```cpp
void f() {
    std::string s = "but I have heard it works even if you don’t believe in it";
    s.replace(0, 4, "").replace(s.find("even"), 4, "only").replace(s.find(" don’t"), 6, "");
    assert(s == "I have heard it works only if you believe in it");  // OK
}
```

— end example

[Note 8: If an operator function is invoked using operator notation, argument evaluation is sequenced as specified for the built-in operator; see 12.2.2.3. — end note]

Example 4:

```cpp
struct S {
    S(int);
};
int operator<<(S, int);
int i, j;
int x = S(i=1) << (i=2);
int y = operator<<(S(j=1), j=2);
```

After performing the initializations, the value of `i` is 2 (see 7.6.7), but it is unspecified whether the value of `j` is 1 or 2. — end example

The result of a function call is the result of the possibly-converted operand of the `return` statement (8.7.4) that transferred control out of the called function (if any), except in a virtual function call if the return type of the final overrider is different from the return type of the statically chosen function, the value returned from the final overrider is converted to the return type of the statically chosen function.

[Note 9: A function can change the values of its non-const parameters, but these changes cannot affect the values of the arguments except where a parameter is of a reference type (9.3.4.3); if the reference is to a const-qualified type, `const_cast` needs to be used to cast away the constness in order to modify the argument’s value. Where a parameter is of `const` reference type a temporary object is introduced if needed (9.2.9, 5.13, 5.13.5, 9.3.4.5, 6.7.7). In addition, it is possible to modify the values of non-constant objects through pointer parameters. — end note]
A function can be declared to accept fewer arguments (by declaring default arguments (9.3.4.7)) or more arguments (by using the ellipsis, ..., or a function parameter pack (9.3.4.6)) than the number of parameters in the function definition (9.5).

[Note 10: This implies that, except where the ellipsis (...) or a function parameter pack is used, a parameter is available for each argument. — end note]

When there is no parameter for a given argument, the argument is passed in such a way that the receiving function can obtain the value of the argument by invoking va_arg (17.13).

[Note 11: This paragraph does not apply to arguments passed to a function parameter pack. Function parameter packs are expanded during template instantiation (13.7.4), thus each such argument has a corresponding parameter when a function template specialization is actually called. — end note]

The lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are performed on the argument expression. An argument that has type cv std::nullptr_t is converted to type void* (7.3.12). After these conversions, if the argument does not have arithmetic, enumeration, pointer, pointer-to-member, or class type, the program is ill-formed. Passing a potentially-evaluated argument of a scoped enumeration type (9.7.1) or of a class type (Clause 11) having an eligible non-trivial copy constructor (11.4.4, 11.4.5.3), an eligible non-trivial move constructor, or a non-trivial destructor (11.4.7), with no corresponding parameter, is conditionally-supported with implementation-defined semantics. If the argument has integral or enumeration type that is subject to the integral promotions (7.3.7), or a floating-point type that is subject to the floating-point promotion (7.3.8), the value of the argument is converted to the promoted type before the call. These promotions are referred to as the default argument promotions.

Recursive calls are permitted, except to the main function (6.9.3.1).

A function call is an lvalue if the result type is an lvalue reference type or an rvalue reference to function type, an xvalue if the result type is an rvalue reference to object type, and a prvalue otherwise.

7.6.1.4 Explicit type conversion (functional notation) [expr.type.conv]

A simple-type-specifier (9.2.9.3) or typename-specifier (13.8) followed by a parenthesized optional expression-list or by a braced-init-list (the initializer) constructs a value of the specified type given the initializer. If the type is a placeholder for a deduced class type, it is replaced by the return type of the function selected by overload resolution for class template deduction (12.2.2.9) for the remainder of this subclause. Otherwise, if the type contains a placeholder type, it is replaced by the type determined by placeholder type deduction (9.2.9.7.2).

[Example 1:

```cpp
struct A {
};
void f(A&); // #1
void f(A&&); // #2
A& g();
void h() {
    f(g()); // calls #1
    f(A(g())); // calls #2 with a temporary object
    f(auto(g())); // calls #2 with a temporary object
}
```
—end example]

If the initializer is a parenthesized single expression, the type conversion expression is equivalent to the corresponding cast expression (7.6.3). Otherwise, if the type is cv void and the initializer is () or {} (after pack expansion, if any), the expression is a prvalue of type void that performs no initialization. Otherwise, the expression is a prvalue of the specified type whose result object is direct-initialized (9.4) with the initializer. If the initializer is a parenthesized optional expression-list, the specified type shall not be an array type.

7.6.1.5 Class member access [expr.ref]

A postfix expression followed by a dot . or an arrow ->, optionally followed by the keyword template, and then followed by an id-expression, is a postfix expression.

[Note 1: If the keyword template is used, the following unqualified name is considered to refer to a template (13.3). If a simple-template-id results and is followed by a ::, the id-expression is a qualified-id. — end note]

For the first option (dot), if the id-expression names a static member or an enumerator, the first expression is a discarded-value expression (7.2.3); if the id-expression names a non-static data member, the first expression shall be a glvalue. For the second option (arrow), the first expression shall be a prvalue having pointer type.
If \(E_1 \rightarrow E_2\) is the object expression, then the expression designates the named member of the class. The type of \(E_1 \rightarrow E_2\) is \(T\).

### Notes

- **Note 1**: The program is ill-formed if the result differs from that when the class is complete (6.5.3). — end note
- **Note 2**: This value can only be used for a notional function call (7.5.5.5). — end note
- **Note 3**: The object expression shall be of class type. The class type shall be complete unless the class member access appears in the definition of that class.

The postfix expression before the dot is evaluated; otherwise, the object expression shall be of class type. The class type shall be complete unless the class member access appears in the definition of that class.

The expression \(E_1.E_2\) is called the object expression. If the object expression is of scalar type, \(E_2\) shall name the pseudo-destructor of that same type (ignoring cv-qualifications) and \(E_1.E_2\) is a prvalue of type “function of () returning void”.

### Examples

**Example 1**:

```cpp
def f() {
    struct A { int i; }
    struct B { int j; }
    struct D : A, B {};
    void f() {
        D d;
```
static_cast<B&>(d).j; // OK, object expression designates the B subobject of d
reinterpret_cast<B&>(d).j; // undefined behavior

—end example—

7.6.1.6 Increment and decrement [expr.post.incr]

1 The value of a postfix ++ expression is the value of its operand.

[Note 1: The value obtained is a copy of the original value. —end note]

The operand shall be a modifiable lvalue. The type of the operand shall be an arithmetic type other than cv bool, or a pointer to a complete object type. An operand with volatile-qualified type is deprecated; see D.4. The value of the operand object is modified (3.1) as if it were the operand of the prefix ++ operator (7.6.2.3). The value computation of the ++ expression is sequenced before the modification of the operand object. With respect to an indeterminately-sequenced function call, the operation of postfix ++ is a single evaluation.

[Note 2: Therefore, a function call cannot intervene between the lvalue-to-rvalue conversion and the side effect associated with any single postfix ++ operator. —end note]

The result is a prvalue. The type of the result is the cv-unqualified version of the type of the operand.

2 The operand of postfix -- is decremented analogously to the postfix ++ operator.

[Note 3: For prefix increment and decrement, see 7.6.2.3. —end note]

7.6.1.7 Dynamic cast [expr.dynamic.cast]

1 The result of the expression dynamic_cast<T>(v) is the result of converting the expression v to type T. T shall be a pointer or reference to a complete class type, or “pointer to cv void”. The dynamic_cast operator shall not cast away constness (7.6.1.11).

2 If T is a pointer type, v shall be a prvalue of a pointer to complete class type, and the result is a prvalue of type T. If T is an lvalue reference type, v shall be an lvalue of a complete class type, and the result is an lvalue of the type referred to by T. If T is an rvalue reference type, v shall be a glvalue having a complete class type, and the result is an xvalue of the type referred to by T.

3 If the type of v is the same as T (ignoring cv-qualifications), the result is v (converted if necessary).

4 If T is “pointer to cv1 B” and v has type “pointer to cv2 D” such that B is a base class of D, the result is a pointer to the unique B subobject of the D object pointed to by v, or a null pointer value if v is a null pointer value. Similarly, if T is “reference to cv1 B” and v has type cv2 D such that B is a base class of D, the result is the unique B subobject of the D object referred to by v.52 In both the pointer and reference cases, the program is ill-formed if B is an inaccessible or ambiguous base class of D.

[Example 1:

```cpp
struct B {
};
struct D : B {
};
void foo(D* dp) {
    B* bp = dynamic_cast<B*>(dp); // equivalent to B* bp = dp;
}
—end example—

5 Otherwise, v shall be a pointer to or a glvalue of a polymorphic type (11.7.3).

6 If v is a null pointer value, the result is a null pointer value.

7 If v has type “pointer to cv U” and v does not point to an object whose type is similar (7.3.6) to U and that is within its lifetime or within its period of construction or destruction (11.9.5), the behavior is undefined. If v is a glvalue of type U and v does not refer to an object whose type is similar to U and that is within its lifetime or within its period of construction or destruction, the behavior is undefined.

8 If T is “pointer to cv void”, then the result is a pointer to the most derived object pointed to by v. Otherwise, a runtime check is applied to see if the object pointed or referred to by v can be converted to the type pointed or referred to by T.

9 Let C be the class type to which T points or refers. The runtime check logically executes as follows:

52) The most derived object (6.7.2) pointed or referred to by v can contain other B objects as base classes, but these are ignored.
If, in the most derived object pointed (referred) to by \( v \), \( v \) points (refers) to a public base class subobject of a \( C \) object, and if only one object of type \( C \) is derived from the subobject pointed (referred) to by \( v \), the result points (refers) to that \( C \) object.

Otherwise, if \( v \) points (refers) to a public base class subobject of the most derived object, and the type of the most derived object has a base class, of type \( C \), that is unambiguous and public, the result points (refers) to the \( C \) subobject of the most derived object.

Otherwise, the runtime check fails.

The value of a failed cast to pointer type is the null pointer value of the required result type. A failed cast to reference type throws an exception (14.2) of a type that would match a handler (14.4) of type \( \text{std}::\text{bad_cast} \) (17.7.4).

Example 2:

```cpp
class A { virtual void f(); }
class B { virtual void g(); }
class D : public virtual A, private B { }
void g() {
    D d;
    B* bp = (B*)&d;  // cast needed to break protection
    A* ap = &d;    // public derivation, no cast needed
    D& dr = dynamic_cast<D&>(*bp);  // fails
    ap = dynamic_cast<A*>(bp);    // fails
    bp = dynamic_cast<B*>(ap);  // fails
    ap = dynamic_cast<A*>(&d);  // succeeds
    bp = dynamic_cast<B*>(&d);  // ill-formed (not a runtime check)
}

class E : public D, public B { }
class F : public E, public D { }
void h() {
    F f;
    A* ap = &f;    // succeeds: finds unique A
    D* dp = dynamic_cast<D*>(ap);  // fails: yields null; \( f \) has two \( D \) subobjects
    E* ep = dynamic_cast<E*>(ap);  // error: cast from virtual base
    E* ep1 = dynamic_cast<E*>(ap); // succeeds
}
```

—end example]

[Note 1: Subclause 11.9.5 describes the behavior of a \( \text{dynamic_cast} \) applied to an object under construction or destruction. —end note]

### 7.6.1.8 Type identification

The result of a \( \text{typeid} \) expression is an lvalue of static type \( \text{const std::type_info} \) (17.7.3) and dynamic type \( \text{const std::type_info} \) or \( \text{const name} \) where \( \text{name} \) is an implementation-defined class publicly derived from \( \text{std::type_info} \) which preserves the behavior described in 17.7.3.\(^{53}\) The lifetime of the object referred to by the \( \text{lvalue} \) extends to the end of the program. Whether or not the destructor is called for the \( \text{std::type_info} \) object at the end of the program is unspecified.

If the type of the \( \text{expression} \) or \( \text{type-id} \) operand is a (possibly cv-qualified) class type or a reference to (possibly cv-qualified) class type, that class shall be completely defined.

If an \( \text{expression} \) operand of \( \text{typeid} \) is a possibly-parenthesized \( \text{unary-expression} \) whose \( \text{unary-operator} \) is \( * \) and whose operand evaluates to a null pointer value (6.8.4), the \( \text{typeid} \) expression throws an exception (14.2) of a type that would match a handler of type \( \text{std::bad_typeid} \) (17.7.5).

[Note 1: In other contexts, evaluating such a \( \text{unary-expression} \) results in undefined behavior (7.6.2.2). —end note]

When \( \text{typeid} \) is applied to a glvalue whose type is a polymorphic class type (11.7.3), the result refers to a \( \text{std::type_info} \) object representing the type of the most derived object (6.7.2) (that is, the dynamic type) to which the glvalue refers.

When \( \text{typeid} \) is applied to an expression other than a glvalue of a polymorphic class type, the result refers to a \( \text{std::type_info} \) object representing the static type of the expression. Lvalue-to-value (7.3.2),

---

\(^{53}\) The recommended name for such a class is \( \text{extended_type_info} \).
array-to-pointer (7.3.3), and function-to-pointer (7.3.4) conversions are not applied to the expression. If the expression is a prvalue, the temporary materialization conversion (7.3.5) is applied. The expression is an unevaluated operand (7.2.3).

When typeid is applied to a type-id, the result refers to a std::type_info object representing the type of the type-id. If the type of the type-id is a reference to a possibly cv-qualified type, the result of the typeid expression refers to a std::type_info object representing the cv-unqualified referenced type.

[Note 2: The type-id cannot denote a function type with a cv-qualifier-seq or a ref-qualifier (9.3.4.6). —end note]

If the expression or type-id is a cv-qualified type, the result of the typeid expression refers to a std::type_info object representing the cv-unqualified type.

[Example 1:]
```cpp
class D { /* ... */ };    
D d1;                     
const D d2;               

typeid(d1) == typeid(d2);  // yields true 
typeid(D) == typeid(const D);  // yields true 
typeid(D) == typeid(d2);  // yields true 
typeid(D) == typeid(const D&); // yields true
```

The type std::type_info (17.7.3) is not predefined; if a standard library declaration (17.7.2, 16.4.2.4) of std::type_info does not precede (6.5.1) a typeid expression, the program is ill-formed.

[Note 3: Subclause 11.9.5 describes the behavior of typeid applied to an object under construction or destruction. —end note]

7.6.1.9 Static cast [expr.static.cast]

The result of the expression static_cast<T>(v) is the result of converting the expression v to type T. If T is an lvalue reference type or an rvalue reference to function type, the result is an lvalue; if T is an rvalue reference to object type, the result is an xvalue; otherwise, the result is a prvalue. The static_cast operator shall not cast away constness (7.6.1.11).

An lvalue of type “cv1 B”, where B is a class type, can be cast to type “reference to cv2 D”, where D is a complete class derived (11.7) from B, if cv2 is the same cv-qualification as, or greater cv-qualification than, cv1. If B is a virtual base class of D or a base class of a virtual base class of D, or if no valid standard conversion from “pointer to D” to “pointer to B” exists (7.3.12), the program is ill-formed. An xvalue of type “cv1 B” can be cast to type “rvalue reference to cv2 D” with the same constraints as for an lvalue of type “cv1 B”. If the object of type “cv1 B” is actually a base class subobject of an object of type D, the result refers to the enclosing object of type D. Otherwise, the behavior is undefined.

[Example 1:]
```cpp
struct B { };                  
struct D : public B { };      
D d;                  
B &br = d;                

static_cast<D&>(br);       // produces lvalue denoting the original d object
```

An lvalue of type T1 can be cast to type “rvalue reference to T2” if T2 is reference-compatible with T1 (9.4.4). If the value is not a bit-field, the result refers to the object or the specified base class subobject thereof; otherwise, the lvalue-to-rvalue conversion (7.3.2) is applied to the bit-field and the resulting prvalue is used as the operand of the static_cast for the remainder of this subclause. If T2 is an inaccessible (11.8) or ambiguous (6.5.2) base class of T1, a program that necessitates such a cast is ill-formed.

Any expression can be explicitly converted to type cv void, in which case the operand is a discarded-value expression (7.2).

[Note 1: Such a static_cast has no result as it is a prvalue of type void; see 7.2.1. —end note]

[Note 2: However, if the value is in a temporary object (6.7.7), the destructor for that object is not executed until the usual time, and the value of the object is preserved for the purpose of executing the destructor. —end note]
Otherwise, an expression $E$ can be explicitly converted to a type $T$ if there is an implicit conversion sequence (12.2.4.2) from $E$ to $T$, if overload resolution for a direct-initialization (9.4) of an object or reference of type $T$ from $E$ would find at least one viable function (12.2.3), or if $T$ is an aggregate type (9.4.2) having a first element $x$ and there is an implicit conversion sequence from $E$ to the type of $x$. If $T$ is a reference type, the effect is the same as performing the declaration and initialization

$$T \ t(E);$$

for some invented temporary variable $t$ (9.4) and then using the temporary variable as the result of the conversion. Otherwise, the result object is direct-initialized from $E$.

[Note 3: The conversion is ill-formed when attempting to convert an expression of class type to an inaccessible or ambiguous base class. — end note]

[Note 4: If $T$ is “array of unknown bound of $U$”, this direct-initialization defines the type of the expression as $U[1]$. — end note]

Otherwise, the inverse of a standard conversion sequence (7.3) not containing an lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), function-to-pointer (7.3.4), null pointer (7.3.12), null member pointer (7.3.13), boolean (7.3.15), or function pointer (7.3.14) conversion, can be performed explicitly using `static_cast`. A program is ill-formed if it uses `static_cast` to perform the inverse of an ill-formed standard conversion sequence.

[Example 2:]

```c
struct B { };  
struct D : private B { };  
void f() {
    static_cast<D*>(0);  // error: B is a private base of D  
    static_cast<int B::*>(0);  // error: B is a private base of D
}  
```

— end example

The lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) conversions are applied to the operand. Such a `static_cast` is subject to the restriction that the explicit conversion does not cast away constness (7.6.1.11), and the following additional rules for specific cases:

A value of a scoped enumeration type (9.7.1) can be explicitly converted to an integral type; the result is the same as that of converting to the enumeration’s underlying type and then to the destination type. A value of a scoped enumeration type can also be explicitly converted to a floating-point type; the result is the same as that of converting from the original value to the floating-point type.

A value of integral or enumeration type can be explicitly converted to a complete enumeration type. If the enumeration type has a fixed underlying type, the value is first converted to that type by integral promotion (7.3.7) or integral conversion (7.3.9), if necessary, and then to the enumeration type. If the enumeration type does not have a fixed underlying type, the value is unchanged if the original value is within the range of the enumeration values (9.7.1), and otherwise, the behavior is undefined. A value of floating-point type can also be explicitly converted to an enumeration type. The resulting value is the same as converting the original value to the underlying type of the enumeration (7.3.11), and subsequently to the enumeration type.

A prvalue of floating-point type can be explicitly converted to any other floating-point type. If the source value can be exactly represented in the destination type, the result of the conversion has that exact representation. If the source value is between two adjacent destination values, the result of the conversion has that exact representation. Otherwise, the behavior is undefined.

A prvalue of type “pointer to cv1 B”, where B is a class type, can be converted to a prvalue of type “pointer to cv2 D”, where D is a complete class derived (11.7) from B, if cv2 is the same cv-qualification as, or greater cv-qualification than, cv1. If B is a virtual base class of D or a base class of a virtual base class of D, or if no valid standard conversion from “pointer to D” to “pointer to B” exists (7.3.12), the program is ill-formed. The null pointer value (6.8.4) is converted to the null pointer value of the destination type. If the prvalue of type “pointer to cv1 B” points to a B that is actually a base class subobject of an object of type D, the resulting pointer points to the enclosing object of type D. Otherwise, the behavior is undefined.

A prvalue of type “pointer to member of D of type cv1 T” can be converted to a prvalue of type “pointer to member of B of type cv2 T”, where D is a complete class type and B is a base class (11.7) of D, if cv2 is the same cv-qualification as, or greater cv-qualification than, cv1.
If no valid standard conversion from “pointer to member of \(B\) of type \(T\)” to “pointer to member of \(D\) of type \(T\)” exists (7.3.13), the program is ill-formed. The null member pointer value (7.3.13) is converted to the null member pointer value of the destination type. If class \(B\) contains the original member, or is a base class of the class containing the original member, the resulting pointer to member points to the original member. Otherwise, the behavior is undefined.

A prvalue of type “pointer to \(cv1\ void\)” can be converted to a prvalue of type “pointer to \(cv2\ T\)”, where \(T\) is an object type and \(cv2\) is the same cv-qualification as, or greater cv-qualification than, \(cv1\). If the original pointer value represents the address \(A\) of a byte in memory and \(A\) does not satisfy the alignment requirement of \(T\), then the resulting pointer value (6.8.4) is unspecified. Otherwise, if the original pointer value points to an object \(a\), and there is an object \(b\) of type similar to \(T\) that is pointer-interconvertible (6.8.4) with \(a\), the result is a pointer to \(b\). Otherwise, the pointer value is unchanged by the conversion.

---

## 7.6.1.10 Reinterpret cast

The result of the expression `reinterpret_cast<T>(v)` is the result of converting the expression \(v\) to type \(T\). If \(T\) is an lvalue reference type or an rvalue reference to function type, the result is an lvalue; if \(T\) is an lvalue reference to object type, the result is an xvalue; otherwise, the result is a prvalue and the lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are performed on the expression \(v\). Conversions that can be performed explicitly using `reinterpret_cast` are listed below. No other conversion can be performed explicitly using `reinterpret_cast`.

A pointer can be explicitly converted to any integral type large enough to hold all values of its type. The mapping function is implementation-defined.  

A value of integral type or enumeration type can be explicitly converted to a pointer. A pointer converted to an integer of sufficient size (if any such exists on the implementation) and back to the same pointer type will have its original value (6.8.4); mappings between pointers and integers are otherwise implementation-defined.

A function pointer can be explicitly converted to a function pointer of a different type.  

Except that converting a prvalue of type “pointer to \(T1\)” to the type “pointer to \(T2\)” (where \(T1\) and \(T2\) are function types) and back to its original type yields the original pointer value, the result of such a pointer conversion is unspecified.

---

[Note 6: Although class \(B\) need not contain the original member, the dynamic type of the object with which indirection through the pointer to member is performed must contain the original member; see 7.6.4. — end note]
An object pointer can be explicitly converted to an object pointer of a different type.\(^5^4\) When a prvalue \(v\) of object pointer type is converted to the object pointer type “pointer to \(cv\) \(T\)”, the result is \(\text{static\_cast}<cv \ T*>(static\_cast<cv \ void*>(v))\).

[Note 6: Converting a prvalue of type “pointer to \(T1\)” that points to an object of type \(T1\) to the type “pointer to \(T2\)” (where \(T2\) is an object type and the alignment requirements of \(T2\) are no stricter than those of \(T1\)) and back to its original type yields the original pointer value. — end note]

Converting a function pointer to an object pointer type or vice versa is conditionally-supported. The meaning of such a conversion is implementation-defined, except that if an implementation supports conversions in both directions, converting a prvalue of one type to the other type and back, possibly with different \(cv\)-qualification, shall yield the original pointer value.

The null pointer value (6.8.4) is converted to the null pointer value of the destination type.

[Note 7: A null pointer constant of type \(\text{std}::\text{nullptr\_t}\) cannot be converted to a pointer type, and a null pointer constant of integral type is not necessarily converted to a null pointer value. — end note]

A prvalue of type “pointer to member of \(X\) of type \(T1\)” can be explicitly converted to a prvalue of a different type “pointer to member of \(Y\) of type \(T2\)” if \(T1\) and \(T2\) are both function types or both object types.\(^5^5\) The null member pointer value (7.3.13) is converted to the null member pointer value of the destination type. The result of this conversion is unspecified, except in the following cases:

1. Converting a prvalue of type “pointer to member function” to a different pointer-to-member-function type and back to its original type yields the original pointer-to-member value.
2. Converting a prvalue of type “pointer to data member of \(X\) of type \(T1\)” to the type “pointer to data member of \(Y\) of type \(T2\)” (where the alignment requirements of \(T2\) are no stricter than those of \(T1\)) and back to its original type yields the original pointer-to-member value.

A glvalue of type \(T1\), designating an object or function \(x\), can be cast to the type “reference to \(T2\)” if an expression of type “pointer to \(T1\)” can be explicitly converted to the type “pointer to \(T2\)” using a \(\text{reinterpret\_cast}\). The result is that of \(\text{reinterpret\_cast}<T2 *p\) where \(p\) is a pointer to \(x\) of type “pointer to \(T1\)”.

No temporary is created, no copy is made, and no constructors (11.4.5) or conversion functions (11.4.8) are called.\(^5^6\)

7.6.1.11 Const cast \[\text{expr.const.cast}\]

The result of the expression \(\text{const\_cast}<T>(v)\) is of type \(T\). If \(T\) is an lvalue reference to object type, the result is an lvalue; if \(T\) is an rvalue reference to object type, the result is an xvalue; otherwise, the result is a prvalue and the lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are performed on the expression \(v\). Conversions that can be performed explicitly using \(\text{const\_cast}\) are listed below. No other conversion shall be performed explicitly using \(\text{const\_cast}\).

1. Subject to the restrictions in this subclause, an expression can be cast to its own type using a \(\text{const\_cast}\) operator. — end note]

For two similar types \(T1\) and \(T2\) (7.3.6), a prvalue of type \(T1\) may be explicitly converted to the type \(T2\) using a \(\text{const\_cast}\) if, considering the qualification-decompositions of both types, each \(P_i^1\) is the same as \(P_i^2\) for all \(i\). The result of a \(\text{const\_cast}\) refers to the original entity.

[Example 1:

\begin{verbatim}
typedef int *A[3]; // array of 3 pointer to int
typedef const int *const CA[3]; // array of 3 const pointer to const int
CA &&r = A{}; // OK, reference binds to temporary array object
CA &&r1 = const_cast<A*>(CA{}); // error: temporary array decayed to pointer
A &&r2 = const_cast<A&>(CA{}); // OK
\end{verbatim}

— end example]

\(^5^4\) The types can have different \(cv\)-qualifiers, subject to the overall restriction that a \(\text{reinterpret\_cast}\) cannot cast away constness.

\(^5^5\) \(T1\) and \(T2\) can have different \(cv\)-qualifiers, subject to the overall restriction that a \(\text{reinterpret\_cast}\) cannot cast away constness.

\(^5^6\) This is sometimes referred to as a type pun when the result refers to the same object as the source glvalue.
For two object types $T_1$ and $T_2$, if a pointer to $T_1$ can be explicitly converted to the type “pointer to $T_2$” using a `const_cast`, then the following conversions can also be made:

1. an lvalue of type $T_1$ can be explicitly converted to an lvalue of type $T_2$ using the cast `const_cast<T2&>`;
2. a glvalue of type $T_1$ can be explicitly converted to an xvalue of type $T_2$ using the cast `const_cast<T2&&>`; and
3. if $T_1$ is a class type, a prvalue of type $T_1$ can be explicitly converted to an xvalue of type $T_2$ using the cast `const_cast<T2&&>`.

The result of a reference `const_cast` refers to the original object if the operand is a glvalue and to the result of applying the temporary materialization conversion (7.3.5) otherwise.

A null pointer value (6.8.4) is converted to the null pointer value of the destination type. The null member pointer value (7.3.13) is converted to the null member pointer value of the destination type.

[Note 2: Depending on the type of the object, a write operation through the pointer, lvalue or pointer to data member resulting from a `const_cast` that casts away a const-qualifier\(^{57}\) can produce undefined behavior (9.2.9.2). — end note]

A conversion from a type $T_1$ to a type $T_2$ casts away constness if $T_1$ and $T_2$ are different, there is a qualification-decomposition (7.3.6) of $T_1$ yielding $n$ such that $T_2$ has a qualification-decomposition of the form

$$cv_0^{c_2} P_0^{c_1} P_1^{c_1} \cdots cv_{n-1}^{c_2} P_{n-1}^{c_1} \cdot cv_n^{c_2} U_2,$$

and there is no qualification conversion that converts $T_1$ to

$$cv_0^{c_2} P_0^{c_1} P_1^{c_1} \cdots cv_{n-1}^{c_2} P_{n-1}^{c_1} cv_n^1 U_1.$$

Casting from an lvalue of type $T_1$ to an lvalue of type $T_2$ using an lvalue reference cast or casting from an expression of type $T_1$ to an xvalue of type $T_2$ using an rvalue reference cast casts away constness if a cast from a prvalue of type “pointer to $T_1$” to the type “pointer to $T_2$” casts away constness.

[Note 3: Some conversions which involve only changes in cv-qualification cannot be done using `const_cast`. For instance, conversions between pointers to functions are not covered because such conversions lead to values whose use causes undefined behavior. For the same reasons, conversions between pointers to member functions, and in particular, the conversion from a pointer to a const member function to a pointer to a non-const member function, are not covered. — end note]

### 7.6.2 Unary expressions

#### 7.6.2.1 General

Expressions with unary operators group right-to-left.

```
unary-expression:
  postfix-expression
  unary-operator cast-expression
  ++ cast-expression
  -- cast-expression
  await-expression
  sizeof unary-expression
  sizeof ( type-id )
  sizeof . . . ( identifier )
  alignof ( type-id )
  noexcept-expression
  new-expression
  delete-expression

unary-operator: one of
  * & + - ! ~
```

#### 7.6.2.2 Unary operators

The unary `*` operator performs *indirection*. Its operand shall be a prvalue of type “pointer to $T$”, where $T$ is an object or function type. The operator yields an lvalue of type $T$. If the operand points to an object or function, the result denotes that object or function; otherwise, the behavior is undefined except as specified in 7.6.1.8.

\(^{57}\) `const_cast` is not limited to conversions that cast away a const-qualifier.
[Note 1: Indirection through a pointer to an incomplete type (other than cv void) is valid. The value thus obtained can be used in limited ways (to initialize a reference, for example); this value must not be converted to a prvalue, see 7.3.2. — end note]

2 Each of the following unary operators yields a prvalue.

3 The operand of the unary & operator shall be an lvalue of some type T.

(3.1) — If the operand is a qualified-id naming a non-static or variant member m of some class C, other than an explicit object member function, the result has type “pointer to member of class C of type T” and designates C::m.

(3.2) — Otherwise, the result has type “pointer to T” and points to the designated object (6.7.1) or function (6.8.4). If the operand names an explicit object member function (9.3.4.6), the operand shall be a qualified-id.

[Note 2: In particular, taking the address of a variable of type “cv T” yields a pointer of type “pointer to cv T”. —end note]

Example 1:

```c
struct A { int i; }
struct B : A { }
... &B::i ... // has type int A::*
int a;
int* p1 = &a;
int* p2 = p1 + 1; // defined behavior
bool b = p2 > p1; // defined behavior, with value true
```

[Note 3: A pointer to member formed from a mutable non-static data member (9.2.2) does not reflect the mutable specifier associated with the non-static data member. —end note]

4 A pointer to member is only formed when an explicit & is used and its operand is a qualified-id not enclosed in parentheses.

[Note 4: That is, the expression &(qualified-id), where the qualified-id is enclosed in parentheses, does not form an expression of type “pointer to member”. Neither does qualified-id, because there is no implicit conversion from a qualified-id for a non-static member function to the type “pointer to member function” as there is from an lvalue of function type to the type “pointer to function” (7.3.4). Nor is &unqualified-id a pointer to member, even within the scope of the unqualified-id’s class. —end note]

5 If & is applied to an lvalue of incomplete class type and the complete type declares operator&(), it is unspecified whether the operator has the built-in meaning or the operator function is called. The operand of & shall not be a bit-field.

[Note 5: The address of an overload set (Clause 12) can be taken only in a context that uniquely determines which function is referred to (see 12.3). Since the context can affect whether the operand is a static or non-static member function, the context can also affect whether the expression has type “pointer to function” or “pointer to member function”. —end note]

7 The operand of the unary + operator shall be a prvalue of arithmetic, unscoped enumeration, or pointer type and the result is the value of the argument. Integral promotion is performed on integral or enumeration operands. The type of the result is the type of the promoted operand.

8 The operand of the unary - operator shall be a prvalue of arithmetic or unscoped enumeration type and the result is the negative of its operand. Integral promotion is performed on integral or enumeration operands. The negative of an unsigned quantity is computed by subtracting its value from $2^n$, where n is the number of bits in the promoted operand. The type of the result is the type of the promoted operand.

[Note 6: The result is the two’s complement of the operand (where operand and result are considered as unsigned). —end note]

9 The operand of the logical negation operator ! is contextually converted to bool (7.3); its value is true if the converted operand is false and false otherwise. The type of the result is bool.

10 The operand of the ~ operator shall be a prvalue of integral or unscoped enumeration type. Integral promotions are performed. The type of the result is the type of the promoted operand. Given the coefficients $x_i$ of the base-2 representation (6.8.2) of the promoted operand $x$, the coefficient $r_i$ of the base-2 representation of the result $r$ is 1 if $x_i$ is 0, and 0 otherwise.
There is an ambiguity in the grammar when \( \sim \) is followed by a `type-name` or `computed-type-specifier`. The ambiguity is resolved by treating \( \sim \) as the operator rather than as the start of an `unqualified-id` naming a destructor.

[Note 8: Because the grammar does not permit an operator to follow the \( . \rightarrow \), or `::` tokens, a \( \sim \) followed by a `type-name` or `computed-type-specifier` in a member access expression or `qualified-id` is unambiguously parsed as a destructor name. — end note]

### 7.6.2.3 Increment and decrement

1. The operand of prefix `++` or `--` shall not be of type `cv bool`. An operand with volatile-qualified type is deprecated; see D.4. The expression `++x` is otherwise equivalent to `x+=1` and the expression `--x` is otherwise equivalent to `x-=1` (7.6.19).

[Note 1: For postfix increment and decrement, see 7.6.1.6. — end note]

#### 7.6.2.4 Await

1. The `co_await` expression is used to suspend evaluation of a coroutine (9.5.4) while awaiting completion of the computation represented by the operand expression. Suspending the evaluation of a coroutine transfers control to its caller or resumer.

   ```cpp
   await-expression:
   co_await cast-expression
   ```

2. An `await-expression` shall appear only as a potentially-evaluated expression within the `compound-statement` of a `function-body` or `lambda-expression`, in either case outside of a `handler` (14.1). In a `declaration-statement` or in the `simple-declaration` (if any) of an `init-statement`, an `await-expression` shall appear only in an `initializer` of that `declaration-statement` or simple-declaration. An `await-expression` shall not appear in a default argument (9.3.4.7). An `await-expression` shall not appear in the initializer of a block variable with static or thread storage duration. A context within a function where an `await-expression` can appear is called a `suspension context` of the function.

3. Evaluation of an `await-expression` involves the following auxiliary types, expressions, and objects:

   - `\( p \)` is an lvalue naming the promise object (9.5.4) of the enclosing coroutine and `P` is the type of that object.
   - Unless the `await-expression` was implicitly produced by a `yield-expression` (7.6.17), an initial await expression, or a final await expression (9.5.4), a search is performed for the name `await_transform` in the scope of `P` (6.5.2). If this search is performed and finds at least one declaration, then `a` is `P.\text{await_transform}(\text{cast-expression})`; otherwise, `a` is the `cast-expression`.
   - `o` is determined by enumerating the applicable `operator co_await` functions for an argument `a` (12.2.2.3), and choosing the best one through overload resolution (12.2). If overload resolution is ambiguous, the program is ill-formed. If no viable functions are found, `o` is `a`. Otherwise, `o` is a call to the selected function with the argument `a`. If `o` would be a prvalue, the temporary materialization conversion (7.3.5) is applied.
   - `\( e \)` is an lvalue referring to the result of evaluating the (possibly-converted) `o`.
   - `h` is an object of type `std::coroutine_handle<\text{P}>` referring to the enclosing coroutine.
   - `\text{await-ready}` is the expression `e.\text{await_ready}()`, contextually converted to `bool`.
   - `\text{await-suspend}` is the expression `e.\text{await_suspend}(h)`, which shall be a prvalue of type `void`, `bool`, or `std::coroutine_handle<Z>` for some type `Z`.
   - `\text{await-resume}` is the expression `e.\text{await_resume}()`.

4. The `await-expression` has the same type and value category as the `await-resume` expression.

5. The `await-expression` evaluates the (possibly-converted) `o` expression and the `await-ready` expression, then:

   - If the result of `await-ready` is `false`, the coroutine is considered suspended. Then:

     - If the type of `await-suspend` is `std::coroutine_handle<Z>`, `await-suspend.\text{resume}()` is evaluated.

       [Note 1: This resumes the coroutine referred to by the result of `await-suspend`. Any number of coroutines can be successively resumed in this fashion, eventually returning control flow to the current coroutine caller or resumer (9.5.4). — end note]
Otherwise, if the type of `await-suspend` is `bool`, `await-suspend` is evaluated, and the coroutine is resumed if the result is `false`.

Otherwise, `await-suspend` is evaluated.

If the evaluation of `await-suspend` exits via an exception, the exception is caught, the coroutine is resumed, and the exception is immediately rethrown (14.2). Otherwise, control flow returns to the current coroutine caller or resumer (9.5.4) without exiting any scopes (8.7). The point in the coroutine immediately prior to control returning to its caller or resumer is a coroutine suspend point.

If the result of `await-ready` is `true`, or when the coroutine is resumed other than by rethrowing an exception from `await-suspend`, the `await-resume` expression is evaluated, and its result is the result of the `await-expression`.

[Note 2: With respect to sequencing, an `await-expression` is indivisible (6.9.1). — end note]

6

[Example 1:

```cpp
template <typename T>
struct my_future {
    /* ... */
    bool await_ready();
    void await_suspend(std::coroutine_handle<>);
    T await_resume();
};

template <class Rep, class Period>
auto operator co_await(std::chrono::duration<Rep, Period> d) {
    struct awaiter {
        std::chrono::system_clock::duration duration;
        /* ... */
        awaiter(std::chrono::system_clock::duration d) : duration(d) {} 
        bool await_ready() const { return duration.count() <= 0; } 
        void await_resume() {} 
        void await_suspend(std::coroutine_handle<> h) { /* ... */ } 
    };
    return awaiter(d);
}

using namespace std::chrono;

my_future<int> h();

my_future<void> g() {
    std::cout << "just about to go to sleep...\n";
    co_await 10ms;
    std::cout << "resumed\n";
    co_await h();
}

auto f(int x = co_await h()); // error: await-expression outside of function suspension context
int a[] = { co_await h() }; // error: await-expression outside of function suspension context

— end example]

7.6.2.5 Sizeof [expr.sizeof]

1 The `sizeof` operator yields the number of bytes occupied by a non-potentially-overlapping object of the type of its operand. The operand is either an expression, which is an unevaluated operand (7.2.3), or a parenthesized `type-id`. The `sizeof` operator shall not be applied to an expression that has function or incomplete type, to the parenthesized name of such types, or to a glvalue that designates a bit-field. The result of `sizeof` applied to any of the narrow character types is 1. The result of `sizeof` applied to any other fundamental type (6.8.2) is implementation-defined.

[Note 1: In particular, the values of `sizeof(bool)`, `sizeof(char16_t)`, `sizeof(char32_t)`, and `sizeof(wchar_t)` are implementation-defined. — end note]
When applied to a reference type, the result is the size of the referenced type. When applied to a class, the result is the number of bytes in an object of that class including any padding required for placing objects of that type in an array. The result of applying `sizeof` to a potentially-overlapping subobject is the size of the type, not the size of the subobject.\footnote{The actual size of a potentially-overlapping subobject can be less than the result of applying `sizeof` to the subobject, due to virtual base classes and less strict padding requirements on potentially-overlapping subobjects.} When applied to an array, the result is the total number of bytes in the array. This implies that the size of an array of \( n \) elements is \( n \) times the size of an element.

The value-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are not applied to the operand of `sizeof`. If the operand is a prvalue, the temporary materialization conversion (7.3.5) is applied.

The `identifier` in a `sizeof...` expression shall name a pack. The `sizeof...` operator yields the number of elements in the pack (13.7.4). A `sizeof...` expression is a pack expansion (13.7.4).

```
example 1:
    template<class... Types>
    struct count {
        static constexpr std::size_t value = sizeof...(Types);
    };

    // end example
```

The result of `sizeof` and `sizeof...` is a prvalue of type `std::size_t`.

```
Note 3: A `sizeof` expression is an integral constant expression (7.7). The type `std::size_t` is defined in the standard header `<cstdint>` (17.2.1, 17.2.4). —end note
```

### 7.6.2.6 Alignof 

1. An `alignof` expression yields the alignment requirement of its operand type. The operand shall be a `type-id` representing a complete object type, or an array thereof, or a reference to one of those types.

2. The result is a prvalue of type `std::size_t`.

```
Note 1: An `alignof` expression is an integral constant expression (7.7). The type `std::size_t` is defined in the standard header `<cstdint>` (17.2.1, 17.2.4). —end note
```

3. When `alignof` is applied to a reference type, the result is the alignment of the referenced type. When `alignof` is applied to an array type, the result is the alignment of the element type.

### 7.6.2.7 noexcept operator

```
noexcept-expression:
    noexcept ( expression )
```

1. The operand of the `noexcept` operator is an unevaluated operand (7.2.3). If the operand is a prvalue, the temporary materialization conversion (7.3.5) is applied.

2. The result of the `noexcept` operator is a prvalue of type `bool`. The result is `false` if the full-expression of the operand is potentially-throwing (14.5), and `true` otherwise.

```
Note 1: A noexcept-expression is an integral constant expression (7.7). —end note
```

### 7.6.2.8 New

```
new-expression:
    ::opt new new-placement_opt new-type-id new-initializer_opt
::opt new new-placement_opt ( type-id ) new-initializer_opt
```

1. The `new-expression` attempts to create an object of the `type-id` or `new-type-id` (9.3.2) to which it is applied. The type of that object is the `allocated type`. This type shall be a complete object type (6.8.1), but not an abstract class type (11.7.4) or array thereof (6.7.2).

```
Note 1: Because references are not objects, references cannot be created by new-expressions. —end note
```

```
Note 2: The `type-id` can be a cv-qualified type, in which case the object created by the `new-expression` has a cv-qualified type. —end note
```

59) The actual size of a potentially-overlapping subobject can be less than the result of applying `sizeof` to the subobject, due to virtual base classes and less strict padding requirements on potentially-overlapping subobjects.
new-type-id:
  type-specifier-seq new-declarator_opt

new-declarator:
  ptr-operator new-declarator_opt
  noptr-new-declarator

noptr-new-declarator:
  [ expression_opt ] attribute-specifier-seq_opt
  noptr-new-declarator [ constant-expression ] attribute-specifier-seq_opt

new-initializer:
  ( expression-list_opt )
  braced-init-list

2 If a placeholder type (9.2.9.7) or a placeholder for a deduced class type (9.2.9.8) appears in the type-specifier-seq of a new-type-id or type-id of a new-expression, the allocated type is deduced as follows: Let `init` be the new-initializer, if any, and `T` be the new-type-id or type-id of the new-expression, then the allocated type is the type deduced for the variable `x` in the invented declaration (9.2.9.7):

```c
T x = init;
```

[Example 1:

```c
new auto(1);
auto x = new auto('a');
```

// allocated type is int
// allocated type is char, x is of type char*
```

3 The new-type-id in a new-expression is the longest possible sequence of new-declarators.

[Note 3: This prevents ambiguities between the declarator operators & & * and [] and their expression counterparts. — end note]

[Example 2:

```c
new int * i;    // syntax error: parsed as (new int*) i, not as (new int)* i
```

The * is the pointer declarator and not the multiplication operator. — end example]

4 [Note 4: Parentheses in a new-type-id of a new-expression can have surprising effects.

[Example 3:

```c
new int(*[10])();    // error
```

is ill-formed because the binding is

```c
(new int)(*[10])();    // error
```

Instead, the explicitly parenthesized version of the new operator can be used to create objects of compound types (6.8.4):

```c
new int (*[10])();
```

allocates an array of 10 pointers to functions (taking no argument and returning int). — end example]

5 The attribute-specifier-seq in a noptr-new-declarator appertains to the associated array type.

6 Every constant-expression in a noptr-new-declarator shall be a converted constant expression (7.7) of type std::size_t and its value shall be greater than zero.

[Example 4: Given the definition int n = 42, new float[n][5] is well-formed (because `n` is the expression of a noptr-new-declarator), but new float[5][n] is ill-formed (because `n` is not a constant expression). — end example]

7 If the type-id or new-type-id denotes an array type of unknown bound (9.3.4.5), the new-initializer shall not be omitted; the allocated object is an array with `n` elements, where `n` is determined from the number of initial elements supplied in the new-initializer (9.4.2, 9.4.3).

8 If the expression in a noptr-new-declarator is present, it is implicitly converted to std::size_t. The value of the expression is invalid if (8.1) — the expression is of non-class type and its value before converting to std::size_t is less than zero;
the expression is of class type and its value before application of the second standard conversion (12.2.4.2.3)\(^{60}\) is less than zero;

— its value is such that the size of the allocated object would exceed the implementation-defined limit (Annex B); or

— the \texttt{new-initializer} is a \texttt{braced-init-list} and the number of array elements for which initializers are provided (including the terminating ‘\texttt{\0}’ in a \texttt{string-literal} (5.13.5)) exceeds the number of elements to initialize.

If the value of the \texttt{expression} is invalid after converting to \texttt{std::size_t}:

— if the \texttt{expression} is invalid after converting to \texttt{std::size_t}, the program is ill-formed;

— otherwise, an allocation function is not called; instead

— if the allocation function that would have been called has a non-throwing exception specification (14.5), the value of the \texttt{new-expression} is the null pointer value of the required result type;

— otherwise, the \texttt{new-expression} terminates by throwing an exception of a type that would match a handler (14.4) of type \texttt{std::bad_array_new_length} (17.6.4.2).

When the value of the \texttt{expression} is zero, the allocation function is called to allocate an array with no elements.

If the allocated type is an array, the \texttt{new-initializer} is a \texttt{braced-init-list}, and the \texttt{expression} is potentially-evaluated and not a core constant expression, the semantic constraints of copy-initializing a hypothetical element of the array from an empty initializer list are checked (9.4.5).

[Note 5: The array can contain more elements than there are elements in the \texttt{braced-init-list}, requiring initialization of the remainder of the array elements from an empty initializer list. — end note]

Objects created by a \texttt{new-expression} have dynamic storage duration (6.7.5.5).

[Note 6: The lifetime of such an object is not necessarily restricted to the scope in which it is created. — end note]

When the allocated type is “array of \texttt{N T}” (that is, the \texttt{nopt-new-declarator} syntax is used or the \texttt{new-type-id} or \texttt{type-id} denotes an array type), the \texttt{new-expression} yields a prvalue of type “pointer to \texttt{T}” that points to the initial element (if any) of the array. Otherwise, let \texttt{T} be the allocated type; the \texttt{new-expression} is a prvalue of type “pointer to \texttt{T}” that points to the object created.

[Note 7: Both \texttt{new int} and \texttt{new int[10]} have type \texttt{int*} and the type of \texttt{new int[i][10]} is \texttt{int (*)(10)}. — end note]

A \texttt{new-expression} may obtain storage for the object by calling an allocation function (6.7.5.5.2). If the \texttt{new-expression} terminates by throwing an exception, it may release storage by calling a deallocation function (6.7.5.5.3). If the allocated type is a non-array type, the allocation function’s name is \texttt{operator new} and the deallocation function’s name is \texttt{operator delete}. If the allocated type is an array type, the allocation function’s name is \texttt{operator new[]} and the deallocation function’s name is \texttt{operator delete[]}.

[Note 8: An implementation is expected to provide default definitions for the global allocation functions (6.7.5.5, 17.6.3.2, 17.6.3.3). A C++ program can provide alternative definitions of these functions (16.4.5.6) and/or class-specific versions (11.4.11). The set of allocation and deallocation functions that can be called by a \texttt{new-expression} can include functions that do not perform allocation or deallocation; for example, see 17.6.3.4. — end note]

If the \texttt{new-expression} does not begin with a unary \texttt{::} operator and the allocated type is a class type \texttt{T} or array thereof, a search is performed for the allocation function’s name in the scope of \texttt{T} (6.5.2). Otherwise, or if nothing is found, the allocation function’s name is looked up by searching for it in the global scope.

An implementation is allowed to omit a call to a replaceable global allocation function (17.6.3.2, 17.6.3.3). When it does so, the storage is instead provided by the implementation or provided by extending the allocation of another \texttt{new-expression}.

During an evaluation of a constant expression, a call to a replaceable allocation function is always omitted (7.7).

The implementation may extend the allocation of a \texttt{new-expression e1} to provide storage for a \texttt{new-expression e2} if the following would be true were the allocation not extended:

— the evaluation of \texttt{e1} is sequenced before the evaluation of \texttt{e2}, and

— \texttt{e2} is evaluated whenever \texttt{e1} obtains storage, and

— both \texttt{e1} and \texttt{e2} invoke the same replaceable global allocation function, and

\(\text{Note 60:}\) If the conversion function returns a signed integer type, the second standard conversion converts to the unsigned type \texttt{std::size_t} and thus thwarts any attempt to detect a negative value afterwards.
— if the allocation function invoked by e1 and e2 is throwing, any exceptions thrown in the evaluation of either e1 or e2 would be first caught in the same handler, and

— the pointer values produced by e1 and e2 are operands to evaluated delete-expressions, and

— the evaluation of e2 is sequenced before the evaluation of the delete-expression whose operand is the pointer value produced by e1.

[Example 5:

```cpp
void can_merge(int x) {
    // These allocations are safe for merging:
    std::unique_ptr<char[]> a{new (std::nothrow) char[8]};
    std::unique_ptr<char[]> b{new (std::nothrow) char[8]};
    std::unique_ptr<char[]> c{new (std::nothrow) char[x]};

g(a.get(), b.get(), c.get());
}

void cannot_merge(int x) {
    std::unique_ptr<char[]> a{new char[8]};
    try {
        // Merging this allocation would change its catch handler.
        std::unique_ptr<char[]> b{new char[x]};
    } catch (const std::bad_alloc& e) {
        std::cerr << "Allocation failed: " << e.what() << std::endl;
        throw;
    }
}
```
—end example]

When a new-expression calls an allocation function and that allocation has not been extended, the new-expression passes the amount of space requested to the allocation function as the first argument of type std::size_t. That argument shall be no less than the size of the object being created; it may be greater than the size of the object being created only if the object is an array and the allocation function is not a non-allocating form (17.6.3.4). For arrays of char, unsigned char, and std::byte, the difference between the result of the new-expression and the address returned by the allocation function shall be an integral multiple of the strictest fundamental alignment requirement (6.7.6) of any object type whose size is no greater than the size of the array being created.

[Note 9: Because allocation functions are assumed to return pointers to storage that is appropriately aligned for objects of any type with fundamental alignment, this constraint on array allocation overhead permits the common idiom of allocating character arrays into which objects of other types will later be placed. — end note]

When a new-expression calls an allocation function and that allocation has been extended, the size argument to the allocation call shall be no greater than the sum of the sizes for the omitted calls as specified above, plus the size for the extended call had it not been extended, plus any padding necessary to align the allocated objects within the allocated memory.

The new-placement syntax is used to supply additional arguments to an allocation function; such an expression is called a placement new-expression.

Overload resolution is performed on a function call created by assembling an argument list. The first argument is the amount of space requested, and has type std::size_t. If the type of the allocated object has new-extended alignment, the next argument is the type’s alignment, and has type std::align_val_t. If the new-placement syntax is used, the initializer-clauses in its expression-list are the succeeding arguments. If no matching function is found then

— if the allocated object type has new-extended alignment, the alignment argument is removed from the argument list;

— otherwise, an argument that is the type’s alignment and has type std::align_val_t is added into the argument list immediately after the first argument;

and then overload resolution is performed again.

[Example 6:

```cpp
— new T results in one of the following calls:
```
operator new(sizeof(T))
operator new(sizeof(T), std::align_val_t(alignof(T)))

(21.2) — new(2,f) T results in one of the following calls:
operator new(sizeof(T), 2, f)
operator new(sizeof(T), std::align_val_t(alignof(T)), 2, f)

(21.3) — new T[5] results in one of the following calls:
operator new[](sizeof(T) * 5 + x)
operator new[](sizeof(T) * 5 + x, std::align_val_t(alignof(T)))

(21.4) — new(2,f) T[5] results in one of the following calls:
operator new[](sizeof(T) * 5 + x, 2, f)
operator new[](sizeof(T) * 5 + x, std::align_val_t(alignof(T)), 2, f)

Here, each instance of x is a non-negative unspecified value representing array allocation overhead; the result of the new-expression will be offset by this amount from the value returned by operator new[]. This overhead may be applied in all array new-expressions, including those referencing a placement allocation function, except when referencing the library function operator new[](std::size_t, void*). The amount of overhead may vary from one invocation of new to another. — end example]

[Note 10: Unless an allocation function has a non-throwing exception specification (14.5), it indicates failure to allocate storage by throwing a std::bad_alloc exception (6.7.5.2, Clause 14, 17.6.4.1); it returns a non-null pointer otherwise. If the allocation function has a non-throwing exception specification, it returns null to indicate failure to allocate storage and a non-null pointer otherwise. — end note]

If the allocation function is a non-allocating form (17.6.3.4) that returns null, the behavior is undefined. Otherwise, if the allocation function returns null, initialization shall not be done, the deallocation function shall not be called, and the value of the new-expression shall be null.

[Note 11: When the allocation function returns a value other than null, it must be a pointer to a block of storage in which space for the object has been reserved. The block of storage is assumed to be appropriately aligned (6.7.6) and of the requested size. The address of the created object will not necessarily be the same as that of the block if the object is an array. — end note]

A new-expression that creates an object of type T initializes that object as follows:

(24.1) — If the new-initializer is omitted, the object is default-initialized (9.4).

[Note 12: If no initialization is performed, the object has an indeterminate value. — end note]

(24.2) — Otherwise, the new-initializer is interpreted according to the initialization rules of 9.4 for direct-initialization.

The invocation of the allocation function is sequenced before the evaluations of expressions in the new-initializer. Initialization of the allocated object is sequenced before the value computation of the new-expression.

If the new-expression creates an array of objects of class type, the destructor is potentially invoked (11.4.7).

If any part of the object initialization described above terminates by throwing an exception and a suitable deallocation function can be found, the deallocation function is called to free the memory in which the object was being constructed, after which the exception continues to propagate in the context of the new-expression. If no unambiguous matching deallocation function can be found, propagating the exception does not cause the object’s memory to be freed.

[Note 13: This is appropriate when the called allocation function does not allocate memory; otherwise, it is likely to result in a memory leak. — end note]

If the new-expression does not begin with a unary :: operator and the allocated type is a class type T or an array thereof, a search is performed for the deallocation function’s name in the scope of T. Otherwise, or if nothing is found, the deallocation function’s name is looked up by searching for it in the global scope.

A declaration of a placement deallocation function matches the declaration of a placement allocation function if it has the same number of parameters and, after parameter transformations (9.3.4.6), all parameter types except the first are identical. If the lookup finds a single matching deallocation function, that function will be called; otherwise, no deallocation function will be called. If the lookup finds a usual deallocation function and that function, considered as a placement deallocation function, would have been selected as a match for the allocation function, the program is ill-formed. For a non-placement allocation function, the normal deallocation function lookup is used to find the matching deallocation function (7.6.2.9). In any case,
the matching deallocation function (if any) shall be non-deleted and accessible from the point where the
new-expression appears.

[Example 7:

```cpp
struct S {
    // Placement allocation function:
    static void* operator new(std::size_t, std::size_t);

    // Usual (non-placement) deallocation function:
    static void operator delete(void*, std::size_t);
};

S* p = new (0) S; // error: non-placement deallocation function matches
// placement allocation function
```
—end example]

If a new-expression calls a deallocation function, it passes the value returned from the allocation function
call as the first argument of type void*. If a placement deallocation function is called, it is passed the same
additional arguments as were passed to the placement allocation function, that is, the same arguments as
those specified with the new-placement syntax. If the implementation is allowed to introduce a temporary
object or make a copy of any argument as part of the call to the allocation function, it is unspecified whether
the same object is used in the call to both the allocation and deallocation functions.

7.6.2.9 Delete [expr.delete]
The delete-expression operator destroys a most derived object (6.7.2) or array created by a new-expression.

delete-expression:
    ::opt delete cast-expression
    ::opt delete [ ] cast-expression

The first alternative is a single-object delete expression, and the second is an array delete expression. Whenever
the delete keyword is immediately followed by empty square brackets, it shall be interpreted as the second
alternative.62 If the operand is of class type, it is contextually implicitly converted (7.3) to a pointer to
object type and the converted operand is used in place of the original operand for the remainder of this
subclause. Otherwise, it shall be a prvalue of pointer to object type. The delete-expression has type void.

In a single-object delete expression, the value of the operand of delete may be a null pointer value, a pointer
value that resulted from a previous non-array new-expression, or a pointer to a base class subobject of an
object created by such a new-expression. If not, the behavior is undefined. In an array delete expression, the
value of the operand of delete may be a null pointer value or a pointer value that resulted from a previous
array new-expression whose allocation function was not a non-allocating form (17.6.3.4).63 If not, the behavior
is undefined.

[Note 1: This means that the syntax of the delete-expression must match the type of the object allocated by new, not
the syntax of the new-expression. — end note]

[Note 2: A pointer to a const type can be the operand of a delete-expression; it is not necessary to cast away the
constness (7.6.1.11) of the pointer expression before it is used as the operand of the delete-expression. — end note]

In a single-object delete expression, if the static type of the object to be deleted is not similar (7.3.6) to its
dynamic type and the selected deallocation function (see below) is not a destroying operator delete, the static
type shall be a base class of the dynamic type of the object to be deleted and the static type shall have a
virtual destructor or the behavior is undefined. In an array delete expression, if the dynamic type of the
object to be deleted is not similar to its static type, the behavior is undefined.

If the object being deleted has incomplete class type at the point of deletion, the program is ill-formed.

If the value of the operand of the delete-expression is not a null pointer value and the selected deallocation
function (see below) is not a destroying operator delete, evaluating the delete-expression invokes the destructor
(if any) for the object or the elements of the array being deleted. The destructor shall be accessible from the
point where the delete-expression appears. In the case of an array, the elements are destroyed in order of
decreasing address (that is, in reverse order of the completion of their constructor; see 11.9.3).

62) A lambda-expression with a lambda-introducer that consists of empty square brackets can follow the delete keyword if the
lambda-expression is enclosed in parentheses.
63) For nonzero-length arrays, this is the same as a pointer to the first element of the array created by that new-expression.
Zero-length arrays do not have a first element.
If the value of the operand of the delete-expression is not a null pointer value, then:

(6.1) If the allocation call for the new-expression for the object to be deleted was not omitted and the allocation was not extended (7.6.2.8), the delete-expression shall call a deallocation function (6.7.5.5.3). The value returned from the allocation call of the new-expression shall be passed as the first argument to the deallocation function.

(6.2) Otherwise, if the allocation was extended or was provided by extending the allocation of another new-expression, and the delete-expression for every other pointer value produced by a new-expression that had storage provided by the extended new-expression has been evaluated, the delete-expression shall call a deallocation function. The value returned from the allocation call of the extended new-expression shall be passed as the first argument to the deallocation function.

(6.3) Otherwise, the delete-expression will not call a deallocation function.

[Note 3: The deallocation function is called regardless of whether the destructor for the object or some element of the array throws an exception. — end note]

If the value of the operand of the delete-expression is a null pointer value, it is unspecified whether a deallocation function will be called as described above.

7 If a deallocation function is called, it is operator delete for a single-object delete expression or operator delete[] for an array delete expression.

[Note 4: An implementation provides default definitions of the global deallocation functions (17.6.3.2, 17.6.3.3). A C++ program can provide alternative definitions of these functions (16.4.5.6), and/or class-specific versions (11.4.11). — end note]

8 If the keyword delete in a delete-expression is not preceded by the unary :: operator and the type of the operand is a pointer to a (possibly cv-qualified) class type T or (possibly multidimensional) array thereof:

(8.1) For a single-object delete expression, if the operand is a pointer to cv T and T has a virtual destructor, the deallocation function is the one selected at the point of definition of the dynamic type’s virtual destructor (11.4.7).

(8.2) Otherwise, a search is performed for the deallocation function’s name in the scope of T. Otherwise, or if nothing is found, the deallocation function’s name is looked up by searching for it in the global scope. In any case, any declarations other than of usual deallocation functions (6.7.5.5.3) are discarded.

[Note 5: If only a placement deallocation function is found in a class, the program is ill-formed because the lookup set is empty (6.5). — end note]

9 The deallocation function to be called is selected as follows:

(9.1) If any of the deallocation functions is a destroying operator delete, all deallocation functions that are not destroying operator deletes are eliminated from further consideration.

(9.2) If the type has new-extended alignment, a function with a parameter of type std::align_val_t is preferred; otherwise a function without such a parameter is preferred. If any preferred functions are found, all non-preferred functions are eliminated from further consideration.

(9.3) If exactly one function remains, that function is selected and the selection process terminates.

(9.4) If the deallocation functions belong to a class scope, the one without a parameter of type std::size_t is selected.

(9.5) If the type is complete and if, for an array delete expression only, the operand is a pointer to a class type with a non-trivial destructor or a (possibly multidimensional) array thereof, the function with a parameter of type std::size_t is selected.

(9.6) Otherwise, it is unspecified whether a deallocation function with a parameter of type std::size_t is selected.

Unless the deallocation function is selected at the point of definition of the dynamic type’s virtual destructor, the selected deallocation function shall be accessible from the point where the delete-expression appears.

10 For a single-object delete expression, the deleted object is the object A pointed to by the operand if the static type of A does not have a virtual destructor, and the most-derived object of A otherwise.

[Note 6: If the deallocation function is not a destroying operator delete and the deleted object is not the most derived object in the former case, the behavior is undefined, as stated above. — end note]
For an array delete expression, the deleted object is the array object. When a *delete-expression* is executed, the selected deallocation function shall be called with the address of the deleted object in a single-object delete expression, or the address of the deleted object suitably adjusted for the array allocation overhead (7.6.2.8) in an array delete expression, as its first argument.

[Note 7: Any cv-qualifiers in the type of the deleted object are ignored when forming this argument. — end note]

If a destroying operator delete is used, an unspecified value is passed as the argument corresponding to the parameter of type `std::destroying_delete_t`. If a deallocation function with a parameter of type `std::align_val_t` is used, the alignment of the type of the deleted object is passed as the corresponding argument. If a deallocation function with a parameter of type `std::size_t` is used, the size of the deleted object in a single-object delete expression, or of the array plus allocation overhead in an array delete expression, is passed as the corresponding argument.

[Note 8: If this results in a call to a replaceable deallocation function, and either the first argument was not the result of a prior call to a replaceable allocation function or the second or third argument was not the corresponding argument in said call, the behavior is undefined (17.6.3.2, 17.6.3.3). — end note]

### 7.6.3 Explicit type conversion (cast notation)

The result of the expression \((T)\) cast-expression is of type \(T\). The result is an lvalue if \(T\) is an lvalue reference type or an rvalue reference to function type and an xvalue if \(T\) is an rvalue reference to object type; otherwise the result is a prvalue.

[Note 1: If \(T\) is a non-class type that is cv-qualified, the cv-qualifiers are discarded when determining the type of the resulting prvalue; see 7.2. — end note]

An explicit type conversion can be expressed using functional notation (7.6.1.4), a type conversion operator (`dynamic_cast`, `static_cast`, `reinterpret_cast`, `const_cast`), or the *cast* notation.

```
cast-expression:
  unary-expression
  ( type-id ) cast-expression
```

Any type conversion not mentioned below and not explicitly defined by the user (11.4.8) is ill-formed.

The conversions performed by

\(\begin{align*}
(4.1) & \quad \text{a } \text{const\_cast} \ (7.6.1.11), \\
(4.2) & \quad \text{a } \text{static\_cast} \ (7.6.1.9), \\
(4.3) & \quad \text{a } \text{static\_cast} \text{ followed by a } \text{const\_cast}, \\
(4.4) & \quad \text{a } \text{reinterpret\_cast} \ (7.6.1.10), \text{ or} \\
(4.5) & \quad \text{a } \text{reinterpret\_cast} \text{ followed by a } \text{const\_cast},
\end{align*}\)

can be performed using the cast notation of explicit type conversion. The same semantic restrictions and behaviors apply, with the exception that in performing a `static_cast` in the following situations the conversion is valid even if the base class is inaccessible:

\(\begin{align*}
(4.6) & \quad \text{a pointer to an object of derived class type or an lvalue or rvalue of derived class type may be explicitly converted to a pointer or reference to an unambiguous base class type, respectively;} \\
(4.7) & \quad \text{a pointer to member of derived class type may be explicitly converted to a pointer to member of an unambiguous non-virtual base class type;} \\
(4.8) & \quad \text{a pointer to an object of an unambiguous non-virtual base class type, a glvalue of an unambiguous non-virtual base class type, or a pointer to member of an unambiguous non-virtual base class type may be explicitly converted to a pointer, a reference, or a pointer to member of a derived class type, respectively.}
\end{align*}\)

If a conversion can be interpreted in more than one of the ways listed above, the interpretation that appears first in the list is used, even if a cast resulting from that interpretation is ill-formed. If a `static_cast` followed by a `const_cast` is used and the conversion can be interpreted in more than one way as such, the conversion is ill-formed.

**Example 1:**

```
struct A { };
struct I1 : A { };
struct I2 : A { };
```
struct D : I1, I2 { };
A* foo( D* p ) {
    return (A*)( p );  // ill-formed static_cast interpretation
}

int*** ptr = 0;
auto t = (int const*const*const*)ptr;  // OK, const_cast interpretation

struct S {
    operator const int*();
    operator volatile int*();
};
int *p = (int*)S();  // error: two possible interpretations using static_cast followed by const_cast
— end example

The operand of a cast using the cast notation can be a prvalue of type “pointer to incomplete class type”. The destination type of a cast using the cast notation can be “pointer to incomplete class type”. If both the operand and destination types are class types and one or both are incomplete, it is unspecified whether the static_cast or the reinterpret_cast interpretation is used, even if there is an inheritance relationship between the two classes.

[Note 2: For example, if the classes were defined later in the translation unit, a multi-pass compiler could validly interpret a cast between pointers to the classes as if the class types were complete at the point of the cast. — end note]

### 7.6.4 Pointer-to-member operators [expr.mptr.oper]

The pointer-to-member operators \(-\to\) and \(\cdot\) group left-to-right.

\[
\text{pm-expression:} \\
\text{cast-expression} \\
\text{pm-expression} \cdot \text{cast-expression} \\
\text{pm-expression} \to \text{cast-expression}
\]

The binary operator \(\cdot\) binds its second operand, which shall be a prvalue of type “pointer to member of T” to its first operand, which shall be a glvalue of class T or of a class of which T is an unambiguous and accessible base class. The result is an object or a function of the type specified by the second operand.

The binary operator \(\to\) binds its second operand, which shall be a prvalue of type “pointer to member of T” to its first operand, which shall be of type “pointer to U” where U is either T or a class of which T is an unambiguous and accessible base class. The expression \(E1\to\cdot E2\) is converted into the equivalent form \((\cdot(E1)).\cdot E2\).

Abbreviating pm-expression \(\cdot\)cast-expression as \(E1\cdot E2\), \(E1\) is called the object expression. If the result of \(E1\) is an object whose type is not similar to the type of \(E1\), or whose most derived object does not contain the member to which \(E2\) refers, the behavior is undefined. The expression \(E1\) is sequenced before the expression \(E2\).

The restrictions on cv-qualification, and the manner in which the cv-qualifiers of the operands are combined to produce the cv-qualifiers of the result, are the same as the rules for \(E1\cdot E2\) given in 7.6.1.5.

[Note 1: It is not possible to use a pointer to member that refers to a mutable member to modify a const class object. For example,

\[
\text{struct S} \\
\text{S() : i(0) \{} \\
\text{mutable int i; \\
\} \\
\text{void f()} \\
\{ \\
\text{const S cs; \\
\text{int S::* pm = &S::i; // pm refers to mutable member S::i} \\
\text{cs.*pm = 88; // error: cs is a const object} \\
\}
\— end note]

If the result of \(\cdot\) or \(\to\) is a function, then that result can be used only as the operand for the function call operator \(()\).
Example 1:

```
(ptr_to_obj->*ptr_to_mfct)(10);
```
calls the member function denoted by `ptr_to_mfct` for the object pointed to by `ptr_to_obj`. — end example

In a `. *` expression whose object expression is an rvalue, the program is ill-formed if the second operand is a pointer to member function whose `ref-qualifier` is `&`, unless its `cv-qualifier-seq` is `const`. In a `. *` expression whose object expression is an lvalue, the program is ill-formed if the second operand is a pointer to member function whose `ref-qualifier` is `&&`. The result of a `. *` expression whose second operand is a pointer to a data member is an lvalue if the first operand is an lvalue and an xvalue otherwise. The result of a `. *` expression whose second operand is a pointer to a member function is a prvalue. If the second operand is the null pointer member value (7.3.13), the behavior is undefined.

### 7.6.5 Multiplicative operators

1. The multiplicative operators `*`, `/`, and `%` group left-to-right.

```
multiplicative-expression:
  pm-expression
  pm-expression * pm-expression
  pm-expression / pm-expression
  pm-expression % pm-expression
```

2. The operands of `*` and `/` shall have arithmetic or unscoped enumeration type; the operands of `%` shall have integral or unscoped enumeration type. The usual arithmetic conversions (7.4) are performed on the operands and determine the type of the result.

3. The binary `*` operator indicates multiplication.

4. The binary `/` operator yields the quotient, and the binary `%` operator yields the remainder from the division of the first expression by the second. If the second operand of `/` or `%` is zero, the behavior is undefined. For integral operands, the `/` operator yields the algebraic quotient with any fractional part discarded.64 if the quotient `a/b` is representable in the type of the result, `(a/b)*b + a%b` is equal to `a`; otherwise, the behavior of both `a/b` and `a%b` is undefined.

### 7.6.6 Additive operators

1. The additive operators `+` and `-` group left-to-right. Each operand shall be a prvalue. If both operands have arithmetic or unscoped enumeration type, the usual arithmetic conversions (7.4) are performed. Otherwise, if one operand has arithmetic or unscoped enumeration type, integral promotion is applied (7.3.7) to that operand. A converted or promoted operand is used in place of the corresponding original operand for the remainder of this section.

```
additive-expression:
  multiplicative-expression
  additive-expression + multiplicative-expression
  additive-expression - multiplicative-expression
```

For addition, either both operands shall have arithmetic type, or one operand shall be a pointer to a completely-defined object type and the other shall have integral type.

2. For subtraction, one of the following shall hold:

   (2.1) — both operands have arithmetic type; or

   (2.2) — both operands are pointers to cv-qualified or cv-unqualified versions of the same completely-defined object type; or

   (2.3) — the left operand is a pointer to a completely-defined object type and the right operand has integral type.

3. The result of the binary `+` operator is the sum of the operands. The result of the binary `-` operator is the difference resulting from the subtraction of the second operand from the first.

4. When an expression `J` that has integral type is added to or subtracted from an expression `P` of pointer type, the result has the type of `P`.

   (4.1) — If `P` evaluates to a null pointer value and `J` evaluates to 0, the result is a null pointer value.

64) This is often called truncation towards zero.
— Otherwise, if \( P \) points to a (possibly-hypothetical) array element \( i \) of an array object \( x \) with \( n \) elements (9.3.4.5),\(^{65} \) the expressions \( P + J \) and \( J + P \) (where \( J \) has the value \( j \)) point to the (possibly-hypothetical) array element \( i + j \) of \( x \) if \( 0 \leq i + j \leq n \) and the expression \( P - J \) points to the (possibly-hypothetical) array element \( i - j \) of \( x \) if \( 0 \leq i - j \leq n \).

— Otherwise, the behavior is undefined.

[Note 1: Adding a value other than 0 or 1 to a pointer to a base class subobject, a member subobject, or a complete object results in undefined behavior. — end note]

When two pointer expressions \( P \) and \( Q \) are subtracted, the type of the result is an implementation-defined signed integral type; this type shall be the same type that is defined as `std::ptrdiff_t` in the `<cstdlib>` header (17.2.4).

— If \( P \) and \( Q \) both evaluate to null pointer values, the result is 0.

— Otherwise, if \( P \) and \( Q \) point to, respectively, array elements \( i \) and \( j \) of the same array object \( x \), the expression \( P - Q \) has the value \( i - j \).

[Note 2: If the value \( i - j \) is not in the range of representable values of type `std::ptrdiff_t`, the behavior is undefined (7.1). — end note]

— Otherwise, the behavior is undefined.

For addition or subtraction, if the expressions \( P \) or \( Q \) have type “pointer to `cv T`”, where \( T \) and the array element type are not similar (7.3.6), the behavior is undefined.

[Example 1:

```c
int arr[5] = {1, 2, 3, 4, 5};
unsigned int *p = reinterpret_cast<unsigned int*>(arr + 1);
unsigned int k = *p; // OK, value of k is 2 (7.3.2)
unsigned int *q = p + 1; // undefined behavior: p points to an int, not an unsigned int object
```
—end example]

### 7.6.7 Shift operators

1. The shift operators `<<` and `>>` group left-to-right.

   ```
   shift-expression:
   additive-expression
   shift-expression << additive-expression
   shift-expression >> additive-expression
   ```

   The operands shall be prvalues of integral or unscoped enumeration type and integral promotions are performed. The type of the result is that of the promoted left operand. The behavior is undefined if the right operand is negative, or greater than or equal to the width of the promoted left operand.

2. The value of \( E_1 << E_2 \) is the unique value congruent to \( E_1 \times 2^{E_2} \mod 2^N \), where \( N \) is the width of the type of the result.

   [Note 1: \( E_1 \) is left-shifted \( E_2 \) bit positions; vacated bits are zero-filled. — end note]

3. The value of \( E_1 >> E_2 \) is \( E_1 / 2^{E_2} \), rounded towards negative infinity.

   [Note 2: \( E_1 \) is right-shifted \( E_2 \) bit positions. Right-shift on signed integral types is an arithmetic right shift, which performs sign-extension. — end note]

4. The expression \( E_1 \) is sequenced before the expression \( E_2 \).

### 7.6.8 Three-way comparison operator

1. The three-way comparison operator groups left-to-right.

   ```
   compare-expression:
   shift-expression
   compare-expression <= compare-expression
   ```

   The expression \( p \leftrightarrow q \) is a prvalue indicating whether \( p \) is less than, equal to, greater than, or incomparable with \( q \).

---

\(^{65}\) As specified in 6.8.4, an object that is not an array element is considered to belong to a single-element array for this purpose and a pointer past the last element of an array of \( n \) elements is considered to be equivalent to a pointer to a hypothetical array element \( n \) for this purpose.
3 If one of the operands is of type `bool` and the other is not, the program is ill-formed.

4 If both operands have arithmetic types, or one operand has integral type and the other operand has unscoped enumeration type, the usual arithmetic conversions (7.4) are applied to the operands. Then:

(4.1) — If a narrowing conversion (9.4.5) is required, other than from an integral type to a floating-point type, the program is ill-formed.

(4.2) — Otherwise, if the operands have integral type, the result is of type `std::strong_ordering`. The result is `std::strong_ordering::equal` if both operands are arithmetically equal, `std::strong_ordering::less` if the first operand is arithmetically less than the second operand, and `std::strong_ordering::greater` otherwise.

(4.3) — Otherwise, the operands have floating-point type, and the result is of type `std::partial_ordering`. The expression `a <=> b` yields `std::partial_ordering::less` if `a` is less than `b`, `std::partial_ordering::greater` if `a` is greater than `b`, `std::partial_ordering::equivalent` if `a` is equivalent to `b`, and `std::partial_ordering::unordered` otherwise.

5 If both operands have the same enumeration type `E`, the operator yields the result of converting the operands to the underlying type of `E` and applying `<>` to the converted operands.

6 If at least one of the operands is of object pointer type and the other operand is of object pointer or array type, array-to-pointer conversions (7.3.3), pointer conversions (7.3.12), and qualification conversions (7.3.6) are performed on both operands to bring them to their composite pointer type (7.2.2). After the conversions, the operands shall have the same type.

[Note 1: If both of the operands are arrays, array-to-pointer conversions (7.3.3) are not applied. — end note]

In this case, `p <> q` is of type `std::strong_ordering` and the result is defined by the following rules:

(6.1) — If two pointer operands `p` and `q` compare equal (7.6.10), `p <> q` yields `std::strong_ordering::equal`;

(6.2) — otherwise, if `p` and `q` compare unequal, `p <> q` yields `std::strong_ordering::less` if `q` compares greater than `p` and `std::strong_ordering::greater` if `p` compares greater than `q` (7.6.9);

(6.3) — otherwise, the result is unspecified.

7 Otherwise, the program is ill-formed.

8 The three comparison category types (17.11.2) (the types `std::strong_ordering`, `std::weak_ordering`, and `std::partial_ordering`) are not predefined; if a standard library declaration (17.11.1, 16.4.2.4) of such a class type does not precede (6.5.1) a use of that type — even an implicit use in which the type is not named (e.g., via the `auto` specifier (9.2.9.7) in a defaulted three-way comparison (11.10.3) or use of the built-in operator) — the program is ill-formed.

### § 7.6.9 Relational operators

1 The relational operators group left-to-right.

[Example 1: `a<b<c` means `(a<b)<c` and not `(a<b)&&(b<c)`. — end example]

```
relational-expression:
  compare-expression
  relational-expression < compare-expression
  relational-expression <= compare-expression
  relational-expression > compare-expression
  relational-expression >= compare-expression
```

The lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are performed on the operands. The comparison is deprecated if both operands were of array type prior to these conversions (D.3).

2 The converted operands shall have arithmetic, enumeration, or pointer type. The operators `<` (less than), `>` (greater than), `<=` (less than or equal to), and `>=` (greater than or equal to) all yield `false` or `true`. The type of the result is `bool`.

3 The usual arithmetic conversions (7.4) are performed on operands of arithmetic or enumeration type. If both operands are pointers, pointer conversions (7.3.12), function pointer conversions (7.3.14), and qualification conversions (7.3.6) are performed to bring them to their composite pointer type (7.2.2). After conversions, the operands shall have the same type.
The result of comparing unequal pointers to objects is defined in terms of a partial order consistent with the following rules:

- If two pointers point to different elements of the same array, or to subobjects thereof, the pointer to the element with the higher subscript is required to compare greater.
- If two pointers point to different non-static data members of the same object, or to subobjects of such members, recursively, the pointer to the later declared member is required to compare greater provided neither member is a subobject of zero size and their class is not a union.
- Otherwise, neither pointer is required to compare greater than the other.

If two operands \( p \) and \( q \) compare equal (7.6.10), \( p \equiv q \) and \( p \equiv q \) both yield \( \text{true} \) and \( p \equiv q \) and \( p \equiv q \) both yield \( \text{false} \). Otherwise, if a pointer to \( p \) compares greater than a pointer \( q \), \( p \equiv q \), \( p > q \), \( q < p \), and \( q < p \) all yield \( \text{true} \) and \( p < q \), \( p < q \), \( q < p \), and \( q < p \) all yield \( \text{false} \). Otherwise, the result of each of the operators is unspecified.

**[Note 1]: A relational operator applied to unequal function pointers yields an unspecified result. A pointer value of type “pointer to cv void” can point to an object (6.8.4). — end note]**

If both operands (after conversions) are of arithmetic or enumeration type, each of the operators shall yield \( \text{true} \) if the specified relationship is true and \( \text{false} \) if it is false.

7.6.10 Equality operators

\[
\begin{align*}
\text{equality-expression} & =\text{relationalexpression} \\
\text{equality-expression} \equiv \text{relationalexpression} \\
\text{equality-expression} \neq \text{relationalexpression}
\end{align*}
\]

1 The \( \equiv \) (equal to) and the \( \neq \) (not equal to) operators group left-to-right. The lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are performed on the operands. The comparison is deprecated if both operands were of array type prior to these conversions (D.3).

2 The converted operands shall have arithmetic, enumeration, pointer, or pointer-to-member type, or type \( \text{std:: nullptr_t} \). The operators \( \equiv \) and \( \neq \) both yield \( \text{true} \) or \( \text{false} \), i.e., a result of type \( \text{bool} \). In each case below, the operands shall have the same type after the specified conversions have been applied.

3 If at least one of the operands is a pointer, pointer conversions (7.3.12), function pointer conversions (7.3.14), and qualification conversions (7.3.6) are performed on both operands to bring them to their composite pointer type (7.2.2). Comparing pointers is defined as follows:

- If one pointer represents the address of a complete object, and another pointer represents the address one past the last element of a different complete object, the result of the comparison is unspecified.
- Otherwise, if the pointers are both null, both point to the same function, or both represent the same address (6.8.4), they compare equal.
- Otherwise, the pointers compare unequal.

4 If at least one of the operands is a pointer to member, pointer-to-member conversions (7.3.13), function pointer conversions (7.3.14), and qualification conversions (7.3.6) are performed on both operands to bring them to their composite pointer type (7.2.2). Comparing pointers to members is defined as follows:

- If two pointers to members are both the null member pointer value, they compare equal.
- If only one of two pointers to members is the null member pointer value, they compare unequal.
- If either is a pointer to a virtual member function, the result is unspecified.
- If one refers to a member of class \( C1 \) and the other refers to a member of a different class \( C2 \), where neither is a base class of the other, the result is unspecified.

**[Example 1]:**

```c
struct A {}
struct B : A { int x; }
struct C : A { int x; }
```
int A::*bx = (int(A::*))&B::x;
int A::*cx = (int(A::*))&C::x;

bool b1 = (bx == cx); // unspecified
— end example

— If both refer to (possibly different) members of the same union (11.5), they compare equal.
— Otherwise, two pointers to members compare equal if they would refer to the same member of the
same most derived object (6.7.2) or the same subobject if indirection with a hypothetical object of the
associated class type were performed, otherwise they compare unequal.

[Example 2:
  struct B {
    int f();
  };
  struct L : B { }
  struct R : B { }
  struct D : L, R { }
  int (B::*pb)() = &B::f;
  int (L::*pl)() = pb;
  int (R::*pr)() = pb;
  int (D::*pdl)() = pl;
  int (D::*pdr)() = pr;
  bool x = (pdl == pdr); // false
  bool y = (pb == pl); // true
— end example]

5 Two operands of type std::nullptr_t or one operand of type std::nullptr_t and the other a null pointer
constant compare equal.

6 If two operands compare equal, the result is true for the == operator and false for the != operator. If two
operands compare unequal, the result is false for the == operator and true for the != operator. Otherwise,
the result of each of the operators is unspecified.

7 If both operands are of arithmetic or enumeration type, the usual arithmetic conversions (7.4) are performed
on both operands; each of the operators shall yield true if the specified relationship is true and false if it is
false.

7.6.11 Bitwise AND operator  [expr.bit.and]

and-expression:
  equality-expression
and-expression & equality-expression

1 The & operator groups left-to-right. The operands shall be of integral or unscoped enumeration type. The usual
arithmetic conversions (7.4) are performed. Given the coefficients \(x_i\) and \(y_i\) of the base-2 representation (6.8.2)
of the converted operands \(x\) and \(y\), the coefficient \(r_i\) of the base-2 representation of the result \(r\) is 1 if both
\(x_i\) and \(y_i\) are 1, and 0 otherwise.

[Note 1: The result is the bitwise AND function of the operands. — end note]

7.6.12 Bitwise exclusive OR operator  [expr.xor]

exclusive-or-expression:
  and-expression
exclusive-or-expression ^ and-expression

1 The ^ operator groups left-to-right. The operands shall be of integral or unscoped enumeration type. The usual
arithmetic conversions (7.4) are performed. Given the coefficients \(x_i\) and \(y_i\) of the base-2 representation (6.8.2)
of the converted operands \(x\) and \(y\), the coefficient \(r_i\) of the base-2 representation of the result \(r\) is 1 if either
(but not both) of \(x_i\) and \(y_i\) is 1, and 0 otherwise.

[Note 1: The result is the bitwise exclusive OR function of the operands. — end note]
7.6.13 Bitwise inclusive OR operator

\[ expr.or \]

\[
\text{inclusive-or-expression:} \\
\quad \text{exclusive-or-expression} \\
\quad \text{inclusive-or-expression} \ |
\]

1 The | operator groups left-to-right. The operands shall be of integral or unscoped enumeration type. The usual arithmetic conversions (7.4) are performed. Given the coefficients \( x_i \) and \( y_i \) of the base-2 representation (6.8.2) of the converted operands \( x \) and \( y \), the coefficient \( r_i \) of the base-2 representation of the result \( r \) is 1 if at least one of \( x_i \) and \( y_i \) is 1, and 0 otherwise.

[Note 1: The result is the bitwise inclusive OR function of the operands. — end note]

7.6.14 Logical AND operator

\[ expr.log.and \]

\[
\text{logical-and-expression:} \\
\quad \text{inclusive-or-expression} \\
\quad \text{logical-and-expression} \ && 
\]

1 The && operator groups left-to-right. The operands are both contextually converted to bool (7.3). The result is true if both operands are true and false otherwise. Unlike &, && guarantees left-to-right evaluation: the second operand is not evaluated if the first operand is false.

2 The result is a bool. If the second expression is evaluated, the first expression is sequenced before the second expression (6.9.1).

7.6.15 Logical OR operator

\[ expr.log.or \]

\[
\text{logical-or-expression:} \\
\quad \text{logical-and-expression} \\
\quad \text{logical-or-expression} \ || 
\]

1 The || operator groups left-to-right. The operands are both contextually converted to bool (7.3). The result is true if either of its operands is true, and false otherwise. Unlike |, || guarantees left-to-right evaluation; moreover, the second operand is not evaluated if the first operand evaluates to true.

2 The result is a bool. If the second expression is evaluated, the first expression is sequenced before the second expression (6.9.1).

7.6.16 Conditional operator

\[ expr.cond \]

\[
\text{conditional-expression:} \\
\quad \text{logical-or-expression} \\
\quad \text{logical-or-expression} \ ? 
\]

1 Conditional expressions group right-to-left. The first expression is contextually converted to bool (7.3). It is evaluated and if it is true, the result of the conditional expression is the value of the second expression, otherwise that of the third expression. Only one of the second and third expressions is evaluated. The first expression is sequenced before the second or third expression (6.9.1).

2 If either the second or the third operand has type void, one of the following shall hold:

(2.1) — The second or the third operand (but not both) is a (possibly parenthesized) throw-expression (7.6.18); the result is of the type and value category of the other. The conditional-expression is a bit-field if that operand is a bit-field.

(2.2) — Both the second and the third operands have type void; the result is of type void and is a prvalue.

[Note 1: This includes the case where both operands are throw-expressions. — end note]

3 Otherwise, if the second and third operand are glvalue bit-fields of the same value category and of types cv1 T and cv2 T, respectively, the operands are considered to be of type cv T for the remainder of this subclause, where cv is the union of cv1 and cv2.

4 Otherwise, if the second and third operand have different types and either has (possibly cv-qualified) class type, or if both are glvalues of the same value category and the same type except for cv-qualification, an attempt is made to form an implicit conversion sequence (12.2.4.2) from each of those operands to the type of the other.

[Note 2: Properties such as access, whether an operand is a bit-field, or whether a conversion function is deleted are ignored for that determination. — end note]
Attempts are made to form an implicit conversion sequence from an operand expression \(E_1\) of type \(T_1\) to a target type related to the type \(T_2\) of the operand expression \(E_2\) as follows:

1. If \(E_2\) is an lvalue, the target type is “lvalue reference to \(T_2\)”, but an implicit conversion sequence can only be formed if the reference would bind directly (9.4.4) to a glvalue.

2. If \(E_2\) is an xvalue, the target type is “rvalue reference to \(T_2\)”, but an implicit conversion sequence can only be formed if the reference would bind directly.

3. If \(E_2\) is a prvalue or if neither of the conversion sequences above can be formed and at least one of the operands has (possibly cv-qualified) class type:
   - if \(T_1\) and \(T_2\) are the same class type (ignoring cv-qualification):
     - if \(T_2\) is at least as cv-qualified as \(T_1\), the target type is \(T_2\),
     - otherwise, no conversion sequence is formed for this operand;
   - otherwise, if \(T_2\) is a base class of \(T_1\), the target type is \(cv\ T_2\), where \(cv\) denotes the cv-qualifiers of \(T_1\);
   - otherwise, the target type is the type that \(E_2\) would have after applying the lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions.

Using this process, it is determined whether an implicit conversion sequence can be formed from the second operand to the target type determined for the third operand, and vice versa. If both sequences can be formed, or one can be formed but it is the ambiguous conversion sequence, the program is ill-formed. If no conversion sequence can be formed, the operands are left unchanged and further checking is performed as described below. Otherwise, if exactly one conversion sequence can be formed, that conversion is applied to the chosen operand and the converted operand is used in place of the original operand for the remainder of this subclause.

[Note 3: The conversion might be ill-formed even if an implicit conversion sequence could be formed. — end note]

If the second and third operands are glvalues of the same value category and have the same type, the result is of that type and value category and it is a bit-field if the second or the third operand is a bit-field, or if both are bit-fields.

Otherwise, the result is a prvalue. If the second and third operands do not have the same type, and either has (possibly cv-qualified) class type, overload resolution is used to determine the conversions (if any) to be applied to the operands (12.2.2.3, 12.5). If the overload resolution fails, the program is ill-formed. Otherwise, the conversions thus determined are applied, and the converted operands are used in place of the original operands for the remainder of this subclause.

Lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions are performed on the second and third operands. After those conversions, one of the following shall hold:

1. The second and third operands have the same type; the result is of that type and the result object is initialized using the selected operand.

2. The second and third operands have arithmetic or enumeration type; the usual arithmetic conversions (7.4) are performed to bring them to a common type, and the result is of that type.

3. One or both of the second and third operands have pointer type; pointer conversions (7.3.12), function pointer conversions (7.3.14), and qualification conversions (7.3.6) are performed to bring them to their composite pointer type (7.2.2). The result is of the composite pointer type.

4. One or both of the second and third operands have pointer-to-member type; pointer to member conversions (7.3.13), function pointer conversions (7.3.14), and qualification conversions (7.3.6) are performed to bring them to their composite pointer type (7.2.2). The result is of the composite pointer type.

5. Both the second and third operands have type \(\text{std::nullptr_t}\) or one has that type and the other is a null pointer constant. The result is of type \(\text{std::nullptr_t}\).

### 7.6.17 Yielding a value

[expr.yield]

- \(\text{co\_yield\ assignment\_expression}\)
- \(\text{co\_yield\ braced\_init\_list}\)
A *yield-expression* shall appear only within a suspension context of a function (7.6.2.4). Let \( e \) be the operand of the *yield-expression* and \( p \) be an lvalue naming the promise object of the enclosing coroutine (9.5.4), then the *yield-expression* is equivalent to the expression `co_await p.yield_value(e)`.

**Example 1:**

```cpp
template <typename T>
struct my_generator {
    struct promise_type {
        T current_value;
        /* ... */
        auto yield_value(T v) {
            current_value = std::move(v);
            return std::suspend_always{};
        }
    }
    struct iterator { /* ... */ }; // iterator begin(); iterator end();
};

my_generator<pair<int,int>> g1() { // error: yield-expression outside of function suspension context
    for (int i = 0; i < 10; ++i) co_yield {i,i};
}
my_generator<pair<int,int>> g2() { // error: yield-expression outside of function suspension context
    for (int i = 0; i < 10; ++i) co_yield make_pair(i,i);
}

auto f(int x = co_yield 5); // error: yield-expression outside of function suspension context
int a[] = { co_yield 1 }; // error: yield-expression outside of function suspension context
```

---

### 7.6.18 Throwing an exception

**throw-expression**: `throw assignment-expression_opt`

A *throw-expression* is of type void.

A *throw-expression* with an operand throws an exception (14.2). The array-to-pointer (7.3.3) and function-to-pointer (7.3.4) standard conversions are performed on the operand. The type of the exception object is determined by removing any top-level `cv-qualifiers` from the type of the (possibly converted) operand. The exception object is copy-initialized (9.4.1) from the (possibly converted) operand.

A *throw-expression* with no operand rethrows the currently handled exception (14.4). If no exception is presently being handled, the function `std::terminate` is invoked (14.6.2). Otherwise, the exception is reactivated with the existing exception object; no new exception object is created. The exception is no longer considered to be caught.

**Example 1:** An exception handler that cannot completely handle the exception itself can be written like this:

```cpp
try {
    // ...
} catch (...) { // catch all exceptions
    // respond (partially) to exception
    throw; // pass the exception to some other handler
}
```

---

§ 7.6.18 © ISO/IEC 156
7.6.19 Assignment and compound assignment operators

The assignment operator (=) and the compound assignment operators all group right-to-left. All require a modifiable lvalue as their left operand; their result is an lvalue of the type of the left operand, referring to the left operand. The result in all cases is a bit-field if the left operand is a bit-field. In all cases, the assignment is sequenced after the value computation of the right and left operands, and before the value computation of the assignment expression. The right operand is sequenced before the left operand. With respect to an indeterminately-sequenced function call, the operation of a compound assignment is a single evaluation.

[Note 1: Therefore, a function call cannot intervene between the lvalue-to-rvalue conversion and the side effect associated with any single compound assignment operator. — end note]

assignment-expression:
  conditional-expression
  yield-expression
  throw-expression
  logical-or-expression assignment-operator initializer-clause

assignment-operator: one of
  = *= /= %= += -= >>= <<= &= ^= |=

In simple assignment (=), the object referred to by the left operand is modified (3.1) by replacing its value with the result of the right operand.

If the right operand is an expression, it is implicitly converted (7.3) to the cv-unqualified type of the left operand.

When the left operand of an assignment operator is a bit-field that cannot represent the value of the expression, the resulting value of the bit-field is implementation-defined.

An assignment whose left operand is of a volatile-qualified type is deprecated (D.4) unless the (possibly parenthesized) assignment is a discarded-value expression or an unevaluated operand (7.2.3).

The behavior of an expression of the form \( E_1 \text{ op } E_2 \) is equivalent to \( E_1 = E_1 \text{ op } E_2 \) except that \( E_1 \) is evaluated only once.

[Note 2: The object designated by \( E_1 \) is accessed twice. — end note]

For += and -=, \( E_1 \) shall either have arithmetic type or be a pointer to a possibly cv-qualified completely-defined object type. In all other cases, \( E_1 \) shall have arithmetic type.

If the value being stored in an object is read via another object that overlaps in any way the storage of the first object, then the overlap shall be exact and the two objects shall have the same type, otherwise the behavior is undefined.

[Note 3: This restriction applies to the relationship between the left and right sides of the assignment operation; it is not a statement about how the target of the assignment can be aliased in general. See 7.2.1. — end note]

8 A braced-init-list \( B \) may appear on the right-hand side of

(8.1) — an assignment to a scalar of type \( T \), in which case \( B \) shall have at most a single element. The meaning of \( x = B \) is \( x = t \), where \( t \) is an invented temporary variable declared and initialized as \( T \ t = B \).

(8.2) — an assignment to an object of class type, in which case \( B \) is passed as the argument to the assignment operator function selected by overload resolution (12.4.3.2, 12.2).

[Example 1:

```c
complex<double> z;
z = { 1,2 }; // meaning z.operator=({1,2})
z += { 1, 2 }; // meaning z.operator+={1,2})
int a, b;
a = b = { 1 }; // meaning a=b=1;
a = { 1 } = b; // syntax error
```

— end example]

7.6.20 Comma operator

The comma operator groups left-to-right.

evaluation:
  assignment-expression
  expression , assignment-expression

§ 7.6.20 ©ISO/IEC 157
A pair of expressions separated by a comma is evaluated left-to-right; the left expression is a discarded-value expression (7.2). The left expression is sequenced before the right expression (6.9.1). The type and value of the result are the type and value of the right operand; the result is of the same value category as its right operand, and is a bit-field if its right operand is a bit-field.

2 [Note 1: In contexts where the comma token is given special meaning (e.g., function calls (7.6.1.3), subscript expressions (7.6.1.2), lists of initializers (9.4), or template-argument-lists (13.3)), the comma operator as described in this subclause can appear only in parentheses.

Example 1:

\[ f(a, (t=3, t+2), c); \]

has three arguments, the second of which has the value 5. —end example]
—end note]

7.7 Constant expressions [expr.const]

Certain contexts require expressions that satisfy additional requirements as detailed in this subclause; other contexts have different semantics depending on whether or not an expression satisfies these requirements. Expressions that satisfy these requirements, assuming that copy elision (11.9.6) is not performed, are called constant expressions.

[Note 1: Constant expressions can be evaluated during translation. —end note]

constant-expression:
conditional-expression

2 A variable or temporary object \( o \) is constant-initialized if

(2.1) — either it has an initializer or its default-initialization results in some initialization being performed, and
(2.2) — the full-expression of its initialization is a constant expression when interpreted as a constant-expression, except that if \( o \) is an object, that full-expression may also invoke constexpr constructors for \( o \) and its subobjects even if those objects are of non-literal class types.

[Note 2: Such a class can have a non-trivial destructor. Within this evaluation, std::is_constant_evaluated() (21.3.11) returns true. —end note]

3 A variable is potentially-constant if it is constexpr or it has reference or non-volatile const-qualified integral or enumeration type.

4 A constant-initialized potentially-constant variable \( V \) is usable in constant expressions at a point \( P \) if \( V \)'s initializing declaration \( D \) is reachable from \( P \) and

(4.1) — \( V \) is constexpr,
(4.2) — \( V \) is not initialized to a TU-local value, or
(4.3) — \( P \) is in the same translation unit as \( D \).

An object or reference is usable in constant expressions if it is

(4.4) — a variable that is usable in constant expressions, or
(4.5) — a template parameter object (13.2), or
(4.6) — a string literal object (5.13.5), or
(4.7) — a temporary object of non-volatile const-qualified literal type whose lifetime is extended (6.7.7) to that of a variable that is usable in constant expressions, or
(4.8) — a non-mutable subobject or reference member of any of the above.

5 An expression \( E \) is a core constant expression unless the evaluation of \( E \), following the rules of the abstract machine (6.9.1), would evaluate one of the following:

(5.1) — this (7.5.3), except
(5.1.1) — in a constexpr function (9.2.6) that is being evaluated as part of \( E \) or
(5.1.2) — when appearing as the postfix-expression of an implicit or explicit class member access expression (7.6.1.5);
(5.2) — a control flow that passes through a declaration of a block variable (6.4.3) with static (6.7.5.2) or thread (6.7.5.3) storage duration, unless that variable is usable in constant expressions;
[**Example 1**]:
```cpp
constexpr char test() {
    static const int x = 5;
    static constexpr char c[] = "Hello World";
    return *(c + x);
}
static_assert(' ' == test());
— end example]
```

- an invocation of a non-constexpr function;
- an invocation of an undefined constexpr function;
- an invocation of an instantiated constexpr function that is not constexpr-suitable;
- an operation that would have undefined or erroneous behavior as specified in Clause 4 through Clause 15, excluding 9.12.3 and 9.12.11;
- an lvalue-to-rvalue conversion (7.3.2) unless it is applied to
  - a non-volatile glvalue that refers to an object that is usable in constant expressions, or
  - a non-volatile glvalue of literal type that refers to a non-volatile object whose lifetime began within the evaluation of E;
- an lvalue-to-rvalue conversion that is applied to a glvalue that refers to a non-active member of a union or a subobject thereof;
- an lvalue-to-rvalue conversion that is applied to an object with an indeterminate value (6.7.4);
- an invocation of an implicitly-defined copy/move constructor or copy/move assignment operator for a union whose active member (if any) is mutable, unless the lifetime of the union object began within the evaluation of E;
- in a *lambda-expression*, a reference to *this* or to a variable with automatic storage duration defined outside that *lambda-expression*, where the reference would be an odr-use (6.3, 7.5.6);

[**Example 2**]:
```cpp
void g() {
    const int n = 0;
    [=] { 
        constexpr int i = n; // OK, n is not odr-used here
        constexpr int j = *(&n); // error: &n would be an odr-use of n
    }
}
— end example]
```

[**Note 3**]: If the odr-use occurs in an invocation of a function call operator of a closure type, it no longer refers to *this* or to an enclosing automatic variable due to the transformation (7.5.6.3) of the *id-expression* into an access of the corresponding data member.

[**Example 3**]:
```cpp
auto monad = [](auto v) { return [=] { return v; }; };
auto bind = [](auto m) {
    return [=](auto fvm) { return fvm(m()); }; 
};
// OK to capture objects with automatic storage duration created during constant expression evaluation.
static_assert(bind(monad(2))(monad)() == monad(2)());
— end example]
— end note]
```

---

68) Overload resolution (12.2) is applied as usual.
69) This includes, for example, signed integer overflow (7.1), certain pointer arithmetic (7.6.6), division by zero (7.6.5), or certain shift operations (7.6.7).
— a conversion from a prvalue P of type “pointer to cv void” to a type “cv1 pointer to T”, where T is not cv2 void, unless P is a null pointer value or points to an object whose type is similar to T;

— a reinterpret_cast (7.6.1.10);

— a modification of an object (7.6.19, 7.6.16, 7.6.23) unless it is applied to a non-volatile value of literal type that refers to a non-volatile object whose lifetime began within the evaluation of E;

— an invocation of a destructor (11.4.7) or a function call whose postfix-expression names a pseudo-destructor (7.6.1.3), in either case for an object whose lifetime did not begin within the evaluation of E;

— a new-expression (7.6.2.8), unless either

— the selected allocation function is a replaceable global allocation function (17.6.3.2, 17.6.3.3) and the allocated storage is deallocated within the evaluation of E, or

— the selected allocation function is a non-allocating form (17.6.3.4) with an allocated type T, where

— the placement argument to the new-expression points to an object that is pointer-interconvertible with an object of type T or, if T is an array type, with the first element of an object of type T, and

— the placement argument points to storage whose duration began within the evaluation of E;

— a delete-expression (7.6.2.9), unless it deallocates a region of storage allocated within the evaluation of E;

— a call to an instance of std::allocator<T>::allocate (20.2.10.2), unless the allocated storage is deallocated within the evaluation of E;

— a call to an instance of std::allocator<T>::deallocate (20.2.10.2), unless it deallocates a region of storage allocated within the evaluation of E;

— an await-expression (7.6.2.4);

— a yield-expression (7.6.17);

— a three-way comparison (7.6.8), relational (7.6.9), or equality (7.6.10) operator where the result is unspecified;

— a throw-expression (7.6.18);

— a dynamic_cast (7.6.1.7) or typeid (7.6.1.8) expression on a glvalue that refers to an object whose dynamic type is constexpr-unknown or that would throw an exception;

— an asm-declaration (9.10);

— an invocation of the va_arg macro (17.13.2);

— a non-constant library call (3.34); or

— a goto statement (8.7.6).

[Note 4: A goto statement introduced by equivalence (Clause 8) is not in scope. For example, a while statement (8.6.2) can be executed during constant evaluation. — end note]

It is unspecified whether E is a core constant expression if E satisfies the constraints of a core constant expression, but evaluation of E would evaluate

— an operation that has undefined behavior as specified in Clause 16 through Clause 33,

— an invocation of the va_start macro (17.13.2),

— a call to a function that was previously declared with the noreturn attribute (9.12.11) and that call returns to its caller, or

— a statement with an assumption (9.12.3) whose converted conditional-expression, if evaluated where the assumption appears, would not disqualify E from being a core constant expression and would not evaluate to true.

[Note 5: E is not disqualified from being a core constant expression if the hypothetical evaluation of the converted conditional-expression would disqualify E from being a core constant expression. — end note]

[Example 4:]

```cpp
int x; // not constant
```
struct A {
    constexpr A(bool b) : m(b ? 42 : x) { }
    int m;
};

constexpr int v = A(true).m; // OK, constructor call initializes m with the value 42
constexpr int w = A(false).m; // error: initializer for m is x, which is non-constant

constexpr int f1(int k) {
    constexpr int x = k; // error: x is not initialized by a constant expression
    return x;
}

constexpr int f2(int k) { // OK, not required to be a constant expression
    int x = k;
    return x;
}

constexpr int incr(int &n) { // OK, incr(k) is not required to be a core constant expression
    return ++n;
}

constexpr int g(int k) { // error: incr(k) is not a core constant expression
    constexpr int x = incr(k); // because lifetime of k began outside the expression incr(k)
    return x;
}

constexpr int h(int k) { // OK, incr(k) is not required to be a core constant expression
    int x = incr(k);
    return x;
}

constexpr int y = h(1); // OK, initializes y with the value 2 // h(1) is a core constant expression because // the lifetime of k begins inside h(1)

— end example]
constexpr auto olympic_mile() {
    const int ledecky = 1500;
    return [](return ledecky);
}
static_assert(olympic_mile() == 1500); // OK

struct Swim {
    constexpr int phelps() { return 28; }
    virtual constexpr int lochte() { return 12; }
    int coughlin = 12;
};
constexpr int how_many(Swim& swam) {
    Swim* p = &swam;
    return (p + 1 - 1)->phelps();
}
void splash(Swim& swam) {
    static_assert(swam.phelps() == 28);
    // OK
    static_assert((&swam)->phelps() == 28);
    // OK
    Swim* pswam = &swam;
    static_assert(pswam->phelps() == 28);
    // error: lvalue-to-rvalue conversion on a pointer
    // not usable in constant expressions
}

extern Swim dc;
extern Swim& trident;
constexpr auto& sandeno = typeid(dc);
// OK, can only be typeid(Swim)
constexpr auto& gallagher = typeid(trident);
// error: constexpr-unknown dynamic type
—end example

10 An object a is said to have constant destruction if
— it is not of class type nor (possibly multidimensional) array thereof, or
— it is of class type or (possibly multidimensional) array thereof, that class type has a constexpr destructor,
and for a hypothetical expression E whose only effect is to destroy a, E would be a core constant expression if the lifetime of a and its non-mutable subobjects (but not its mutable subobjects) were considered to start within E.

11 An integral constant expression is an expression of integral or unscoped enumeration type, implicitly converted to a prvalue, where the converted expression is a core constant expression.

[Note 7: Such expressions can be used as bit-field lengths (11.4.10), as enumerator initializers if the underlying type is not fixed (9.7.1), and as alignments (9.12.2). —end note]

12 If an expression of literal class type is used in a context where an integral constant expression is required, then that expression is contextually implicitly converted (7.3) to an integral or unscoped enumeration type and the selected conversion function shall be constexpr.

[Example 6:
struct A {
    constexpr A(int i) : val(i) { }
    constexpr operator int() const { return val; }
    constexpr operator long() const { return 42; }
}  

§ 7.7 ©ISO/IEC 162
private:
    int val;
};
constexpr A a = alignof(int);
alignas(a) int n;  // error: ambiguous conversion
struct B { int n : a; };  // error: ambiguous conversion

A converted constant expression of type `T` is an expression, implicitly converted to type `T`, where the converted expression is a constant expression and the implicit conversion sequence contains only

- user-defined conversions,
- value-to-value conversions (7.3.2),
- array-to-pointer conversions (7.3.3),
- function-to-pointer conversions (7.3.4),
- qualification conversions (7.3.6),
- integral promotions (7.3.7),
- integral conversions (7.3.9) other than narrowing conversions (9.4.5),
- floating-point promotions (7.3.8),
- floating-point conversions (7.3.10) where the source value can be represented exactly in the destination type,
- null pointer conversions (7.3.12) from `std::nullptr_t`,
- null member pointer conversions (7.3.13) from `std::nullptr_t`, and
- function pointer conversions (7.3.14),

and where the reference binding (if any) binds directly.

[Note 8: Such expressions can be used in `new` expressions (7.6.2.8), as case expressions (8.5.3), as enumerator initializers if the underlying type is fixed (9.7.1), as array bounds (9.3.4.5), and as non-type template arguments (13.4). — end note]

A contextually converted constant expression of type `bool` is an expression, contextually converted to `bool` (7.3), where the converted expression is a constant expression and the conversion sequence contains only the conversions above.

A constant expression is either a glvalue core constant expression that refers to an entity that is a permitted result of a constant expression (as defined below), or a prvalue core constant expression whose value satisfies the following constraints:

- if the value is an object of class type, each non-static data member of reference type refers to an entity that is a permitted result of a constant expression,
- if the value is an object of scalar type, it does not have an indeterminate or erroneous value (6.7.4),
- if the value is of pointer type, it contains the address of an object with static storage duration, the address past the end of such an object (7.6.6), the address of a non-immediate function, or a null pointer value,
- if the value is of pointer-to-member-function type, it does not designate an immediate function, and
- if the value is an object of class or array type, each subobject satisfies these constraints for the value.

An entity is a permitted result of a constant expression if it is an object with static storage duration that either is not a temporary object or is a temporary object whose value satisfies the above constraints, or if it is a non-immediate function.

[Note 9: A glvalue core constant expression that either refers to or points to an unspecified object is not a constant expression. — end note]

[Example 7:

```cpp
consteval int f() { return 42; }
consteval auto g() { return f; }
consteval int h(int (*p)()) = g() { return p(); }
constexpr int r = h();  // OK
```
constexpr auto e = g(); // error: a pointer to an immediate function is
// not a permitted result of a constant expression

struct S {
    int x;
    constexpr S() {} // error: s.x has erroneous value
};
int i() {
    constexpr S s;
}

— end example]

Recommended practice: Implementations should provide consistent results of floating-point evaluations, irrespective of whether the evaluation is performed during translation or during program execution.

[Note 10: Since this document imposes no restrictions on the accuracy of floating-point operations, it is unspecified whether the evaluation of a floating-point expression during translation yields the same result as the evaluation of the same expression (or the same operations on the same values) during program execution.

[Example 8:

```cpp
bool f() {
    char array[1 + int(1 + 0.2 - 0.1 - 0.1)]; // Must be evaluated during translation
    int size = 1 + int(1 + 0.2 - 0.1 - 0.1); // May be evaluated at runtime
    return sizeof(array) == size;
}
```

It is unspecified whether the value of f() will be true or false. — end example]
— end note]

An expression or conversion is in an immediate function context if it is potentially evaluated and either:
(16.1) — its innermost enclosing non-block scope is a function parameter scope of an immediate function,
(16.2) — it is a subexpression of a manifestly constant-evaluated expression or conversion, or
(16.3) — its enclosing statement is enclosed (8.1) by the compound-statement of a consteval if statement (8.5.2).

An invocation is an immediate invocation if it is a potentially-evaluated explicit or implicit invocation of an immediate function and is not in an immediate function context. An aggregate initialization is an immediate invocation if it evaluates a default member initializer that has a subexpression that is an immediate-escalating expression.

An expression or conversion is immediate-escalating if it is not initially in an immediate function context and it is either
(17.1) — a potentially-evaluated id-expression that denotes an immediate function that is not a subexpression of an immediate invocation, or
(17.2) — an immediate invocation that is not a constant expression and is not a subexpression of an immediate invocation.

An immediate-escalating function is
(18.1) — the call operator of a lambda that is not declared with the consteval specifier,
(18.2) — a defaulted special member function that is not declared with the consteval specifier, or
(18.3) — a function that results from the instantiation of a templated entity defined with the constexpr specifier.

An immediate-escalating expression shall appear only in an immediate-escalating function.

An immediate function is a function or constructor that is
(19.1) — declared with the consteval specifier, or
(19.2) — an immediate-escalating function F whose function body contains an immediate-escalating expression E such that E’s innermost enclosing non-block scope is F’s function parameter scope.

[Note 11: Default member initializers used to initialize a base or member subobject (11.9.3) are considered to be part of the function body (9.5.1). — end note]

[Example 9:

```cpp
constexpr int id(int i) { return i; }
```
constexpr char id(char c) { return c; }

template<class T>
constexpr int f(T t) {
    return t + id(t);
}

auto a = &f<char>; // OK, f<char> is not an immediate function
auto b = &f<int>;  // error: f<int> is an immediate function
static_assert(f(3) == 6); // OK

template<class T>
constexpr int g(T t) { // g<int> is not an immediate function
    return t + id(42); // because id(42) is already a constant
}

template<class T, class F>
constexpr bool is_not(T t, F f) {
    return not f(t);
}

consteval bool is_even(int i) { return i % 2 == 0; }
static_assert(is_not(5, is_even)); // OK

int x = 0;

template<class T>
constexpr T h(T t = id(x)) { // h<int> is not an immediate function
    return t; // id(x) is not evaluated when parsing the default argument (9.3.4.7, 13.9.2)
}

template<class T>
constexpr T hh() { // hh<int> is an immediate function because of the invocation
    return h<T>(); // of the immediate function id in the default argument of h<int>
}

int i = hh<int>(); // error: hh<int>() is an immediate-escalating expression // outside of an immediate-escalating function

struct A {
    int x;
    int y = id(x);
};

template<class T>
constexpr int k(int) { // k<int> is not an immediate function because A(42) is a
    return A(42).y; // constant expression and thus not immediate-escalating
}

— end example]

An expression or conversion is **manifestly constant-evaluated** if it is:

1. a constant-expression, or
2. the condition of a constexpr if statement (8.5.2), or
3. an immediate invocation, or
4. the result of substitution into an atomic constraint expression to determine whether it is satisfied (13.5.2.3), or
5. the initializer of a variable that is usable in constant expressions or has constant initialization (6.9.3.2).\(^70\)

\(^70\) Testing this condition can involve a trial evaluation of its initializer as described above.

§ 7.7
Example 10:

```cpp
template<bool> struct X {};
X<std::is_constant_evaluated()> x;  // type X<true>
int y;
const int a = std::is_constant_evaluated() ? y : 1;  // dynamic initialization to 1
double z[a];  // error: a is not usable
const int b = std::is_constant_evaluated() ? 2 : y;  // static initialization to 2
int c = y + (std::is_constant_evaluated() ? 2 : y);  // dynamic initialization to y+y

costexpr int f() {
    const int n = std::is_constant_evaluated() ? 13 : 17;  // n is 13
    int m = std::is_constant_evaluated() ? 13 : 17;  // m can be 13 or 17 (see below)
    char arr[n] = {};  // char[13]
    return m + sizeof(arr);
}
int p = f();  // m is 13; initialized to 26
int q = p + f();  // m is 17 for this call; initialized to 56
```

—end example—

Note 12: Except for a static_assert-message, a manifestly constant-evaluated expression is evaluated even in an unevaluated operand (7.2.3). —end note—

An expression or conversion is potentially constant evaluated if it is:

(21.1) a manifestly constant-evaluated expression,

(21.2) a potentially-evaluated expression (6.3),

(21.3) an immediate subexpression of a braced-init-list,71

(21.4) an expression of the form & cast-expression that occurs within a templated entity,72 or

(21.5) a potentially-evaluated subexpression (6.9.1) of one of the above.

A function or variable is needed for constant evaluation if it is:

(21.6) a constexpr function that is named by an expression (6.3) that is potentially constant evaluated, or

(21.7) a potentially-constant variable named by a potentially constant evaluated expression.

71) In some cases, constant evaluation is needed to determine whether a narrowing conversion is performed (9.4.5).
72) In some cases, constant evaluation is needed to determine whether such an expression is value-dependent (13.8.3.4).
8 Statements

8.1 Preamble

1 Except as indicated, statements are executed in sequence (6.9.1).

```
statement:
  labeled-statement
  attribute-specifier-seq\opt expression-statement
  attribute-specifier-seq\opt compound-statement
  attribute-specifier-seq\opt selection-statement
  attribute-specifier-seq\opt iteration-statement
  attribute-specifier-seq\opt jump-statement
  declaration-statement
  attribute-specifier-seq\opt try-block

init-statement:
  expression-statement
  simple-declaration
  alias-declaration

condition:
  expression
  attribute-specifier-seq\opt decl-specifier-seq declarator brace-or-equal-initializer
  structured-binding-declaration initializer
```

The optional `attribute-specifier-seq` appertains to the respective statement.

2 A `substatement` of a `statement` is one of the following:

1. for a `labeled-statement`, its `statement`,
2. for a `compound-statement`, any `statement` of its `statement-seq`,
3. for a `selection-statement`, any of its `statements` or `compound-statements` (but not its `init-statement`), or
4. for an `iteration-statement`, its `statement` (but not an `init-statement`).

[Note 1: The `compound-statement` of a `lambda-expression` is not a substatement of the `statement` (if any) in which the `lambda-expression` lexically appears. — end note]

3 A `statement S1` encloses a `statement S2` if

1. `S2` is a `substatement` of `S1`,
2. `S1` is a `selection-statement` or `iteration-statement` and `S2` is the `init-statement` of `S1`,
3. `S1` is a `try-block` and `S2` is its `compound-statement` or any of the `compound-statements` of its `handlers`, or
4. `S1` encloses a `statement S3` and `S3` encloses `S2`.

A `statement S1` is `enclosed` by a `statement S2` if `S2` encloses `S1`.

4 The rules for `conditions` apply both to `selection-statements` (8.5) and to the `for` and `while` statements (8.6). If a `structured-binding-declaration` appears in a `condition`, the `condition` is a structured binding declaration (9.1). A `condition` that is neither an `expression` nor a structured binding declaration is a declaration (Clause 9). The `declarator` shall not specify a function or an array. The `decl-specifier-seq` shall not define a class or enumeration. If the `auto` `type-specifier` appears in the `decl-specifier-seq`, the type of the identifier being declared is deduced from the initializer as described in 9.2.9.7.

5 The `decision variable` of a `condition` that is neither an `expression` nor a structured binding declaration is the declared variable. The decision variable of a `condition` that is a structured binding declaration is specified in 9.6.

6 The value of a `condition` that is not an `expression` in a `statement` other than a `switch` statement is the value of the decision variable contextually converted to `bool` (7.3). If that conversion is ill-formed, the program is ill-formed. The value of a `condition` that is an `expression` is the value of the expression, contextually converted to `bool` for statements other than `switch`; if that conversion is ill-formed, the program is ill-formed. The value of the condition will be referred to as simply “the condition” where the usage is unambiguous.
If a condition can be syntactically resolved as either an expression or a declaration, it is interpreted as the latter.

In the decl-specifier-seq of a condition, including that of any structured-binding-declaration of the condition, each decl-specifier shall be either a type-specifier or constexpr.

8.2 Label

A label can be added to a statement or used anywhere in a compound-statement.

\[
\begin{align*}
\text{label:} & \quad \text{attribute-specifier-seq}_{\text{opt}} \ \text{identifier} : \\
& \quad \text{attribute-specifier-seq}_{\text{opt}} \ \text{case} \ \text{constant-expression} : \\
& \quad \text{attribute-specifier-seq}_{\text{opt}} \ \text{default} : \\
\text{labeled-statement:} & \quad \text{label} \ \text{statement}
\end{align*}
\]

The optional attribute-specifier-seq appertains to the label. The only use of a label with an identifier is as the target of a goto. No two labels in a function shall have the same identifier. A label can be used in a goto statement before its introduction.

A labeled-statement whose label is a case or default label shall be enclosed by (8.1) a switch statement (8.5.3).

A control-flow-limited statement is a statement $S$ for which:

1. A case or default label appearing within $S$ shall be associated with a switch statement (8.5.3) within $S$, and
2. A label declared in $S$ shall only be referred to by a statement (8.7.6) in $S$.

8.3 Expression statement

Expression statements have the form

\[
\begin{align*}
\text{expression-statement:} & \quad \text{expression}_{\text{opt}} ; \\
\end{align*}
\]

The expression is a discarded-value expression (7.2.3). All side effects from an expression statement are completed before the next statement is executed. An expression statement with the expression missing is called a null statement.

*Note 1: Most statements are expression statements — usually assignments or function calls. A null statement is useful to supply a null body to an iteration statement such as a while statement (8.6.2). — end note*

8.4 Compound statement or block

A compound statement (also known as a block) groups a sequence of statements into a single statement.

\[
\begin{align*}
\text{compound-statement:} & \quad \{ \ \text{statement-seq}_{\text{opt}} \ \text{label-seq}_{\text{opt}} \ \} \\
\text{statement-seq:} & \quad \text{statement} \\
& \quad \text{statement-seq} \ \text{statement} \\
\text{label-seq:} & \quad \text{label} \\
& \quad \text{label-seq} \ \text{label}
\end{align*}
\]

A label at the end of a compound-statement is treated as if it were followed by a null statement.

*Note 1: A compound statement defines a block scope (6.4). A declaration is a statement (8.8). — end note*

8.5 Selection statements

8.5.1 General

Selection statements choose one of several flows of control.
selection-statement:
    if constexpr (init-statement, condition) statement
    if constexpr (init-statement, condition) statement else statement
    if !opt constexpr compound-statement
    if !opt constexpr compound-statement else statement
    switch (init-statement, condition) statement

See 9.3.4 for the optional attribute-specifier-seq in a condition.

[Note 1: An init-statement ends with a semicolon. — end note]

[Note 2: Each selection-statement and each substatement of a selection-statement has a block scope (6.4.3). — end note]

8.5.2 The if statement

If the condition (8.1) yields true, the first substatement is executed. If the else part of the selection statement is present and the condition yields false, the second substatement is executed. If the first substatement is reached via a label, the condition is not evaluated and the second substatement is not executed. In the second form of if statement (the one including else), if the first substatement is also an if statement then that inner if statement shall contain an else part.73

If the if statement is of the form if constexpr, the value of the condition is contextually converted to bool and the converted expression shall be a constant expression (7.7); this form is called a constexpr if statement.

If the value of the converted condition is false, the first substatement is a discarded statement, otherwise the second substatement, if present, is a discarded statement. During the instantiation of an enclosing templated entity (13.1), if the condition is not value-dependent after its instantiation, the discarded substatement (if any) is not instantiated. Each substatement of a constexpr if statement is a control-flow-limited statement (8.2).

[Example 1:
    if constexpr (sizeof(int[2])) {}
    // OK, narrowing allowed
—end example]

[Note 1: Odr-uses (6.3) in a discarded statement do not require an entity to be defined. — end note]

[Example 2:
    template<typename T, typename ... Rest> void g(T&& p, Rest&& ...rs) {
        // ... handle p
        if constexpr (sizeof...(rs) > 0)
            g(rs...);
            // never instantiated with an empty argument list
    }
    extern int x;  // no definition of x required

int f() {
    if constexpr (true)
        return 0;
    else if (x)
        return x;
    else
        return -x;
}
—end example]

An if statement of the form
    if constexpr (init-statement condition) statement

is equivalent to
    {
        init-statement
        if constexpr (condition) statement
    }

and an if statement of the form

73) In other words, the else is associated with the nearest un-elsed if.
if constexpr
(opt
(init-statement condition)
) statement else statement

is equivalent to

{" 
  init-statement
  if constexpr
  (condition)
  statement else statement
}

except that the init-statement is in the same scope as the condition.

An if statement of the form if constexpr is called a constexpr if statement. The statement, if any, in a constexpr if statement shall be a compound-statement.

[Example 3:
constexpr void f(bool b) {
  if (true)
    if constexpr {} 
  else ; // error: not a compound-statement; else not associated with outer if
}
—end example]

If a constexpr if statement is evaluated in a context that is manifestly constant-evaluated (7.7), the first substatement is executed.

[Note 2: The first substatement is an immediate function context. — end note]

Otherwise, if the else part of the selection statement is present, then the second substatement is executed. Each substatement of a constexpr if statement is a control-flow-limited statement (8.2).

An if statement of the form

if ! constexpr compound-statement

is not itself a constexpr if statement, but is equivalent to the constexpr if statement

if constexpr {} else compound-statement

An if statement of the form

if ! constexpr compound-statement, else statement

is not itself a constexpr if statement, but is equivalent to the constexpr if statement

if constexpr statement else compound-statement

8.5.3 The switch statement

The switch statement causes control to be transferred to one of several statements depending on the value of a condition.

If the condition is an expression, the value of the condition is the value of the expression; otherwise, it is the value of the decision variable. The value of the condition shall be of integral type, enumeration type, or class type. If of class type, the condition is contextually implicitly converted (7.3) to an integral or enumeration type. If the (possibly converted) type is subject to integral promotions (7.3.7), the condition is converted to the promoted type. Any statement within the switch statement can be labeled with one or more case labels as follows:

case constant-expression :

where the constant-expression shall be a converted constant expression (7.7) of the adjusted type of the switch condition. No two of the case constants in the same switch shall have the same value after conversion.

There shall be at most one label of the form

default :

within a switch statement.

Switch statements can be nested; a case or default label is associated with the smallest switch enclosing it.

When the switch statement is executed, its condition is evaluated. If one of the case constants has the same value as the condition, control is passed to the statement following the matched case label. If no case constant matches the condition, and if there is a default label, control passes to the statement labeled by the default label. If no case matches and if there is no default then none of the statements in the switch is executed.
case and default labels in themselves do not alter the flow of control, which continues unimpeded across such labels. To exit from a switch, see break, 8.7.2.

[Note 1: Usually, the substatement that is the subject of a switch is compound and case and default labels appear on the top-level statements contained within the (compound) substatement, but this is not required. Declarations can appear in the substatement of a switch statement. — end note]

A switch statement of the form

```
switch ( init-statement condition ) statement
```

is equivalent to

```
{ 
  init-statement 
  switch ( condition ) statement 
}
```

except that the init-statement is in the same scope as the condition.

8.6 Iteration statements

8.6.1 General

Iteration statements specify looping.

```
iteration-statement:
  while ( condition ) statement 
  do statement while ( expression ) ; 
  for ( init-statement condition_{opt} ; expression_{opt} ) statement 
  for ( init-statement_{opt} for-range-declaration : for-range-initializer ) statement 

for-range-declaration:
  attribute-specifier-seq_{opt} decl-specifier-seq declarator 
  structured-binding-declaration 

for-range-initializer:
  expr-or-braced-init-list 
```

See 9.3.4 for the optional attribute-specifier-seq in a for-range-declaration.

[Note 1: An init-statement ends with a semicolon. — end note]

The substatement in an iteration-statement implicitly defines a block scope (6.4) which is entered and exited each time through the loop. If the substatement in an iteration-statement is a single statement and not a compound-statement, it is as if it was rewritten to be a compound-statement containing the original statement.

[Example 1:

```
while (--x >= 0)
  int i;
```

can be equivalently rewritten as

```
while (--x >= 0) {
  int i;
}
```

Thus after the while statement, i is no longer in scope. — end example]

A trivially empty iteration statement is an iteration statement matching one of the following forms:

```
(3.1)  — while ( expression ) ; 
(3.2)  — while ( expression ) { } 
(3.3)  — do ; while ( expression ) ; 
(3.4)  — do { } while ( expression ) ; 
(3.5)  — for ( init-statement expression_{opt} ; ) ; 
(3.6)  — for ( init-statement expression_{opt} ; ) { } 
```

The controlling expression of a trivially empty iteration statement is the expression of a while, do, or for statement (or true, if the for statement has no expression). A trivial infinite loop is a trivially empty iteration statement for which the converted controlling expression is a constant expression, when interpreted as a constant-expression (7.7), and evaluates to true. The statement of a trivial infinite loop is replaced with a call
to the function `std::this_thread::yield` (33.4.5); it is implementation-defined whether this replacement occurs on freestanding implementations.

[Note 2: In a freestanding environment, concurrent forward progress is not guaranteed; such systems therefore require explicit cooperation. A call to `yield` can add implicit cooperation where none is otherwise intended. — end note]

8.6.2 The while statement

In the while statement, the substatement is executed repeatedly until the value of the condition (8.1) becomes `false`. The test takes place before each execution of the substatement.

A while statement is equivalent to

```c
label:
    if (condition) {
        statement
        goto label;
    }
```

[Note 1: The variable created in the condition is destroyed and created with each iteration of the loop.

[Example 1:

```c
struct A {
    int val;
    A(int i) : val(i) { }
    ~A() { }
    operator bool() { return val != 0; }
};
int i = 1;
while (A a = i) {
    // ...
    i = 0;
}
```

In the while-loop, the constructor and destructor are each called twice, once for the condition that succeeds and once for the condition that fails. — end example]

—end note]

8.6.3 The do statement

The expression is contextually converted to `bool` (7.3); if that conversion is ill-formed, the program is ill-formed.

In the do statement, the substatement is executed repeatedly until the value of the expression becomes `false`. The test takes place after each execution of the statement.

8.6.4 The for statement

The for statement

```c
for (init-statement condition; expression) statement
```

is equivalent to

```c
{ 
    init-statement
    while (condition) {
        statement
        expression;
    }
}
```

except that the `init-statement` is in the same scope as the `condition`, and except that a `continue` in `statement` (not enclosed in another iteration statement) will execute `expression` before re- Evaluating `condition`.

[Note 1: Thus the first statement specifies initialization for the loop; the condition (8.1) specifies a test, sequenced before each iteration, such that the loop is exited when the condition becomes `false`; the expression often specifies incrementing that is sequenced after each iteration. — end note]
Either or both of the condition and the expression can be omitted. A missing condition makes the implied while clause equivalent to while(true).

8.6.5 The range-based for statement

The range-based for statement

```c
for (init-statement_opt for-range-declaration : for-range-initializer) statement
```

is equivalent to

```c
{
    init-statement_opt
    auto &range = for-range-initializer;
    auto begin = begin-expr;
    auto end = end-expr;
    for (; begin != end; ++begin) {
        for-range-declaration = *begin;
        statement
    }
}
```

where

(1.1) if the for-range-initializer is an expression, it is regarded as if it were surrounded by parentheses (so that a comma operator cannot be reinterpreted as delimiting two init-declarators);

(1.2) range, begin, and end are variables defined for exposition only; and

(1.3) begin-expr and end-expr are determined as follows:

(1.3.1) if the type of range is a reference to an array type R, begin-expr and end-expr are range and range + N, respectively, where N is the array bound. If R is an array of unknown bound or an array of incomplete type, the program is ill-formed;

(1.3.2) if the type of range is a reference to a class type C, and searches in the scope of C (6.5.2) for the names begin and end each find at least one declaration, begin-expr and end-expr are range.begin() and range.end(), respectively;

(1.3.3) otherwise, begin-expr and end-expr are begin(range) and end(range), respectively, where begin and end undergo argument-dependent lookup (6.5.4).

[Note 1: Ordinary unqualified lookup (6.5.3) is not performed. —end note]

[Example 1:

```c
int array[5] = { 1, 2, 3, 4, 5 };
for (int& x : array)
    x *= 2;
```

—end example]

[Note 2: The lifetime of some temporaries in the for-range-initializer is extended to cover the entire loop (6.7.7). —end note]

[Example 2:

```c
using T = std::list<int>;
const T& f1(const T& t) { return t; }
const T& f2(T t) { return t; }
T g();

void foo() {
    for (auto e : f1(g())) {} // OK, lifetime of return value of g() extended
    for (auto e : f2(g())) {} // undefined behavior
}
```

—end example]

In the decl-specifier-seq of a for-range-declaration, each decl-specifier shall be either a type-specifier or constexpr. The decl-specifier-seq shall not define a class or enumeration.
8.7 Jump statements [stmt.jump]

8.7.1 General [stmt.jump.general]

1 Jump statements unconditionally transfer control.

\[
\text{jump-statement:}
\begin{align*}
\text{break ;} \\
\text{continue ;} \\
\text{return expr-or-braced-init-list_opt ;} \\
\text{coroutine-return-statement} \\
\text{goto identifier ;}
\end{align*}
\]

2 \[\text{Note 1:} \text{On exit from a scope (however accomplished), objects with automatic storage duration (6.7.5.4) that have been constructed in that scope are destroyed in the reverse order of their construction (8.8). For temporaries, see 6.7.7. However, the program can be terminated (by calling std::exit() or std::abort() (17.5), for example) without destroying objects with automatic storage duration. — end note}\]

3 \[\text{Note 2:} \text{A suspension of a coroutine (7.6.2.4) is not considered to be an exit from a scope. — end note}\]

8.7.2 The break statement [stmt.break]

1 A \text{break} statement shall be enclosed by (8.1) an \text{iteration-statement} (8.6) or a \text{switch} statement (8.5.3). The \text{break} statement causes termination of the smallest such enclosing statement; control passes to the statement following the terminated statement, if any.

8.7.3 The continue statement [stmt.cont]

1 A \text{continue} statement shall be enclosed by (8.1) an \text{iteration-statement} (8.6). The \text{continue} statement causes control to pass to the loop-continuation portion of the smallest such enclosing statement, that is, to the end of the loop. More precisely, in each of the statements

\[
\begin{align*}
\text{while (foo) \{} & \text{ do \{} \text{ for (\{} ; \text{\{} \{
               \{
                  // ... \text{;} // ... \text{ ;}
               \}
            \}
         \}
      \}
   \}
\end{align*}
\]

\text{a continue not contained in an enclosed iteration statement is equivalent to goto contin.}

8.7.4 The return statement [stmt.return]

1 A function returns control to its caller by the \text{return} statement.

2 The \text{expr-or-braced-init-list} of a \text{return} statement is called its operand. A \text{return} statement with no operand shall be used only in a function whose return type is \text{cv void}, a constructor (11.4.5), or a destructor (11.4.7). A \text{return} statement with an operand of type \text{void} shall be used only in a function that has a \text{cv void} return type. A \text{return} statement with any other operand shall be used only in a function that has a return type other than \text{cv void}; the \text{return} statement initializes the returned reference or prvalue result object of the (explicit or implicit) function call by copy-initialization (9.4) from the operand.

\[\text{Note 1:} \text{A constructor or destructor does not have a return type. — end note}\]

\[\text{Note 2:} \text{A return statement can involve an invocation of a constructor to perform a copy or move of the operand if it is not a prvalue or if its type differs from the return type of the function. A copy operation associated with a return statement can be elided or converted to a move operation if an automatic storage duration variable is returned (11.9.6). — end note}\]

3 The destructor for the result object is potentially invoked (11.4.7, 14.3).

\[\text{Example 1:}\]

\begin{verbatim}
class A {
    -A();
};
A f() { return A(); }    // error: destructor of A is private (even though it is never invoked)
\end{verbatim}

\[\text{— end example}\]

4 Flowing off the end of a constructor, a destructor, or a non-coroutine function with a \text{cv void} return type is equivalent to \text{return} with no operand. Otherwise, flowing off the end of a function that is neither \text{main} (6.9.3.1) nor a coroutine (9.5.4) results in undefined behavior.
The copy-initialization of the result of the call is sequenced before the destruction of temporaries at the end of the full-expression established by the operand of the return statement, which, in turn, is sequenced before the destruction of local variables (8.7) of the block enclosing the return statement.

In a function whose return type is a reference, other than an invented function for std::is_convertible (21.3.7), a return statement that binds the returned reference to a temporary expression (6.7.7) is ill-formed.

Example 2:
```cpp
auto&& f1() {
    return 42; // ill-formed
}
const double& f2() {
    static int x = 42;
    return x;  // ill-formed
}
auto&& id(auto&& r) {
    return static_cast<decltype(r)&&>(r);
}
auto&& f3() {
    return id(42); // OK, but probably a bug
}
```

—end example—

8.7.5 The co_return statement

A co_return statement transfers control to the caller or resumer of a coroutine (9.5.4). A coroutine shall not enclose a return statement (8.7.4).

1. A co_return statement transfers control to the caller or resumer of a coroutine (9.5.4). A coroutine shall not enclose a return statement (8.7.4).

2. The expr-or-braced-init-list of a co_return statement is called its operand. Let \( p \) be an lvalue naming the coroutine promise object (9.5.4). A co_return statement is equivalent to:

\[
\begin{align*}
\{ & S; \text{ goto final-suspend; } \} \\
\text{where final-suspend is the exposition-only label defined in 9.5.4 and } S & \text{ is defined as follows:}
\end{align*}
\]

(2.1) — If the operand is a braced-init-list or an expression of non-void type, \( S \) is \( p\text{.return_value(expr-or-braced-init-list)\; opt} \). The expression \( S \) shall be a prvalue of type void.

(2.2) — Otherwise, \( S \) is the compound-statement \( \{ \text{expression\; opt; } p\text{.return_void(); } \\} \). The expression \( p\text{.return_void()\; opt} \) shall be a prvalue of type void.

3. If a search for the name return_void in the scope of the promise type finds any declarations, flowing off the end of a coroutine’s function-body is equivalent to a co_return with no operand; otherwise flowing off the end of a coroutine’s function-body results in undefined behavior.

8.7.6 The goto statement

The goto statement unconditionally transfers control to the statement labeled by the identifier. The identifier shall be a label (8.2) located in the current function.

8.8 Declaration statement

A declaration statement introduces one or more new names into a block; it has the form

\[
\begin{align*}
\text{declaration-statement:} & \quad \text{block-declaration}
\end{align*}
\]

[Note 1: If an identifier introduced by a declaration was previously declared in an outer block, the outer declaration is hidden for the remainder of the block (6.5.3), after which it resumes its force. — end note]
all such variables have vacuous initialization (6.7.3), the transfer of control shall not be a jump.\footnote{74} When a declaration-statement is executed, \( P \) and \( Q \) are the points immediately before and after it; when a function returns, \( Q \) is after its body.

\[\text{Example 1:}\]

```c
void f() {
    // ...
    goto lx;           // error: jump into scope of a
    // ...
    ly:
    X a = 1;
    // ...
    lx:
    goto ly;           // OK, jump implies destructor call for a followed by
                       // construction again immediately following label ly
}
```

--- end example]

3 Dynamic initialization of a block variable with static storage duration (6.7.5.2) or thread storage duration (6.7.5.3) is performed the first time control passes through its declaration; such a variable is considered initialized upon the completion of its initialization. If the initialization exits by throwing an exception, the initialization is not complete, so it will be tried again the next time control enters the declaration. If control enters the declaration concurrently while the variable is being initialized, the concurrent execution shall wait for completion of the initialization.

\[\text{Note 2:} \text{A conforming implementation cannot introduce any deadlock around execution of the initializer. Deadlocks might still be caused by the program logic; the implementation need only avoid deadlocks due to its own synchronization operations.} \quad \text{— end note}\]

If control re-enters the declaration recursively while the variable is being initialized, the behavior is undefined.

\[\text{Example 2:}\]

```c
int foo(int i) {
    static int s = foo(2*i);       // undefined behavior: recursive call
    return i+1;
}
```

--- end example]

4 An object associated with a block variable with static or thread storage duration will be destroyed if and only if it was constructed.

\[\text{Note 3:} \text{6.9.3.4 describes the order in which such objects are destroyed.} \quad \text{— end note}\]

8.9 Ambiguity resolution \[\text{stmt.ambig}\]

1 There is an ambiguity in the grammar involving expression-statements and declarations: An expression-statement with a function-style explicit type conversion (7.6.1.4) as its leftmost subexpression can be indistinguishable from a declaration where the first declarator starts with a \( ( \). In those cases the statement is considered a declaration, except as specified below.

\[\text{Note 1:} \text{If the statement cannot syntactically be a declaration, there is no ambiguity, so this rule does not apply. In some cases, the whole statement needs to be examined to determine whether this is the case. This resolves the meaning of many examples.}\]

\[\text{Example 1:} \text{Assuming}\ T\ \text{is a simple-type-specifier (9.2.9),}\]

\[\begin{align*}
    T(a)\rightarrow m &= 7;       & \text{expression-statement} \\
    T(a)++ &= \text{expression-statement} \\
    T(a,5)<<c &= \text{expression-statement} \\
    T(*d)(int) &= \text{declaration} \\
    T(e)[5] &= \text{declaration} \\
    T(f) &= \{ 1, 2 \} & \text{declaration} \\
    T(*g)(double(3)) &= \text{declaration}
\end{align*}\]

In the last example above, \( g \), which is a pointer to \( T \), is initialized to \( \text{double(3)} \). This is of course ill-formed for semantic reasons, but that does not affect the syntactic analysis. \( \text{— end example}\]

\footnote{74} The transfer from the condition of a switch statement to a case label is considered a jump in this respect.
The remaining cases are declarations.

[Example 2:

```cpp
class T {
    // ...
public:
    T();
    T(int);
    T(int, int);
};
T(a); // declaration
T(*b)(); // declaration
T(c)=7; // declaration
T(d),e,f=3;
extern int h;
T(g)(h,2); // declaration
```
—end example]
—end note]

3 The disambiguation is purely syntactic; that is, the meaning of the names occurring in such a statement, beyond whether they are type-names or not, is not generally used in or changed by the disambiguation. Class templates are instantiated as necessary to determine if a qualified name is a type-name. Disambiguation precedes parsing, and a statement disambiguated as a declaration may be an ill-formed declaration. If, during parsing, lookup finds that a name in a template argument is bound to (part of) the declaration being parsed, the program is ill-formed. No diagnostic is required.

[Example 3:

```cpp
struct T1 {
    T1 operator()(int x) { return T1(x); }
    int operator=(int x) { return x; }
    T1(int) { }
};
struct T2 { T2(int) { } }
int a, (*(*b)(T2))(int), c, d;

void f() {
    // disambiguation requires this to be parsed as a declaration:
    T1(a) = 3,
    T2(4),
    (**b)(T2(c))(int(d)); // allow the last part of the declaration to parse properly, since it depends on T2 being a type-name
}
```
—end example]

4 A syntactically ambiguous statement that can syntactically be a declaration with an outermost declarator with a trailing-return-type is considered a declaration only if it starts with auto.

[Example 4:

```cpp
struct M;
struct S {
    S* operator()();
    int N;
    int M;

    void mem(S s) {
        auto(s)() -> M; // expression, S::M hides ::M
    }
};

void f(S s) {
    auto(s)() -> N; // expression
    auto(s)() -> M; // function declaration
}
```

§ 8.9
{ 
    S(a) () -> N;  // expression
    S(a) () -> M;  // expression
}

—end example]
9 Declarations

9.1 Preamble

1 Declarations generally specify how names are to be interpreted. Declarations have the form

```
declaration-seq:
    declaration
    declaration-seq declaration

declaration:
    name-declaration
    special-declaration

name-declaration:
    block-declaration
    nodeclspec-function-declaration
    function-definition
    friend-type-declaration
    template-declaration
    deduction-guide
    linkage-specification
    namespace-definition
    empty-declaration
    attribute-declaration
    module-import-declaration

special-declaration:
    explicit-instantiation
    explicit-specialization
    export-declaration

block-declaration:
    simple-declaration
    asm-declaration
    namespace-alias-definition
    using-declaration
    using-enumeration-declaration
    using-directive
    static_assert-declaration
    alias-declaration
    opaque-enumeration-declaration

nodeclspec-function-declaration:
    attribute-specifier-seq_opt declarator ;

alias-declaration:
    using identifier attribute-specifier-seq_opt = defining-type-id ;

attributed-identifier:
    identifier attribute-specifier-seq_opt

attributed-identifier-list:
    attributed-identifier
    attributed-identifier-list , attributed-identifier

structured-binding-declaration:
    attribute-specifier-seq_opt decl-specifier-seq ref-qualifier_opt [ attributed-identifier-list ]

simple-declaration:
    decl-specifier-seq init-declarator-list_opt ;
    attribute-specifier-seq decl-specifier-seq init-declarator-list ;
    structured-binding-declaration initializer ;

static_assert-message:
    unevaluated-string
    constant-expression
```
static_assert-declaration:
  static_assert ( constant-expression ) ;
  static_assert ( constant-expression , static_assert-message ) ;
empty-declaration:
;  attribute-declaration:
  attribute-specifier-seq ;

[Note 1: asm-declarations are described in 9.10, and linkage-specifications are described in 9.11; function-definitions are described in 9.5 and template-declarations and deduction-guides are described in 13.7.2.3; namespace-definitions are described in 9.8.2, using-declarations are described in 9.9 and using-directives are described in 9.8.4. — end note]

2 Certain declarations contain one or more scopes (6.4.1). Unless otherwise stated, utterances in Clause 9 about components in, of, or contained by a declaration or subcomponent thereof refer only to those components of the declaration that are not nested within scopes nested within the declaration.

3 If a name-declaration matches the syntactic requirements of friend-type-declaration, it is a friend-type-declaration.

4 A simple-declaration or nodeclspec-function-declaration of the form
   attribute-specifier-seqopt decl-specifier-seqopt init-declarator-listopt ;
is divided into three parts. Attributes are described in 9.12. decl-specifiers, the principal components of a decl-specifier-seq, are described in 9.2. declarators, the components of an init-declarator-list, are described in 9.3. The attribute-specifier-seq appertains to each of the entities declared by the declarators of the init-declarator-list.

[Note 2: In the declaration for an entity, attributes appertaining to that entity can appear at the start of the declaration and after the declarator-id for that declaration. — end note]

[Example 1:
   [[noreturn]] void f [[noreturn]] () ; // OK
— end example]

5 If a declarator-id is a name, the init-declarator and (hence) the declaration introduce that name.

[Note 3: Otherwise, the declarator-id is a qualified-id or names a destructor or its unqualified-id is a template-id and no name is introduced. — end note]

The defining-type-specifiers (9.2.9) in the decl-specifier-seq and the recursive declarator structure describe a type (9.3.4), which is then associated with the declarator-id.

6 In a simple-declaration, the optional init-declarator-list can be omitted only when declaring a class (11.1) or enumeration (9.7.1), that is, when the decl-specifier-seq contains either a class-specifier, an elaborated-type-specifier with a class-key (11.3), or an enum-specifier. In these cases and whenever a class-specifier or enum-specifier is present in the decl-specifier-seq, the identifiers in these specifiers are also declared (as class-names, enum-names, or enumerators, depending on the syntax). In such cases, the decl-specifier-seq shall (re)introduce one or more names into the program.

[Example 2:
   enum { } ; // error
typedef class { } ; // error
— end example]

7 A simple-declaration or a condition with a structured-binding-declaration is called a structured binding declaration (9.6). Each decl-specifier in the decl-specifier-seq shall be static, thread_local, auto (9.2.9.7), or a cv-qualifier.

[Example 3:
   template<class T> concept C = true;
   C auto [x, y] = std::pair{1, 2} ; // error: constrained placeholder-type-specifier
   // not permitted for structured bindings
— end example]

The initializer shall be of the form “= assignment-expression”, of the form “{ assignment-expression }”, or of the form “( assignment-expression )”. If the structured-binding-declaration appears as a condition, the assignment-expression shall be of non-union class type. Otherwise, the assignment-expression shall be of array or non-union class type.
If the `decl-specifier-seq` contains the `typedef` specifier, the declaration is a `typedef declaration` and each `declarator-id` is declared to be a `typedef-name`, synonymous with its associated type (9.2.4).

[Note 4: Such a `declarator-id` is an `identifier` (11.4.8.3). — end note]

Otherwise, if the type associated with a `declarator-id` is a function type (9.3.4.6), the declaration is a `function declaration`. Otherwise, if the type associated with a `declarator-id` is an object or reference type, the declaration is an `object declaration`. Otherwise, the program is ill-formed.

[Example 4:]
```
int f(), x;  // OK, function declaration for f and object declaration for x
extern void g(), y;  // OK, function declaration for g
```

— end example]

An object definition causes storage of appropriate size and alignment to be reserved and any appropriate initialization (9.4) to be done.

Syntactic components beyond those found in the general form of `simple-declaration` are added to a function declaration to make a `function-definition`. A token sequence starting with `{` or `=` is treated as a `function-body` (9.5.1) if the type of the `declarator-id` (9.3.4.1) is a function type, and is otherwise treated as a `brace-or-equal-initializer` (9.4.1).

[Note 5: If the declaration acquires a function type through template instantiation, the program is ill-formed; see 13.9.1. The function type of a function definition cannot be specified with a `typedef-name` (9.3.4.6). — end note]

A `nodeclspec-function-declaration` shall declare a constructor, destructor, or conversion function.

[Note 6: Because a member function cannot be subject to a non-defining declaration outside of a class definition (11.4.2), a `nodeclspec-function-declaration` can only be used in a `template-declaration` (13.1), `explicit-instantiation` (13.9.3), or `explicit-specialization` (13.9.4). — end note]

If a `static_assert-message` matches the syntactic requirements of `unevaluated-string`, it is an `unevaluated-string` and the text of the `static_assert-message` is the text of the `unevaluated-string`. Otherwise, a `static_assert-message` shall be an expression `M` such that

(12.1)  the expression `M.size()` is implicitly convertible to the type `std::size_t`, and

(12.2)  the expression `M.data()` is implicitly convertible to the type “pointer to `const char`”.

In a `static_assert-declaration`, the constant-expression `E` is contextually converted to `bool` and the converted expression shall be a constant expression (7.7). If the value of the expression `E` when so converted is `true` or the expression is evaluated in the context of a template definition, the declaration has no effect and the `static_assert-message` is an unevaluated operand (7.2.3). Otherwise, the `static_assert-declaration` fails and

(13.1)  the program is ill-formed, and

(13.2)  if the `static_assert-message` is a constant-expression `M`,

(13.2.1)  `M.size()` shall be a converted constant expression of type `std::size_t` and let `N` denote the value of that expression,

(13.2.2)  `M.data()`, implicitly converted to the type “pointer to `const char`”, shall be a core constant expression and let `D` denote the converted expression,

(13.2.3)  for each `i` where `0 ≤ i < N`, `D[i]` shall be an integral constant expression, and

(13.2.4)  the text of the `static_assert-message` is formed by the sequence of `N` code units, starting at `D`, of the ordinary literal encoding (5.3).

Recommended practice: When a `static_assert-declaration` fails, the resulting diagnostic message should include the text of the `static_assert-message`, if one is supplied.

[Example 5:]
```
static_assert(sizeof(int) == sizeof(void*), "wrong pointer size");
static_assert(sizeof(int[2]));  // OK, narrowing allowed
```

```template <class T>
void f(T t) {
    if constexpr (sizeof(T) == sizeof(int)) {
        use(t);
    } else {
        ```
```
static_assert(false, "must be int-sized");
}

void g(char c) {
  f(0);  // OK
  f(c);  // error on implementations where sizeof(int) > 1: must be int-sized
}
—end example]}

An empty-declaration has no effect.

15 Except where otherwise specified, the meaning of an attribute-declaration is implementation-defined.

9.2 Specifiers [dcl.spec]

9.2.1 General [dcl.spec.general]

1 The specifiers that can be used in a declaration are

dcl-specifier:
  storage-class-specifier
  defining-type-specifier
  function-specifier
  friend
typedef
typedef
constexpr
consteval
constinit
inline
decl-specifier-seq:
  decl-specifier attribute-specifier-seq_opt
  decl-specifier decl-specifier-seq

The optional attribute-specifier-seq in a decl-specifier-seq appertains to the type determined by the preceding
decl-specifiers (9.3.4). The attribute-specifier-seq affects the type only for the declaration it appears in, not
other declarations involving the same type.

2 Each decl-specifier shall appear at most once in a complete decl-specifier-seq, except that long may appear
twice. At most one of the constexpr, consteval, and constinit keywords shall appear in a decl-specifier-seq.

3 If a type-name is encountered while parsing a decl-specifier-seq, it is interpreted as part of the decl-specifier-seq
if and only if there is no previous defining-type-specifier other than a cv-qualifier in the decl-specifier-seq. The
sequence shall be self-consistent as described below.

[Example 1:

typedef char* Pc;
static Pc;  // error: name missing

Here, the declaration static Pc is ill-formed because no name was specified for the static variable of type Pc. To get a
variable called Pc, a type-specifier (other than const or volatile) has to be present to indicate that the typedef-name
Pc is the name being (re)declared, rather than being part of the decl-specifier sequence. For another example,

void f(const Pc);  // void f(char* const) (not const char*)
void g(const int Pc);  // void g(const int)
—end example]

4 [Note 1: Since signed, unsigned, long, and short by default imply int, a type-name appearing after one of those
specifiers is treated as the name being (re)declared.

[Example 2:

void h(unsigned Pc);  // void h(unsigned int)
void k(unsigned int Pc);  // void k(unsigned int)
—end example]
—end note]

9.2.2 Storage class specifiers [dcl.stc]

1 The storage class specifiers are
storage-class-specifier:
  static
  thread_local
  extern
  mutable

At most one storage-class-specifier shall appear in a given decl-specifier-seq, except that thread_local may appear with static or extern. If thread_local appears in any declaration of a variable it shall be present in all declarations of that entity. If a storage-class-specifier appears in a decl-specifier-seq, there can be no typedef specifier in the same decl-specifier-seq and the init-declarator-list or member-declarator-list of the declaration shall not be empty (except for an anonymous union declared in a namespace scope (11.5.2)). The storage-class-specifier applies to the name declared by each init-declarator in the list and not to any names declared by other specifiers.

[Note 1: See 13.9.4 and 13.9.3 for restrictions in explicit specializations and explicit instantiations, respectively. — end note]

2 [Note 2: A variable declared without a storage-class-specifier at block scope or declared as a function parameter has automatic storage duration by default (6.7.5.4). — end note]

3 The thread_local specifier indicates that the named entity has thread storage duration (6.7.5.3). It shall be applied only to the declaration of a variable of namespace or block scope, to a structured binding declaration (9.6), or to the declaration of a static data member. When thread_local is applied to a variable of block scope the storage-class-specifier static is implied if no other storage-class-specifier appears in the decl-specifier-seq.

4 The static specifier shall be applied only to the declaration of a variable or function, to a structured binding declaration (9.6), or to the declaration of an anonymous union (11.5.2). There can be no static function declarations within a block, nor any static function parameters. A static specifier used in the declaration of a variable declares the variable to have static storage duration (6.7.5.2), unless accompanied by the thread_local specifier, which declares the variable to have thread storage duration (6.7.5.3). A static specifier can be used in declarations of class members; 11.4.9 describes its effect. For the linkage of a name declared with a static specifier, see 6.6.

5 The extern specifier shall be applied only to the declaration of a variable or function. The extern specifier shall not be used in the declaration of a class member or function parameter. For the linkage of a name declared with an extern specifier, see 6.6.

[Note 3: The extern keyword can also be used in explicit-instantiations and linkage-specifications, but it is not a storage-class-specifier in such contexts. — end note]

6 All declarations for a given entity shall give its name the same linkage.

[Note 4: The linkage given by some declarations is affected by previous declarations. Overloads are distinct entities. — end note]

[Example 1:

```c
static char* f();  // f() has internal linkage
c()               // f() still has internal linkage

char* g();    // g() has external linkage
static char* g() // error: inconsistent linkage

void h();   // external linkage
inline void h();  // external linkage
inline void l();  // external linkage
void l();    // external linkage
inline void m();  // external linkage
extern void m(); // external linkage
static void n();  // internal linkage
inline void n();  // internal linkage
```
The name of a declared but undefined class can be used in an \texttt{extern} declaration. Such a declaration can only be used in ways that do not require a complete class type.

[Example 2]:
\begin{verbatim}
struct S;
extern S a;
extern S f();
extern void g(S);

void h() {
  g(a);
  f();
}
\end{verbatim}

9 The \texttt{mutable} specifier shall appear only in the declaration of a non-static data member (11.4) whose type is neither \texttt{const}-qualified nor a reference type.

[Example 3]:
\begin{verbatim}
class X {
  mutable const int* p; // OK
  mutable int* const q; // error
};
\end{verbatim}

9 [Note 5: The \texttt{mutable} specifier on a class data member nullifies a \texttt{const} specifier applied to the containing class object and permits modification of the mutable class member even though the rest of the object is \texttt{const} (6.8.5, 9.2.9.2). —end note]
Declarations containing the declarative typedef declare identifiers that can be used later for naming fundamental (6.8.2) or compound (6.8.4) types. The typedef specifier shall not be combined in a declarative-seq with any other kind of specifiers except a defining-type-specifier, and it shall not be used in the declarative-seq of a parameter-declaration (9.3.4.6) nor in the declarative-seq of a function-definition (9.5). If a typedef specifier appears in a declaration without a declarator, the program is ill-formed.

typedef-name:
  identifier
  simple-template-id

A name declared with the typedef specifier becomes a typedef-name. A typedef-name names the type associated with the identifier (9.3) or simple-template-id (13.1); a typedef-name is thus a synonym for another type. A typedef-name does not introduce a new type the way a class declaration (11.3) or enum declaration (9.7.1) does.

[Example 1: After
typedef int MILES, *KLICKSP;
the constructions

MILES distance;
extern KLICKSP metricp;

are all correct declarations; the type of distance is int and that of metricp is “pointer to int.” — end example]

A typedef-name can also be introduced by an alias-declaration. The identifier following the using keyword is not looked up; it becomes a typedef-name and the optional attribute-specifier-seq following the identifier appertains to that typedef-name. Such a typedef-name has the same semantics as if it were introduced by the typedef specifier. In particular, it does not define a new type.

[Example 2:
using handler_t = void (*)(int);
extern handler_t ignore;
extern void (*ignore)(int);          // redeclare ignore
template<class T> struct P { };
using cell = P<cell*>;              // error: cell not found (6.4.2)
— end example]

The defining-type-specifier-seq of the defining-type-id shall not define a class or enumeration if the alias-declaration is the declaration of a template-declaration.

A simple-template-id is only a typedef-name if its template-name names an alias template or a template template-parameter.

[Note 1: A simple-template-id that names a class template specialization is a class-name (11.3). If a typedef-name is used to identify the subject of an elaborated-type-specifier (9.2.9.5), a class definition (Clause 11), a constructor declaration (11.4.5), or a destructor declaration (11.4.7), the program is ill-formed. — end note]

[Example 3:
struct S {
  S();
  ~S();
};

typedef struct S T;

S a = T();          // OK
struct T * p;      // error
— end example]

An unnamed class or enumeration C defined in a typedef declaration has the first typedef-name declared by the declaration to be of type C as its typedef name for linkage purposes (6.6).
[Note 2: A typedef declaration involving a lambda-expression does not itself define the associated closure type, and so the closure type is not given a typedef name for linkage purposes. — end note]

[Example 4:

typedef struct { } *ps, S; // S is the typedef name for linkage purposes
typedef decltype([]{}{ }) C; // the closure type has no typedef name for linkage purposes
— end example]

5 An unnamed class with a typedef name for linkage purposes shall not

(5.1) — declare any members other than non-static data members, member enumerations, or member classes,
(5.2) — have any base classes or default member initializers, or
(5.3) — contain a lambda-expression,

and all member classes shall also satisfy these requirements (recursively).

[Example 5:

typedef struct {
    int f() {}
} X;
// error: struct with typedef name for linkage has member functions
— end example]

9.2.5 The friend specifier

The friend specifier is used to specify access to class members; see 11.8.4.

9.2.6 The constexpr and consteval specifiers

The constexpr specifier shall be applied only to the definition of a variable or variable template or the declaration of a function or function template. The constexpr specifier shall be applied only to the declaration of a function or function template. A function or static data member declared with the constexpr or consteval specifier on its first declaration is implicitly an inline function or variable (9.2.8). If any declaration of a function or function template has a constexpr or consteval specifier, then all its declarations shall contain the same specifier.

[Note 1: An explicit specialization can differ from the template declaration with respect to the constexpr or consteval specifier. — end note]

[Note 2: Function parameters cannot be declared constexpr. — end note]

[Example 1:

constexpr void square(int &x); // OK, declaration
constexpr int bufsz = 1024; // OK, definition
constexpr struct pixel {
    int x;
    int y;
    constexpr pixel(int);
};
constexpr pixel::pixel(int a)
: x(a), y(x) // OK, definition
{ square(x); }
constexpr pixel small(2); // error: square not defined, so small(2)
// not constant (7.7) so constexpr not satisfied

constexpr void square(int &x) { // OK, definition
    x *= x;
}
constexpr pixel large(4); // OK, square defined
int next(constexpr int x) { // error: not for parameters
    return x + 1;
}
extern constexpr int memsz; // error: not a definition
— end example]

2 A constexpr or consteval specifier used in the declaration of a function declares that function to be a constexpr function.
A function or constructor declared with the `constexpr` specifier is an immediate function (7.7). — end note

A destructor, an allocation function, or a deallocation function shall not be declared with the `constexpr` specifier.

A function is `constexpr-suitable` if

1. it is not a coroutine (9.5.4), and
2. if the function is a constructor or destructor, its class does not have any virtual base classes.

Except for instantiated `constexpr` functions, non-templated `constexpr` functions shall be `constexpr-suitable`.

```
constexpr int square(int x) { return x * x; } // OK
constexpr long long_max() { return 2147483647; } // OK
constexpr int abs(int x) {
    if (x < 0)
        x = -x;
    return x; // OK
}
constexpr int constant_non_42(int n) { // OK
    if (n == 42) {
        static int value = n;
        return value;
    }
    return n;
}
constexpr int uninit() {
    struct { int a; } s;
    return s.a; // error: uninitialized read of s.a
}
constexpr int prev(int x) { return --x; } // OK
constexpr int g(int x, int n) { // OK
    int r = 1;
    while (--n > 0) r *= x;
    return r;
}
```

— end example]

An invocation of a `constexpr` function in a given context produces the same result as an invocation of an equivalent non-`constexpr` function in the same context in all respects except that

1. an invocation of a `constexpr` function can appear in a constant expression (7.7) and
2. copy elision is not performed in a constant expression (11.9.6).

[Note 4: Declaring a function `constexpr` can change whether an expression is a constant expression. This can indirectly cause calls to `std::is_constant_evaluated` within an invocation of the function to produce a different value. — end note]

[Note 5: It is possible to write a `constexpr` function for which no invocation satisfies the requirements of a core constant expression. — end note]

The `constexpr` and `consteval` specifiers have no effect on the type of a `constexpr` function.

```
constexpr int bar(int x, int y) // OK
    { return x + y + x*y; }
// ...
int bar(int x, int y) // error: redefinition of bar
    { return x * 2 + 3 * y; }
```

— end example]

A `constexpr` specifier used in an object declaration declares the object as `const`. Such an object shall have literal type and shall be initialized. In any `constexpr` variable declaration, the full-expression of the
initialization shall be a constant expression (7.7). A constexpr variable that is an object, as well as any temporary to which a constexpr reference is bound, shall have constant destruction.

[Example 4:

```cpp
struct pixel {
    int x, y;
};
constexpr pixel ur = { 1294, 1024 }; // OK
constexpr pixel origin; // error: initializer missing
```

—end example]

9.2.7 The constexpr specifier

The constexpr specifier shall be applied only to a declaration of a variable with static or thread storage duration. If the specifier is applied to any declaration of a variable, it shall be applied to the initializing declaration. No diagnostic is required if no constexpr declaration is reachable at the point of the initializing declaration.

If a variable declared with the constexpr specifier has dynamic initialization (6.9.3.3), the program is ill-formed, even if the implementation would perform that initialization as a static initialization (6.9.3.2).

[Note 1: The constexpr specifier ensures that the variable is initialized during static initialization. —end note]

[Example 1:

```cpp
const char * g() { return "dynamic initialization"; }
constexpr const char * f(bool p) { return p ? "constant initializer" : g(); }
constexpr const char * c = f(true); // OK
constexpr const char * d = f(false); // error
```

—end example]

9.2.8 The inline specifier

The inline specifier shall be applied only to the declaration of a variable or function.

A function declaration (9.3.4.6, 11.4.2, 11.8.4) with an inline specifier declares an inline function. The inline specifier indicates to the implementation that inline substitution of the function body at the point of call is to be preferred to the usual function call mechanism. An implementation is not required to perform this inline substitution at the point of call; however, even if this inline substitution is omitted, the other rules for inline functions specified in this subclause shall still be respected.

[Note 1: The inline keyword has no effect on the linkage of a function. In certain cases, an inline function cannot use names with internal linkage; see 6.6. —end note]

A variable declaration with an inline specifier declares an inline variable.

The inline specifier shall not appear on a block scope declaration or on the declaration of a function parameter. If the inline specifier is used in a friend function declaration, that declaration shall be a definition or the function shall have previously been declared inline.

If a definition of a function or variable is reachable at the point of its first declaration as inline, the program is ill-formed. If a function or variable with external or module linkage is declared inline in one definition domain, an inline declaration of it shall be reachable from the end of every definition domain in which it is declared; no diagnostic is required.

[Note 2: A call to an inline function or a use of an inline variable can be encountered before its definition becomes reachable in a translation unit. —end note]

[Note 3: An inline function or variable with external or module linkage can be defined in multiple translation units (6.3), but is one entity with one address. A type or static variable defined in the body of such a function is therefore a single entity. —end note]

If an inline function or variable that is attached to a named module is declared in a definition domain, it shall be defined in that domain.

[Note 4: A constexpr function (9.2.6) is implicitly inline. In the global module, a function defined within a class definition is implicitly inline (11.4.2, 11.8.4). —end note]
9.2.9 Type specifiers

9.2.9.1 General

The type-specifiers are

\[
\text{type-specifier:}
\begin{align*}
\text{simple-type-specifier} & , \\
\text{elaborated-type-specifier} & , \\
\text{typename-specifier} & , \\
\text{cv-qualifier} & .
\end{align*}
\]

\[
\text{type-specifier-seq:}
\begin{align*}
\text{type-specifier} & , \\
\text{attribute-specifier-seq} & , \\
\text{opt} & , \\
\text{type-specifier-seq} & , \\
\text{type-specifier-seq} & , \\
\text{defined-type-specifier} & , \\
\text{class-specifier} & , \\
\text{enum-specifier} & .
\end{align*}
\]

\[
\text{defining-type-specifier:}
\begin{align*}
\text{type-specifier} & , \\
\text{attribute-specifier-seq} & , \\
\text{opt} & , \\
\text{defining-type-specifier} & , \\
\text{defining-type-specifier-seq} & .
\end{align*}
\]

The optional \textit{attribute-specifier-seq} in a \textit{type-specifier-seq} or a \textit{defining-type-specifier-seq} appertains to the type denoted by the preceding \textit{type-specifiers} or \textit{defining-type-specifiers} (9.3.4). The \textit{attribute-specifier-seq} affects the type only for the declaration it appears in, not other declarations involving the same type.

As a general rule, at most one \textit{defining-type-specifier} is allowed in the complete \textit{decl-specifier-seq} of a \textit{declaration} or in a \textit{defining-type-specifier-seq}, and at most one \textit{type-specifier} is allowed in a \textit{type-specifier-seq}. The only exceptions to this rule are the following:

\begin{enumerate}
\item \textit{const} can be combined with any type specifier except itself.
\item \textit{volatile} can be combined with any type specifier except itself.
\item \textit{signed} or \textit{unsigned} can be combined with \textit{char}, \textit{long}, \textit{short}, or \textit{int}.
\item \textit{short} or \textit{long} can be combined with \textit{int}.
\item \textit{long} can be combined with \textit{double}.
\item \textit{long} can be combined with \textit{long}.
\end{enumerate}

Except in a declaration of a constructor, destructor, or conversion function, at least one \textit{defining-type-specifier} that is not a \textit{cv-qualifier} shall appear in a complete \textit{type-specifier-seq} or a complete \textit{decl-specifier-seq}.

[Note 1: \textit{enum-specifiers}, \textit{class-specifiers}, and \textit{typename-specifiers} are discussed in 9.7.1, Clause 11, and 13.8, respectively. The remaining \textit{type-specifiers} are discussed in the rest of 9.2.9. — end note]

9.2.9.2 The \textit{cv-qualifiers}

There are two \textit{cv-qualifiers}, \textit{const} and \textit{volatile}. Each \textit{cv-qualifier} shall appear at most once in a \textit{cv-qualifier-seq}. If a \textit{cv-qualifier} appears in a \textit{decl-specifier-seq}, the \textit{init-declarator-list} or \textit{member-declarator-list} of the declaration shall not be empty.

[Note 1: 6.8.5 and 9.3.4.6 describe how \textit{cv-qualifiers} affect object and function types. — end note]

Redundant \textit{cv-qualifications} are ignored.

[Note 2: For example, these could be introduced by typedefs. — end note]

[Note 3: Declaring a variable \textit{const} can affect its linkage (9.2.2) and its usability in constant expressions (7.7). As described in 9.4, the definition of an object or subobject of \textit{const}-qualified type must specify an initializer or be subject to default-initialization. — end note]

A pointer or reference to a \textit{cv-qualified} type need not actually point or refer to a \textit{cv-qualified} object, but it is treated as if it does; a \textit{const}-qualified access path cannot be used to modify an object even if the object referenced is a non-\textit{const} object and can be modified through some other access path.

[Note 4: \textit{Cv-qualifiers} are supported by the type system so that they cannot be subverted without casting (7.6.1.11). — end note]

\[75\] There is no special provision for a \textit{decl-specifier-seq} that lacks a \textit{type-specifier} or that has a \textit{type-specifier} that only specifies \textit{cv-qualifiers}. The “implicit int” rule of C is no longer supported.
Any attempt to modify (7.6.19, 7.6.1.6, 7.6.2.3) a const object (6.8.5) during its lifetime (6.7.3) results in undefined behavior.

**Example 1:**

```
const int ci = 3; // cv-qualified (initialized as required)
    ci = 4;       // error: attempt to modify const
int i = 2;   // not cv-qualified
const int* cip; // pointer to const int
cip = &i;   // OK, cv-qualified access path to unqualified
*cip = 4;  // error: attempt to modify through ptr to const
int* ip;
ip = const_cast<int*>(cip);  // cast needed to convert const int* to int*
    *ip = 4;      // defined: *ip points to i, a non-const object
const int* ciq = new const int(3);  // initialized as required
int* iq = const_cast<int*>(ciq);  // cast required
    *iq = 4;      // undefined behavior: modifies a const object
```

For another example,

```
struct X {
    mutable int i;
    int j;
};
struct Y {
    X x;
    Y y;
};

const Y y;
y.x.i++; // well-formed: mutable member can be modified
    y.x.j++; // error: const-qualified member modified
Y* p = const_cast<Y*>(&y);  // cast away const-ness of y
    p->x.i = 99;  // well-formed: mutable member can be modified
    p->x.j = 99;  // undefined behavior: modifies a const subobject
```

The semantics of an access through a volatile glvalue are implementation-defined. If an attempt is made to access an object defined with a volatile-qualified type through the use of a non-volatile glvalue, the behavior is undefined.

**Note 5:** `volatile` is a hint to the implementation to avoid aggressive optimization involving the object because it is possible for the value of the object to change by means undetectable by an implementation. Furthermore, for some implementations, `volatile` can indicate that special hardware instructions are needed to access the object. See 6.9.1 for detailed semantics. In general, the semantics of `volatile` are intended to be the same in C++ as they are in C. —end note

### 9.2.9.3 Simple type specifiers [dcl.type.simple]

The simple type specifiers are
simple-type-specifier:
  nested-name-specifier_opt type-name
  nested-name-specifier template simple-template-id
  computed-type-specifier
  placeholder-type-specifier
  nested-name-specifier_opt template-name
  char
  char8_t
  char16_t
  char32_t
  wchar_t
  bool
  short
  int
  long
  signed
  unsigned
  float
  double
  void

type-name:
  class-name
  enum-name
  typedef-name

computed-type-specifier:
  decltype-specifier
  pack-index-specifier

2 The component names of a simple-type-specifier are those of its nested-name-specifier, type-name, simple-template-id, template-name, and/or type-constraint (if it is a placeholder-type-specifier). The component name of a type-name is the first name in it.

3 A placeholder-type-specifier is a placeholder for a type to be deduced (9.2.9.7). A type-specifier of the form typename_opt nested-name-specifier_opt template-name is a placeholder for a deduced class type (9.2.9.8). The nested-name-specifier, if any, shall be non-dependent and the template-name shall name a deducible template. A deducible template is either a class template or is an alias template whose defining-type-id is of the form
typename_opt nested-name-specifier_opt template_opt simple-template-id

where the nested-name-specifier (if any) is non-dependent and the template-name of the simple-template-id names a deducible template.

[Note 1: An injected-class-name is never interpreted as a template-name in contexts where class template argument deduction would be performed (13.8.2). — end note]

The other simple-type-specifiers specify either a previously-declared type, a type determined from an expression, or one of the fundamental types (6.8.2). Table 17 summarizes the valid combinations of simple-type-specifiers and the types they specify.

4 When multiple simple-type-specifiers are allowed, they can be freely intermixed with other decl-specifiers in any order.

[Note 2: It is implementation-defined whether objects of char type are represented as signed or unsigned quantities. The signed specifier forces char objects to be signed; it is redundant in other contexts. — end note]

9.2.9.4 Pack indexing specifier
[dcl.type.pack.index]

pack-index-specifier:
  typedef-name ... [ constant-expression ]

1 The typedef-name P in a pack-index-specifier shall denote a pack.

2 The constant-expression shall be a converted constant expression (7.7) of type std::size_t whose value V, termed the index, is such that 0 ≤ V < sizeof... (P).

3 A pack-index-specifier is a pack expansion (13.7.4).

[Note 1: The pack-index-specifier denotes the type of the Vth element of the pack. — end note]
Table 17 — simple-type-specifiers and the types they specify

<table>
<thead>
<tr>
<th>Specifier(s)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-name</td>
<td>the type named</td>
</tr>
<tr>
<td>simple-template-id</td>
<td>the type as defined in 13.3</td>
</tr>
<tr>
<td>decltype-specifier</td>
<td>the type as defined in 9.2.9.6</td>
</tr>
<tr>
<td>pack-index-specifier</td>
<td>the type as defined in 9.2.9.4</td>
</tr>
<tr>
<td>placeholder-type-specifier</td>
<td>the type as defined in 9.2.9.7</td>
</tr>
<tr>
<td>template-name</td>
<td>the type as defined in 9.2.9.8</td>
</tr>
<tr>
<td>char</td>
<td>“char”</td>
</tr>
<tr>
<td>unsigned char</td>
<td>“unsigned char”</td>
</tr>
<tr>
<td>signed char</td>
<td>“signed char”</td>
</tr>
<tr>
<td>char8_t</td>
<td>“char8_t”</td>
</tr>
<tr>
<td>char16_t</td>
<td>“char16_t”</td>
</tr>
<tr>
<td>char32_t</td>
<td>“char32_t”</td>
</tr>
<tr>
<td>bool</td>
<td>“bool”</td>
</tr>
<tr>
<td>unsigned</td>
<td>“unsigned int”</td>
</tr>
<tr>
<td>unsigned int</td>
<td>“unsigned int”</td>
</tr>
<tr>
<td>signed</td>
<td>“int”</td>
</tr>
<tr>
<td>signed int</td>
<td>“int”</td>
</tr>
<tr>
<td>int</td>
<td>“int”</td>
</tr>
<tr>
<td>unsigned short int</td>
<td>“unsigned short int”</td>
</tr>
<tr>
<td>unsigned short</td>
<td>“unsigned short int”</td>
</tr>
<tr>
<td>unsigned long int</td>
<td>“unsigned long int”</td>
</tr>
<tr>
<td>unsigned long</td>
<td>“unsigned long int”</td>
</tr>
<tr>
<td>unsigned long long int</td>
<td>“unsigned long long int”</td>
</tr>
<tr>
<td>unsigned long long</td>
<td>“unsigned long long int”</td>
</tr>
<tr>
<td>signed long int</td>
<td>“long int”</td>
</tr>
<tr>
<td>signed long</td>
<td>“long int”</td>
</tr>
<tr>
<td>signed long long int</td>
<td>“long long int”</td>
</tr>
<tr>
<td>signed long long</td>
<td>“long long int”</td>
</tr>
<tr>
<td>long long int</td>
<td>“long long int”</td>
</tr>
<tr>
<td>long long int</td>
<td>“long long int”</td>
</tr>
<tr>
<td>long int</td>
<td>“long int”</td>
</tr>
<tr>
<td>long</td>
<td>“long int”</td>
</tr>
<tr>
<td>signed short int</td>
<td>“short int”</td>
</tr>
<tr>
<td>signed short</td>
<td>“short int”</td>
</tr>
<tr>
<td>short int</td>
<td>“short int”</td>
</tr>
<tr>
<td>short</td>
<td>“short int”</td>
</tr>
<tr>
<td>wchar_t</td>
<td>“wchar_t”</td>
</tr>
<tr>
<td>float</td>
<td>“float”</td>
</tr>
<tr>
<td>double</td>
<td>“double”</td>
</tr>
<tr>
<td>long double</td>
<td>“long double”</td>
</tr>
<tr>
<td>void</td>
<td>“void”</td>
</tr>
</tbody>
</table>

9.2.9.5 Elaborated type specifiers

elaborated-type-specifier:

class-key attribute-specifier-seqopt nested-name-specifieropt identifier
class-key simple-template-id
class-key nested-name-specifier templateopt simple-template-id
enum nested-name-specifieropt identifier

1 The component names of an elaborated-type-specifier are its identifier (if any) and those of its nested-name-specifier and simple-template-id (if any).

2 If an elaborated-type-specifier is the sole constituent of a declaration, the declaration is ill-formed unless it is an explicit specialization (13.9.4), a partial specialization (13.7.6), an explicit instantiation (13.9.3), or it has one of the following forms:
In the first case, the elaborated-type-specifier declares the identifier as a class-name. The second case shall appear only in an explicit-specialization (13.9.4) or in a template-declaration (where it declares a partial specialization). The attribute-specifier-seq, if any, appertains to the class or template being declared.

Otherwise, an elaborated-type-specifier E shall not have an attribute-specifier-seq. If E contains an identifier but no nested-name-specifier and (unqualified) lookup for the identifier finds nothing, E shall not be introduced by the enum keyword and declares the identifier as a class-name. The target scope of E is the nearest enclosing namespace or block scope.

A friend-type-specifier that is an elaborated-type-specifier shall have one of the following forms:

\[
\begin{align*}
&\text{class-key attribute-specifier-seqopt identifier; } \\
&\text{class-key attribute-specifier-seqopt simple-template-id; }
\end{align*}
\]

Any unqualified lookup for the identifier (in the first case) does not consider scopes that contain the nearest enclosing namespace or block scope; no name is bound.

[Note 1: A using-directive in the target scope is ignored if it refers to a namespace not contained by that scope. — end note]

[Note 2: 6.5.6 describes how name lookup proceeds in an elaborated-type-specifier. An elaborated-type-specifier can be used to refer to a previously declared class-name or enum-name even if the name has been hidden by a non-type declaration. — end note]

If the identifier or simple-template-id in an elaborated-type-specifier resolves to a class-name or enum-name, the elaborated-type-specifier introduces it into the declaration the same way a simple-type-specifier introduces its type-name (9.2.9.3). If the identifier or simple-template-id resolves to a typedef-name (9.2.4, 13.3), the elaborated-type-specifier is ill-formed.

[Note 3: This implies that, within a class template with a template type-parameter T, the declaration

\[
\text{friend class T;
}\]

is ill-formed. However, the similar declaration friend T; is well-formed. (11.8.4). — end note]

The class-key or enum keyword present in an elaborated-type-specifier shall agree in kind with the declaration to which the name in the elaborated-type-specifier refers. This rule also applies to the form of elaborated-type-specifier that declares a class-name or friend class since it can be construed as referring to the definition of the class. Thus, in any elaborated-type-specifier, the enum keyword shall be used to refer to an enumeration (9.7.1), the union class-key shall be used to refer to a union (11.5), and either the class or struct class-key shall be used to refer to a non-union class (11.1).

[Example 1:]

\[
\begin{align*}
\text{enum class E \{ a, b \}; } \\
\text{enum E x = E::a;} & \quad // OK \\
\text{struct S \{ \} s;} & \quad // OK \\
\text{class S* p = \&s;} & \quad // OK
\end{align*}
\]

---

### 9.2.9.6 Decltype specifiers

*decltype-specifier:*

\[
\text{decltype ( expression )}
\]

1. For an expression E, the type denoted by \texttt{decltype}(E) is defined as follows:

\[
\begin{align*}
&\text{— if E is an unparenthesized id-expression naming a structured binding (9.6), } \texttt{decltype}(E) \text{ is the referenced type as given in the specification of the structured binding declaration;} \\
&\text{— otherwise, if E is an unparenthesized id-expression naming a non-type template-parameter (13.2), } \texttt{decltype}(E) \text{ is the type of the template-parameter after performing any necessary type deduction (9.2.9.7, 9.2.9.8);} \\
&\text{— otherwise, if E is an unparenthesized id-expression or an unparenthesized class member access (7.6.1.5), } \texttt{decltype}(E) \text{ is the type of the entity named by E. If there is no such entity, the program is ill-formed;} \\
&\text{— otherwise, if E is an xvalue, } \texttt{decltype}(E) \text{ is } \texttt{T}\&\&, \text{ where } \texttt{T} \text{ is the type of } E; \\
&\text{— otherwise, if E is an lvalue, } \texttt{decltype}(E) \text{ is } \texttt{T}\&, \text{ where } \texttt{T} \text{ is the type of } E;
\end{align*}
\]
otherwise, `decltype(E)` is the type of `E`.

The operand of the `decltype` specifier is an unevaluated operand (7.2.3).

*Example 1:*

```cpp
class int&& foo()
int i;
struct A { double x; }
const A* a = new A();
decltype(foo()) x1 = 17; // type is const int&&
decltype(i) x2; // type is int
decltype(a->x) x3; // type is double
decltype((a->x)) x4 = x3; // type is const double&
```

```cpp
void f() {
    (auto ...pack) {
        decltype(pack...[0]) x5; // type is int
decltype((pack...[0])) x6; // type is int&
    )<0>;
}
```

*Note 1: The rules for determining types involving `decltype(auto)` are specified in 9.2.9.7. — end note*

2 If the operand of a `decltype-specifier` is a prvalue and is not a (possibly parenthesized) immediate invocation (7.7), the temporary materialization conversion is not applied (7.3.5) and no result object is provided for the prvalue. The type of the prvalue may be incomplete or an abstract class type.

*Note 2: As a result, storage is not allocated for the prvalue and it is not destroyed. Thus, a class type is not instantiated as a result of being the type of a function call in this context. In this context, the common purpose of writing the expression is merely to refer to its type. In that sense, a `decltype-specifier` is analogous to a use of a typedef-name, so the usual reasons for requiring a complete type do not apply. In particular, it is not necessary to allocate storage for a temporary object or to enforce the semantic constraints associated with invoking the type's destructor. — end note*

*Note 3: Unlike the preceding rule, parentheses have no special meaning in this context. — end note*

*Example 2:*

```cpp
template<class T> struct A { ~A() = delete; }
template<class T> auto h() -> A<T>;
template<class T> auto i(T) -> T; // identity
template<class T> auto f(T) -> decltype(i(h<T>())); // #1
    // forces completion of A<T> and implicitly uses A<T>::~A()
    // for the temporary introduced by the use of h().
    // (A temporary is not introduced as a result of the use of i().)
template<class T> auto f(T) -> void; // #2
auto g() -> void {
    f(42); // OK, calls #2. (#1 is not a viable candidate: type deduction
    // fails (13.10.3) because A<int>::~A() is implicitly used in its
    // decltype-specifier)
}
template<class T> auto q(T) -> decltype((h<T>())); // does not force completion of A<T>; A<T>::~A() is not implicitly
    // used within the context of this decltype-specifier
void r() {
    q(42); // error: deduction against q succeeds, so overload resolution selects
    // the specialization "q(T) -> decltype((h<T>())") with T=int;
    // the return type is A<int>, so a temporary is introduced and its
    // destructor is used, so the program is ill-formed
}
```

— end example]
9.2.9.7 Placeholder type specifiers

9.2.9.7.1 General

A placeholder-type-specifier designates a placeholder type that will be replaced later, typically by deduction from an initializer.

1. The type of a parameter-declaration of a function declaration (9.3.4.6), lambda-expression (7.5.6), or template-parameter (13.2) can be declared using a placeholder-type-specifier of the form type-constraint auto. The placeholder type shall appear as one of the decl-specifiers in the decl-specifier-seq or as one of the type-specifiers in a trailing-return-type that specifies the type that replaces such a decl-specifier (see below); the placeholder type is a generic parameter type placeholder of the function declaration, lambda-expression, or template-parameter, respectively.

[Note 1: Having a generic parameter type placeholder signifies that the function is an abbreviated function template (9.3.4.6) or the lambda is a generic lambda (7.5.6). — end note]

2. A placeholder type can appear in the decl-specifier-seq for a function declarator that includes a trailing-return-type.

3. A placeholder type can appear in the decl-specifier-seq or type-specifier-seq in the declared return type of a function declarator that declares a function; the return type of the function is deduced from non-discarded return statements, if any, in the body of the function (8.5.2).

4. The type of a variable declared using a placeholder type is deduced from its initializer. This use is allowed in an initializing declaration (9.4) of a variable. The placeholder type shall appear as one of the decl-specifiers in the decl-specifier-seq or as one of the type-specifiers in a trailing-return-type that specifies the type that replaces such a decl-specifier; the decl-specifier-seq shall be followed by one or more declarators, each of which shall be followed by a non-empty initializer.

[Example 1:

```c
auto x = 5;
const auto *v = &x, u = 6;  // OK, x has type int
static auto y = 0.0;         // OK, y has type double
auto int r;                  // error: auto is not a storage-class-specifier
auto f() -> int;             // OK, f returns int
auto g() { return 0.0; }     // OK, g returns double
auto (*fp)() -> auto = f;    // OK
auto h();                     // OK, h’s return type will be deduced when it is defined
```

— end example]

The auto type-specifier can also be used to introduce a structured binding declaration (9.6).

5. A placeholder type can also be used in the type-specifier-seq of the new-type-id or in the type-id of a new-expression (7.6.2.8). In such a type-id, the placeholder type shall appear as one of the type-specifiers in the type-specifier-seq or as one of the type-specifiers in a trailing-return-type that specifies the type that replaces such a type-specifier.

6. The auto type-specifier can also be used as the simple-type-specifier in an explicit type conversion (functional notation) (7.6.1.4).

7. A program that uses a placeholder type in a context not explicitly allowed in 9.2.9.7 is ill-formed.

8. If the init-declarator-list contains more than one init-declarator, they shall all form declarations of variables. The type of each declared variable is determined by placeholder type deduction (9.2.9.7.2), and if the type that replaces the placeholder type is not the same in each deduction, the program is ill-formed.

[Example 2:

```c
auto x = 5, *y = &x;     // OK, auto is int
auto a = 5, b = { 1, 2 }; // error: different types for auto
```

— end example]

9. If a function with a declared return type that contains a placeholder type has multiple non-discarded return statements, the return type is deduced for each such return statement. If the type deduced is not the same in each deduction, the program is ill-formed.
If a function with a declared return type that uses a placeholder type has no non-discarded return statements, the return type is deduced as though from a return statement with no operand at the closing brace of the function body.

[Example 3:

```
auto f() { }  // OK, return type is void
auto* g() { } // error: cannot deduce auto* from void()

— end example]

An exported function with a declared return type that uses a placeholder type shall be defined in the translation unit containing its exported declaration, outside the private-module-fragment (if any).

[Note 2: The deduced return type cannot have a name with internal linkage (6.6). — end note]

If a variable or function with an undeduced placeholder type is named by an expression (6.3), the program is ill-formed. Once a non-discarded return statement has been seen in a function, however, the return type deduced from that statement can be used in the rest of the function, including in other return statements.

[Example 4:

```
auto n = n;  // error: n’s initializer refers to n
auto f();
void g() { &f; } // error: f’s return type is unknown
auto sum(int i) {
    if (i == 1)
        return i;
    else
        return sum(i-1)+i;  // OK, sum’s return type has been deduced
}

— end example]

Return type deduction for a templated function with a placeholder in its declared type occurs when the definition is instantiated even if the function body contains a return statement with a non-type-dependent operand.

[Note 3: Therefore, any use of a specialization of the function template will cause an implicit instantiation. Any errors that arise from this instantiation are not in the immediate context of the function type and can result in the program being ill-formed (13.10.3). — end note]

[Example 5:

```
template <class T> auto f(T t) { return t; }  // return type deduced at instantiation time
typedef decltype(f(1)) fint_t;  // instantiates f<int> to deduce return type
template<class T> auto f(T* t) { return *t; }  // instantiates both f's to determine return types, chooses second
void g() { int (*p)(int*) = &f; }

— end example]

If a function or function template $F$ has a declared return type that uses a placeholder type, redeclarations or specializations of $F$ shall use that placeholder type, not a deduced type; otherwise, they shall not use a placeholder type.

[Example 6:

```
auto f();  // return type is int
auto f() { return 42; }  // OK
auto f();  // error: auto and int don’t match
decltype(auto) f();  // error: auto and decltype(auto) don’t match

template <typename T> auto g(T t) { return t; }  // #1

template auto g(int);  // OK, return type is int

template char g(char);  // error: no matching template
template<> auto g(double);  // OK, forward declaration with unknown return type

template <class T> T g(T t) { return t; }  // OK, not functionally equivalent to #1

template char g(char);  // OK, now there is a matching template
template auto g(float);  // still matches #1

§ 9.2.9.7.1 ©ISO/IEC 196
A function declared with a return type that uses a placeholder type shall not be virtual (11.7.3).

A function declared with a return type that uses a placeholder type shall not be a coroutine (9.5.4).

An explicit instantiation declaration (13.9.3) does not cause the instantiation of an entity declared using a placeholder type, but it also does not prevent that entity from being instantiated as needed to determine its type.

[Example 7:

template <typename T> auto f(T t) { return t; }
extern template auto f(int);

int (*p)(int) = f;  // instantiates f<int> to determine its return type, but an explicit instantiation definition is still required somewhere in the program

—end example]

§ 9.2.9.7.2 Placeholder type deduction [dcl.type.auto.deduct]

Placeholder type deduction is the process by which a type containing a placeholder type is replaced by a deduced type.

A type T containing a placeholder type, and a corresponding initializer-clause E, are determined as follows:

1. For a non-discarded return statement that occurs in a function declared with a return type that contains a placeholder type, T is the declared return type.
2. If the return statement has no operand, then E is void().
3. If the operand is a braced-init-list (9.4.5), the program is ill-formed.
4. If the operand is an expression X that is not an assignment-expression, E is (X).
   [Note 1: A comma expression (7.6.20) is not an assignment-expression. —end note]
5. Otherwise, E is the operand of the return statement.

If E has type void, T shall be either type-constraintopt decltype(auto) or cv type-constraintopt auto.

1. For a variable declared with a type that contains a placeholder type, T is the declared type of the variable.
2. If the initializer of the variable is a brace-or-equal-initializer of the form = initializer-clause, E is the initializer-clause.
3. If the initializer is a braced-init-list, it shall consist of a single brace-enclosed assignment-expression and E is the assignment-expression.
4. If the initializer is a parenthesized expression-list, the expression-list shall be a single assignment-expression and E is the assignment-expression.

1. For an explicit type conversion (7.6.1.4), T is the specified type, which shall be auto.
2. If the initializer is a braced-init-list, it shall consist of a single brace-enclosed assignment-expression and E is the assignment-expression.
3. If the initializer is a parenthesized expression-list, the expression-list shall be a single assignment-expression and E is the assignment-expression.
4. For a non-type template parameter declared with a type that contains a placeholder type, T is the declared type of the non-type template parameter and E is the corresponding template argument.
T shall not be an array type.

If the placeholder-type-specifier is of the form type-constraint\_opt auto, the deduced type $T'$ replacing T is determined using the rules for template argument deduction. If the initialization is copy-list-initialization, a declaration of std::initializer\_list shall precede (6.5.1) the placeholder-type-specifier. Obtain P from T by replacing the occurrences of type-constraint\_opt auto either with a new invented type template parameter U or, if the initialization is copy-list-initialization, with std::initializer\_list\<U>. Deduce a value for U using the rules for template argument deduction from a function call (13.10.3.2), where P is a function template parameter type and the corresponding argument is E. If the deduction fails, the declaration is ill-formed. Otherwise, $T'$ is obtained by substituting the deduced U into P.

[Example 1:

```cpp
auto x1 = { 1, 2 };  // decltype(x1) is std::initializer\_list\<int>
auto x2 = { 1, 2.0 };  // error: cannot deduce element type
auto x3{ 1, 2 };  // error: not a single element
auto x4 = { 3 };  // decltype(x4) is std::initializer\_list\<int>
auto x5{ 3 };  // decltype(x5) is int

— end example]

[Example 2:

```cpp
const auto &i = expr;
The type of i is the deduced type of the parameter u in the call f(expr) of the following invented function template:

```cpp
template <class U> void f(const U& u);

— end example]

4 If the placeholder-type-specifier is of the form type-constraint\_opt decltype(auto), T shall be the placeholder alone. The type deduced for T is determined as described in 9.2.9.6, as though E had been the operand of the decltype.

[Example 3:

```cpp
int i;
int& f();
auto x2a(i);  // decltype(x2a) is int
decType(auto) x2d(i);  // decltype(x2d) is int
auto x3a = i;  // decltype(x3a) is int
decType(auto) x3d = i;  // decltype(x3d) is int
auto x4a = i;  // decltype(x4a) is int
decType(auto) x4d = i;  // decltype(x4d) is int&
auto x5a = f();  // decltype(x5a) is int
decType(auto) x5d = f();  // decltype(x5d) is int&
auto x6a = { 1, 2 };  // decltype(x6a) is std::initializer\_list\<int>
decType(auto) x6d = { 1, 2 };  // error: { 1, 2 } is not an expression
auto x7a = i;  // decltype(x7a) is int*
decType(auto)x7d = &i;  // error: declared type is not plain decltype(auto)
auto f1(int x) -> decltype((x)) { return (x); }  // return type is int&
auto f2(int x) -> decltype(auto) { return (x); }  // return type is int&

— end example]

5 For a placeholder-type-specifier with a type-constraint, the immediately-declared constraint (13.2) of the type-constraint for the type deduced for the placeholder shall be satisfied.

9.2.9.8 Deduced class template specialization types

If a placeholder for a deduced class type appears as a decl-specifier in the decl-specifier-seq of an initializing declaration (9.4) of a variable, the declared type of the variable shall be cv $T$, where T is the placeholder.

[Example 1:

```cpp
template <class ...T> struct A {
    A(T...) {}
};
A x[29]{};  // error: no declarator operators allowed
const & y{};  // error: no declarator operators allowed

— end example]
The placeholder is replaced by the return type of the function selected by overload resolution for class template deduction (12.2.2.9). If the decl-specifier-seq is followed by an init-declarator-list or member-declarator-list containing more than one declarator, the type that replaces the placeholder shall be the same in each deduction.

A placeholder for a deduced class type can also be used in the type-specifier-seq in the new-type-id or type-id of a new-expression (7.6.2.8), as the simple-type-specifier in an explicit type conversion (functional notation) (7.6.1.4), or as the type-specifier in the parameter-declaration of a template-parameter (13.2). A placeholder for a deduced class type shall not appear in any other context.

[Example 2:

```cpp
template<class T> struct container {
    container(T t) {}
    template<class Iter> container(Iter beg, Iter end);
};
template<class Iter>
container<Iter b, Iter e> -> container<typename std::iterator_traits<Iter>::value_type>;
std::vector<double> v = { /* ... */ };
container c(7); // OK, deduces int for T
auto d = container(v.begin(), v.end()); // OK, deduces double for T
container e{5, 6}; // error: int is not an iterator
```

—end example]

9.3 Declarators [dcl.decl]

9.3.1 General [dcl.decl.general]

A declarator declares a single variable, function, or type, within a declaration. The init-declarator-list appearing in a simple-declaration is a comma-separated sequence of declarators, each of which can have an initializer.

```cpp
init-declarator-list:
    init-declarator
init-declarator-list , init-declarator

init-declarator:
    declarator initializeropt
    declarator requires-clause
```

In all contexts, a declarator is interpreted as given below. Where an abstract-declarator can be used (or omitted) in place of a declarator (9.3.4.6, 14.1), it is as if a unique identifier were included in the appropriate place (9.3.2). The preceding specifiers indicate the type, storage duration, linkage, or other properties of the entity or entities being declared. Each declarator specifies one entity and (optionally) names it and/or modifies the type of the specifiers with operators such as * (pointer to) and () (function returning).

[Note 1: An init-declarator can also specify an initializer (9.4). —end note]

Each init-declarator or member-declarator in a declaration is analyzed separately as if it were in a declaration by itself.

[Note 2: A declaration with several declarators is usually equivalent to the corresponding sequence of declarations each with a single declarator. That is,

```cpp
T D1, D2, ... Dn;
```

is usually equivalent to

```cpp
T D1; T D2; ... T Dn;
```

where T is a decl-specifier-seq and each Di is an init-declarator or member-declarator. One exception is when a name introduced by one of the declarators hides a type name used by the decl-specifiers, so that when the same decl-specifiers are used in a subsequent declaration, they do not have the same meaning, as in

```cpp
struct S { /* ... */ };
S S, T; // declare two instances of struct S
```

which is not equivalent to

```cpp
struct S { /* ... */ };
S S;
S T; // error
```
Another exception is when \( T \) is auto (9.2.9.7), for example:

```cpp
auto i = 1, j = 2.0;  // error: deduced types for \( i \) and \( j \) do not match
```
as opposed to

```cpp
auto i = 1;          // OK, \( i \) deduced to have type int
auto j = 2.0;        // OK, \( j \) deduced to have type double
```

—end note

4 The optional \textit{requires-clause} in an \textit{init-declarator} or \textit{member-declarator} shall be present only if the declarator declares a templated function (13.1). When present after a declarator, the \textit{requires-clause} is called the \textit{trailing \textit{requires-clause}}. The trailing \textit{requires-clause} introduces the \textit{constraint-expression} that results from interpreting its \textit{constraint-logical-or-expression} as a \textit{constraint-expression}.

[Example 1:

```cpp
void f1(int a) requires true;  // error: non-templated function

template<typename T>
  auto f2(T a) -> bool requires true; // OK

template<typename T>
  auto f3(T a) requires true -> bool;  // error: \textit{requires-clause} precedes trailing-return-type

void (*pf)() requires true;       // error: constraint on a variable

void g(int (*)() requires true);  // error: constraint on a parameter-declaration

auto* p = new void(*)(char) requires true; // error: not a function declaration
```
—end example]

5 Declarators have the syntax

```
declarator:
  ptr-declarator
  noptr-declarator parameters-and-qualifiers trailing-return-type

ptr-declarator:
  noptr-declarator
  ptr-operator ptr-declarator

noptr-declarator:
  declarator-id attribute-specifier-seq_opt
  noptr-declarator parameters-and-qualifiers
  noptr-declarator [ constant-expression_opt ] attribute-specifier-seq_opt
  ( ptr-declarator )

parameters-and-qualifiers:
  ( parameter-declaration-clause ) cv-qualifier-seq_opt
  ref-qualifier_opt noexcept-specifier_opt attribute-specifier-seq_opt

trailing-return-type:
  -> type-id

ptr-operator:
  * attribute-specifier-seq_opt cv-qualifier-seq_opt
  & attribute-specifier-seq_opt
  && attribute-specifier-seq_opt
  nested-name-specifier * attribute-specifier-seq_opt cv-qualifier-seq_opt

cv-qualifier-seq:
  cv-qualifier cv-qualifier-seq_opt

cv-qualifier:
  const
  volatile

ref-qualifier:
  &
  &&

declarator-id:
  ...opt id-expression
```
9.3.2 Type names

To specify type conversions explicitly, and as an argument of `sizeof`, `alignof`, `new`, or `typeid`, the name of a type shall be specified. This can be done with a `type-id` or `new-type-id` (7.6.2.8), which is syntactically a declaration for a variable or function of that type that omits the name of the entity.

- `type-id`: `type-specifier-seq abstract-declarator_opt`
- `defining-type-id`: `defining-type-specifier-seq abstract-declarator_opt`
- `ptr-abstract-declarator`: `noptr-abstract-declarator` `ptr-operator ptr-abstract-declarator_opt`

It is possible to identify uniquely the location in the `abstract-declarator` where the identifier would appear if the construction were a declarator in a declaration. The named type is then the same as the type of the hypothetical identifier.

[Example 1:

```c
int     // int i
int *   // int *pi
int *[]  // int *p[3]
int (*[])[3] // int (*p3i)[3]
int *()  // int *f()
int (*)(double) // int (*pf)(double)
```

name respectively the types “int”, “pointer to int”, “array of 3 pointers to int”, “pointer to array of 3 int”, “function of (no parameters) returning pointer to int”, and “pointer to a function of (double) returning int”. — end example]

9.3.3 Ambiguity resolution

The ambiguity arising from the similarity between a function-style cast and a declaration mentioned in 8.9 can also occur in the context of a declaration. In that context, the choice is between an object declaration with a function-style cast as the initializer and a declaration involving a function declarator with a redundant set of parentheses around a parameter name. Just as for the ambiguities mentioned in 8.9, the resolution is to consider any construct, such as the potential parameter declaration, that could possibly be a declaration to be a declaration. However, a construct that can syntactically be a declaration whose outermost declarator would match the grammar of a declarator with a trailing-return-type is a declaration only if it starts with `auto`.

[Note 1: A declaration can be explicitly disambiguated by adding parentheses around the argument. The ambiguity can be avoided by use of copy-initialization or list-initialization syntax, or by use of a non-function-style cast. — end note]

[Example 1:

```c
struct S {
    S(int);
};
typedef struct BB { int C[2]; } *B, C;
```
An ambiguity can arise from the similarity between a function-style cast and a type-id. The resolution is that any construct that could possibly be a type-id in its syntactic context shall be considered a type-id. However, a construct that can syntactically be a type-id whose outermost abstract-declarator would match the grammar of an abstract-declarator with a trailing-return-type is considered a type-id only if it starts with auto.

[Example 2:]

```c
template <class T> struct X {};  
template <int N> struct Y {};  
X<int()> a;  // type-id  
X<int(1)> b;  // expression (ill-formed)  
Y<int()> c;  // type-id (ill-formed)  
Y<int(1)> d;  // expression

void foo(signed char a) {  
    sizeof(int());  // type-id (ill-formed)  
    sizeof(int(a));  // expression  
    sizeof(int(unsigned(a)));  // type-id (ill-formed)  
    (int())+1;  // type-id (ill-formed)  
    (int(a))+1;  // expression  
    (int(unsigned(a))+1;  // type-id (ill-formed)  
}

typedef struct BB { int C[2]; } *B, C;  
void g() {  
    sizeof(B()->C[1]);  // OK, sizeof(expression)  
    sizeof(auto()->C[1]);  // error: sizeof of a function returning an array
}
```

Another ambiguity arises in a parameter-declaration-clause when a type-name is nested in parentheses. In this case, the choice is between the declaration of a parameter of type pointer to function and the declaration of a parameter with redundant parentheses around the declarator-id. The resolution is to consider the type-name as a simple-type-specifier rather than a declarator-id.

[Example 3:]

```c
class C { };  
void f(int(C)) { }  // void f(int(*fp)(C c)) { }  // not: void f(int C) { }

int g(C);

void foo() {  
    f(1);  // error: cannot convert 1 to function pointer  
    f(g);  // OK  
}
```

For another example,

```c
class C { };  
void h(int *(C[10]));  // void h(int (*_fp)(C _parm[10]));  // not: void h(int *C[10]);
```
9.3.4 Meaning of declarators  

9.3.4.1 General

A declarator contains exactly one declarator-id; it names the entity that is declared. If the unqualified-id occurring in a declarator-id is a template-id, the declarator shall appear in the declaration of a template-declaration (13.7), explicit-specialization (13.9.4), or explicit-instantiation (13.9.3).

[Note 1: An unqualified-id that is not an identifier is used to declare certain functions (11.4.8.3, 11.4.7, 12.4, 12.6). —end note]

The optional attribute-specifier-seq following a declarator-id appertains to the entity that is declared.

2 If the declaration is a friend declaration:

(2.1) — The declarator does not bind a name.

(2.2) — If the id-expression E in the declarator-id of the declarator is a qualified-id or a template-id:

(2.2.1) — If the friend declaration is not a template declaration, then in the lookup for the terminal name of E:

(2.2.1.1) — if the unqualified-id in E is a template-id, all function declarations are discarded;

(2.2.1.2) — otherwise, if the declarator corresponds (6.4.1) to any declaration found of a non-template function, all function template declarations are discarded;

(2.2.1.3) — each remaining function template is replaced with the specialization chosen by deduction from the friend declaration (13.10.3.7) or discarded if deduction fails.

(2.2.2) — The declarator shall correspond to one or more declarations found by the lookup; they shall all have the same target scope, and the target scope of the declarator is that scope.

(2.3) — Otherwise, the terminal name of E is not looked up. The declaration’s target scope is the innermost enclosing namespace scope; if the declaration is contained by a block scope, the declaration shall correspond to a reachable (10.7) declaration that inhabits the innermost block scope.

3 Otherwise:

(3.1) — If the id-expression in the declarator-id of the declarator is a qualified-id Q, let S be its lookup context (6.5.5); the declaration shall inhabit a namespace scope.

(3.2) — Otherwise, let S be the entity associated with the scope inhabited by the declarator.

(3.3) — If the declarator declares an explicit instantiation or a partial or explicit specialization, the declarator does not bind a name. If it declares a class member, the terminal name of the declarator-id is not looked up; otherwise, only those lookup results that are nominable in S are considered when identifying any function template specialization being declared (13.10.3.7).

[Example 1:

```c
namespace N {
    inline namespace O {
        template<class T> void f(T);  // #1
        template<class T> void g(T) {}  
    }
    namespace P {
        template<class T> void f(T*);
        template<class> int g;
    } using P::f,P::g;
    template<> void N::f(int*) {}  // OK, #2 is not nominable
    template void N::g(int);      // error: lookup is ambiguous
}
```

—end example]

(3.4) — Otherwise, the terminal name of the declarator-id is not looked up. If it is a qualified name, the declarator shall correspond to one or more declarations nominable in S; all the declarations shall have the same target scope and the target scope of the declarator is that scope.

[Example 2:
namespace Q {
namespace V {
    void f();
}
void V::f() { /* ... */ } // OK
void V::g() { /* ... */ } // error: g() is not yet a member of V
namespace V {
    void g();
}
}
namespace R {
    void Q::V::g() { /* ... */ }
    // error: R doesn't enclose Q
}
—end example

(3.5) — If the declaration inhabits a block scope \( S \) and declares a function (9.3.4.6) or uses the `extern` specifier, the declaration shall not be attached to a named module (10.1); its target scope is the innermost enclosing namespace scope, but the name is bound in \( S \).

[Example 3:
namespace X {
    void p() {
        q(); // error: q not yet declared         
        extern void q(); // q is a member of namespace X
        extern void r(); // r is a member of namespace X
    }

    void middle() {
        q(); // error: q not found
    }

    void q() { /* ... */ } // definition of X::q
}

void q() { /* ... */ } // some other, unrelated q
void X::r() { /* ... */ } // error: r cannot be declared by qualified-id
—end example]

4 A `static`, `thread_local`, `extern`, `mutable`, `friend`, `inline`, `virtual`, `constexpr`, `consteval`, `constinit`, or `typedef` specifier or an `explicit-specifier` applies directly to each `declarator-id` in a declaration; the type specified for each `declarator-id` depends on both the `decl-specifier-seq` and its `declarator`.

5 Thus, (for each `declarator`) a declaration has the form

\[ T \left(D\right) \]

where \( T \) is of the form `attribute-specifier-seq_opt decl-specifier-seq` and \( D \) is a declarator. Following is a recursive procedure for determining the type specified for the contained `declarator-id` by such a declaration.

6 First, the `decl-specifier-seq` determines a type. In a declaration

\[ T \left(D\right) \]

the `decl-specifier-seq` \( T \) determines the type \( T \).

[Example 4: In the declaration

\[ int unsigned i; \]

the type specifiers `int unsigned` determine the type “unsigned int” (9.2.9.3). —end example]

7 In a declaration `attribute-specifier-seq_opt T D` where \( D \) is an unadorned `declarator-id`, the type of the declared entity is “\( T \)”.

8 In a declaration \( T \left(D\right) \) where \( D \) has the form

\[ \left(D1\right) \]

the type of the contained `declarator-id` is the same as that of the contained `declarator-id` in the declaration \( T \left(D1\right) \).
Parentheses do not alter the type of the embedded declarator-id, but they can alter the binding of complex declarators.

### 9.3.4.2 Pointers

In a declaration T D where D has the form

```c
* attribute-specifier-seq_opt cv-qualifier-seq_opt D1
```

and the type of the contained declarator-id in the declaration T D1 is "derived-declarator-type-list T", the type of the declarator-id in D is "derived-declarator-type-list cv-qualifier-seq pointer to T". The cv-qualifiers apply to the pointer and not to the object pointed to. Similarly, the optional attribute-specifier-seq (9.12.1) appertains to the pointer and not to the object pointed to.

#### Example 1

The declarations

```c
const int ci = 10, *pc = &ci, *const cpc = pc, **ppc;
int i, *p, *const cp = &i;
```

declare ci, a constant integer; pc, a pointer to a constant integer; cpc, a constant pointer to a constant integer; ppc, a pointer to a pointer to a constant integer; i, an integer; p, a pointer to a pointer to a constant integer; and cp, a constant pointer to integer. The value of ci, cpc, and cp cannot be changed after initialization. The value of pc can be changed, and so can the object pointed to by cp. Examples of some correct operations are

```c
i = ci;
*pc = ci;
pc++;
pc = cpc;
p = p;
ppc = &pc;
```

Examples of ill-formed operations are

```c
*ppc = &ci; // OK, but would make p point to ci because of previous error
*p = 5; // clobber ci
```

Each is unacceptable because it would either change the value of an object declared const or allow it to be changed through a cv-unqualified pointer later, for example:

```c
*ppc = &ci; // OK, but would make p point to ci because of previous error
*p = 5; // clobber ci
```

---

### 9.3.4.3 References

In a declaration T D where D has either of the forms

```c
& attribute-specifier-seq_opt cv-qualifier-seq_opt D1
&& attribute-specifier-seq_opt cv-qualifier-seq_opt D1
```

and the type of the contained declarator-id in the declaration T D1 is "derived-declarator-type-list T", the type of the declarator-id in D is "derived-declarator-type-list reference to T". The optional attribute-specifier-seq appertains to the reference type. C&v-qualified references are ill-formed except when the cv-qualifiers are introduced through the use of a typedef-name (9.2.4, 13.2) or decltype-specifier (9.2.9.6), in which case the cv-qualifiers are ignored.

#### Example 1

```c
typedef int& A;
const A aref = 3; // error: lvalue reference to non-const initialized with rvalue
```

The type of aref is "lvalue reference to int", not "lvalue reference to const int". — end example

[Note 1: A reference can be thought of as a name of an object. — end note]
Forming the type “reference to cv void” is ill-formed.

A reference type that is declared using & is called an lvalue reference, and a reference type that is declared using && is called an rvalue reference. Lvalue references and rvalue references are distinct types. Except where explicitly noted, they are semantically equivalent and commonly referred to as references.

[Example 2:

    void f(double& a) { a += 3.14; }
    // ...
    f(d);

declares a to be a reference parameter of f so the call f(d) will add 3.14 to d.

    int v[20];
    // ...
    int& g(int i) { return v[i]; }
    // ...
    g(3) = 7;

declares the function g() to return a reference to an integer so g(3)=7 will assign 7 to the fourth element of the array v. For another example,

    struct link {
        link* next;
    };
    link* first;

    void h(link*& p) {
        p->next = first;
        first = p;
        p = 0;
    }

    void k() {
        link* q = new link;
    
        h(q);
    }

declares p to be a reference to a pointer to link so h(q) will leave q with the value zero. See also 9.4.4. — end example]

It is unspecified whether or not a reference requires storage (6.7.5).

There shall be no references to references, no arrays of references, and no pointers to references. The declaration of a reference shall contain an initializer (9.4.4) except when the declaration contains an explicit extern specifier (9.2.2), is a class member (11.4) declaration within a class definition, or is the declaration of a parameter or a return type (9.3.4.6); see 6.2.

Attempting to bind a reference to a function where the converted initializer is a glvalue whose type is not call-compatible (7.6.1.3) with the type of the function’s definition results in undefined behavior. Attempting to bind a reference to an object where the converted initializer is a glvalue through which the object is not type-accessible (7.2.1) results in undefined behavior.

[Note 2: The object designated by such a glvalue can be outside its lifetime (6.7.3). Because a null pointer value or a pointer past the end of an object does not point to an object, a reference in a well-defined program cannot refer to such things; see 7.6.2.2. As described in 11.4.10, a reference cannot be bound directly to a bit-field. — end note]

The behavior of an evaluation of a reference (7.5.5, 7.6.1.5) that does not happen after (6.9.2.2) the initialization of the reference is undefined.

[Example 3:

    int &f(int&);
    int &g();
    extern int &ir3;
    int *ip = 0;
    int &ir1 = *ip; // undefined behavior: null pointer
    int &ir2 = f(ir3); // undefined behavior: ir3 not yet initialized
    int &ir3 = g();]
int &ir4 = f(ir4); // undefined behavior: ir4 used in its own initializer

char x alignas(int);
int &ir5 = *reinterpret_cast<int *>(&x); // undefined behavior: initializer refers to char object
—end example

If a typedef-name (9.2.4, 13.2) or a decltype-specifier (9.2.9.6) denotes a type TR that is a reference to a type T, an attempt to create the type “lvalue reference to cv TR” creates the type “lvalue reference to T”, while an attempt to create the type “rvalue reference to cv TR” creates the type TR.

[Note 3: This rule is known as reference collapsing. — end note]

[Example 4:]

```cpp
int i;
typedef int& LRI;
typedef int&& RRI;

LRI& r1 = i;         // r1 has the type int&
const LRI& r2 = i;   // r2 has the type int&
const LRI&& r3 = i;  // r3 has the type int&&

RRI& r4 = i;         // r4 has the type int&&
RRI&& r5 = 5;        // r5 has the type int&&

decatype(r2)& r6 = i; // r6 has the type int&
decatype(r2)&& r7 = i; // r7 has the type int&&
—end example
```

[Note 4: Forming a reference to function type is ill-formed if the function type has cv-qualifiers or a ref-qualifier; see 9.3.4.6. — end note]

9.3.4.4 Pointers to members [dcl.mptr]

The component names of a ptr-operator are those of its nested-name-specifier, if any.

In a declaration T D where D has the form

```
nested-name-specifier * attribute-specifier-seq_opt cv-qualifier-seq_opt D1
```

and the nested-name-specifier denotes a class, and the type of the contained declarator-id in the declaration T D1 is “derived-declarator-type-list T”, the type of the declarator-id in D is “derived-declarator-type-list cv-qualifier-seq pointer to member of class nested-name-specifier of type T”. The optional attribute-specifier-seq (9.12.1) appertains to the pointer-to-member.

[Example 1:]

```cpp
struct X {
    void f(int);
    int a;
};
struct Y;

int X::* pmi = &X::a;
void (X::* pmf)(int) = &X::f;
double X::* pmd;
char Y::* pmc;
```
declares pmi, pmf, pmd and pmc to be a pointer to a member of X of type int, a pointer to a member of X of type void(int), a pointer to a member of X of type double and a pointer to a member of Y of type char respectively. The declaration of pmd is well-formed even though X has no members of type double. Similarly, the declaration of pmc is well-formed even though Y is an incomplete type. pmi and pmf can be used like this:

```
X obj;
// ...
obj.*pmi = 7;    // assign 7 to an integer member of obj
(obj.*pmf)(7);    // call a function member of obj with the argument 7
—end example
```
A pointer to member shall not point to a static member of a class (11.4.9), a member with reference type, or “cv void”.

[Note 1: See also 7.6.2 and 7.6.4. The type “pointer to member” is distinct from the type “pointer”, that is, a pointer to member is declared only by the pointer-to-member declarator syntax, and never by the pointer declarator syntax. There is no “reference-to-member” type in C++. — end note]

9.3.4.5 Arrays

In a declaration $T D$ where $D$ has the form

$$D1 \ [ \ constant-expression_{opt} ] \ attribute-specifier-seq_{opt}$$

and the type of the contained declarator-id in the declaration $T D1$ is “derived-declarator-type-list $T$”, the type of the declarator-id in $D$ is “derived-declarator-type-list array of N $T$”. The constant-expression shall be a converted constant expression of type std::size_t (7.7). Its value $N$ specifies the array bound, i.e., the number of elements in the array; $N$ shall be greater than zero.

In a declaration $T D$ where $D$ has the form

$$D1 \ [ \ ] \ attribute-specifier-seq_{opt}$$

and the type of the contained declarator-id in the declaration $T D1$ is “derived-declarator-type-list $T$”, the type of the declarator-id in $D$ is “derived-declarator-type-list array of unknown bound of $T$”, except as specified below.

A type of the form “array of N $U$” or “array of unknown bound of $U$” is an array type. The optional attribute-specifier-seq appertains to the array type.

$U$ is called the array element type; this type shall not be a reference type, a function type, an array of unknown bound, or cv void.

[Note 1: An array can be constructed from one of the fundamental types (except void), from a pointer, from a pointer to member, from a class, from an enumeration type, or from an array of known bound. — end note]

[Example 1: float fa[17], *afp[17]; declares an array of float numbers and an array of pointers to float numbers. — end example]

Any type of the form “cv-qualified-seq array of N $U$” is adjusted to “array of N cv-qualified-seq $U$”, and similarly for “array of unknown bound of $U$”.

[Example 2: typedef int A[5], AA[2][3]; typedef const A CA; // type is “array of 5 const int” typedef const AA CAA; // type is “array of 2 array of 3 const int” — end example]

[Note 2: An “array of N cv-qualified-seq $U$” has cv-qualified type; see 6.8.5. — end note]

An object of type “array of N $U$” consists of a contiguously allocated non-empty set of N subobjects of type $U$, known as the elements of the array, and numbered 0 to N-1.

In addition to declarations in which an incomplete object type is allowed, an array bound may be omitted in some cases in the declaration of a function parameter (9.3.4.6). An array bound may also be omitted when an object (but not a non-static data member) of array type is initialized and the declarator is followed by an initializer (9.4, 11.4, 7.6.1.4, 7.6.2.8). In these cases, the array bound is calculated from the number of initial elements (say, $N$) supplied (9.4.2), and the type of the array is “array of N $U$”.

Furthermore, if there is a reachable declaration of the entity that inhabits the same scope in which the bound was specified, an omitted array bound is taken to be the same as in that earlier declaration, and similarly for the definition of a static data member of a class.

[Example 3: extern int x[10]; struct S {
    static int y[10];
}; int x[]; // OK, bound is 10 int S::y[]; // OK, bound is 10
void f() {
    extern int x[];
    int i = sizeof(x);  // error: incomplete object type
}

[Note 3: When several “array of” specifications are adjacent, a multidimensional array type is created; only the first of the constant expressions that specify the bounds of the arrays can be omitted.

[Example 4:

    int x3d[3][5][7];

declares an array of three elements, each of which is an array of five elements, each of which is an array of seven integers. The overall array can be viewed as a three-dimensional array of integers, with rank $3 \times 5 \times 7$. Any of the expressions $x3d$, $x3d[i]$, $x3d[i][j]$, $x3d[i][j][k]$ can reasonably appear in an expression. The expression $x3d[i]$ is equivalent to $*(x3d + i)$; in that expression, $x3d$ is subject to the array-to-pointer conversion (7.3.3) and is first converted to a pointer to a 2-dimensional array with rank $5 \times 7$ that points to the first element of $x3d$. Then $i$ is added, which on typical implementations involves multiplying $i$ by the length of the object to which the pointer points, which is $\text{sizeof(int)} \times 5 \times 7$. The result of the addition and indirection is an lvalue denoting the $i^{th}$ array element of $x3d$ (an array of five arrays of seven integers). If there is another subscript, the same argument applies again, so $x3d[i][j]$ is an lvalue denoting the $j^{th}$ array element of the $i^{th}$ array element of $x3d$, and $x3d[i][j][k]$ is an lvalue denoting the $k^{th}$ array element of the $j^{th}$ array element of the $i^{th}$ array element of $x3d$ (an integer). — end example]

The first subscript in the declaration helps determine the amount of storage consumed by an array but plays no other part in subscript calculations. — end note]

[Note 4: Conversions affecting expressions of array type are described in 7.3.3. — end note]

[Note 5: The subscript operator can be overloaded for a class (12.4.5). For the operator's built-in meaning, see 7.6.1.2. — end note]

9.3.4.6 Functions [dcl.fct]

In a declaration $T \ D$ where $T$ may be empty and $D$ has the form

\[
D1 \ (\text{parameter-declaration-clause}) \ cv-qualifier-seqopt
\begin{align*}
\text{ref-qualifier_opt} & \ 
\text{noexcept-specifier_opt} & \ 
\text{attribute-specifier-seqopt} & \ 
\text{trailing-return-type_opt}
\end{align*}
\]

a derived-declarator-type-list is determined as follows:

(1.1) — If the unqualified-id of the declarator-id is a conversion-function-id, the derived-declarator-type-list is empty.

(1.2) — Otherwise, the derived-declarator-type-list is as appears in the type “derived-declarator-type-list $T$” of the contained declarator-id in the declaration $T \ D1$.

The declared return type $U$ of the function type is determined as follows:

(1.3) — If the trailing-return-type is present, $T$ shall be the single type-specifier auto, and $U$ is the type specified by the trailing-return-type.

(1.4) — Otherwise, if the declaration declares a conversion function, see 11.4.8.3.

(1.5) — Otherwise, $U$ is $T$.

The type of the declarator-id in $D$ is “derived-declarator-type-list noexceptopt function of parameter-type-list cv-qualifier-seqopt ref-qualifier_opt returning $U$”, where

(1.6) — the parameter-type-list is derived from the parameter-declaration-clause as described below and

(1.7) — the optional noexceptopt is present if and only if the exception specification (14.5) is non-throwing.

The optional attribute-specifier-seq appertains to the function type.

A type of either form is a function type.\(^{76}\)

\[
\text{parameter-declaration-clause:}
\begin{align*}
\text{parameter-declaration-listopt} & \ 
\ldots opt
\end{align*}
\begin{align*}
\text{parameter-declaration-list} & \ , \ 
\ldots
\end{align*}
\begin{align*}
\text{parameter-declaration-list:}
\text{parameter-declaration} & \ 
\text{parameter-declaration-list} & \ , \ 
\text{parameter-declaration}
\end{align*}
\]

\(^{76}\) As indicated by syntax, cv-qualifiers are a significant component in function return types.

\(\S\text{ 9.3.4.6}\)
parameter-declaration:
  attribute-specifier-seq\_opt this\_opt decl-specifier-seq declarator
  attribute-specifier-seq\_opt decl-specifier-seq declarator = initializer-clause
  attribute-specifier-seq\_opt this\_opt decl-specifier-seq abstract-declarator\_opt
  attribute-specifier-seq\_opt decl-specifier-seq abstract-declarator\_opt = initializer-clause

The optional attribute-specifier-seq in a parameter-declaration appertains to the parameter.

The parameter-declaration-clause determines the arguments that can be specified, and their processing, when the function is called.

*[Note 1: The parameter-declaration-clause is used to convert the arguments specified on the function call; see 7.6.1.3. — end note]*

If the parameter-declaration-clause is empty, the function takes no arguments. A parameter list consisting of a single unnamed parameter of non-dependent type void is equivalent to an empty parameter list. Except for this special case, a parameter shall not have type cv void. A parameter with volatile-qualified type is deprecated; see D.4. If the parameter-declaration-clause terminates with an ellipsis or a function parameter pack (13.7.4), the number of arguments shall be equal to or greater than the number of parameters that do not have a default argument and are not function parameter packs. Where syntactically correct and where “...” is not part of an abstract-declarator, “, ...” is synonymous with “...”.

*[Example 1: The declaration]*

```c
int printf(const char*, ...);
```

declares a function that can be called with varying numbers and types of arguments.

```c
printf("hello world");
printf("a=%d b=%d", a, b);
```

However, the first argument must be of a type that can be converted to a const char*. — end example*

*[Note 2: The standard header <stdarg> (17.13.2) contains a mechanism for accessing arguments passed using the ellipsis (see 7.6.1.3 and 17.13). — end note]*

The type of a function is determined using the following rules. The type of each parameter (including function parameter packs) is determined from its own parameter-declaration (9.3). After determining the type of each parameter, any parameter of type “array of T” or of function type T is adjusted to be “pointer to T”. After producing the list of parameter types, any top-level cv-qualifiers modifying a parameter type are deleted when forming the function type. The resulting list of transformed parameter types and the presence or absence of the ellipsis or a function parameter pack is the function’s parameter-type-list.

*[Note 3: This transformation does not affect the types of the parameters. For example, int(*)(const int p, decltype(p)*) and int(*)(int, const int*) are identical types. — end note]*

*[Example 2:]*

```c
void f(char*);
void f(char[]) {} // #1
void f(const char*) {} // OK, another overload
void f(char *const) {} // error: redefines #1

void g(char(*)[2]); // #2
void g(char[3][2]) {} // defines #2
void g(char[3][3]) {} // OK, another overload

void h(int x(const int)); // #3
void h(int (*)(int)) {} // defines #3
```

— end example*

An explicit-object-parameter-declaration is a parameter-declaration with a this specifier. An explicit-object-parameter-declaration shall appear only as the first parameter-declaration of a parameter-declaration-list of one of:

*(5.1) — a declaration of a member function or member function template (11.4), or*
*(5.2) — an explicit instantiation (13.9.3) or explicit specialization (13.9.4) of a templated member function, or*
*(5.3) — a lambda-declarator (7.5.6).*

A member-declarator with an explicit-object-parameter-declaration shall not include a ref-qualifier or a cv-qualifier-seq and shall not be declared static or virtual.
[Example 3:

```cpp
struct C {
    void f(this C& self);
    template <typename Self> void g(this Self&& self, int);
    void h(this C) const;        // error: const not allowed here
};

void test(C c) {
    c.f();                       // OK, calls C::f
    c.g(42);                     // OK, calls C::g<C&>
    std::move(c).g(42);          // OK, calls C::g<C>
}
—end example]
```

6 A function parameter declared with an explicit-object-parameter-declaration is an *explicit object parameter*. An explicit object parameter shall not be a function parameter pack (13.7.4). An *explicit object member function* is a non-static member function with an explicit object parameter. An *implicit object member function* is a non-static member function without an explicit object parameter.

7 The *object parameter* of a non-static member function is either the explicit object parameter or the implicit object parameter (12.2.2).

8 A *non-object parameter* is a function parameter that is not the explicit object parameter. The *non-object-parameter-type-list* of a member function is the parameter-type-list of that function with the explicit object parameter, if any, omitted.

[Note 4: The non-object-parameter-type-list consists of the adjusted types of all the non-object parameters. — end note]

9 A function type with a *cv-qualifier-seq* or a *ref-qualifier* (including a type named by *typedef-name* (9.2.4, 13.2)) shall appear only as:

9.1 — the function type for a non-static member function,

9.2 — the function type to which a pointer to member refers,

9.3 — the top-level function type of a function typedef declaration or *alias-declaration*,

9.4 — the *type-id* in the default argument of a *type-parameter* (13.2), or

9.5 — the *type-id* of a *template-argument* for a *type-parameter* (13.4.2).

[Example 4:

```cpp
typedef int FIC(int) const;
FIC f;                        // error: does not declare a member function
struct S {
    FIC f;                   // OK
};
FIC S::*pm = &S::f;           // OK
—end example]
```

10 The effect of a *cv-qualifier-seq* in a function declarator is not the same as adding cv-qualification on top of the function type. In the latter case, the cv-qualifiers are ignored.

[Note 5: A function type that has a *cv-qualifier-seq* is not a cv-qualified type; there are no cv-qualified function types. — end note]

[Example 5:

```cpp
typedef void F();
struct S {
    const F f;              // OK, equivalent to: void f();
};
—end example]
```

11 The return type, the parameter-type-list, the *ref-qualifier*, the *cv-qualifier-seq*, and the exception specification, but not the default arguments (9.3.4.7) or the trailing *requires-clause* (9.3), are part of the function type.
Note 6: Function types are checked during the assignments and initializations of pointers to functions, references to functions, and pointers to member functions. — end note

Example 6: The declaration

```c
int fseek(FILE*, long, int);
```
declares a function taking three arguments of the specified types, and returning int (9.2.9). — end example

Note 7: A single name can be used for several different functions in a single scope; this is function overloading (Clause 12). — end note

The return type shall be a non-array object type, a reference type, or cv void.

Example 8: An array of placeholder type is considered an array type. — end note

A volatile-qualified return type is deprecated; see D.4.

Types shall not be defined in return or parameter types.

A typedef of function type may be used to declare a function but shall not be used to define a function (9.5).

Example 7:

```c
typedef void F();
F fv;        // OK, equivalent to void fv();
F fv { }    // error
void fv() { } // OK, definition of fv
```

An identifier can optionally be provided as a parameter name; if present in a function definition (9.5), it names a parameter.

Example 8: The declaration

```c
int i,
*pi,
f(),
*fpi(int),
(*pf)(const char*, const char*),
(*pf)(int))(int);
```
declares an integer i, a pointer pi to an integer, a function f taking no arguments and returning an integer, a function fpi taking an integer argument and returning a pointer to an integer, a pointer pif to a function which takes two pointers to constant characters and returns an integer, a function fpif taking an integer argument and returning a pointer to a function that takes an integer argument and returns an integer. It is especially useful to compare fpi and pif. The binding of *fpi(int) is *(fpi(int)), so the declaration suggests, and the same construction in an expression requires, the calling of a function fpif, and then using indirection through the (pointer) result to yield an integer. In the declarator (*pif)(const char*, const char*), the extra parentheses are necessary to indicate that indirection through a pointer to a function yields a function, which is then called. — end example

Note 10: Typedefs and trailing-return-types are sometimes convenient when the return type of a function is complex. For example, the function fpif above can be declared

```c
typedef int IFUNC(int);
IFUNC* fpif(int);
```
or

```c
auto fpif(int)->int(*)(int);
```
A trailing-return-type is most useful for a type that would be more complicated to specify before the declarator-id:

```c
template <class T, class U> auto add(T t, U u) -> decltype(t + u);
```
rather than

```c
template <class T, class U> decltype((*(T*)0) + (*(U*)0)) add(T t, U u);
```
— end note

A non-template function is a function that is not a function template specialization.

Note 11: A function template is not a function. — end note

An abbreviated function template is a function declaration that has one or more generic parameter type placeholders (9.2.9.7). An abbreviated function template is equivalent to a function template (13.7.7)
whose template-parameter-list includes one invented type template-parameter for each generic parameter type placeholder of the function declaration, in order of appearance. For a placeholder-type-specifier of the form auto, the invented parameter is an unconstrained type-parameter. For a placeholder-type-specifier of the form type-constraint auto, the invented parameter is a type-parameter with that type-constraint. The invented type template-parameter is a template parameter pack if the corresponding parameter-declaration declares a function parameter pack. If the placeholder contains decltype(auto), the program is ill-formed. The adjusted function parameters of an abbreviated function template are derived from the parameter-declaration-clause by replacing each occurrence of a placeholder with the name of the corresponding invented template-parameter.

[Example 9:]
```cpp
template<typename T> concept C1 = /* ... */;
template<typename T> concept C2 = /* ... */;
template<typename... Ts> concept C3 = /* ... */;

void g1(const C1 auto*, C2 auto&);
void g2(C1 auto&...);
void g3(C3 auto...);
void g4(C3 auto);
```

The declarations above are functionally equivalent (but not equivalent) to their respective declarations below:
```cpp
template<C1 T, C2 U> void g1(const T*, U&);
template<C1... Ts> void g2(Ts&...);
template<C3... Ts> void g3(Ts...);
template<C3 T> void g4(T);
```

Abbreviated function templates can be specialized like all function templates.
```cpp
#template<> void g1<int>(const int*, const double&); // OK, specialization of g1<int, const double>
```

—end example]

22 An abbreviated function template can have a template-head. The invented template-parameters are appended to the template-parameter-list after the explicitly declared template-parameters.

[Example 10:]
```cpp
template<typename> concept C = /* ... */;

template <typename T, C U>
void g(T x, U y, C auto z);
```

This is functionally equivalent to each of the following two declarations.
```cpp
template<typename T, C U, C W>
void g(T x, U y, W z);

template<typename T, typename U, typename W>
requires C<U> && C<W>
void g(T x, U y, W z);
```

—end example]

23 A function declaration at block scope shall not declare an abbreviated function template.

24 A declarator-id or abstract-declarator containing an ellipsis shall only be used in a parameter-declaration. When it is part of a parameter-declaration-clause, the parameter-declaration declares a function parameter pack (13.7.4). Otherwise, the parameter-declaration is part of a template-parameter-list and declares a template parameter pack; see 13.2. A function parameter pack is a pack expansion (13.7.4).

[Example 11:]
```cpp
template<typename... T> void f(T (* ...t)(int, int));
```

```cpp
int add(int, int);
float subtract(int, int);

void g() {
    f(add, subtract);
}
```

—end example]
There is a syntactic ambiguity when an ellipsis occurs at the end of a parameter-declaration-clause without a preceding comma. In this case, the ellipsis is parsed as part of the abstract-declarator if the type of the parameter either names a template parameter pack that has not been expanded or contains auto; otherwise, it is parsed as part of the parameter-declaration-clause.\(^{77}\)

### 9.3.4.7 Default arguments

1. If an initializer-clause is specified in a parameter-declaration this initializer-clause is used as a default argument. [Note 1: Default arguments will be used in calls where trailing arguments are missing (7.6.1.3). — end note]

2. [Example 1: The declaration]

   ```
   void point(int = 3, int = 4);
   ```

   declares a function that can be called with zero, one, or two arguments of type `int`. It can be called in any of these ways:

   ```
   point(1,2); point(1); point();
   ```

   The last two calls are equivalent to `point(1,4)` and `point(3,4)`, respectively. — end example]

3. A default argument shall be specified only in the parameter-declaration-clause of a function declaration or lambda-declarator or in a template-parameter (13.2). A default argument shall not be specified for a template parameter pack or a function parameter pack. If it is specified in a parameter-declaration-clause, it shall not occur within a declarator or abstract-declarator of a parameter-declaration.\(^{78}\)

4. For non-template functions, default arguments can be added in later declarations of a function that inhabit the same scope. Declarations that inhabit different scopes have completely distinct sets of default arguments. That is, declarations in inner scopes do not acquire default arguments from declarations in outer scopes, and vice versa. In a given function declaration, each parameter subsequent to a parameter with a default argument shall have a default argument supplied in this or a previous declaration, unless the parameter was expanded from a parameter pack, or shall be a function parameter pack.

   [Note 2: A default argument cannot be redefined by a later declaration (not even to the same value) (6.3). — end note]

   [Example 2:

   ```
   void g(int = 0, ...);
   ```

   // OK, ellipsis is not a parameter so it can follow

   ```
   void f(int, int);
   ```

   // a parameter with a default argument

   ```
   void f(int, int = 7);
   ```

   ```
   void h() {
     f(3);
     void f(int = 1, int);
   }
   ```

   // OK, calls f(3, 7)

   ```
   } void m() {
     void f(int, int);
     f(4); // error: does not use default from surrounding scope
   }
   ```

   // has no defaults

   ```
   void f(int, int = 5);
   ```

   // error: wrong number of arguments

   ```
   f(4); // OK
   ```

   ```
   f(4); // OK, calls f(4, 5); // error: cannot redefine, even to same value
   ```

   ```
   void n() {
     f(6); // OK, calls f(6, 7)
   }
   ```

   ```
   template<class ... T> struct C {
     void f(int n = 0, T...);
   };
   ```

   ```
   C<int> c; // OK, instantiates declaration void C::f(int n = 0, int)
   ```

   — end example]

For a given inline function defined in different translation units, the accumulated sets of default arguments at the end of the translation units shall be the same; no diagnostic is required. If a friend declaration `D`
specifies a default argument expression, that declaration shall be a definition and there shall be no other
declaration of the function or function template which is reachable from \( D \) or from which \( D \) is reachable.

5 The default argument has the same semantic constraints as the initializer in a declaration of a variable of the
parameter type, using the copy-initialization semantics (9.4). The names in the default argument are looked
up, and the semantic constraints are checked, at the point where the default argument appears, except that
an immediate invocation (7.7) that is a potentially-evaluated subexpression (6.9.1) of the \textit{initializer-clause}
in a \textit{parameter-declaration} is neither evaluated nor checked for whether it is a constant expression at that
point. Name lookup and checking of semantic constraints for default arguments of templated functions are
performed as described in 13.9.2.

\[\text{Example 3: In the following code, } g \text{ will be called with the value } f(2)\::\]

\begin{verbatim}
int a = 1;
int f(int);
int g(int x = f(a));    // default argument: f(::a)

void h() {
    a = 2;
    { int a = 3;
      g();    // g(f(::a))
    }
}
\end{verbatim}

\[\text{—end example}\]

\[\text{Note 3: A default argument is a complete-class context (11.4). Access checking applies to names in default arguments
as described in 11.8. —end note}\]

6 Except for member functions of templated classes, the default arguments in a member function definition
that appears outside of the class definition are added to the set of default arguments provided by the member
function declaration in the class definition; the program is ill-formed if a default constructor (11.4.5.2),
copy or move constructor (11.4.5.3), or copy or move assignment operator (11.4.6) is so declared. Default
arguments for a member function of a templated class shall be specified on the initial declaration of the
member function within the templated class.

\[\text{Example 4:}\]

\begin{verbatim}
class C {
    void f(int i = 3);
    void g(int i, int j = 99);
};

void C::f(int i = 3) {}    // error: default argument already specified in class scope
void C::g(int i = 99, int j) {}    // in this translation unit, C::g can be called with no arguments
\end{verbatim}

\[\text{—end example}\]

7 \[\text{Note 4: A local variable cannot be odr-used (6.3) in a default argument. —end note}\]

\[\text{Example 5:}\]

\begin{verbatim}
void f() {
    int i;
    extern void g(int x = i);    // error
    extern void h(int x = sizeof(i));   // OK
    // ...
}
\end{verbatim}

\[\text{—end example}\]

8 \[\text{Note 5: The keyword } \texttt{this} \text{ cannot appear in a default argument of a member function; see 7.5.3.}\]

\[\text{Example 6:}\]

\begin{verbatim}
class A {
    void f(A* p = this) { }    // error
};
\end{verbatim}

\[\text{—end example}\]

\[\text{—end note}\]
A default argument is evaluated each time the function is called with no argument for the corresponding parameter. A parameter shall not appear as a potentially-evaluated expression in a default argument.

[Note 6: Parameters of a function declared before a default argument are in scope and can hide namespace and class member names. — end note]

[Example 7:

```c
int a;
int f(int a, int b = a);    // error: parameter a used as default argument
typedef int I;
int g(float I, int b = I(2));    // error: parameter I found
int h(int a, int b = sizeof(a));  // OK, unevaluated operand (7.2.3)
```
—end example]

A non-static member shall not appear in a default argument unless it appears as the *id-expression* of a class member access expression (7.6.1.5) or unless it is used to form a pointer to member (7.6.2.2).

[Example 8: The declaration of `X::mem1()` in the following example is ill-formed because no object is supplied for the non-static member `X::a` used as an initializer.

```c
int b;
class X {
    int a;
    int mem1(int i = a);    // error: non-static member a used as default argument
    int mem2(int i = b);    // OK; use X::b
    static int b;
};
```

The declaration of `X::mem2()` is meaningful, however, since no object is needed to access the static member `X::b`. Classes, objects, and members are described in Clause 11. — end example]

A default argument is not part of the type of a function.

[Example 9:

```c
int f(int = 0);
void h() {
    int j = f(1);
    int k = f();    // OK, means f(0)
}
int (*p1)(int) = &f;
int (*p2)() = &f;    // error: type mismatch
```
—end example]

When an overload set contains a declaration of a function that inhabits a scope `S`, any default argument associated with any reachable declaration that inhabits `S` is available to the call.

[Note 7: The candidate might have been found through a *using-declarator* from which the declaration that provides the default argument is not reachable. — end note]

A virtual function call (11.7.3) uses the default arguments in the declaration of the virtual function determined by the static type of the pointer or reference denoting the object. An overriding function in a derived class does not acquire default arguments from the function it overrides.

[Example 10:

```c
struct A {
    virtual void f(int a = 7);
};
struct B : public A {
    void f(int a);
};
void m() {
    B* pb = new B;
    A* pa = pb;
    pa->f();    // OK, calls pa->B::f(7)
    pb->f();    // error: wrong number of arguments for B::f()
}
```
The process of initialization described in 9.4 applies to all initializations regardless of syntactic context, including the initialization of a function parameter (7.6.1.3), the initialization of a return value (8.7.4), or when an initializer follows a declarator.

```
initializer:
  brace-or-equal-initializer
    ( expression-list )
brace-or-equal-initializer:
  = initializer-clause
  braced-init-list
initializer-clause:
  assignment-expression
  braced-init-list
braced-init-list:
  { initializer-list , opt }
  { designated-initializer-list , opt }
  { }
initializer-list:
  initializer-clause . . . , opt
  initializer-list , initializer-clause . . . , opt
designated-initializer-list:
  designated-initializer-clause
  designated-initializer-list , designated-initializer-clause
designated-initializer-clause:
  designated-initializer-clause
  designator brace-or-equal-initializer
designator:
  . identifier
expr-or-braced-init-list:
  expression
  braced-init-list
```

[Note 1: The rules in 9.4 apply even if the grammar permits only the `brace-or-equal-initializer` form of `initializer` in a given context. — end note]

2 Except for objects declared with the `constexpr` specifier, for which see 9.2.6, an `initializer` in the definition of a variable can consist of arbitrary expressions involving literals and previously declared variables and functions, regardless of the variable’s storage duration.

[Example 1:]
```
int f(int);
int a = 2;
int b = f(a);
int c(b);
```

[Note 2: Default arguments are more restricted; see 9.3.4.7. — end note]

3 [Note 3: The order of initialization of variables with static storage duration is described in 6.9.3 and 8.8. — end note]

4 A declaration \( D \) of a variable with linkage shall not have an `initializer` if \( D \) inhabits a block scope.

To `zero-initialize` an object or reference of type \( T \) means:

5.1 — if \( T \) is a scalar type (6.8.1), the object is initialized to the value obtained by converting the integer literal 0 (zero) to \( T \),

79) As specified in 7.3.12, converting an integer literal whose value is 0 to a pointer type results in a null pointer value.
— if \( T \) is a (possibly cv-qualified) non-union class type, its padding bits (6.8.1) are initialized to zero bits and each non-static data member, each non-virtual base class subobject, and, if the object is not a base class subobject, each virtual base class subobject is zero-initialized;

— if \( T \) is a (possibly cv-qualified) union type, its padding bits (6.8.1) are initialized to zero bits and the object’s first non-static named data member is zero-initialized;

— if \( T \) is an array type, each element is zero-initialized;

— if \( T \) is a reference type, no initialization is performed.

7 To default-initialize an object of type \( T \) means:

— If \( T \) is a (possibly cv-qualified) class type (Clause 11), constructors are considered. The applicable constructors are enumerated (12.2.2.4), and the best one for the initializer \( \ell \) is chosen through overload resolution (12.2). The constructor thus selected is called, with an empty argument list, to initialize the object.

— If \( T \) is an array type, the semantic constraints of default-initializing a hypothetical element shall be met and each element is default-initialized.

— Otherwise, no initialization is performed.

8 A class type \( T \) is const-default-constructible if default-initialization of \( T \) would invoke a user-provided constructor of \( T \) (not inherited from a base class) or if

— each direct non-variant non-static data member \( M \) of \( T \) has a default member initializer or, if \( M \) is of class type \( X \) (or array thereof), \( X \) is const-default-constructible,

— if \( T \) is a union with at least one non-static data member, exactly one variant member has a default member initializer,

— if \( T \) is not a union, for each anonymous union member with at least one non-static data member (if any), exactly one non-static data member has a default member initializer, and

— each potentially constructed base class of \( T \) is const-default-constructible.

If a program calls for the default-initialization of an object of a const-qualified type \( T \), \( T \) shall be a const-default-constructible class type or array thereof.

9 To value-initialize an object of type \( T \) means:

— If \( T \) is a (possibly cv-qualified) class type (Clause 11), then let \( C \) be the constructor selected to default-initialize the object, if any. If \( C \) is not user-provided, the object is first zero-initialized. In all cases, the object is then default-initialized.

— If \( T \) is an array type, the semantic constraints of value-initializing a hypothetical element shall be met and each element is value-initialized.

— Otherwise, the object is zero-initialized.

10 A program that calls for default-initialization or value-initialization of an entity of reference type is ill-formed.

[Note 4: For every object of static storage duration, static initialization (6.9.3.2) is performed at program startup before any other initialization takes place. In some cases, additional initialization is done later. — end note]

11 If no initializer is specified for an object, the object is default-initialized.

12 If the entity being initialized does not have class or array type, the expression-list in a parenthesized initializer shall be a single expression.

13 The initialization that occurs in the \( \ell = \) form of a brace-or-equal-initializer or condition (8.5), as well as in argument passing, function return, throwing an exception (14.2), handling an exception (14.4), and aggregate member initialization other than by a designated-initializer-clause (9.4.2), is called copy-initialization.

[Note 5: Copy-initialization can invoke a move (11.4.5.3). — end note]

14 The initialization that occurs

— for an initializer that is a parenthesized expression-list or a braced-init-list,

— for a new-initializer (7.6.2.8),

— in a static_cast expression (7.6.1.9),

— in a functional notation type conversion (7.6.1.4), and

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— in the \textit{braced-init-list} form of a \textit{condition}

is called \textit{direct-initialization}.

The semantics of initializers are as follows. The \textit{destination type} is the cv-unqualified type of the object or reference being initialized and the \textit{source type} is the type of the initializer expression. If the initializer is not a single (possibly parenthesized) expression, the source type is not defined.

— If the initializer is a (non-parenthesized) \textit{braced-init-list} or is = \textit{braced-init-list}, the object or reference is list-initialized (9.4.5).

— If the destination type is a reference type, see 9.4.4.

— If the destination type is an array of characters, an array of \texttt{char8\_t}, an array of \texttt{char16\_t}, an array of \texttt{char32\_t}, or an array of \texttt{wchar\_t}, and the initializer is a \textit{string-literal}, see 9.4.3.

— If the initializer is an object or reference is value-initialized.

[\textit{Note 6: Since () is not permitted by the syntax for initializer, X a();

is not the declaration of an object of class X, but the declaration of a function taking no arguments and returning an X. The form () can appear in certain other initialization contexts (7.6.2.8, 7.6.1.4, 11.9.3). — end note}]

— Otherwise, if the destination type is an array, the object is initialized as follows. The \textit{initializer} shall be of the form \(( \textit{expression-list} )\). Let \(x_1, \ldots, x_k\) be the elements of the \textit{expression-list}. If the destination type is an array of unknown bound, it is defined as having \(k\) elements. Let \(n\) denote the array size after this potential adjustment. If \(k\) is greater than \(n\), the program is ill-formed. Otherwise, the \(i^{th}\) array element is copy-initialized with \(x_i\) for each \(1 \leq i \leq k\), and value-initialized for each \(k < i \leq n\). For each \(1 \leq i < j \leq n\), every value computation and side effect associated with the initialization of the \(i^{th}\) element of the array is sequenced before those associated with the initialization of the \(j^{th}\) element.

— Otherwise, if the destination type is a class type:

— If the initializer expression is a prvalue and the cv-unqualified version of the source type is the same as or is derived from the class of the destination type, constructors are considered. The applicable constructors are enumerated (12.2.2.4), and the best one is chosen through overload resolution (12.2). Then:

— If overload resolution is successful, the selected constructor is called to initialize the object, with the initializer expression or \textit{expression-list} as its argument(s).

— Otherwise, if no constructor is viable, the destination type is an aggregate class, and the initializer is a parenthesized \textit{expression-list}, the object is initialized as follows. Let \(e_1, \ldots, e_n\) be the elements of the aggregate (9.4.2). Let \(x_1, \ldots, x_k\) be the elements of the \textit{expression-list}. If \(k\) is greater than \(n\), the program is ill-formed. The element \(e_i\) is copy-initialized with \(x_i\) for \(1 \leq i \leq k\). The remaining elements are initialized with their default member initializers, if any, and otherwise are value-initialized. For each \(1 \leq i < j \leq n\), every value computation and side effect associated with the initialization of \(e_i\) is sequenced before those associated with the initialization of \(e_j\).

[Note 7: By contrast with direct-list-initialization, narrowing conversions (9.4.5) can appear, designators are not permitted, a temporary object bound to a reference does not have its lifetime extended (6.7.7), and there is no brace elision.

\textit{Example 3:}

\begin{verbatim}
struct A {
    int a;
    int&& r;
};

int f();
int n = 10;

A a1{1, f()}; // OK, lifetime is extended
\end{verbatim}
A a2(1, f());                        // well-formed, but dangling reference
A a3{1.0, 1};                        // error: narrowing conversion
A a4(1.0, 1);                        // well-formed, but dangling reference
A a5(1.0, std::move(n));            // OK

— end example]

— end note]

— Otherwise, the initialization is ill-formed.

— Otherwise (i.e., for the remaining copy-initialization cases), user-defined conversions that can convert from the source type to the destination type or (when a conversion function is used) to a derived class thereof are enumerated as described in 12.2.2.5, and the best one is chosen through overload resolution (12.2). If the conversion cannot be done or is ambiguous, the initialization is ill-formed. The function selected is called with the initializer expression as its argument; if the function is a constructor, the call is a prvalue of the cv-unqualified version of the destination type whose result object is initialized by the constructor. The call is used to direct-initialize, according to the rules above, the object that is the destination of the copy-initialization.

— Otherwise, if the source type is a (possibly cv-qualified) class type, conversion functions are considered. The applicable conversion functions are enumerated (12.2.2.6), and the best one is chosen through overload resolution (12.2). The user-defined conversion so selected is called to convert the initializer expression into the object being initialized. If the conversion cannot be done or is ambiguous, the initialization is ill-formed.

— Otherwise, if the initialization is direct-initialization, the source type is std::nullptr_t, and the destination type is bool, the initial value of the object being initialized is false.

— Otherwise, the initial value of the object being initialized is the (possibly converted) value of the initializer expression. A standard conversion sequence (7.3) is used to convert the initializer expression to a prvalue of the destination type; no user-defined conversions are considered. If the conversion cannot be done, the initialization is ill-formed. When initializing a bit-field with a value that it cannot represent, the resulting value of the bit-field is implementation-defined.

[Note 8: An expression of type “cv1 T” can initialize an object of type “cv2 T” independently of the cv-qualifiers cv1 and cv2.

    int a;
    const int b = a;
    int c = b;

— end note]

An immediate invocation (7.7) that is not evaluated where it appears (9.3.4.7, 11.4.1) is evaluated and checked for whether it is a constant expression at the point where the enclosing initializer is used in a function call, a constructor definition, or an aggregate initialization.

An initializer-clause followed by an ellipsis is a pack expansion (13.7.4).

Initialization includes the evaluation of all subexpressions of each initializer-clause of the initializer (possibly nested within braced-init-lists) and the creation of any temporary objects for function arguments or return values (6.7.7).

If the initializer is a parenthesized expression-list, the expressions are evaluated in the order specified for function calls (7.6.1.3).

The same identifier shall not appear in multiple designators of a designated-initializer-list.

An object whose initialization has completed is deemed to be constructed, even if the object is of non-class type or no constructor of the object’s class is invoked for the initialization.

[Note 9: Such an object might have been value-initialized or initialized by aggregate initialization (9.4.2) or by an inherited constructor (11.9.4). — end note]

Destroying an object of class type invokes the destructor of the class. Destroying a scalar type has no effect other than ending the lifetime of the object (6.7.3). Destroying an array destroys each element in reverse subscript order.

A declaration that specifies the initialization of a variable, whether from an explicit initializer or by default-initialization, is called the initializing declaration of that variable.
[Note 10: In most cases this is the defining declaration (6.2) of the variable, but the initializing declaration of a non-inline static data member (11.4.9.3) can be the declaration within the class definition and not the definition (if any) outside it. —end note]

9.4.2 Aggregates

An aggregate is an array or a class (Clause 11) with

1. no user-declared or inherited constructors (11.4.5),
2. no private or protected direct non-static data members (11.8),
3. no private or protected direct base classes (11.8.3), and
4. no virtual functions (11.7.3) or virtual base classes (11.7.2).

[Note 1: Aggregate initialization does not allow accessing protected and private base class’ members or constructors. —end note]

The elements of an aggregate are:

1. for an array, the array elements in increasing subscript order, or
2. for a class, the direct base classes in declaration order, followed by the direct non-static data members (11.4) that are not members of an anonymous union, in declaration order.

When an aggregate is initialized by an initializer list as specified in 9.4.5, the elements of the initializer list are taken as initializers for the elements of the aggregate. The explicitly initialized elements of the aggregate are determined as follows:

1. If the initializer list is a brace-enclosed designated-initializer-list, the aggregate shall be of class type, the identifier in each designator shall name a direct non-static data member of the class, and the explicitly initialized elements of the aggregate are the elements that are, or contain, those members.

2. Otherwise, the initializer list must be {}, and there are no explicitly initialized elements.

For each explicitly initialized element:

1. If the element is an anonymous union member and the initializer list is a brace-enclosed designated-initializer-list, the element is initialized by the braced-init-list { D }, where D is the designated-initializer-clause naming a member of the anonymous union member. There shall be only one such designated-initializer-clause.

[Example 1:

```c
struct C {
    union {
        int a;
        const char* p;
    };
    int x;
} c = { .a = 1, .x = 3 };
initializes c.a with 1 and c.x with 3. —end example]
```

2. Otherwise, if the initializer list is a brace-enclosed designated-initializer-list, the element is initialized with the brace-or-equal-initializer of the corresponding designated-initializer-clause. If that initializer is of the form = assignment-expression and a narrowing conversion (9.4.5) is required to convert the expression, the program is ill-formed.

[Note 2: The form of the initializer determines whether copy-initialization or direct-initialization is performed. —end note]

3. Otherwise, the initializer list is a brace-enclosed initializer-list. If an initializer-clause appertains to the aggregate element, then the aggregate element is copy-initialized from the initializer-clause. Otherwise, the aggregate element is copy-initialized from a brace-enclosed initializer-list consisting of all of the initializer-clauses that appertain to subobjects of the aggregate element, in the order of appearance.

[Note 3: If an initializer is itself an initializer list, the element is list-initialized, which will result in a recursive application of the rules in this subclause if the element is an aggregate. —end note]
[Example 2:

```c
struct A {
    int x;
    struct B {
        int i;
        int j;
    } b;
} a = { 1, { 2, 3 } };
```

initializes `a.x` with 1, `a.b.i` with 2, and `a.b.j` with 3.

```c
struct base1 { int b1, b2 = 42; };
struct base2 {
    base2() {
        b3 = 42;
    }
    int b3;
};
struct derived : base1, base2 {
    int d;
};
```

d1 = {{1, 2}, {}, 4};
d2 = {{}, {}, 4};

initializes `d1.b1` with 1, `d1.b2` with 2, `d1.b3` with 42, `d1.d` with 4, and `d2.b1` with 0, `d2.b2` with 42, `d2.b3` with 42, and `d2.d` with 4. —end example]

5 For a non-union aggregate, each element that is not an explicitly initialized element is initialized as follows:

- If the element has a default member initializer (11.4), the element is initialized from that initializer.
- Otherwise, if the element is not a reference, the element is copy-initialized from an empty initializer list (9.4.5).
- Otherwise, the program is ill-formed.

If the aggregate is a union and the initializer list is empty, then

- if any variant member has a default member initializer, that member is initialized from its default member initializer;
- otherwise, the first member of the union (if any) is copy-initialized from an empty initializer list.

6 [Example 3:

```c
struct S { int a; const char* b; int c; int d = b[a]; };
S ss = { 1, "asdf" };
```

initializes `ss.a` with 1, `ss.b` with "asdf", `ss.c` with the value of an expression of the form `int{}` (that is, 0), and `ss.d` with the value of `ss.b[ss.a]` (that is, 's').

```c
struct A {
    string a;
    int b = 42;
    int c = -1;
};
```

A{.c=21} has the following steps:

- Initialize `a` with `{}`
- Initialize `b` with 42
- Initialize `c` with 21

—end example]

7 The initializations of the elements of the aggregate are evaluated in the element order. That is, all value computations and side effects associated with a given element are sequenced before those of any element that follows it in order.

8 An aggregate that is a class can also be initialized with a single expression not enclosed in braces, as described in 9.4.
The destructor for each element of class type other than an anonymous union member is potentially invoked (11.4.7) from the context where the aggregate initialization occurs.

[Note 4: This provision ensures that destructors can be called for fully-constructed subobjects in case an exception is thrown (14.3). — end note]

The number of elements (9.3.4.5) in an array of unknown bound initialized with a brace-enclosed initializer-list is the number of explicitly initialized elements of the array.

[Example 4:
    int x[] = { 1, 3, 5 };
declares and initializes x as a one-dimensional array that has three elements since no size was specified and there are three initializers. — end example]

[Example 5: In
    struct X { int i, j, k; };
    X a[] = { 1, 2, 3, 4, 5, 6 };
    X b[2] = { { 1, 2, 3 }, { 4, 5, 6 } };
a and b have the same value. — end example]

An array of unknown bound shall not be initialized with an empty braced-init-list {}.

[Note 5: A default member initializer does not determine the bound for a member array of unknown bound. Since the default member initializer is ignored if a suitable mem-initializer is present (11.9.3), the default member initializer is not considered to initialize the array of unknown bound.

[Example 6:
    struct S {
        int y[] = { 0 }; // error: non-static data member of incomplete type
    };
    — end example]

— end note]

Static data members, non-static data members of anonymous union members, and unnamed bit-fields are not considered elements of the aggregate.

[Example 7:
    struct A {
        int i;
        static int s;
        int j;
        int :17;
        int k;
    } a = { 1, 2, 3 }; Here, the second initializer 2 initializes a.j and not the static data member A::s, and the third initializer 3 initializes a.k and not the unnamed bit-field before it. — end example]

— end note]

If a member has a default member initializer and a potentially-evaluated subexpression thereof is an aggregate initialization that would use that default member initializer, the program is ill-formed.

[Example 8:
    struct A;
    extern A a;
    struct A {
        const & a1 { A(a, a) }; // OK
        const & a2 { A() }; // error
    };
    A a(a, a); // OK
    struct B {
        int n = B{}.n; // error
    };
    — end example]

80) The syntax provides for empty braced-init-lists, but nonetheless C++ does not have zero length arrays.
When initializing a multidimensional array, the *initializer-clauses* initialize the elements with the last (rightmost) index of the array varying the fastest (9.3.4.5).

**Example 9**:  
```cpp
int x[2][2] = { 3, 1, 4, 2 };
```
initializes \( x[0][0] \) to 3, \( x[0][1] \) to 1, \( x[1][0] \) to 4, and \( x[1][1] \) to 2. On the other hand,

```cpp
float y[4][3] = {
  { 1 }, { 2 }, { 3 }, { 4 }
};
```
initializes the first column of \( y \) (regarded as a two-dimensional array) and leaves the rest zero.  — *end example*

Each *initializer-clause* in a brace-enclosed *initializer-list* is said to *appertain* to an element of the aggregate being initialized or to an element of one of its subaggregates. Considering the sequence of *initializer-clauses*, and the sequence of aggregate elements initially formed as the sequence of elements of the aggregate being initialized and potentially modified as described below, each *initializer-clause* appertains to the corresponding aggregate element if

1. the aggregate element is not an aggregate, or
2. the *initializer-clause* begins with a left brace, or
3. the *initializer-clause* is an expression and an implicit conversion sequence can be formed that converts the expression to the type of the aggregate element, or
4. the aggregate element is an aggregate that itself has no aggregate elements.

Otherwise, the aggregate element is an aggregate and that subaggregate is replaced in the list of aggregate elements by the sequence of its own aggregate elements, and the appertainment analysis resumes with the first such element and the same *initializer-clause*.

[Note 7: These rules apply recursively to the aggregate's subaggregates.]

**Example 10**: In

```cpp
struct S1 { int a, b; };
struct S2 { S1 s, t; };

S2 x[2] = { 1, 2, 3, 4, 5, 6, 7, 8 };
S2 y[2] = {
  {
    { 1, 2 },
    { 3, 4 }
  },
  {
    { 5, 6 },
    { 7, 8 }
  }
};
```

\( x \) and \( y \) have the same value.  — *end example*

— *end note*

This process continues until all *initializer-clauses* have been exhausted. If any *initializer-clause* remains that does not appertain to an element of the aggregate or one of its subaggregates, the program is ill-formed.

**Example 11**:  
```cpp
char cv[4] = { 'a', 's', 'd', 'f', 0 };  // error: too many initializers
```

— *end example*

**Example 12**:  
```cpp
float y[4][3] = {
  { 1, 3, 5 },
  { 2, 4, 6 },
  { 3, 5, 7 },
};
```
is a completely-braced initialization: 1, 3, and 5 initialize the first row of the array \( y[0] \), namely \( y[0][0] \), \( y[0][1] \), and \( y[0][2] \). Likewise the next two lines initialize \( y[1] \) and \( y[2] \). The initializer ends early and therefore \( y[3]\)'s
elements are initialized as if explicitly initialized with an expression of the form float(), that is, are initialized with 0.0. In the following example, braces in the initializer-list are elided; however the initializer-list has the same effect as the completely-braced initializer-list of the above example,

```c
float y[4][3] = {
    1, 3, 5, 2, 4, 6, 3, 5, 7
};
```

The initializer for y begins with a left brace, but the one for y[0] does not, therefore three elements from the list are used. Likewise the next three are taken successively for y[1] and y[2]. **— end example**

[Note 8: The initializer for an empty subaggregate is needed if any initializers are provided for subsequent elements.]

**Example 13:**
```c
struct S { } s;
struct A {
    S s1;
    int i1;
    S s2;
    int i2;
    S s3;
    int i3;
} a = {
    { },       // Required initialization
    0,
    s,          // Required initialization
    0
};          // Initialization not required for A::s3 because A::i3 is also not initialized
```

**— end example**

[Note 9: An aggregate array or an aggregate class can contain elements of a class type with a user-declared constructor (11.4.5). Initialization of these aggregate objects is described in 11.9.2. **— end note**]

[Note 10: Whether the initialization of aggregates with static storage duration is static or dynamic is specified in 6.9.3.2, 6.9.3.3, and 8.8. **— end note**]

When a union is initialized with an initializer list, there shall not be more than one explicitly initialized element.

**Example 15:**
```c
union u { int a; const char* b; }
union u a = { 1 },
             u b = a;
            u c = 1;      // error
            u d = { 0, "asdf" };  // error
            u e = { "asdf" };      // error
            u f = { .b = "asdf" };  // error
            u g = { .a = 1, .b = "asdf" }; // error
```

**— end example**

[Note 11: As described above, the braces around the initializer-clause for a union member can be omitted if the union is a member of another aggregate. **— end note**]
9.4.3 Character arrays

An array of ordinary character type (6.8.2), char8_t array, char16_t array, char32_t array, or wchar_t array may be initialized by an ordinary string literal, UTF-8 string literal, UTF-16 string literal, UTF-32 string literal, or wide string literal, respectively, or by an appropriately-typed string-literal enclosed in braces (5.13.5). Additionally, an array of char or unsigned char may be initialized by a UTF-8 string literal, or by such a string literal enclosed in braces. Successive characters of the value of the string-literal initialize the elements of the array, with an integral conversion (7.3.9) if necessary for the source and destination value.

[Example 1:
  char msg[] = "Syntax error on line %s\n";
shows a character array whose members are initialized with a string-literal. Note that because ‘\n’ is a single character and because a trailing ‘\0’ is appended, sizeof(msg) is 25. — end example]

2 There shall not be more initializers than there are array elements.

[Example 2:
  char cv[4] = "asdf";  // error
is ill-formed since there is no space for the implied trailing ‘\0’. — end example]

3 If there are fewer initializers than there are array elements, each element not explicitly initialized shall be zero-initialized (9.4).

9.4.4 References

A variable whose declared type is “reference to T” (9.3.4.3) shall be initialized.

[Example 1:
  int g(int) noexcept;
  void f() {
    int i;
    int& r = i;  // r refers to i
    r = 1;   // the value of i becomes 1
    int* p = &r;  // p points to i
    int& rr = r;  // rr refers to what r refers to, that is, to i
    int (&rg)(int) = g;  // rg refers to the function g
    rg(1);  // calls function g
    int a[3];
    int (&ra)[3] = a;  // ra refers to the array a
    ra[1] = i;  // modifies a[1]
  }
— end example]

2 A reference cannot be changed to refer to another object after initialization.

[Note 1: Assignment to a reference assigns to the object referred to by the reference (7.6.19). — end note]

Argument passing (7.6.1.3) and function value return (8.7.4) are initializations.

3 The initializer can be omitted for a reference only in a parameter declaration (9.3.4.6), in the declaration of a function return type, in the declaration of a class member within its class definition (11.4), and where the extern specifier is explicitly used.

[Example 2:
  int& r1;  // error: initializer missing
  extern int& r2;  // OK
— end example]

4 Given types “cv1 T1” and “cv2 T2”, “cv1 T1” is reference-related to “cv2 T2” if T1 is similar (7.3.6) to T2, or T1 is a base class of T2. “cv1 T1” is reference-compatible with “cv2 T2” if a prvalue of type “pointer to cv2 T2” can be converted to the type “pointer to cv1 T1” via a standard conversion sequence (7.3). In all cases where the reference-compatible relationship of two types is used to establish the validity of a reference binding and the standard conversion sequence would be ill-formed, a program that necessitates such a binding is ill-formed.

5 A reference to type “cv1 T1” is initialized by an expression of type “cv2 T2” as follows:

(5.1) — If the reference is an lvalue reference and the initializer expression
— is an lvalue (but is not a bit-field), and “cv1 T1” is reference-compatible with “cv2 T2”, or
— has a class type (i.e., T2 is a class type), where T1 is not reference-related to T2, and can be
converted to an lvalue of type “cv3 T3”, where “cv1 T1” is reference-compatible with “cv3 T3”\(^{81}\)
(this conversion is selected by enumerating the applicable conversion functions (12.2.2.7) and
choosing the best one through overload resolution (12.2)),
then the reference binds to the initializer expression lvalue in the first case and to the lvalue result
of the conversion in the second case (or, in either case, to the appropriate base class subobject of
the object).

[Note 2: The usual lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard
conversions are not needed, and therefore are suppressed, when such direct bindings to lvalues are done. — end
note]

[Example 3:]

double d = 2.0;
double& rd = d; // rd refers to d
const double& rcd = d; // rcd refers to d

struct A { };
struct B : A { operator int&(); } b;
A& ra = b; // ra refers to A subobject in b
const & rca = b; // rca refers to A subobject in b
int& ir = B(); // ir refers to the result of B::operator int&
— end example]

— Otherwise, if the reference is an lvalue reference to a type that is not const-qualified or is volatile-qualified,
the program is ill-formed.

[Example 4:

double& rd2 = 2.0; // error: not an lvalue and reference not const
int i = 2;
double& rd3 = i; // error: type mismatch and reference not const
— end example]

— Otherwise, if the initializer expression
— is an rvalue (but not a bit-field) or an lvalue of function type and “cv1 T1” is reference-compatible
with “cv2 T2”, or
— has a class type (i.e., T2 is a class type), where T1 is not reference-related to T2, and can be
converted to an rvalue of type “cv3 T3” or an lvalue of function type “cv3 T3”, where “cv1 T1” is
reference-compatible with “cv3 T3” (see 12.2.2.7),
then the initializer expression in the first case and the converted expression in the second case is called
the converted initializer. If the converted initializer is a prvalue, let its type be denoted by T4; the
temporary materialization conversion (7.3.5) is applied, considering the type of the prvalue to be “cv1 T4” (7.3.6). In any case, the reference binds to the resulting glvalue (or to an appropriate base class
subobject).

[Example 5:

struct A { };
struct B : A { } b;
extern B f();
const & rca2 = f(); // binds to the A subobject of the B rvalue.
A&& rra = f(); // same as above
struct X {
operator B();
operator int&();
} x;
const & x = x; // binds to the A subobject of the result of the conversion
int i2 = 42;
int&& rri = static_cast<int&&>(i2); // binds directly to i2
B&& rrb = x; // binds directly to the result of operator B

\(^{81}\) This requires a conversion function (11.4.8.3) returning a reference type.
constexpr int f() {
    const int &x = 42;
    const_cast<int &>(x) = 1;  // undefined behavior
    return x;
}

constexpr int z = f();  // error: not a constant expression
— end example

— Otherwise, \( T_1 \) shall not be reference-related to \( T_2 \).

— If \( T_1 \) or \( T_2 \) is a class type, user-defined conversions are considered using the rules for copy-initialization of an object of type "\( cv_1 T_1 \)" by user-defined conversion (9.4, 12.2.2.5, 12.2.2.6); the program is ill-formed if the corresponding non-reference copy-initialization would be ill-formed. The result of the call to the conversion function, as described for the non-reference copy-initialization, is then used to direct-initialize the reference. For this direct-initialization, user-defined conversions are not considered.

— Otherwise, the initializer expression is implicitly converted to a prvalue of type "\( T_1 \)". The temporary materialization conversion is applied, considering the type of the prvalue to be "\( cv_1 T_1 \)". In all cases except the last (i.e., implicitly converting the initializer expression to the referenced type), the reference is said to bind directly to the initializer expression.

Note 3: 6.7.7 describes the lifetime of temporaries bound to references. — end note

9.4.5 List-initialization

List-initialization is initialization of an object or reference from a braced-init-list. Such an initializer is called an initializer list, and the comma-separated initializer-clauses of the initializer-list or designated-initializer-clauses of the designated-initializer-list are called the elements of the initializer list. An initializer list may be empty. List-initialization can occur in direct-initialization or copy-initialization contexts; list-initialization in a direct-initialization context is called direct-list-initialization and list-initialization in a copy-initialization context is called copy-list-initialization. Direct-initialization that is not list-initialization is called direct-non-list-initialization.

Note 1: List-initialization can be used

1 as the initializer in a variable definition (9.4).

constexpr int f() {
    const int &x = 42;
    const_cast<int &>(x) = 1;  // undefined behavior
    return x;
}

constexpr int z = f();  // error: not a constant expression
— end example

(5.4) Otherwise, \( T_1 \) shall not be reference-related to \( T_2 \).

(5.4.1) If \( T_1 \) or \( T_2 \) is a class type, user-defined conversions are considered using the rules for copy-initialization of an object of type "\( cv_1 T_1 \)" by user-defined conversion (9.4, 12.2.2.5, 12.2.2.6); the program is ill-formed if the corresponding non-reference copy-initialization would be ill-formed. The result of the call to the conversion function, as described for the non-reference copy-initialization, is then used to direct-initialize the reference. For this direct-initialization, user-defined conversions are not considered.

(5.4.2) Otherwise, the initializer expression is implicitly converted to a prvalue of type "\( T_1 \)". The temporary materialization conversion is applied, considering the type of the prvalue to be "\( cv_1 T_1 \)". In all cases except the last (i.e., implicitly converting the initializer expression to the referenced type), the reference is said to bind directly to the initializer expression.

Example 6:

```cpp
struct Banana { }
struct Enigma { operator const Banana(); }
struct Alaska { operator Banana&(); }
void enigmatic() {
    typedef const Banana ConstBanana;
    Banana &&banana1 = ConstBanana();  // error
    Banana &&banana2 = Enigma();  // error
    Banana &&banana3 = Alaska();  // error
}

const double& rcd2 = 2;  // rcd2 refers to temporary with type const double and value 2.0
double&& rrd = 2;  // rrd refers to temporary with value 2.0
const volatile int cvi = 1;
const int& r2 = cvi;  // error: cv-qualifier dropped
struct A { operator volatile int&(); } a;
const int& r3 = a;  // error: cv-qualifier dropped
    // from result of conversion function
double d2 = 1.0;
double&& rrd2 = d2;  // error: initializer is lvalue of reference-related type
struct X { operator int&(); };
int&& rri2 = X();  // error: result of conversion function is
    // lvalue of reference-related type
int i3 = 2;
double&& rrd3 = i3;  // rrd3 refers to temporary with value 2.0
— end example
```

In all cases except the last (i.e., implicitly converting the initializer expression to the referenced type), the reference is said to bind directly to the initializer expression.
— as the initializer in a *new-expression* (7.6.2.8),
— in a *return* statement (8.7.4),
— as a *for-range-initializer* (8.6),
— as a function argument (7.6.1.3),
— as a *mem-initializer* (11.9.3), or
— on the right-hand side of an assignment (7.6.19).

**Example 1:**

```cpp
int a = {1};
std::complex<double> z{1,2};
new std::vector<std::string> {"once", "upon", "a", "time"}; // 4 string elements
f ({"Nicholas","Annemarie"}); // pass list of two elements
return { "Norah" }; // return list of one element
int* e {};
// initialization to zero / null pointer
x = double{1}; // explicitly construct a double
std::map<std::string,int> anim = { {"bear",4}, {"cassowary",2}, {"tiger",7} };
```

**Example 2:**

```cpp
struct A { int x; int y; int z; };
A a {.y = 2, .x = 1}; // error: designator order does not match declaration order
A b {.x = 1, .z = 2}; // OK, b.y initialized to 0
```

**Example 3:**

```cpp
double ad[] = { 1, 2.0 }; // OK
int ai[] = { 1, 2.0 }; // error: narrowing
```
struct S2 {
    int m1;
    double m2, m3;
};
S2 s21 = { 1, 2, 3.0 };  // OK
S2 s22 { 1.0, 2, 3 };    // error: narrowing
S2 s23 { };            // OK, default to 0,0,0
— end example

(3.5) — Otherwise, if the initializer list has no elements and T is a class type with a default constructor, the object is value-initialized.

(3.6) — Otherwise, if T is a specialization of std::initializer_list, the object is constructed as described below.

(3.7) — Otherwise, if T is a class type, constructors are considered. The applicable constructors are enumerated and the best one is chosen through overload resolution (12.2, 12.2.2.8). If a narrowing conversion (see below) is required to convert any of the arguments, the program is ill-formed.

[Example 4]:
struct S {
    S(std::initializer_list<double>); // #1
    S(std::initializer_list<int>);    // #2
    S(std::initializer_list<S>);      // #3
    S();                             // #4
    // ...
    S s1 = { 1.0, 2.0, 3.0 };        // invoke #1
    S s2 = { 1, 2, 3 };              // invoke #2
    S s3{s2};                       // invoke #3 (not the copy constructor)
    S s4 = { };                     // invoke #4
— end example

[Example 5]:
struct Map {
    Map(std::initializer_list<std::pair<std::string, int>>);  // #1
};
Map ship = {{"Sophie",14},{"Surprise",28}};
— end example

[Example 6]:
struct S {
    // no initializer-list constructors
    S(int, double, double);       // #1
    S();                          // #2
    // ...
    S s1 = { 1, 2, 3.0 };         // OK, invoke #1
    S s2 { 1.0, 2, 3 };           // error: narrowing
    S s3 { };                     // OK, invoke #2
— end example

(3.8) — Otherwise, if T is an enumeration with a fixed underlying type (9.7.1) U, the initializer-list has a single element v of scalar type, v can be implicitly converted to U, and the initialization is direct-list-initialization, the object is initialized with the value T(v) (7.6.1.4); if a narrowing conversion is required to convert v to U, the program is ill-formed.

[Example 7]:
enum byte : unsigned char { };  
byte b { 42 };                      // OK
byte c = { 42 };                    // error
byte d = byte{ 42 };                // OK; same value as b
byte e { -1 };                      // error
```c
struct A { byte b; };  
A a1 = { { 42 } };  // error  
A a2 = { byte( 42 ) };  // OK  

void f(byte);  
f( { 42 } );  // error  

enum class Handle : uint32_t { Invalid = 0 };  
Handle h { 42 };  // OK
```

(3.9) — Otherwise, if the initializer list is not a designated-initializer-list and has a single element of type E and either T is not a reference type or its referenced type is reference-related to E, the object or reference is initialized from that element (by copy-initialization for copy-list-initialization, or by direct-initialization for direct-list-initialization); if a narrowing conversion (see below) is required to convert the element to T, the program is ill-formed.

[Example 8]:
```c
int x1 {2};  // OK  
int x2 {2.0};  // error: narrowing  
```

— end example

(3.10) — Otherwise, if T is a reference type, a prvalue is generated. The prvalue initializes its result object by copy-list-initialization from the initializer list. The prvalue is then used to direct-initialize the reference. The type of the prvalue is the type referenced by T, unless T is “reference to array of unknown bound of U”, in which case the type of the prvalue is the type of x in the declaration U x[] H, where H is the initializer list.

[Note 3: As usual, the binding will fail and the program is ill-formed if the reference type is an lvalue reference to a non-const type. — end note]

[Example 9]:
```c
struct S {
    S(std::initializer_list<double>);  // #1  
    S(const std::string&);  // #2  
    // ...
};
const S& r1 = { 1, 2, 3.0 };  // OK, invoke #1  
const S& r2 { "Spinach" };  // OK, invoke #2  
S& r3 = { 1, 2, 3 };  // error: initializer is not an value  
const int& i1 = { 1 };  // OK  
const int& i2 = { 1.1 };  // error: narrowing  
const int (&iar)[2] = { 1, 2 };  // OK, iar is bound to temporary array
```

— end example

(3.11) — Otherwise, if the initializer list has no elements, the object is value-initialized.

[Example 10]:
```c
int** pp {};  // initialized to null pointer  
```

— end example

(3.12) — Otherwise, the program is ill-formed.

[Example 11]:
```c
struct A { int i; int j; };  
A a1 { 1, 2 };  // aggregate initialization  
A a2 { 1.2 };  // error: narrowing
```

§ 9.4.5 ©ISO/IEC 231
struct B {
    B(std::initializer_list<int>);
};
B b1 { 1, 2 }; // creates initializer_list<int> and calls constructor
B b2 { 1, 2.0 }; // error: narrowing
struct C {
    C(int i, double j);
};
C c1 = { 1, 2.2 }; // calls constructor with arguments (1, 2.2)
C c2 = { 1.1, 2 }; // error: narrowing
int j { 1 }; // initialize to 1
int k { }; // initialize to 0
—end example]

4 Within the initializer-list of a braced-init-list, the initializer-clauses, including any that result from pack expansions (13.7.4), are evaluated in the order in which they appear. That is, every value computation and side effect associated with a given initializer-clause is sequenced before every value computation and side effect associated with any initializer-clause that follows it in the comma-separated list of the initializer-list.
[Note 4: This evaluation ordering holds regardless of the semantics of the initialization; for example, it applies when the elements of the initializer-list are interpreted as arguments of a constructor call, even though ordinarily there are no sequencing constraints on the arguments of a call. —end note]

5 An object of type std::initializer_list<E> is constructed from an initializer list as if the implementation generated and materialized (7.3.5) a prvalue of type “array of N const E”, where N is the number of elements in the initializer list; this is called the initializer list’s backing array. Each element of the backing array is copy-initialized with the corresponding element of the initializer list, and the std::initializer_list<E> object is constructed to refer to that array.
[Note 5: A constructor or conversion function selected for the copy needs to be accessible (11.8) in the context of the initializer list. —end note]

If a narrowing conversion is required to initialize any of the elements, the program is ill-formed.
[Note 6: Backing arrays are potentially non-unique objects (6.7.2). —end note]

6 The backing array has the same lifetime as any other temporary object (6.7.7), except that initializing an initializer_list object from the array extends the lifetime of the array exactly like binding a reference to a temporary.

[Example 12:

void f(std::initializer_list<double> il);
void g(float x) {
    f({1, x, 3});
}
void h() {
    f({1, 2, 3});
}

struct A {
    mutable int i;
};
void q(std::initializer_list<A>);
void r() {
    q({A{1}, A{2}, A{3}});
}

The initialization will be implemented in a way roughly equivalent to this:

void g(float x) {
    const double __a[3] = {double{1}, double{x}, double{3}}; // backing array
    f(std::initializer_list<double>(__a, __a+3));
}
void h() {
    static constexpr double __b[3] = {double{1}, double{2}, double{3}}; // backing array
    f(std::initializer_list<double>(__b, __b+3));
}
```cpp
void r() {
    const A __c[3] = {A{1}, A{2}, A{3}}; // backing array
    q(std::initializer_list<A>(__c, __c+3));
}
```

assuming that the implementation can construct an `initializer_list` object with a pair of pointers, and with the understanding that `__b` does not outlive the call to `f`. — end example

[Example 13:]

typedef std::complex<double> cmplx;
std::vector<cmplx> v1 = { 1, 2, 3 };

void f() {
    std::vector<cmplx> v2{ 1, 2, 3 };
    std::initializer_list<int> i3 = { 1, 2, 3 };
}

struct A {
    std::initializer_list<int> i4;
    A() : i4{ 1, 2, 3 } {} // ill-formed, would create a dangling reference
};

For `v1` and `v2`, the `initializer_list` object is a parameter in a function call, so the array created for `{ 1, 2, 3 }` has full-expression lifetime. For `i3`, the `initializer_list` object is a variable, so the array persists for the lifetime of the variable. For `i4`, the `initializer_list` object is initialized in the constructor’s `ctor-initializer` as if by binding a temporary array to a reference member, so the program is ill-formed (11.9.3). — end example

7 A narrowing conversion is an implicit conversion

   (7.1) — from a floating-point type to an integer type, or

   (7.2) — from a floating-point type `T` to another floating-point type whose floating-point conversion rank is neither greater than nor equal to that of `T`, except where the result of the conversion is a constant expression and either its value is finite and the conversion did not overflow, or the values before and after the conversion are not finite, or

   (7.3) — from an integer type or unscoped enumeration type to a floating-point type, except where the source is a constant expression and the actual value after conversion will fit into the target type and will produce the original value when converted back to the original type, or

   (7.4) — from an integer type or unscoped enumeration type to an integer type that cannot represent all the values of the original type, except where

   (7.4.1) — the source is a bit-field whose width `w` is less than that of its type (or, for an enumeration type, its underlying type) and the target type can represent all the values of a hypothetical extended integer type with width `w` and with the same signedness as the original type or

   (7.4.2) — the source is a constant expression whose value after integral promotions will fit into the target type, or

   (7.5) — from a pointer type or a pointer-to-member type to `bool`.

[Note 7: As indicated above, such conversions are not allowed at the top level in list-initializations. — end note]

[Example 14:

```cpp
int x = 999; // x is not a constant expression
const int y = 999;
const int z = 99;
char c1 = x; // OK, though it potentially narrows (in this case, it does narrow)
char c2(x);
    // error: potentially narrows
char c3(y);
    // error: narrows (assuming char is 8 bits)
char c4(z);
    // OK, no narrowing needed
unsigned char uc1 = {5}; // OK, no narrowing needed
unsigned char uc2 = {-1}; // error: narrows
unsigned int ui1 = (-1); // error: narrows
signed int si1 = { (unsigned int)-1 ]; // error: narrows
int ii = {2.0}; // error: narrows
float f1 { x }; // error: potentially narrows
```
float f2 { 7 }; // OK, 7 can be exactly represented as a float
bool b = {"meow"}; // error: narrows
int f(int);
int a[] = { 2, f(2), f(2.0) }; // OK, the double-to-int conversion is not at the top level
— end example

9.5 Function definitions [dcl.fct.def]

9.5.1 General [dcl.fct.def.general]

Function definitions have the form

\[
\text{function-definition}:
\begin{align*}
\text{attribute-specifier-seq} \opt & \text{ decl-specifier-seq} \opt \text{ declarator virt-specifier-seq} \opt \text{ function-body} \\
\text{function-body} & : \\
\text{ctor-initializer} \opt & \text{ compound-statement} \\
& = \text{ default } \\
& = \text{ deleted-function-body} \\
\text{deleted-function-body} & : \\
& = \text{ delete } \\
& = \text{ delete ( unevaluated-string ) } \\
\end{align*}
\]

Any informal reference to the body of a function should be interpreted as a reference to the non-terminal function-body, including, for a constructor, default member initializers or default initialization used to initialize a base or member subobject in the absence of a mem-initializer-id (11.9.3). The optional attribute-specifier-seq in a function-definition appertains to the function. A function-definition with a virt-specifier-seq shall be a member-declaration (11.4). A function-definition with a requires-clause shall define a templated function.

In a function-definition, either void declarator ; or declarator ; shall be a well-formed function declaration as described in 9.3.4.6. A function shall be defined only in namespace or class scope. The type of a parameter or the return type for a function definition shall not be a (possibly cv-qualified) class type that is incomplete or abstract within the function body unless the function is deleted (9.5.3).

Example 1: A simple example of a complete function definition is

\[
\text{int max(int a, int b, int c) } \{ \\
\text{ int m = (a > b) ? a : b; } \\
\text{ return (m > c) ? m : c; } \\
\} \\
\]

Here int is the decl-specifier-seq; max(int a, int b, int c) is the declarator; \{ /* ... */ \} is the function-body. — end example]

A ctor-initializer is used only in a constructor; see 11.4.5 and 11.9.

Note 1: A cv-qualifier-seq affects the type of this in the body of a member function; see 7.5.3. — end note

Note 2: Unused parameters need not be named. For example,

\[
\text{void print(int a, int) } \{ \\
\text{ std::printf("a = %d\n",a); } \\
\} \\
\]

— end note

A function-local predefined variable is a variable with static storage duration that is implicitly defined in a function parameter scope.  

The function-local predefined variable __func__ is defined as if a definition of the form

\[
\text{static const char \_\_func\_\_[]} = "\text{function-name}";
\]

had been provided, where function-name is an implementation-defined string. It is unspecified whether such a variable has an address distinct from that of any other object in the program.\[82\]

\[82\) Implementations are permitted to provide additional predefined variables with names that are reserved to the implementation (5.10). If a predefined variable is not odr-used (6.3), its string value need not be present in the program image. \]

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Example 2:

```cpp
struct S {
    S() : s(__func__) { } // OK
    const char* s;
};

void f(const char* s = __func__); // error: __func__ is undeclared

— end example
```

9.5.2 Explicitly-defaulted functions

A function definition whose function-body is of the form `= default;` is called an explicitly-defaulted definition. A function that is explicitly defaulted shall

1. be a special member function (11.4.4) or a comparison operator function (12.4.3, 11.10.1), and
2. not have default arguments (9.3.4.7).

An explicitly defaulted special member function \( F_1 \) is allowed to differ from the corresponding special member function \( F_2 \) that would have been implicitly declared, as follows:

1. \( F_1 \) and \( F_2 \) may have differing ref-qualifiers;
2. if \( F_2 \) has an implicit object parameter of type “reference to \( C \)”, \( F_1 \) may be an explicit object member function whose explicit object parameter is of (possibly different) type “reference to \( C \)”, in which case the type of \( F_1 \) would differ from the type of \( F_2 \) in that the type of \( F_1 \) has an additional parameter;
3. \( F_1 \) and \( F_2 \) may have differing exception specifications; and
4. if \( F_2 \) has a non-object parameter of type `const C&`, the corresponding non-object parameter of \( F_1 \) may be of type \( C& \).

If the type of \( F_1 \) differs from the type of \( F_2 \) in a way other than as allowed by the preceding rules, then:

1. if \( F_1 \) is an assignment operator, and the return type of \( F_1 \) differs from the return type of \( F_2 \) or \( F_1 \)'s non-object parameter type is not a reference, the program is ill-formed;
2. otherwise, if \( F_1 \) is explicitly defaulted on its first declaration, it is defined as deleted;
3. otherwise, the program is ill-formed.

A function explicitly defaulted on its first declaration is implicitly inline (9.2.8), and is implicitly constexpr (9.2.6) if it is constexpr-suitable.

[Note 1: Other defaulted functions are not implicitly constexpr. — end note]

Example 1:

```cpp
struct S {
    S(int a = 0) = default; // error: default argument
    void operator=(const S&) = default; // error: non-matching return type
    ~S() noexcept(false) = default; // OK, despite mismatched exception specification

private:
    int i;
    S(S&); // OK, private copy constructor
};

S::S(S&) = default; // OK, defines copy constructor

struct T {
    T();
    T(T&&) noexcept(false);
};

struct U {
    T t;
    U();
    U(U&&) noexcept = default;
};

U u1;
U u2 = static_cast<U&&>(u1); // OK, calls std::terminate if T::T(T&&) throws

— end example
```
Explicitly-defaulted functions and implicitly-declared functions are collectively called defaulted functions, and the implementation shall provide implicit definitions for them (11.4.5, 11.4.7, 11.4.5.3, 11.4.6) as described below, including possibly defining them as deleted. A defaulted prospective destructor (11.4.7) that is not a destructor is defined as deleted. A defaulted special member function that is neither a prospective destructor nor an eligible special member function (11.4.4) is defined as deleted. A function is user-provided if it is user-declared and not explicitly defaulted or deleted on its first declaration. A user-provided explicitly-defaulted function (i.e., explicitly defaulted after its first declaration) is implicitly defined at the point where it is explicitly defaulted; if such a function is implicitly defined as deleted, the program is ill-formed.

[Note 2: Declaring a function as defaulted after its first declaration can provide efficient execution and concise definition while enabling a stable binary interface to an evolving code base. — end note]

A non-user-provided defaulted function (i.e., implicitly declared or explicitly defaulted in the class) that is not defined as deleted is implicitly defined when it is odr-used (6.3) or needed for constant evaluation (7.7).

[Note 3: The implicit definition of a non-user-provided defaulted function does not bind any names. — end note]

[Example 2:

```cpp
struct trivial {
  trivial() = default;
  trivial(const trivial&) = default;
  trivial(trivial&&) = default;
  trivial& operator=(const trivial&) = default;
  trivial& operator=(trivial&&) = default;
  ~trivial() = default;
};

struct nontrivial1 {
  nontrivial1();
};
nontrivial1::nontrivial1() = default;  // not first declaration
```

— end example]

9.5.3 Deleted definitions

A deleted definition of a function is a function definition whose function-body is a deleted-function-body or an explicitly-defaulted definition of the function where the function is defined as deleted. A deleted function is a function with a deleted definition or a function that is implicitly defined as deleted.

A program that refers to a deleted function implicitly or explicitly, other than to declare it, is ill-formed.

Recommended practice: The resulting diagnostic message should include the text of the unevaluated-string, if one is supplied.

[Note 1: This includes calling the function implicitly or explicitly and forming a pointer or pointer-to-member to the function. It applies even for references in expressions that are not potentially-evaluated. For an overload set, only the function selected by overload resolution is referenced. The implicit odr-use (6.3) of a virtual function does not, by itself, constitute a reference. The unevaluated-string, if present, can be used to explain the rationale for deletion and/or to suggest an alternative. — end note]

[Example 1: One can prevent default initialization and initialization by non-doubles with

```cpp
struct onlydouble {
  onlydouble() = delete;  // OK, but redundant
  template<class T>
  onlydouble(T) = delete;
  onlydouble(double);
};
```

— end example]

[Example 2: One can prevent use of a class in certain new-expressions by using deleted definitions of a user-declared operator new for that class.

```cpp
struct sometype {
  void* operator new(std::size_t) = delete;
  void* operator new[](std::size_t) = delete;
};
sometype* p = new sometype;  // error: deleted class operator new
sometype* q = new sometype[3];  // error: deleted class operator new[]
```
Example 3: One can make a class uncopyable, i.e., move-only, by using deleted definitions of the copy constructor and copy assignment operator, and then providing defaulted definitions of the move constructor and move assignment operator.

```cpp
struct moveonly {
    moveonly() = default;
    moveonly(const moveonly&) = delete;
    moveonly(moveonly&&) = default;
    moveonly& operator=(const moveonly&) = delete;
    moveonly& operator=(moveonly&&) = default;
    ~moveonly() = default;
};
moveonly* p;
moveonly q(*p);  // error: deleted copy constructor
```

Example 4:

```cpp
struct sometype {
    sometype();
};
sometype::sometype() = delete;  // error: not first declaration
```

9.5.4 Coroutine definitions

A function is a coroutine if its function-body encloses a coroutine-return-statement (8.7.5), an await-expression (7.6.2.4), or a yield-expression (7.6.17). The parameter-declaration-clause of the coroutine shall not terminate with an ellipsis that is not part of a parameter-declaration.

Example 1:

```cpp
task<int> f();
task<void> g1() {
    int i = co_await f();
    std::cout << "f() => " << i << std::endl;
}
template <typename... Args>
task<void> g2(Args&&...) {
    // OK, ellipsis is a pack expansion
    int i = co_await f();
    std::cout << "f() => " << i << std::endl;
}
task<void> g3(int a, ...) {
    // error: variable parameter list not allowed
    int i = co_await f();
    std::cout << "f() => " << i << std::endl;
}
```

The promise type of a coroutine is `std::coroutine_traits<R, P1, ..., Pn>::promise_type`, where `R` is the return type of the function, and `P1 ... Pn` is the sequence of types of the non-object function parameters, preceded by the type of the object parameter (9.3.4.6) if the coroutine is a non-static member function. The promise type shall be a class type.

In the following, `Pi` is an lvalue of type `P`, where `P1` denotes the object parameter and `Pi+1` denotes the `i`th non-object function parameter for an implicit object member function, and `Pi` denotes the `i`th function parameter for a non-static member function.
A coroutine behaves as if its function-body were replaced by:

```cpp
{
    promise-type promise promise-constructor-arguments ;
    try {
        co_await promise.initial_suspend() ;
        function-body
    } catch (...) {
        if (!initial-await-resume-called)
            throw ;
        promise.unhandled_exception();
    }

    final-suspend :
    co_await promise.final_suspend();
}
```

where

1. the await-expression containing the call to `initial_suspend` is the initial await expression, and
2. the await-expression containing the call to `final_suspend` is the final await expression, and
3. `initial-await-resume-called` is initially `false` and is set to `true` immediately before the evaluation of the await-resume expression (7.6.2.4) of the initial await expression, and
4. `promise-type` denotes the promise type, and
5. the object denoted by the exposition-only name `promise` is the promise object of the coroutine, and
6. the label denoted by the name `final-suspend` is defined for exposition only (8.7.5), and
7. `promise-constructor-arguments` is determined as follows: overload resolution is performed on a promise constructor call created by assembling an argument list `q_1`...`q_n`. If a viable constructor is found (12.2.3), then `promise-constructor-arguments` is `(q_1, ..., q_n)`, otherwise `promise-constructor-arguments` is empty, and
8. a coroutine is suspended at the initial suspend point if it is suspended at the initial await expression, and
9. a coroutine is suspended at a final suspend point if it is suspended
10. at a final await expression or
11. due to an exception exiting from `unhandled_exception()`.

If searches for the names `return_void` and `return_value` in the scope of the promise type each find any declarations, the program is ill-formed.

[Note 1: If `return_void` is found, flowing off the end of a coroutine is equivalent to a `co_return` with no operand. Otherwise, flowing off the end of a coroutine results in undefined behavior (8.7.5). — end note]

The expression `promise.get_return_object()` is used to initialize the returned reference or prvalue result object of a call to a coroutine. The call to `get_return_object` is sequenced before the call to `initial_suspend` and is invoked at most once.

A suspended coroutine can be resumed to continue execution by invoking a resumption member function (17.12.4.6) of a coroutine handle (17.12.4) that refers to the coroutine. The evaluation that invoked a resumption member function is called the resumer. Invoking a resumption member function for a coroutine that is not suspended results in undefined behavior.

An implementation may need to allocate additional storage for a coroutine. This storage is known as the coroutine state and is obtained by calling a non-array allocation function (6.7.5.5.2). The allocation function’s name is looked up by searching for it in the scope of the promise type.

1. If the search finds any declarations, overload resolution is performed on a function call created by assembling an argument list. The first argument is the amount of space requested, and is a prvalue of type `std::size_t`. The lvalues `p_1`...`p_n` are the successive arguments. If no viable function is found (12.2.3), overload resolution is performed again on a function call created by passing just the amount of space required as a prvalue of type `std::size_t`. 

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If the search finds no declarations, a search is performed in the global scope. Overload resolution is performed on a function call created by passing the amount of space required as a prvalue of type `std::size_t`.

If a search for the name `get_return_object_on_allocation_failure` in the scope of the promise type (6.5.2) finds any declarations, then the result of a call to an allocation function used to obtain storage for the coroutine state is assumed to return `nullptr` if it fails to obtain storage, and if a global allocation function is selected, the `::operator new(size_t, nothrow_t)` form is used. The allocation function used in this case shall have a non-throwing `noexcept-specifier`. If the allocation function returns `nullptr`, the coroutine transfers control to the caller of the coroutine and the return value is obtained by a call to `T::get_return_object_on_allocation_failure()`, where `T` is the promise type.

Example 2:

```cpp
#include <iostream>
#include <coroutine>

// ::operator new(size_t, nothrow_t) will be used if allocation is needed
struct generator {
  struct promise_type {
    int current_value;
    static auto get_return_object_on_allocation_failure() { return generator(nullptr); }
    auto get_return_object() { return generator(handle::from_promise(*this)); }
    auto initial_suspend() { return std::suspend_always{}; }
    auto final_suspend() noexcept { return std::suspend_always{}; }
    void unhandled_exception() { std::terminate(); }
    void return_void() {}
    auto yield_value(int value) {
      current_value = value;
      return std::suspend_always{};
    }
  };
  bool move_next() { return coro ? (coro.resume(), !coro.done()) : false; }
  int current_value() { return coro.promise().current_value; }
  generator(generator const&) = delete;
  generator(generator && rhs) : coro(rhs.coro) { rhs.coro = nullptr; }
  ~generator() { if (coro) coro.destroy(); }
private:
  generator(handle h) : coro(h) {}
  handle coro;
};
generator f() { co_yield 1; co_yield 2; }
int main() {
  auto g = f();
  while (g.move_next()) std::cout << g.current_value() << std::endl;
}
```

The coroutine state is destroyed when control flows off the end of the coroutine or the `destroy` member function (17.12.4.6) of a coroutine handle (17.12.4) that refers to the coroutine is invoked. In the latter case, control in the coroutine is considered to be transferred out of the function (8.8). The storage for the coroutine state is released by calling a non-array deallocation function (6.7.5.5.3). If `destroy` is called for a coroutine that is not suspended, the program has undefined behavior.

The deallocation function’s name is looked up by searching for it in the scope of the promise type. If nothing is found, a search is performed in the global scope. If both a usual deallocation function with only a pointer parameter and a usual deallocation function with both a pointer parameter and a size parameter are found, then the selected deallocation function shall be the one with two parameters. Otherwise, the selected deallocation function shall be the function with one parameter. If no usual deallocation function is found, the program is ill-formed. The selected deallocation function shall be called with the address of the block of storage to be reclaimed as its first argument. If a deallocation function with a parameter of type `std::size_t` is used, the size of the block is passed as the corresponding argument.
When a coroutine is invoked, after initializing its parameters (7.6.1.3), a copy is created for each coroutine parameter. For a parameter of type \( cv \ T \), the copy is a variable of type \( cv \ T \) with automatic storage duration that is direct-initialized from an xvalue of type \( T \) referring to the parameter.

[Note 2: An original parameter object is never a const or volatile object (6.8.5). — end note]

The initialization and destruction of each parameter copy occurs in the context of the called coroutine. Initializations of parameter copies are sequenced before the call to the coroutine promise constructor and indeterminately sequenced with respect to each other. The lifetime of parameter copies ends immediately after the lifetime of the coroutine promise object ends.

[Note 3: If a coroutine has a parameter passed by reference, resuming the coroutine after the lifetime of the entity referred to by that parameter has ended is likely to result in undefined behavior. — end note]

If the evaluation of the expression \( promise \cdot \text{unhandled_exception()} \) exits via an exception, the coroutine is considered suspended at the final suspend point and the exception propagates to the caller or resumer.

The expression \( \text{co\_await promise} \cdot \text{final\_suspend()} \) shall not be potentially-throwing (14.5).

### 9.6 Structured binding declarations

A structured binding declaration introduces the identifiers \( v_0, v_1, v_2, \ldots \) of the attributed-identifier-list as names of structured bindings. The optional attribute-specifier-seq of an attributed-identifier appertains to the structured binding so introduced. Let \( cv \) denote the cv-qualifiers in the decl-specifier-seq and \( S \) consist of the storage-class-specifiers of the decl-specifier-seq (if any). A \( cv \) that includes volatile is deprecated; see D.4.

First, a variable with a unique name \( e \) is introduced. If the assignment-expression in the initializer has array type \( cvT \) and no ref-qualifier is present, \( e \) is defined by

\[
\begin{align*}
\text{attribute-specifier-seq}_{\text{opt}} & \quad \text{S} \quad cv \quad e; \\
\end{align*}
\]

and each element is copy-initialized or direct-initialized from the corresponding element of the assignment-expression as specified by the form of the initializer. Otherwise, \( e \) is defined as-if by

\[
\begin{align*}
\text{attribute-specifier-seq}_{\text{opt}} & \quad \text{decl-specifier-seq} \quad \text{ref-qualifier}_{\text{opt}} \quad e \quad \text{initializer}; \\
\end{align*}
\]

where the declaration is never interpreted as a function declaration and the parts of the declaration other than the declator-id are taken from the corresponding structured binding declaration. The type of the id-expression \( e \) is called \( E \).

[Note 1: \( E \) is never a reference type (7.2). — end note]

If a structured binding declaration appears as a condition, the decision variable (8.1) of the condition is \( e \).

If the initializer refers to one of the names introduced by the structured binding declaration, the program is ill-formed.

If \( E \) is an array type with element type \( T \), the number of elements in the attributed-identifier-list shall be equal to the number of elements of \( E \). Each \( v_i \) is the name of an lvalue that refers to the element \( i \) of the array and whose type is \( T \); the referenced type is \( T \).

[Note 2: The top-level cv-qualifiers of \( T \) are \( cv \). — end note]

[Example 1:]

```c
auto f() -> int(&)[2];
auto [ x, y ] = f(); \quad // x and y refer to elements in a copy of the array return value
auto& [ xr, yr ] = f(); \quad // xr and yr refer to elements in the array referred to by f’s return value

— end example]
```

Otherwise, if the qualified-id std\::tuple\_size\<E\> names a complete class type with a member named value, the expression \( \text{std} \cdot \text{tuple\_size} \cdot \text{value} \) shall be a well-formed integral constant expression and the number of elements in the attributed-identifier-list shall be equal to the value of that expression. Let \( i \) be an index prvalue of type std\::size\_<T> corresponding to \( v_i \). If a search for the name get in the scope of \( E \) (6.5.2) finds at least one declaration that is a function template whose first template parameter is a non-type parameter, the initializer is \( e \cdot \text{get} < i > () \). Otherwise, the initializer is \( \text{get} < i > (e) \), where get undergoes argument-dependent lookup (6.5.4). In either case, \( \text{get} < i > \) is interpreted as a template-id.

[Note 3: Ordinary unqualified lookup (6.5.3) is not performed. — end note]

In either case, \( e \) is an lvalue if the type of the entity \( e \) is an lvalue reference and an xvalue otherwise. Given the type \( T_i \) designated by std\::tuple\_element\<i, E\>:type and the type \( U_i \) designated by either \( T_i \& \) or...
\[ T_i && \&\&, \text{ where } U_i \text{ is an lvalue reference if the initializer is an lvalue and an rvalue reference otherwise, variables are introduced with unique names } r_i \text{ as follows:} \]

\[ S U_i r_i = \text{ initializer ;} \]

Each \( v_i \) is the name of an lvalue of type \( T_i \) that refers to the object bound to \( r_i \); the referenced type is \( T_i \). The initialization of \( e \) and any conversion of \( e \) considered as a decision variable (8.1) is sequenced before the initialization of any \( r_i \). The initialization of each \( r_i \) is sequenced before the initialization of any \( r_j \) where \( i < j \).

6 Otherwise, all of \( E \)'s non-static data members shall be direct members of \( E \) or of the same base class of \( E \), well-formed when named as \texttt{e\_name} in the context of the structured binding. \( E \) shall not have an anonymous union member, and the number of elements in the \texttt{attributed-identifier-list} shall be equal to the number of non-static data members of \( E \). Designating the non-static data members of \( E \) as \( m_0, m_1, m_2, \ldots \) (in declaration order), each \( v_i \) is the name of an lvalue that refers to the member \( m_i \) of \( e \) and whose type is that of \texttt{e\_m_i} (7.6.1.5); the referenced type is the declared type of \( m_i \) if that type is a reference type, or the type of \texttt{e\_m_i} otherwise. The lvalue is a bit-field if that member is a bit-field.

\[ \text{Example 2:} \]

\begin{verbatim}
struct S { mutable int x1 : 2; volatile double y1; }
S f();
const auto [ x, y ] = f();
\end{verbatim}

The type of the \texttt{id-expression x} is “\texttt{int}”, the type of the \texttt{id-expression y} is “\texttt{const volatile double}”. — end example]

9.7 Enumerations

9.7.1 Enumeration declarations

An enumeration is a distinct type (6.8.4) with named constants. Its name becomes an \textit{enum-name} within its scope.

\begin{verbatim}
enum-name:
  identifier

enum-specifier:
  enum-head { enumerator-list_opt }
  enum-head { enumerator-list , }

enum-head:
  enum-key attribute-specifier-seq_opt enum-head-name_opt enum-base_opt

enum-head-name:
  nested-name-specifier_opt identifier

opaque-enum-declaration:
  enum-key attribute-specifier-seq_opt enum-head-name enum-base_opt ;

enum-key:
  enum
  enum class
  enum struct

enum-base:
  : type-specifier-seq

enumerator-list:
  enumerator-definition
  enumerator-list , enumerator-definition

enumerator-definition:
  enumerator
  enumerator = constant-expression

enumerator:
  identifier attribute-specifier-seq_opt
\end{verbatim}

The optional \texttt{attribute-specifier-seq} in the \texttt{enum-head} and the \texttt{opaque-enum-declaration} appertains to the enumeration; the attributes in that \texttt{attribute-specifier-seq} are thereafter considered attributes of the enumeration whenever it is named. A : following “\texttt{enum nested-name-specifier_opt identifier}” within the \texttt{decl-specifier-seq} of a \texttt{member-declaration} is parsed as part of an \texttt{enum-base}.
Note 1: This resolves a potential ambiguity between the declaration of an enumeration with an enum-base and the declaration of an unnamed bit-field of enumeration type.

Example 1:

```c
struct S {
    enum E : int {};
    enum E : int {}; // error: redeclaration of enumeration
};
```

—end example
—end note

The identifier in an enum-head-name is not looked up and is introduced by the enum-specifier or opaque-enum-declaration. If the enum-head-name of an opaque-enum-declaration contains a nested-name-specifier, the declaration shall be an explicit specialization (13.9.4).

Example 2:

```c
enum { a, b, c=0 };
enum { d, e, f=e+2 };
```

defines a, c, and d to be zero, b and e to be 1, and f to be 3. —end example

The optional attribute-specifier-seq in an enumerator appertains to that enumerator.

Note 2: An enumeration declared by an opaque-enum-declaration has a fixed underlying type and is a complete type. The list of enumerators can be provided in a later redeclaration with an enum-specifier. —end note

A scoped enumeration shall not be later redeclared as unscoped or with a different underlying type. An unscoped enumeration shall not be later redeclared as scoped and each redeclaration shall include an enum-base specifying the same underlying type as in the original declaration.

If an enum-head-name contains a nested-name-specifier, the enclosing enum-specifier or opaque-enum-declaration D shall not inhabit a class scope and shall correspond to one or more declarations nominable in the class, class template, or namespace to which the nested-name-specifier refers (6.4.1). All those declarations shall have the same target scope; the target scope of D is that scope.

Each enumeration defines a type that is different from all other types. Each enumeration also has an underlying type. The underlying type can be explicitly specified using an enum-base. For a scoped enumeration type, the underlying type is int if it is not explicitly specified. In both of these cases, the underlying type is said to be fixed. Following the closing brace of an enum-specifier, each enumerator has the type of its enumeration. If the underlying type is fixed, the type of each enumerator prior to the closing brace is the underlying type and the constant-expression in the enumerator-definition shall be a converted constant expression of the underlying type (7.7). If the underlying type is not fixed, the type of each enumerator prior to the closing brace is determined as follows:

(5.1) — If an initializer is specified for an enumerator, the constant-expression shall be an integral constant expression (7.7). If the expression has unscoped enumeration type, the enumerator has the underlying type of that enumeration type, otherwise it has the same type as the expression.

(5.2) — If no initializer is specified for the first enumerator, its type is an unspecified signed integral type.
Otherwise the type of the enumerator is the same as that of the preceding enumerator unless the incremented value is not representable in that type, in which case the type is an unspecified integral type sufficient to contain the incremented value. If no such type exists, the program is ill-formed.

An enumeration whose underlying type is fixed is an incomplete type until immediately after its `enum-base` (if any), at which point it becomes a complete type. An enumeration whose underlying type is not fixed is an incomplete type until the closing `}` of its `enum-specifier`, at which point it becomes a complete type.

For an enumeration whose underlying type is not fixed, the underlying type is an integral type that can represent all the enumerator values defined in the enumeration. If no integral type can represent all the enumerator values, the enumeration is ill-formed. It is implementation-defined which integral type is used as the underlying type except that the underlying type shall not be larger than `int` unless the value of an enumerator cannot fit in an `int` or `unsigned int`. If the `enumerator-list` is empty, the underlying type is as if the enumeration had a single enumerator with value 0.

For an enumeration whose underlying type is fixed, the values of the enumeration are the values of the underlying type. Otherwise, the values of the enumeration are the values representable by a hypothetical integer type with minimal width $M$ such that all enumerators can be represented. The width of the smallest bit-field large enough to hold all the values of the enumeration type is $M$. It is possible to define an enumeration that has values not defined by any of its enumerators. If the `enumerator-list` is empty, the values of the enumeration are as if the enumeration had a single enumerator with value 0.\(^{83}\)

An enumeration has the same size, value representation, and alignment requirements (6.7.6) as its underlying type. Furthermore, each value of an enumeration has the same representation as the corresponding value of the underlying type. Two enumeration types are layout-compatible enumerations if they have the same underlying type.

The value of an enumerator or an object of an unscoped enumeration type is converted to an integer by integral promotion (7.3.7).

```cpp
enum color { red, yellow, green=20, blue };  
color col = red;  
color* cp = &col;  
if (*cp == blue)    // ...
```

makes `color` a type describing various colors, and then declares `col` as an object of that type, and `cp` as a pointer to an object of that type. The possible values of an object of type `color` are `red, yellow, green, blue`; these values can be converted to the integral values 0, 1, 20, and 21. Since enumerations are distinct types, objects of type `color` can be assigned only values of type `color`.

```cpp
color c = 1;    // error: type mismatch, no conversion from int to color
int i = yellow; // OK, yellow converted to integral value 1, integral promotion
```

Note that this implicit `enum to int` conversion is not provided for a scoped enumeration:

```cpp
enum class Col { red, yellow, green };  
int x = Col::red;                      // error: no Col to int conversion
Col y = Col::red;                      // error: no Col to bool conversion
```

The name of each unscoped enumerator is also bound in the scope that immediately contains the `enum-specifier`. An unnamed enumeration that does not have a typedef name for linkage purposes (9.2.4) and that has a first enumerator is denoted, for linkage purposes (6.6), by its underlying type and its first enumerator; such an enumeration is said to have an enumerator as a name for linkage purposes.

Each unnamed enumeration with no enumerators is a distinct type. — end note]

```cpp
enum direction { left='l', right='r' };  
void g() {  
direction d;                         // OK
d = left;                             // OK
```

\(^{83}\) This set of values is used to define promotion and conversion semantics for the enumeration type. It does not preclude an expression of enumeration type from having a value that falls outside this range.
d = direction::right;  // OK
}

enum class altitude { high='h', low='l' }

void h() {
    altitude a;  // OK
    a = high;  // error: high not in scope
    a = altitude::low;  // OK
}
—end example

9.7.2 The using enum declaration

using enum-declaration:
    using enum using-enum-declarator;
using-enum-declarator:
    nested-name-specifier_opt identifier
    nested-name-specifier_opt simple-template-id

A using-enum-declarator names the set of declarations found by type-only lookup (6.5.1) for the using-enum-declarator (6.5.3, 6.5.5). The using-enum-declarator shall designate a non-dependent type with a reachable enum-specifier.

[Example 1:

    enum E { x }
    void f() {
        int E;
        using enum E;  // OK
    }
    using F = E;
    using enum F;  // OK
    template<class T> using EE = T;
    void g() {
        using enum EE<E>;
    }
—end example]

A using-enum-declaration is equivalent to a using-declaration for each enumerator.

[Note 1: A using-enum-declaration in class scope makes the enumerators of the named enumeration available via member lookup.

[Example 2:

    enum class fruit { orange, apple }
    struct S {
        using enum fruit;  // OK, introduces orange and apple into S
    }
    void f() {
        S s;
        s.orange;  // OK, names fruit::orange
        S::orange;  // OK, names fruit::orange
    }
—end example]
—end note]

Two using-enum-declarations that introduce two enumerators of the same name conflict.

[Example 3:

    enum class fruit { orange, apple }
    enum class color { red, orange }
    void f() {
        using enum fruit;  // OK
        using enum color;  // error: color::orange and fruit::orange conflict
    }
]
9.8 Namespaces

9.8.1 General

1 A namespace is an optionally-named entity whose scope can contain declarations of any kind of entity. The name of a namespace can be used to access entities that belong to that namespace; that is, the members of the namespace. Unlike other entities, the definition of a namespace can be split over several parts of one or more translation units and modules.

2 [Note 1: A namespace-definition is exported if it contains any export-declarations (10.2). A namespace is never attached to a named module and never has a name with module linkage. — end note]

[Example 1:

```cpp
event module M;
namespace N1 {} // N1 is not exported
export namespace N2 {} // N2 is exported
namespace N3 { export int n; } // N3 is exported
```
—end example]

3 There is a global namespace with no declaration; see 6.4.6. The global namespace belongs to the global scope; it is not an unnamed namespace (9.8.2.2).

[Note 2: Lacking a declaration, it cannot be found by name lookup. — end note]

9.8.2 Namespace definition

9.8.2.1 General

```cpp
namespace-name:
  identifier
namespace-alias

namespace-definition:
  named-name-space-definition
  unnamed-name-space-definition
  nested-name-space-definition

named-name-space-definition:
  inline-opt namespace attribute-specifier-seq-opt identifier { namespace-body }

unnamed-name-space-definition:
  inline-opt namespace attribute-specifier-seq-opt { namespace-body }

nested-name-space-definition:
  namespace enclosing-name-space-specifier:: inline-opt identifier { namespace-body }

enclosing-name-space-specifier:
  identifier
  enclosing-name-space-specifier :: inline-opt identifier

namespace-body:
  declaration-seq-opt
```

1 Every namespace-definition shall inhabit a namespace scope (6.4.6).

2 In a named-name-space-definition D, the identifier is the name of the namespace. The identifier is looked up by searching for it in the scopes of the namespace A in which D appears and of every element of the inline namespace set of A. If the lookup finds a namespace-definition for a namespace N, D extends N, and the target scope of D is the scope to which N belongs. If the lookup finds nothing, the identifier is introduced as a namespace-name into A.

3 Because a namespace-definition contains declarations in its namespace-body and a namespace-definition is itself a declaration, it follows that namespace-declarations can be nested.

[Example 1:

```cpp
namespace Outer {
  int i;
  namespace Inner {
    void f() { i++; } // Outer::i
  }
```
]
int i;
void g() { i++; } // Inner::i
}

—end example

4 If the optional initial inline keyword appears in a namespace-definition for a particular namespace, that namespace is declared to be an inline namespace. The inline keyword may be used on a namespace-definition that extends a namespace only if it was previously used on the namespace-definition that initially declared the namespace-name for that namespace.

5 The optional attribute-specifier-seq in a named-namespace-definition appertains to the namespace being defined or extended.

6 Members of an inline namespace can be used in most respects as though they were members of the innermost enclosing namespace. Specifically, the inline namespace and its enclosing namespace are both added to the set of associated namespaces used in argument-dependent lookup (6.5.4) whenever one of them is, and a using-directive (9.8.4) that names the inline namespace is implicitly inserted into the enclosing namespace as for an unnamed namespace (9.8.2.2). Furthermore, each member of the inline namespace can subsequently be partially specialized (13.7.6), explicitly instantiated (13.9.3), or explicitly specialized (13.9.4) as though it were a member of the enclosing namespace. Finally, looking up a name in the enclosing namespace via explicit qualification (6.5.5.3) will include members of the inline namespace even if there are declarations of that name in the enclosing namespace.

7 These properties are transitive: if a namespace N contains an inline namespace M, which in turn contains an inline namespace O, then the members of O can be used as though they were members of M or N. The inline namespace set of N is the transitive closure of all inline namespaces in N.

8 A nested-namespace-definition with an enclosing-namespace-specifier E, identifier I and namespace-body B is equivalent to

namespace E { inline opt namespace I { B } }

where the optional inline appears if and only if it appears in the unnamed-namespace-definition and all occurrences of unique in a translation unit are replaced by the same identifier, and this identifier differs from all other identifiers in the translation unit. The optional attribute-specifier-seq in the unnamed-namespace-definition appertains to unique.

[Example 2:]
namespace A::inline B::C {
  int i;
}
The above has the same effect as:
namespace A {
  inline namespace B {
    namespace C {
      int i;
    }
  }
}

—end example

9.8.2.2 Unnamed namespaces

An unnamed-namespace-definition behaves as if it were replaced by

inline_opt namespace unique { /* empty body */ }
using namespace unique;
namespace unique { namespace-body }

where inline appears if and only if it appears in the unnamed-namespace-definition and all occurrences of unique in a translation unit are replaced by the same identifier, and this identifier differs from all other identifiers in the translation unit. The optional attribute-specifier-seq in the unnamed-namespace-definition appertains to unique.

[Example 1:]
namespace { int i; } // unique::i
void f() { i++; } // unique::i++
namespace A {
    namespace {
        int i;        // A::unique::i
        int j;        // A::unique::j
    }
    void g() { i++; }        // A::unique::i++
}

using namespace A;

void h() {
    i++;        // error: unique::i or A::unique::i
    A::i++;     // A::unique::i
    j++;        // A::unique::j
}

—end example

9.8.3 Namespace alias

A namespace-alias-definition declares an alternate name for a namespace according to the following grammar:

namespace-alias-definition:
    identifier

declares an alternate name for a namespace.

qualified-name-specifier:
    namespace-alias-definition
    namespace-name

The identifier in a namespace-alias-definition becomes a namespace-alias and denotes the namespace denoted by the qualified-name-specifier.

[Note 1: When looking up a namespace-name in a namespace-alias-definition, only namespace names are considered, see 6.5.7. — end note]

9.8.4 Using namespace directive

A using-directive shall not appear in class scope, but may appear in namespace scope or in block scope.

[Note 1: When looking up a namespace-name in a using-directive, only namespace names are considered, see 6.5.7. — end note]

[Note 2: A using-directive makes the names in the nominated namespace usable in the scope in which the using-directive appears after the using-directive (6.5.3, 6.5.5.3). During unqualified name lookup, the names appear as if they were declared in the nearest enclosing namespace which contains both the using-directive and the nominated namespace. — end note]

[Note 3: A using-directive does not introduce any names. — end note]

[Example 1:

namespace A {
    int i;
    namespace B {
        namespace C {
            int i;
        }
        using namespace A::B::C;
        void f1() {
            i = 5;        // OK, C::i visible in B and hides A::i
        }
    }
}

namespace D {
    using namespace B;
    using namespace C;
    void f2() {
        i = 5;        // ambiguous, B::C::i or A::i?
    }
}
```cpp
void f3() {
    i = 5;          // uses A::i
}

void f4() {
    i = 5;          // error: neither i is visible
}

4 [Note 4: A using-directive is transitive: if a scope contains a using-directive that nominates a namespace that itself contains using-directives, the namespaces nominated by those using-directives are also eligible to be considered. — end note]

[Example 2:

namespace M {
    int i;
}
namespace N {
    int i;
    using namespace M;
}
void f() {
    using namespace N;
    i = 7;          // error: both M::i and N::i are visible
}

For another example,

namespace A {
    int i;
}
namespace B {
    int i;
    int j;
    namespace C {
        namespace D {
            using namespace A;
            int j;
            int k;
            int a = i;      // B::i hides A::i
        }
        using namespace D;
        int k = 89;      // no problem yet
        int l = k;       // ambiguous: C::k or D::k
        int m = i;       // B::i hides A::i
        int n = j;       // D::j hides B::j
    }
}

5 [Note 5: Declarations in a namespace that appear after a using-directive for that namespace can be found through that using-directive after they appear. — end note]

6 [Note 6: If name lookup finds a declaration for a name in two different namespaces, and the declarations do not declare the same entity and do not declare functions or function templates, the use of the name is ill-formed (6.5). In particular, the name of a variable, function or enumerator does not hide the name of a class or enumeration declared in a different namespace. For example,

namespace A {
    class X { };  
    extern "C" int g();
    extern "C++" int h();
}
```
namespace B {
    void X(int);
    extern "C" int g();
    extern "C++" int h(int);
}
using namespace A;
using namespace B;

void f() {
    X(1); // error: name X found in two namespaces
    g();  // OK, name g refers to the same entity
    h();  // OK, overload resolution selects A::h
}
—end note]

[Note 7: The order in which namespaces are considered and the relationships among the namespaces implied by the
using-directives do not affect overload resolution. Neither is any function excluded because another has the same
signature, even if one is in a namespace reachable through using-directives in the namespace of the other. —end note]

[Example 3:]
namespace D {
    int d1;
    void f(char);
}
using namespace D;
int d1;       // OK, no conflict with D::d1

namespace E {
    int e;
    void f(int);
}

namespace D {    // namespace extension
    int d2;
    using namespace E;
    void f(int);
}

void f() {
    d1++; // error: ambiguous ::d1 or D::d1?
    ::d1++; // OK
    D::d1++; // OK
    d2++;  // OK, D::d2
    e++;   // OK, E::e
    f(1);  // error: ambiguous: D::f(int) or E::f(int)?
    f('a');  // OK, D::f(char)
}
—end example]

9.9 The using declaration

using-declaration:
    using using-declarator-list ;

using-declarator-list:
    using-declarator ...opt
    using-declarator-list , using-declarator ...opt

using-declarator:
    typename opt nested-name-specifier unqualified-id

84) During name lookup in a class hierarchy, some ambiguities can be resolved by considering whether one member hides the
other along some paths (6.5.2). There is no such disambiguation when considering the set of names found as a result of following
using-directives.
The component names of a using-declarator are those of its nested-name-specifier and unqualified-id. Each using-declarator in a using-declaration names the set of declarations found by lookup (6.5.5) for the using-declarator, except that class and enumeration declarations that would be discarded are merely ignored when checking for ambiguity (6.5), conversion function templates with a dependent return type are ignored, and certain functions are hidden as described below. If the terminal name of the using-declarator is dependent (13.8.3.2), the using-declarator is considered to name a constructor if and only if the nested-name-specifier has a terminal name that is the same as the unqualified-id. If the lookup in any instantiation finds that a using-declarator that is not considered to name a constructor does do so, or that a using-declarator that is considered to name a constructor does not, the program is ill-formed.

If the using-declarator names a constructor, it declares that the class inherits the named set of constructor declarations from the nominated base class.

[Note 1: Otherwise, the unqualified-id in the using-declarator is bound to the using-declarator, which is replaced during name lookup with the declarations it names (6.5). If such a declaration is of an enumeration, the names of its enumerators are not bound. For the keyword typename, see 13.8. — end note]

In a using-declaration used as a member-declaration, each using-declarator shall either name an enumerator or have a nested-name-specifier naming a base class of the current class (7.5.3).

[Example 1:

```
enum class button { up, down);
struct S {
    using button::up;
    button b = up;  // OK
};
```

—end example]

If a using-declarator names a constructor, its nested-name-specifier shall name a direct base class of the current class. If the immediate (class) scope is associated with a class template, it shall derive from the specified base class or have at least one dependent base class.

[Example 2:

```
struct B {
    void f(char);
    enum E { e };
    union { int x; };
};

struct C {
    int f();
};

struct D : B {
    using B::f;  // OK, B is a base of D
    using B::e;  // OK, e is an enumerator of base B
    using B::x;  // OK, x is a union member of base B
    using C::f;  // error: C isn’t a base of D
    void f(int) { f('c'); }  // calls B::f(char)
    void g(int) { g('c'); }  // recursively calls D::g(int)
};

template <typename... bases>
struct X : bases... {
    using bases::f...;
};

X<X::B, C> x;  // OK, B::f and C::f named
```

—end example]

[Note 2: Since destructors do not have names, a using-declaration cannot refer to a destructor for a base class. — end note]

If a constructor or assignment operator brought from a base class into a derived class has the signature of a copy/move constructor or assignment operator for the derived class (11.4.5.3, 11.4.6), the using-declaration

85) A using-declaration with more than one using-declarator is equivalent to a corresponding sequence of using-declarations with one using-declarator each.
does not by itself suppress the implicit declaration of the derived class member; the member from the base class is hidden or overridden by the implicitly-declared copy/move constructor or assignment operator of the derived class, as described below.

5 A `using-declaration` shall not name a `template-id`.

[Example 3:

```cpp
struct A {
    template <class T> void f(T);
    template <class T> struct X { };
};
struct B : A {
    using A::f<double>; // error
    using A::X<int>;    // error
};
```

—end example]

6 A `using-declaration` shall not name a namespace.

7 A `using-declaration` that names a class member other than an enumerator shall be a `member-declaration`.

[Example 4:

```cpp
struct X {
    int i;
    static int s;
};
void f() {
    using X::i; // error: `X::i` is a class member and this is not a member declaration.
    using X::s; // error: `X::s` is a class member and this is not a member declaration.
}
```

—end example]

8 If a declaration is named by two `using-declarators` that inhabit the same class scope, the program is ill-formed.

[Example 5:

```cpp
struct C {
    int i;
};
struct D1 : C { };
struct D2 : C { };
struct D3 : D1, D2 {
    using D1::i; // OK, equivalent to using C::i
    using D1::i; // error: duplicate
    using D2::i; // error: duplicate, also names C::i
};
```

—end example]

9 [Note 3: A `using-declarator` whose `nested-name-specifier` names a namespace does not name declarations added to the namespace after it. Thus, additional overloads added after the `using-declaration` are ignored, but default function arguments (9.3.4.7), default template arguments (13.2), and template specializations (13.7.6, 13.9.4) are considered. —end note]

[Example 6:

```cpp
namespace A {
    void f(int);
}
using A::f; // `f` is a synonym for `A::f`; that is, for `A::f(int)`.
namespace A {
    void f(char);
}
```
void foo() {
    f('a');       // calls f(int), even though f(char) exists.
}

void bar() {
    using A::f;   // f is a synonym for A::f; that is, for A::f(int) and A::f(char).
    f('a');       // calls f(char)
}

— end example]

10 If a declaration named by a using-declaration that inhabits the target scope of another declaration B potentially conflicts with it (6.4.1), and either is reachable from the other, the program is ill-formed unless B is name-independent and the using-declaration precedes B.

[Example 7:
  int _;
  void f() {
    int _;
    _ = 0;
    using ::_;  // error: using-declaration does not precede B
  }
— end example]

If two declarations named by using-declarations that inhabit the same scope potentially conflict, either is reachable from the other, and they do not both declare functions or function templates, the program is ill-formed.

[Note 4: Overload resolution possibly cannot distinguish between conflicting function declarations. — end note]

[Example 8:
namespace A {
    int x;
    int f(int);
    int g;
    void h();
}

namespace B {
    int i;
    struct g {};
    struct x {};
    void f(int);
    void f(double);
    void g(char);                               // OK, hides struct g
}

void func() {
    int i;
    using B::i;                                  // error: conflicts
    void f(char);
    using B::f;                                  // OK, each f is a function
    using B::f;
    using A::f;                                  // OK, but interferes with B::f(int)
    f(i);                                        // error: ambiguous
    static_cast<int(*)(int)>(f)(i);              // OK, calls A::f
    f(3.5);                                      // calls B::f(double)
    using B::g;
    g('a');                                      // calls B::g(char)
    struct g g1;
    using A::g;                                  // error: conflicts with B::g
    void h();
    using A::h;
    using B::x;
    using A::x;                                  // OK, hides struct B::x
    using A::x;
    x = 99;                                      // OK, does not conflict with previous using A::x
    x = 99;                                      // assigns to A::x

§ 9.9
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The set of declarations named by a using-declarator that inhabits a class `C` does not include member functions and member function templates of a base class that correspond to (and thus would conflict with) a declaration of a function or function template in `C`.

**Example 9:**

```cpp
class B {
  virtual void f(int);
  virtual void f(char);
  void g(int);
  void h(int);
};

class D : B {
  using B::f;
  void f(int); // OK, D::f(int) overrides B::f(int);
  using B::g;
  void g(char); // OK
  using B::h;
  void h(int); // OK, D::h(int) hides B::h(int)
};

void k(D* p) {
  p->f(1); // calls D::f(int)
  p->f('a'); // calls B::f(char)
  p->g(1); // calls B::g(int)
  p->g('a'); // calls D::g(char)
}

class B1 {
  B1(int);
};

class B2 {
  B2(int);
};

class D1 : B1, B2 {
  using B1::B1;
  using B2::B2;
};

D1 d1(0); // error: ambiguous

class D2 : B1, B2 {
  using B1::B1;
  using B2::B2;
  D2(int); // OK, D2::D2(int) hides B1::B1(int) and B2::B2(int)
};

D2 d2(0); // calls D2::D2(int)
```

**Note 5:** For the purpose of forming a set of candidates during overload resolution, the functions named by a using-declaration in a derived class are treated as though they were direct members of the derived class. In particular, the implicit object parameter is treated as if it were a reference to the derived class rather than to the base class (**12.2.2**). This has no effect on the type of the function, and in all other respects the function remains part of the base class.

---

Note that the example code is not included here, but it is referenced in the text. The code demonstrates the use of using-declarators to override virtual functions and hide other functions in derived classes. The example also shows how the implicit object parameter is treated differently in derived classes compared to base classes.
Constructors that are named by a *using-declaration* are treated as though they were constructors of the derived class when looking up the constructors of the derived class (6.5.5.2) or forming a set of overload candidates (12.2.2.4, 12.2.2.5, 12.2.2.8).

**Note 6**: If such a constructor is selected to perform the initialization of an object of class type, all subobjects other than the base class from which the constructor originated are implicitly initialized (11.9.4). A constructor of a derived class is sometimes preferred to a constructor of a base class if they would otherwise be ambiguous (12.2.4). — end note

In a *using-declarator* that does not name a constructor, every declaration named shall be accessible. In a *using-declarator* that names a constructor, no access check is performed.

**Note 7**: Because a *using-declarator* designates a base class member (and not a member subobject or a member function of a base class subobject), a *using-declarator* cannot be used to resolve inherited member ambiguities.

**Example 10**:

```cpp
struct A { int x();};
struct B : A {};
struct C : A {
    using A::x;
    int x(int);
};

struct D : B, C {
    using C::x;
    int x(double);
    int f(D* d) {
        return d->x();  // error: overload resolution selects A::x, but A is an ambiguous base class
    }
} — end example
 — end note
```

A *using-declaration* has the usual accessibility for a *member-declaration*. Base-class constructors considered because of a *using-declarator* are accessible if they would be accessible when used to construct an object of the base class; the accessibility of the *using-declaration* is ignored.

**Example 11**:

```cpp
class A {
private:
    void f(char);
public:
    void f(int);
protected:
    void g();
};
class B : public A {
    using A::f;  // error: A::f(char) is inaccessible
public:
    using A::g;  // B::g is a public synonym for A::g
};
— end example
```

### 9.10 The *asm* declaration

An *asm* declaration has the form

```
asm-declaration:
    attribute-specifier-seqopt asm (balanced-token-seq);
```

The *asm* declaration is conditionally-supported; any restrictions on the *balanced-token-seq* and its meaning are implementation-defined. The optional *attribute-specifier-seq* in an *asm-declaration* appertains to the *asm* declaration.

**Note 1**: Typically it is used to pass information through the implementation to an assembler. — end note
9.11 Linkage specifications

1 All functions and variables whose names have external linkage and all function types have a language linkage.

[Note 1: Some of the properties associated with an entity with language linkage are specific to each implementation and are not described here. For example, a particular language linkage might be associated with a particular form of representing names of objects and functions with external linkage, or with a particular calling convention, etc. — end note]

The default language linkage of all function types, functions, and variables is C++ language linkage. Two function types with different language linkages are distinct types even if they are otherwise identical.

2 Linkage (6.6) between C++ and non-C++ code fragments can be achieved using a linkage-specification:

```
linkage-specification:
  extern unevaluated-string { declaration-seq, opt }
  extern unevaluated-string name-declaration
```

The unevaluated-string indicates the required language linkage.

[Note 2: Escape sequences and universal-character-names have been replaced (5.13.6). — end note]

This document specifies the semantics for the unevaluated-strings "C" and "C++". Use of an unevaluated-string other than "C" or "C++" is conditionally-supported, with implementation-defined semantics.

[Note 3: Therefore, a linkage-specification with a language linkage that is unknown to the implementation requires a diagnostic. — end note]

Recommended practice: The spelling of the language linkage should be taken from the document defining that language. For example, Ada (not ADA) and Fortran or FORTRAN, depending on the vintage.

3 Every implementation shall provide for linkage to the C programming language, "C", and C++, "C++".

[Example 1:
```
complex sqrt(complex); // C++ language linkage by default
extern "C" {
  double sqrt(double); // C language linkage
}
```
—end example]

4 A module-import-declaration appearing in a linkage specification with other than C++ language linkage is conditionally-supported with implementation-defined semantics.

5 Linkage specifications nest. When linkage specifications nest, the innermost one determines the language linkage.

[Note 4: A linkage specification does not establish a scope. — end note]

A linkage-specification shall inhabit a namespace scope. In a linkage-specification, the specified language linkage applies to the function types of all function declarators and to all functions and variables whose names have external linkage.

[Example 2:
```
extern "C" // f1 and its function type have C language linkage;
void f1(void(*pf)(int)); // pf is a pointer to a C function

extern "C" typedef void FUNC();
FUNC f2; // f2 has C++ language linkage and
        // its type has C language linkage

extern "C" FUNC f3; // f3 and its type have C language linkage
void (*pf2)(FUNC*); // the variable pf2 has C++ language linkage; its type
                    // is “pointer to C++ function that takes one parameter of type
                    // pointer to C function"

extern "C" {
  static void f4(); // the name of the function f4 has internal linkage,
                    // so f4 has no language linkage; its type has C language linkage
}

extern "C" void f5() { // OK, name linkage (internal) and function type linkage (C language linkage)

  extern void f4();
```

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A C language linkage is ignored in determining the language linkage of class members, friend functions with a trailing `requires-clause`, and the function type of non-static class member functions.

[Example 3]:

```c
extern "C" typedef void FUNC_c();

class C {
  void mf1(FUNC_c*);
  // the function `mf1` and its type have C++ language linkage;
  // the parameter has type "pointer to C function"
  FUNC_c mf2;
  // the function `mf2` and its type have C++ language linkage
  static FUNC_c* q;
  // the data member `q` has C++ language linkage;
  // its type is "pointer to C function"
};

extern "C" {
  class X {
    void mf();
    // the function `mf` and its type have C++ language linkage
    void mf2(void(*)());
    // the function `mf2` has C++ language linkage;
    // the parameter has type "pointer to C function"
  }
}
```

—end example]
A declaration directly contained in a linkage-specification is treated as if it contains the `extern` specifier (9.2.2) for the purpose of determining the linkage of the declared name and whether it is a definition. Such a declaration shall not have a `storage-class-specifier`.

**Example 5:**
```c
extern "C" double f();
static double f();  // error
extern "C" int i;  // declaration
extern "C" {
  int i;  // definition
}
extern "C" static void g();  // error
```

**Note 5:** Because the language linkage is part of a function type, when indirectiong through a pointer to C function, the function to which the resulting lvalue refers is considered a C function. — end note

Linkage from C++ to objects defined in other languages and to objects defined in C++ from other languages is implementation-defined and language-dependent. Only where the object layout strategies of two language implementations are similar enough can such linkage be achieved.

### 9.12 Attributes

#### 9.12.1 Attribute syntax and semantics

Attributes specify additional information for various source constructs such as types, variables, names, blocks, or translation units.

```
attribute-specifier-seq:
  attribute-specifier-seq\_opt attribute-specifier

attribute-specifier:
  [ [ attribute-using-prefix\_opt attribute-list ] ]
  alignment-specifier

alignment-specifier:
  alignas ( type-id ...\_opt )
  alignas ( constant-expression ...\_opt )

attribute-using-prefix:
  using attribute-namespace :

attribute-list:
  attribute\_opt
  attribute-list , attribute\_opt
  attribute ...
  attribute-list , attribute ...

attribute:
  attribute-token attribute-argument-clause\_opt

attribute-token:
  identifier
  attribute-scoped-token

attribute-scoped-token:
  attribute-namespacem:: identifier

attribute-namespace:
  identifier

attribute-argument-clause:
  ( balanced-token-seq\_opt )

balanced-token-seq:
  balanced-token
  balanced-token-seq balanced-token

balanced-token:
  ( balanced-token-seq\_opt )
  [ balanced-token-seq\_opt ]
  { balanced-token-seq\_opt }
  any token other than a parenthesis, a bracket, or a brace
```
If an attribute-specifier contains an attribute-using-prefix, the attribute-list following that attribute-using-prefix shall not contain an attribute-scoped-token and every attribute-token in that attribute-list is treated as if its identifier were prefixed with \texttt{N::}; where \texttt{N} is the attribute-namespace specified in the attribute-using-prefix.

\begin{note}
This rule imposes no constraints on how an attribute-using-prefix affects the tokens in an attribute-argument-clause. — end note\end{note}

\begin{example}
\begin{verbatim}
[[using CC: opt(1), debug]] // same as [[CC::opt(1), CC::debug]]
void f() {}
[[using CC::opt(1)]] [[CC::debug]] // same as [[CC::opt(1)]] [[CC::debug]]
void g() {}
[[using CC::opt(1)]] // error: cannot combine using and scoped attribute token
void h() {}
\end{verbatim}
— end example\end{example}

\begin{note}
For each individual attribute, the form of the balanced-token-seq will be specified. — end note\end{note}

\begin{note}
In an attribute-list, an ellipsis may appear only if that attribute's specification permits it. An attribute followed by an ellipsis is a pack expansion (13.7.4). An attribute-specifier that contains no attributes has no effect. The order in which the attribute-tokens appear in an attribute-list is not significant. If a keyword (5.11) or an alternative token (5.5) that satisfies the syntactic requirements of an identifier (5.10) is contained in an attribute-token, it is considered an identifier. No name lookup (6.5) is performed on any of the identifiers contained in an attribute-token. The attribute-token determines additional requirements on the attribute-argument-clause (if any).
\end{note}

Each attribute-specifier-seq is said to appertain to some entity or statement, identified by the syntactic context where it appears (Clause 8, Clause 9, 9.3). If an attribute-specifier-seq that appertains to some entity or statement contains an attribute or alignment-specifier that is not allowed to apply to that entity or statement, the program is ill-formed. If an attribute-specifier-seq appertains to a friend declaration (11.8.4), that declaration shall be a definition.

\begin{note}
An attribute-specifier-seq cannot appertain to an explicit instantiation (13.9.3). — end note\end{note}

\begin{note}
For an attribute-token (including an attribute-scoped-token) not specified in this document, the behavior is implementation-defined; any such attribute-token that is not recognized by the implementation is ignored.
\end{note}

\begin{note}
A program is ill-formed if it contains an attribute specified in 9.12 that violates the rules specifying to which entity or statement the attribute can apply or the syntax rules for the attribute's attribute-argument-clause, if any. — end note\end{note}

\begin{note}
The attributes specified in 9.12 have optional semantics: given a well-formed program, removing all instances of any one of those attributes results in a program whose set of possible executions (4.1.2) for a given input is a subset of those of the original program for the same input, absent implementation-defined guarantees with respect to that attribute. — end note\end{note}

An attribute-token is reserved for future standardization if

\begin{enumerate}
\item it is not an attribute-scoped-token and is not specified in this document, or
\item it is an attribute-scoped-token and its attribute-namespace is std followed by zero or more digits.
\end{enumerate}

Each implementation should choose a distinctive name for the attribute-namespace in an attribute-scoped-token.

Two consecutive left square bracket tokens shall appear only when introducing an attribute-specifier or within the balanced-token-seq of an attribute-argument-clause.

\begin{note}
If two consecutive left square brackets appear where an attribute-specifier is not allowed, the program is ill-formed even if the brackets match an alternative grammar production. — end note\end{note}

\begin{example}
\begin{verbatim}
int p[10];
void f() {
  int x = 42, y[5];
  int p[5] { return x; }(); // error: invalid attribute on a nested declarator-id and
  // not a function-style cast of an element of p.
  y[] { return 2; }() = 2;
  int i { [vendor::attr({})]}; // well-formed implementation-defined attribute.
}
— end example\end{verbatim}
\end{example}
9.12.2 Alignment specifier

An alignment-specifier may be applied to a variable or to a class data member, but it shall not be applied to a bit-field, a function parameter, or an exception-declaration (14.4). An alignment-specifier may also be applied to the declaration of a class (in an elaborated-type-specifier (9.2.9.5) or class-head (Clause 11), respectively). An alignment-specifier with an ellipsis is a pack expansion (13.7.4).

When the alignment-specifier is of the form alignas( constant-expression ):

(2.1) — the constant-expression shall be an integral constant expression

(2.2) — if the constant expression does not evaluate to an alignment value (6.7.6), or evaluates to an extended alignment and the implementation does not support that alignment in the context of the declaration, the program is ill-formed.

An alignment-specifier of the form alignas( type-id ) has the same effect as alignas(alignof( type-id )). (7.6.2.6).

The alignment requirement of an entity is the strictest nonzero alignment specified by its alignment-specifiers, if any; otherwise, the alignment-specifiers have no effect.

The combined effect of all alignment-specifiers in a declaration shall not specify an alignment that is less strict than the alignment that would be required for the entity being declared if all alignment-specifiers appertaining to that entity were omitted.

[Example 1:

```cpp
struct alignas(8) S {};
struct alignas(1) U {
    S s;
}; // error: U specifies an alignment that is less strict than if the alignas(1) were omitted.
```

—end example]

If the defining declaration of an entity has an alignment-specifier, any non-defining declaration of that entity shall either specify equivalent alignment or have no alignment-specifier. Conversely, if any declaration of an entity has an alignment-specifier, every defining declaration of that entity shall specify an equivalent alignment. No diagnostic is required if declarations of an entity have different alignment-specifiers in different translation units.

[Example 2:

```cpp
// Translation unit #1:
struct { int x; } s, *p = &s;

// Translation unit #2:
struct alignas(16) S; // ill-formed, no diagnostic required: definition of S lacks alignment
extern S* p;
```

—end example]

[Example 3: An aligned buffer with an alignment requirement of A and holding N elements of type T can be declared as:

```cpp
alignas(T) alignas(A) T buffer[N];
```

Specifying alignas(T) ensures that the final requested alignment will not be weaker than alignof(T), and therefore the program will not be ill-formed. —end example]

[Example 4:

```cpp
alignas(double) void f(); // error: alignment applied to function
alignas(double) unsigned char c[sizeof(double)]; // array of characters, suitably aligned for a double
extern unsigned char c[sizeof(double)]; // no alignas necessary
alignas(float)
    extern unsigned char c[sizeof(double)]; // error: different alignment in declaration
```

—end example]

9.12.3 Assumption attribute

The attribute-token assume may be applied to a null statement; such a statement is an assumption. An attribute-argument-clause shall be present and shall have the form:

( conditional-expression )

§ 9.12.3
The expression is contextually converted to `bool` (7.3.1). The expression is not evaluated. If the converted expression would evaluate to `true` at the point where the assumption appears, the assumption has no effect. Otherwise, the behavior is undefined.

[Note 1: The expression is potentially evaluated (6.3). The use of assumptions is intended to allow implementations to analyze the form of the expression and deduce information used to optimize the program. Implementations are not required to deduce any information from any particular assumption. It is expected that the value of a `has-attribute-expression` for the `assume` attribute is 0 if an implementation does not attempt to deduce any such information from assumptions. — end note]

[Example 1:]

```c
int divide_by_32(int x) {
    [[assume(x >= 0)]];
    return x/32;   // The instructions produced for the division
                 // may omit handling of negative values.
}

int f(int y) {
    [[assume(++y == 43)]];  // y is not incremented
    return y;              // statement may be replaced with return 42;
}
```

— end example —

9.12.4 Carries dependency attribute [dcl.attr.depend]

1 The attribute-token `carries_dependency` specifies dependency propagation into and out of functions. No `attribute-argument-clause` shall be present. The attribute may be applied to a parameter of a function or lambda, in which case it specifies that the initialization of the parameter carries a dependency to each lvalue-to-rvalue conversion (7.3.2) of that object. The attribute may also be applied to a function or a lambda call operator, in which case it specifies that the return value, if any, carries a dependency to the evaluation of the function call expression.

2 The first declaration of a function shall specify the `carries_dependency` attribute for its `declarator-id` if any declaration of the function specifies the `carries_dependency` attribute. Furthermore, the first declaration of a function shall specify the `carries_dependency` attribute for a parameter if any declaration of that function specifies the `carries_dependency` attribute for that parameter. If a function or one of its parameters is declared with the `carries_dependency` attribute in its first declaration in one translation unit and the same function or one of its parameters is declared without the `carries_dependency` attribute in its first declaration in another translation unit, the program is ill-formed, no diagnostic required.

3 [Note 1: The `carries_dependency` attribute does not change the meaning of the program, but might result in generation of more efficient code. — end note]
The carries_dependency attribute on function f means that the return value carries a dependency out of f, so that the implementation need not constrain ordering upon return from f. Implementations of f and its caller may choose to preserve dependencies instead of emitting hardware memory ordering instructions (a.k.a. fences). Function g’s second parameter has a carries_dependency attribute, but its first parameter does not. Therefore, function h’s first call to g carries a dependency into g, but its second call does not. The implementation might need to insert a fence prior to the second call to g. — end example]
switch (n) {
  case 1:
  case 2:
    g();
    [[fallthrough]];
  case 3: // warning on fallthrough discouraged
    do {
      [[fallthrough]];
    } while (false);
  case 6:
    do {
      [[fallthrough]];
    } while (n--);
  case 7:
    while (false) {
      [[fallthrough]];
    }
  case 5:
    h();
  case 4: // implementation may warn on fallthrough
    i();
    [[fallthrough]];
  }
}

9.12.7 Indeterminate storage

The attribute-token indeterminate may be applied to the definition of a block variable with automatic storage duration or to a parameter-declaration of a function declaration. No attribute-argument-clause shall be present. The attribute specifies that the storage of an object with automatic storage duration is initially indeterminate rather than erroneous (6.7.4).

If a function parameter is declared with the indeterminate attribute, it shall be so declared in the first declaration of its function. If a function parameter is declared with the indeterminate attribute in the first declaration of its function in one translation unit and the same function is declared without the indeterminate attribute on the same parameter in its first declaration in another translation unit, the program is ill-formed, no diagnostic required.

[Note 1: Reading from an uninitialized variable that is marked [[indeterminate]] can cause undefined behavior.

```c
void f(int);
void g() {
  int x [[indeterminate]], y;
  f(y); // erroneous behavior (6.7.4)
  f(x); // undefined behavior
}

struct T {
  T() {}  
  int x;
};
int h(T t [[indeterminate]]) {
  f(t.x); // undefined behavior when called below
  return 0;
}
int _ = h(T());

— end note]

9.12.8 Likelihood attributes

The attribute-tokens likely and unlikely may be applied to labels or statements. No attribute-argument-clause shall be present. The attribute-token likely shall not appear in an attribute-specifier-seq that contains the attribute-token unlikely.
2 [Note 1: The use of the `likely` attribute is intended to allow implementations to optimize for the case where paths of execution including it are arbitrarily more likely than any alternative path of execution that does not include such an attribute on a statement or label. The use of the `unlikely` attribute is intended to allow implementations to optimize for the case where paths of execution including it are arbitrarily more unlikely than any alternative path of execution that does not include such an attribute on a statement or label. It is expected that the value of a `has-attribute-expression` for the `likely` and `unlikely` attributes is 0 if the implementation does not attempt to use these attributes for such optimizations. A path of execution includes a label if and only if it contains a jump to that label. — end note]

[Note 2: Excessive usage of either of these attributes is liable to result in performance degradation. — end note]

3 [Example 1:

```c
void g(int);
int f(int n) {
    if (n > 5) [[unlikely]] { // n > 5 is considered to be arbitrarily unlikely
        g(0);
        return n * 2 + 1;
    }

    switch (n) {
        case 1:
            g(1);
            [[fallthrough]];

        [[likely]] case 2: // n == 2 is considered to be arbitrarily more
            g(2); // likely than any other value of n
            break;
    }
    return 3;
}
```

—end example]

9.12.9 Maybe unused attribute [dcl.attr.unused]

1 The attribute-token `maybe_unused` indicates that a name, label, or entity is possibly intentionally unused. No `attribute-argument-clause` shall be present.

2 The attribute may be applied to the declaration of a class, `typedef-name`, variable (including a structured binding declaration), structured binding, non-static data member, function, enumeration, or enumerator, or to an `identifier` label (8.2).

3 A name or entity declared without the `maybe_unused` attribute can later be redeclared with the attribute and vice versa. An entity is considered marked after the first declaration that marks it.

4 Recommended practice: For an entity marked `maybe_unused`, implementations should not emit a warning that the entity or its structured bindings (if any) are used or unused. For a structured binding declaration not marked `maybe_unused`, implementations should not emit such a warning unless all of its structured bindings are unused. For a label to which `maybe_unused` is applied, implementations should not emit a warning that the label is used or unused. The value of a `has-attribute-expression` for the `maybe_unused` attribute should be 0 if the attribute does not cause suppression of such warnings.

5 [Example 1:

```c
[[maybe_unused]] void f([[maybe_unused]] bool thing1, [[maybe_unused]] bool thing2) {
    [[maybe_unused]] bool b = thing1 && thing2;
    assert(b);
    #ifdef NDEBUG
goto x;
    #endif
    [[maybe_unused]] x:
}
```

Implementations should not warn that `b` or `x` is unused, whether or not `NDEBUG` is defined. — end example]
9.12.10 Nodiscard attribute

The attribute-token nodiscard may be applied to a function or a lambda call operator or to the declaration of a class or enumeration. An attribute-argument-clause may be present and, if present, shall have the form:

( unevaluated-string )

A name or entity declared without the nodiscard attribute can later be redeclared with the attribute and vice-versa.

[Note 1: Thus, an entity initially declared without the attribute can be marked as nodiscard by a subsequent redeclaration. However, after an entity is marked as nodiscard, later redeclarations do not remove the nodiscard from the entity. —end note]

Redeclarations using different forms of the attribute (with or without the attribute-argument-clause or with different attribute-argument-clauses) are allowed.

A nodiscard type is a (possibly cv-qualified) class or enumeration type marked nodiscard in a reachable declaration. A nodiscard call is either

(a) a function call expression (7.6.1.3) that calls a function declared nodiscard in a reachable declaration or whose return type is a nodiscard type, or

(b) an explicit type conversion (7.6.1.4, 7.6.1.9, 7.6.3) that constructs an object through a constructor declared nodiscard in a reachable declaration, or that initializes an object of a nodiscard type.

Recommended practice: Appearance of a nodiscard call as a potentially-evaluated discarded-value expression (7.2) is discouraged unless explicitly cast to void. Implementations should issue a warning in such cases. The value of a has-attribute-expression for the nodiscard attribute should be 0 unless the implementation can issue such warnings.

[Note 2: This is typically because discarding the return value of a nodiscard call has surprising consequences. —end note]

The unevaluated-string in a nodiscard attribute-argument-clause should be used in the message of the warning as the rationale for why the result should not be discarded.

Example 1:

```c
struct [[nodiscard]] my_scopeguard { /* ... */ };
struct my_unique {
    my_unique() = default; // does not acquire resource
    [[nodiscard]] my_unique(int fd) { /* ... */ } // acquires resource
    -my_unique() noexcept { /* ... */ } // releases resource, if any
    /* ... */
};
struct [[nodiscard]] error_info { /* ... */ };
error_info enable_missile_safety_mode();
void launch_missiles();
void test_missiles() {
    my_scopeguard(); // warning encouraged
    (void)my_scopeguard(), // warning not encouraged, cast to void
    launch_missiles(); // comma operator, statement continues
    my_unique(42); // warning encouraged
    my_unique(); // warning not encouraged
    enable_missile_safety_mode(); // warning encouraged
    launch_missiles();
}
error_info &foo();
void f() { foo(); } // warning not encouraged: not a nodiscard call, because neither
                // the (reference) return type nor the function is declared nodiscard

—end example]

9.12.11 Noreturn attribute

The attribute-token noreturn specifies that a function does not return. No attribute-argument-clause shall be present. The attribute may be applied to a function or a lambda call operator. The first declaration of a function shall specify the noreturn attribute if any declaration of that function specifies the noreturn attribute. If a function is declared with the noreturn attribute in one translation unit and the same function
is declared without the `noreturn` attribute in another translation unit, the program is ill-formed, no diagnostic required.

2 If a function `f` is called where `f` was previously declared with the `noreturn` attribute and `f` eventually returns, the behavior is undefined.

[Note 1: The function can terminate by throwing an exception. — end note]

3 Recommended practice: Implementations should issue a warning if a function marked `[[noreturn]]` might return. The value of a `has-attribute-expression` for the `noreturn` attribute should be 0 unless the implementation can issue such warnings.

4 [Example 1:]

```
[[ noreturn ]] void f() {
    throw "error";       // OK
}
```

```
[[ noreturn ]] void q(int i) {
    // behavior is undefined if called with an argument <= 0
    if (i > 0)
        throw "positive";
}
```

—end example]

### 9.12.12 No unique address attribute

The `attribute-token` `no_unique_address` specifies that a non-static data member is a potentially-overlapping subobject (6.7.2). No `attribute-argument-clause` shall be present. The attribute may appertain to a non-static data member other than a bit-field.

2 [Note 1: The non-static data member can share the address of another non-static data member or that of a base class, and any padding that would normally be inserted at the end of the object can be reused as storage for other members. — end note]

Recommended practice: The value of a `has-attribute-expression` for the `no_unique_address` attribute should be 0 for a given implementation unless this attribute can cause a potentially-overlapping subobject to have zero size.

[Example 1:]

```
template<typename Key, typename Value, 
        typename Hash, typename Pred, typename Allocator>
class hash_map {
    [[no_unique_address]] Hash hasher;
    [[no_unique_address]] Pred pred;
    [[no_unique_address]] Allocator alloc;
    Bucket *buckets;
    // ...
    public:
    // ...
};
```

Here, `hasher`, `pred`, and `alloc` could have the same address as `buckets` if their respective types are all empty. — end example]
10 Modules

10.1 Module units and purviews

A module unit is a translation unit that contains a module-declaration. A named module is the collection of module units with the same module-name. The identifiers module and import shall not appear as identifiers in a module-name or module-partition. All module-names either beginning with an identifier consisting of std followed by zero or more digits or containing a reserved identifier (5.10) are reserved and shall not be specified in a module-declaration; no diagnostic is required. If any identifier in a reserved module-name is a reserved identifier, the module name is reserved for use by C++ implementations; otherwise it is reserved for future standardization. The optional attribute-specifier-seq appertains to the module-declaration.

A module interface unit is a module unit whose module-declaration starts with export-keyword; any other module unit is a module implementation unit. A named module shall contain exactly one module interface unit with no module-partition, known as the primary module interface unit of the module; no diagnostic is required.

A module partition is a module unit whose module-declaration contains a module-partition. A named module shall not contain multiple module partitions with the same module-partition. All module partitions of a module that are module interface units shall be directly or indirectly exported by the primary module interface unit (10.3). No diagnostic is required for a violation of these rules.

Example 1:

Translation unit #1:

```
export module A;
export import :Foo;
export int baz();
```

Translation unit #2:

```
export module A:Foo;
import :Internals;
export int foo() { return 2 * (bar() + 1); }
```

Translation unit #3:

```
module A:Internals;
int bar();
```

Translation unit #4:

```
module A;
import :Internals;
int bar() { return baz() - 10; }
int baz() { return 30; }
```

Module A contains four translation units:

1. a primary module interface unit,
2. a module partition A:Foo, which is a module interface unit forming part of the interface of module A,
A module partition \( A: \text{Internals} \), which does not contribute to the external interface of module \( A \), and

---

A module implementation unit providing a definition of \( \text{bar} \) and \( \text{baz} \), which cannot be imported because it does not have a partition name.

---

A module unit purview is the sequence of tokens starting at the module-declaration and extending to the end of the translation unit. The purview of a named module \( M \) is the set of module unit purviews of \( M \)’s module units.

The global module is the collection of all global-module-fragments and all translation units that are not module units. Declarations appearing in such a context are said to be in the purview of the global module.

[Note 2: The global module has no name, no module interface unit, and is not introduced by any module-declaration. —end note]

A module is either a named module or the global module. A declaration is attached to a module as follows:

---

If the declaration is a non-dependent friend declaration that nominates a function with a declarator-id that is a qualified-id or template-id or that nominates a class other than with an elaborated-type-specifier with neither a nested-name-specifier nor a simple-template-id, it is attached to the module to which the friend is attached (6.6).

---

Otherwise, if the declaration

---

is a namespace-definition with external linkage or

---

appears within a linkage-specification (9.11) it is attached to the global module.

---

Otherwise, the declaration is attached to the module in whose purview it appears.

---

A module-declaration that contains neither an export-keyword nor a module-partition implicitly imports the primary module interface unit of the module as if by a module-import-declaration.

[Example 2:

Translation unit #1:

```cpp
module B:Y;
int y();
```

// does not implicitly import B

Translation unit #2:

```cpp
export module B;
import :Y;
int n = y();
```

// OK, does not create interface dependency cycle

Translation unit #3:

```cpp
module B:X1;
int &a = n;
```

// does not implicitly import B

// error: n not visible here

Translation unit #4:

```cpp
module B:X2;
import B;
int &b = n;
```

// does not implicitly import B

// OK

Translation unit #5:

```cpp
module B;
int &c = n;
```

// implicitly imports B

// OK

---

10.2 Export declaration

export-declaration:

```
export name-declaration
export { declaration-seqopt }
export-keyword module-import-declaration
```
An export-declaration shall inhabit a namespace scope and appear in the purview of a module interface unit. An export-declaration shall not appear directly or indirectly within an unnamed namespace or a private-module-fragment. An export-declaration has the declarative effects of its name-declaration, declaration-seq (if any), or module-import-declaration. The name-declaration of an export-declaration shall not declare a partial specialization (13.7.1). The declaration-seq of an export-declaration shall not contain an export-declaration or module-import-declaration.

[Note 1: An export-declaration does not establish a scope. — end note]

A declaration is exported if it is declared within an export-declaration and inhabits a namespace scope or it is

1. a namespace-definition that contains an exported declaration, or
2. a declaration within a header unit (10.3) that introduces at least one name.

If an exported declaration is not within a header unit, it shall not declare a name with internal linkage.

Example 1:

Source file "a.h":

export int x;

Translation unit #1:

module;
#include "a.h" // error: declaration of x is not in the
// purview of a module interface unit
export module M;
export namespace {} // error: namespace has internal linkage
namespace {
  export int a2; // error: export of name with internal linkage
}
export static int b; // error: b explicitly declared static
export int f(); // OK
export namespace N { } // OK
export using namespace N; // OK

—end example

If an exported declaration is a using-declaration (9.9) and is not within a header unit, all entities to which all of the using-declarators ultimately refer (if any) shall have been introduced with a name having external linkage.

Example 2:

Source file "b.h":

int f();

Importable header "c.h":

int g();

Translation unit #1:

export module X;
export int h();

Translation unit #2:

module;
#include "b.h"
export module M;
import "c.h";
import X;
export using ::f, ::g, ::h; // OK
struct S;
export using ::S; // error: S has module linkage
namespace N {
  export int h();
  static int h(int); // #1
}
export using N::*h; // error: #1 has internal linkage
Note 2: These constraints do not apply to type names introduced by typedef declarations and alias-declarations.

Example 3:
```plaintext
export module M;
struct S;
export using T = S; // OK, exports name T denoting type S
```

Example 4:
```plaintext
export module M;
struct S { int n; };
typedef S S;
export typedef S S; // OK, does not redeclare an entity
export struct S; // error: exported declaration follows non-exported declaration
```

Note 3: Names introduced by exported declarations have either external linkage or no linkage; see 6.6. Namespacerange declarations exported by a module can be found by name lookup in any translation unit importing that module (6.5). Class and enumeration member names can be found by name lookup in any context in which a definition of the type is reachable.

Example 5:

Interface unit of M:
```plaintext
export module M;
export struct X {
    static void f();
    struct Y {
    }
};
namespace {
    struct S {
    }
} export void f(S); // OK
struct T { }
export T id(T); // OK
export struct A; // A exported as incomplete
export auto rootFinder(double a) {
    return [=](double x) { return (x + a/x)/2; };
}
export const int n = 5; // OK, n has external linkage

module M;
struct A {
    int value;
};
```

Implementation unit of M:

Main program:
```plaintext
import M;
int main() {
    X::f(); // OK, X is exported and definition of X is reachable
    X::Y y; // OK, X::Y is exported as a complete type
    auto f = rootFinder(2); // OK
    return A{45}.value; // error: A is incomplete
}
```
8 [Note 4: Declarations in an exported namespace-definition or in an exported linkage-specification (9.11) are exported and subject to the rules of exported declarations.

[Example 6:

```c
export module M;
int g;
export namespace N {
    int x; // OK
    using ::g; // error: ::g has module linkage
}
```—end example]

—end note]

10.3 Import declaration

[module.import]

```
module-import-declaration:
    import-keyword module-name attribute-specifier-seqopt ;
    import-keyword module-partition attribute-specifier-seqopt ;
    import-keyword header-name attribute-specifier-seqopt ;
```

1 A module-import-declaration shall inhabit the global namespace scope. In a module unit, all module-import-declarations and export-declarations exporting module-import-declarations shall appear before all other declarations in the declaration-seq of the translation-unit and of the private-module-fragment (if any). The optional attribute-specifier-seq appertains to the module-import-declaration.

2 A module-import-declaration imports a set of translation units determined as described below.

[Note 1: Namespace-scope declarations exported by the imported translation units can be found by name lookup (6.5) in the importing translation unit and declarations within the imported translation units become reachable (10.7) in the importing translation unit after the import declaration. — end note]

3 A module-import-declaration that specifies a module-name \( \mathcal{M} \) imports all module interface units of \( \mathcal{M} \).

4 A module-import-declaration that specifies a module-partition shall only appear after the module-declaration in a module unit of some module \( \mathcal{M} \). Such a declaration imports the so-named module partition of \( \mathcal{M} \).

5 A module-import-declaration that specifies a header-name \( \mathcal{H} \) imports a synthesized header unit, which is a translation unit formed by applying phases 1 to 7 of translation (5.2) to the source file or header nominated by \( \mathcal{H} \), which shall not contain a module-declaration.

[Note 2: A header unit is a separate translation unit with an independent set of defined macros. All declarations within a header unit are implicitly exported (10.2), and are attached to the global module (10.1). — end note]

An importable header is a member of an implementation-defined set of headers that includes all importable C++ library headers (16.4.2.3). \( \mathcal{H} \) shall identify an importable header. Given two such module-import-declarations:

(5.1) — if their header-names identify different headers or source files (15.3), they import distinct header units;
(5.2) — otherwise, if they appear in the same translation unit, they import the same header unit;
(5.3) — otherwise, it is unspecified whether they import the same header unit.

[Note 3: It is therefore possible that multiple copies exist of entities declared with internal linkage in an importable header. — end note]

[Note 4: A module-import-declaration nominating a header-name is also recognized by the preprocessor, and results in macros defined at the end of phase 4 of translation of the header unit being made visible as described in 15.5. Any other module-import-declaration does not make macros visible. — end note]

6 A declaration of a name with internal linkage is permitted within a header unit despite all declarations being implicitly exported (10.2).

[Note 5: A definition that appears in multiple translation units cannot in general refer to such names (6.3). — end note]

A header unit shall not contain a definition of a non-inline function or variable whose name has external linkage.

7 When a module-import-declaration imports a translation unit \( T \), it also imports all translation units imported by exported module-import-declarations in \( T \); such translation units are said to be exported by \( T \). Additionally, when a module-import-declaration in a module unit of some module \( \mathcal{M} \) imports another module unit \( \mathcal{U} \) of \( \mathcal{M} \),
it also imports all translation units imported by non-exported module-import-declarations in the module unit purview of \( U \). 86 These rules can in turn lead to the importation of yet more translation units.

[Note 6: Such indirect importation does not make macros available, because a translation unit is a sequence of tokens in translation phase 7 (5.2). Macros can be made available by directly importing header units as described in 15.5. — end note]

A module implementation unit shall not be exported.

[Example 1:

Translation unit #1:

\[
\text{module } M: \text{Part};
\]

Translation unit #2:

\[
\text{export module } M;
\]

\[
\text{export import } : \text{Part}; \quad \text{// error: exported partition } : \text{Part} \text{ is an implementation unit}
\]— end example]

A module implementation unit of a module \( M \) that is not a module partition shall not contain a module-import-declaration nominating \( M \).

[Example 2:

\[
\text{module } M;
\]

\[
\text{import } M; \quad \text{// error: cannot import } M \text{ in its own unit}
\]— end example]

A translation unit has an interface dependency on a translation unit \( U \) if it contains a declaration (possibly a module-declaration) that imports \( U \) or if it has an interface dependency on a translation unit that has an interface dependency on \( U \). A translation unit shall not have an interface dependency on itself.

[Example 3:

Interface unit of \( M_1 \):

\[
\text{export module } M_1;
\]

\[
\text{import } M_2;
\]

Interface unit of \( M_2 \):

\[
\text{export module } M_2;
\]

\[
\text{import } M_3;
\]

Interface unit of \( M_3 \):

\[
\text{export module } M_3;
\]

\[
\text{import } M_1; \quad \text{// error: cyclic interface dependency } M_3 \rightarrow M_1 \rightarrow M_2 \rightarrow M_3
\]— end example]

10.4 Global module fragment

[module.global.frag]

A global-module-fragment specifies the contents of the global module fragment for a module unit. The global module fragment can be used to provide declarations that are attached to the global module and usable within the module unit.

A declaration \( D \) is decl-reachable from a declaration \( S \) in the same translation unit if

1. \( D \) does not declare a function or function template and \( S \) contains an id-expression, namespace-name, type-name, template-name, or concept-name naming \( D \), or
2. \( D \) declares a function or function template that is named by an expression (6.3) appearing in \( S \), or

\[86\) This is consistent with the lookup rules for imported names (6.5).\]
N4986

(3.3) — S contains a dependent call E (13.8.3) and D is found by any name lookup performed for an expression synthesized from E by replacing each type-dependent argument or operand with a value of a placeholder type with no associated namespaces or entities, or

[Note 2: This includes the lookup for operator== performed when considering rewriting an != expression, the lookup for operator<=> performed when considering rewriting a relational comparison, and the lookup for operator!= when considering whether an operator== is a rewrite target. — end note]

(3.4) — S contains an expression that takes the address of an overload set (12.3) that contains D and for which the target type is dependent, or

(3.5) — there exists a declaration M that is not a namespace-definition for which M is decl-reachable from S and either

(3.5.1) — D is decl-reachable from M, or

(3.5.2) — D and M declare the same entity, and D neither is a friend declaration nor inhabits a block scope, or

(3.5.3) — D declares a namespace N and M is a member of N, or

(3.5.4) — one of D and M declares a class or class template C and the other declares a member or friend of C, or

(3.5.5) — one of D and M declares an enumeration E and the other declares an enumerator of E, or

(3.5.6) — D declares a function or variable and M is declared in D,\(^\text{87}\) or

(3.5.7) — one of D and M declares a template and the other declares a partial or explicit specialization or an implicit or explicit instantiation of that template, or

(3.5.8) — M declares a class template and D is a deduction guide for that template, or

(3.5.9) — one of D and M declares a class or enumeration type and the other introduces a typedef name for linkage purposes for that type.

In this determination, it is unspecified

(3.6) — whether a reference to an alias-declaration, typedef declaration, using-declaration, or namespace-alias-definition is replaced by the declarations they name prior to this determination,

(3.7) — whether a simple-template-id that does not denote a dependent type and whose template-name names an alias template is replaced by its denoted type prior to this determination,

(3.8) — whether a decltype-specifier that does not denote a dependent type is replaced by its denoted type prior to this determination, and

(3.9) — whether a non-value-dependent constant expression is replaced by the result of constant evaluation prior to this determination.

4 A declaration D in a global module fragment of a module unit is discarded if D is not decl-reachable from any declaration in the declaration-seq of the translation-unit.

[Note 3: A discarded declaration is neither reachable nor visible to name lookup outside the module unit, nor in template instantiations whose points of instantiation (13.8.4.1) are outside the module unit, even when the instantiation context (10.6) includes the module unit. — end note]

5 [Example 1:

```cpp
const int size = 2;
int ary1[size]; // unspecified whether size is decl-reachable from ary1
constexpr int identity(int x) { return x; }
int ary2[identity(2)]; // unspecified whether identity is decl-reachable from ary2

template<typename> struct S;
template<typename, int> struct S2;
constexpr int g(int);

template<typename T, int N>
S<S2<T, g(N)> f(); // S, S2, g, and :: are decl-reachable from f
```

\(^{87}\) A declaration can appear within a lambda-expression in the initializer of a variable.
template<int N>
void h() noexcept(g(N) == N); // g and :: are decl-reachable from h
— end example]

[Example 2:

Source file "foo.h":

namespace N {
    struct X {};
    int d();
    int e();
    inline int f(X, int = d()) { return e(); }
    int g(X);
    int h(X);
}

Module M interface:

module;  // OK
#include "foo.h"
export module M;

template<typename T> int use_f() {
    N::X x;  // N::X, N, and :: are decl-reachable from use_f
    return f(x, 123);  // N::f is decl-reachable from use_f,
                       // N::e is indirectly decl-reachable from use_f
                       // because it is decl-reachable from N::f, and
                       // N::d is decl-reachable from use_f
                       // because it is decl-reachable from N::f
                       // even though it is not used in this call
}

template<typename T> int use_g() {
    N::X x;  // N::X, N, and :: are decl-reachable from use_g
    return g((T()), x);  // N::g is not decl-reachable from use_g
}

template<typename T> int use_h() {
    N::X x;  // N::X, N, and :: are decl-reachable from use_h
    return h((T()), x);  // N::h is not decl-reachable from use_h, but
                        // N::h is decl-reachable from use_h<int>
}

int k = use_h<int>();  // use_h<int> is decl-reachable from k, so
                        // N::h is decl-reachable from k

Module M implementation:

module M;
int a = use_f<int>();  // OK
int b = use_g<int>();  // error: no viable function for call to g;
                        // g is not decl-reachable from purview of
                        // module M's interface, so is discarded
int c = use_h<int>();  // OK
— end example]

10.5 Private module fragment

private-module-fragment: private ; declaration-seq_opt

A private-module-fragment shall appear only in a primary module interface unit (10.1). A module unit with a private-module-fragment shall be the only module unit of its module; no diagnostic is required.

[Note 1: A private-module-fragment ends the portion of the module interface unit that can affect the behavior of other translation units. A private-module-fragment allows a module to be represented as a single translation unit without making all of the contents of the module reachable to importers. The presence of a private-module-fragment affects:

(2.1) — the point by which the definition of an inline function or variable is required (9.2.8),
(2.2) — the point by which the definition of an exported function with a placeholder return type is required (9.2.9.7),
whether a declaration is required not to be an exposure (6.6),
where definitions for inline functions and templates must appear (6.3, 9.2.8, 13.1),
the instantiation contexts of templates instantiated before it (10.6), and
the reachability of declarations within it (10.7).

— end note

Example 1:

```c
export module A;
export inline void fn_e(); // error: exported inline function fn_e not defined
inline void fn_m(); // error: non-exported inline function fn_m not defined
static void fn_s();
export struct X;
export void g(X *x) {
    fn_s(); // OK, call to static function in same translation unit
}
export X *factory(); // OK
module :private;
struct X {};
X *factory() {
    return new X();
}
void fn_e() {}
void fn_m() {}
void fn_s() {}
```

— end example

10.6 instantiation context

The instantiation context is a set of points within the program that determines which declarations are found by argument-dependent name lookup (6.5.4) and which are reachable (10.7) in the context of a particular declaration or template instantiation.

During the implicit definition of a defaulted function (11.4.4, 11.10.1), the instantiation context is the union of the instantiation context from the definition of the class and the instantiation context of the program construct that resulted in the implicit definition of the defaulted function.

During the implicit instantiation of a template whose point of instantiation is specified as that of an enclosing specialization (13.8.4.1), the instantiation context is the union of the instantiation context of the enclosing specialization and, if the template is defined in a module interface unit of a module M and the point of instantiation is not in a module interface unit of M, the point at the end of the declaration-seq of the primary module interface unit of M (prior to the private-module-fragment, if any).

During the implicit instantiation of a template that is implicitly instantiated because it is referenced from within the implicit definition of a defaulted function, the instantiation context is the instantiation context of the defaulted function.

During the instantiation of any other template specialization, the instantiation context comprises the point of instantiation of the template.

In any other case, the instantiation context at a point within the program comprises that point.

Example 1:

Translation unit #1:

```c
export module stuff;
export template<typically T, typename U> void foo(T, U u) { auto v = u; }
export template<typically T, typename U> void bar(T, U u) { auto v = *u; }
```

Translation unit #2:

```c
export module M1;
import "defn.h"; // provides struct X {};
import stuff;
```
export template<typename T> void f(T t) {
  X x;
  foo(t, x);
}

Translation unit #3:

export module M2;
import "decl.h"; // provides struct X; (not a definition)
import stuff;
export template<typename T> void g(T t) {
  X *x;
  bar(t, x);
}

Translation unit #4:

import M1;
import M2;
void test() {
  f(0);
  g(0);
}

The call to f(0) is valid; the instantiation context of foo<int, X> comprises

(7.1) — the point at the end of translation unit #1,
(7.2) — the point at the end of translation unit #2, and
(7.3) — the point of the call to f(0),
so the definition of X is reachable (10.7).

It is unspecified whether the call to g(0) is valid: the instantiation context of bar<int, X> comprises

(7.4) — the point at the end of translation unit #1,
(7.5) — the point at the end of translation unit #3, and
(7.6) — the point of the call to g(0),
so the definition of X need not be reachable, as described in 10.7. — end example

10.7 Reachability [module.reach]

A translation unit U is necessarily reachable from a point P if U is a module interface unit on which the translation unit containing P has an interface dependency, or the translation unit containing P imports U, in either case prior to P (10.3).

[Note 1: While module interface units are reachable even when they are only transitively imported via a non-exported import declaration, namespace-scope names from such module interface units are not found by name lookup (6.5). — end note]

All translation units that are necessarily reachable are reachable. Additional translation units on which the point within the program has an interface dependency may be considered reachable, but it is unspecified which are and under what circumstances. [88]

[Note 2: It is advisable to avoid depending on the reachability of any additional translation units in programs intending to be portable. — end note]

A declaration D is reachable from a point P if

(3.1) — D appears prior to P in the same translation unit, or
(3.2) — D is not discarded (10.4), appears in a translation unit that is reachable from P, and does not appear within a private-module-fragment.

A declaration is reachable if it is reachable from any point in the instantiation context (10.6).

[Note 3: Whether a declaration is exported has no bearing on whether it is reachable. — end note]

The accumulated properties of all reachable declarations of an entity within a context determine the behavior of the entity within that context.

[88] Implementations are therefore not required to prevent the semantic effects of additional translation units involved in the compilation from being observed.

§ 10.7
[Note 4: These reachable semantic properties include type completeness, type definitions, initializers, default arguments of functions or template declarations, attributes, names bound, etc. Since default arguments are evaluated in the context of the call expression, the reachable semantic properties of the corresponding parameter types apply in that context.

[Example 1:]

Translation unit #1:

```plaintext
export module M:A;
export struct B;
```

Translation unit #2:

```plaintext
module M:B;
struct B {
  operator int();
};
```

Translation unit #3:

```plaintext
module M:C;
import :A;
B b1;
```

```plaintext
// error: no reachable definition of struct B
```

Translation unit #4:

```plaintext
export module M;
export import :A;
import :B;
B b2;
export void f(B b = B());
```

Translation unit #5:

```plaintext
import M;
B b3;
void g() { f(); }
```

```plaintext
// error: no reachable definition of struct B
// error: no reachable definition of struct B
```

— end example — end note — end example

[Note 5: Declarations of an entity can be reachable even where they cannot be found by name lookup. — end note]

[Example 2:]

Translation unit #1:

```plaintext
export module A;
struct X {};
export using Y = X;
```

Translation unit #2:

```plaintext
import A;
Y y;  // OK, definition of X is reachable
X x;  // error: X not visible to unqualified lookup
```

— end example]
11 Classes

11.1 Preamble

A class is a type. Its name becomes a class-name within its scope.

class-name:
  identifier
  simple-template-id

A class-specifier or an elaborated-type-specifier is used to make a class-name. An object of a class consists of a (possibly empty) sequence of members and base class objects.

class-specifier:
  class-head { member-specification_opt }

class-head:
  class-key attribute-specifier-seq_opt class-head-name class-virt-specifier_opt base-clause_opt
class-key attribute-specifier-seq_opt base-clause_opt

class-head-name:
  nested-name-specifier_opt class-name

class-virt-specifier:
  final
class-key:
  class
  struct
  union

A class declaration where the class-name in the class-head-name is a simple-template-id shall be an explicit specialization or a partial specialization. A class-specifier whose class-head omits the class-head-name defines an unnamed class.

[Note 1: An unnamed class thus can’t be final. — end note]

Otherwise, the class-name is an identifier; it is not looked up, and the class-specifier introduces it.

The component name of the class-name is also bound in the scope of the class (template) itself; this is known as the injected-class-name. For purposes of access checking, the injected-class-name is treated as if it were a public member name. A class-specifier is commonly referred to as a class definition. A class is considered defined after the closing brace of its class-specifier has been seen even though its member functions are in general not yet defined. The optional attribute-specifier-seq appertains to the class; the attributes in the attribute-specifier-seq are thereafter considered attributes of the class whenever it is named.

If a class-head-name contains a nested-name-specifier, the class-specifier shall not inhabit a class scope. If its class-name is an identifier, the class-specifier shall correspond to one or more declarations nominable in the class, class template, or namespace to which the nested-name-specifier refers; they shall all have the same target scope, and the target scope of the class-specifier is that scope.

[Example 1:
  namespace N {
    template<class>
    struct A {
      struct B;
    };
  }
  using N::A;
  template<class T> struct A<T>::B {}; // OK
  template<> struct A<void> {}; // OK
  — end example]

[Note 2: The class-key determines whether the class is a union and whether access is public or private by default. A union holds the value of at most one data member at a time. — end note]
If a class is marked with the class-virt-specifier `final` and it appears as a class-or-decltype in a base-clause (11.7), the program is ill-formed. Whenever a class-key is followed by a class-head-name, the identifier `final`, and a colon or left brace, `final` is interpreted as a class-virt-specifier.

[Example 2:]

```c
struct A;
struct A final {}; // OK, definition of struct A,
// not value-initialization of variable final

struct X {
    struct C { constexpr operator int() { return 5; } };
    struct B final : C{}; // OK, definition of nested class B,
    // not declaration of a bit-field member final
};
```

—end example—

[Note 3: Complete objects of class type have nonzero size. Base class subobjects and members declared with the no_unique_address attribute (9.12.12) are not so constrained. —end note]

[Note 4: Class objects can be assigned (12.4.3.2, 11.4.6), passed as arguments to functions (9.4, 11.4.5.3), and returned by functions (except objects of classes for which copying or moving has been restricted; see 9.5.3 and 11.8). Other plausible operators, such as equality comparison, can be defined by the user; see 12.4. —end note]

### 11.2 Properties of classes [class.prop]

A trivially copyable class is a class:

1. (1.1) — that has at least one eligible copy constructor, move constructor, copy assignment operator, or move assignment operator (11.4.4, 11.4.5.3, 11.4.6),
2. (1.2) — where each eligible copy constructor, move constructor, copy assignment operator, and move assignment operator is trivial, and
3. (1.3) — that has a trivial, non-deleted destructor (11.4.7).

A trivial class is a class that is trivially copyable and has one or more eligible default constructors (11.4.5.2), all of which are trivial.

[Note 1: In particular, a trivially copyable or trivial class does not have virtual functions or virtual base classes. —end note]

A class `S` is a standard-layout class if it:

1. (3.1) — has no non-static data members of type non-standard-layout class (or array of such types) or reference,
2. (3.2) — has no virtual functions (11.7.3) and no virtual base classes (11.7.2),
3. (3.3) — has the same access control (11.8) for all non-static data members,
4. (3.4) — has no non-standard-layout base classes,
5. (3.5) — has at most one base class subobject of any given type,
6. (3.6) — has all non-static data members and bit-fields in the class and its base classes first declared in the same class, and
7. (3.7) — has no element of the set \( M(S) \) of types as a base class, where for any type `X`, \( M(X) \) is defined as follows.\(^{89}\)

\[ M(X) = \{ \text{the set of the types of all non-base-class subobjects that can be at a zero offset in } X \}. \]

[Note 2: \( M(X) \) is the set of the types of all non-base-class subobjects that can be at a zero offset in `X`. —end note]

\[^{89}\] This ensures that two subobjects that have the same class type and that belong to the same most derived object are not allocated at the same address (7.6.10).
(3.7.4) If X is an array type with element type X_e, the set M(X) consists of X_e and the elements of M(X_e).

(3.7.5) If X is a non-class, non-array type, the set M(X) is empty.

[Example 1:

```c
struct B { int i; }; // standard-layout class
struct C : B { };  // standard-layout class
struct D : C { };  // standard-layout class
struct E : D { char : 4; }; // not a standard-layout class

struct Q {};
struct S : Q { };  
struct T : Q { };  
struct U : S, T { }; // not a standard-layout class
```

—end example]

A standard-layout struct is a standard-layout class defined with the class-key struct or the class-key class. A standard-layout union is a standard-layout class defined with the class-key union.

[Note 3: Standard-layout classes are useful for communicating with code written in other programming languages. Their layout is specified in 11.4. — end note]

[Example 2:

```c
struct N { // neither trivial nor standard-layout
    int i;
    int j;
    virtual ~N();
};

struct T { // trivial but not standard-layout
    int i;
    private:
    int j;
};

struct SL { // standard-layout but not trivial
    int i;
    int j;
    ~SL();
};

struct POD { // both trivial and standard-layout
    int i;
    int j;
};
```

—end example]

[Note 4: Aggregates of class type are described in 9.4.2. — end note]

A class S is an implicit-lifetime class if

(9.1) it is an aggregate whose destructor is not user-provided or

(9.2) it has at least one trivial eligible constructor and a trivial, non-deleted destructor.

11.3 Class names

A class definition introduces a new type.

[Example 1:

```c
struct X { int a; };
struct Y { int a; };
X a1;
Y a2;
int a3;
```

declares three variables of three different types. This implies that

```c
a1 = a2; // error: Y assigned to X
```
\[
a_1 = a_3; \quad \text{// error: int assigned to X}
\]
are type mismatches, and that
\[
\begin{align*}
\text{int } f(X); \\
\text{int } f(Y);
\end{align*}
\]
declare overloads (Clause 12) named \(f\) and not simply a single function \(f\) twice. For the same reason,
\[
\begin{align*}
\text{struct } \& S \{ \text{int } a; \}; \\
\text{struct } S \{ \text{int } a; \}; \quad \text{// error: double definition}
\end{align*}
\]
is ill-formed because it defines \(S\) twice. —end example\]

\[2\]
[Note 1: It can be necessary to use an \textit{elaborated-type-specifier} to refer to a class that belongs to a scope in which its name is also bound to a variable, function, or enumerator (6.5.6).

[Example 2:]
\[
\begin{align*}
\text{struct stat} & \{ \\
\text{// ...} & \} \\
\text{stat } & \text{gstat}; \quad \text{// use plain stat to define variable} \\
\text{int stat} & (\text{struct stat*}); \quad \text{// stat now also names a function} \\
\text{void } & f() \{ \\
\text{struct stat* } & \text{ps}; \quad \text{// struct prefix needed to name struct stat} \\
\text{stat}(&\text{ps}); \quad \text{// call stat function}
\}
\end{align*}
\]
—end example\]

An \textit{elaborated-type-specifier} can also be used to declare an \textit{identifier} as a \textit{class-name}.

[Example 3:]
\[
\begin{align*}
\text{struct } & \{ \text{int } a; \}; \\
\text{void } & g() \{ \\
\text{struct } & s; \quad \text{// hide global struct } s \text{ with a block-scope declaration} \\
\& & s; \quad \text{// refer to local struct } s \\
\text{struct } & s \{ \text{char* } p; \}; \quad \text{// define local struct } s \\
\text{struct } & s; \quad \text{// redeclaration, has no effect}
\}
\end{align*}
\]
—end example\]

Such declarations allow definition of classes that refer to each other.

[Example 4:]
\[
\begin{align*}
\text{class } & \text{Vector}; \\
\text{class } & \text{Matrix} \{ \\
\text{// ...} & \}
\end{align*}
\]
\[
\begin{align*}
\quad & \quad \text{friend Vector operator*(const Matrix&}, \text{ const Vector&);} \\
\text{class } & \text{Vector} \{ \\
\text{// ...} & \}
\end{align*}
\]
\end{align*}
\]

Declaration of friends is described in 11.8.4, operator functions in 12.4. —end example\]

—end note\]

\[3\]
[Note 2: An \textit{elaborated-type-specifier} (9.2.9.5) can also be used as a \textit{type-specifier} as part of a declaration. It differs from a class declaration in that it can refer to an existing class of the given name. —end note\]

[Example 5:]
\[
\begin{align*}
\text{struct } & \{ \text{int } a; \};
\end{align*}
\]

\section*{§ 11.3}
void g(int s) {
  struct s* p = new struct s; // global s
  p->a = s; // parameter s
}

—end example

4 [Note 3: The declaration of a class name takes effect immediately after the identifier is seen in the class definition or elaborated-type-specifier.

[Example 6:

class A * A;
first specifies A to be the name of a class and then redefines it as the name of a pointer to an object of that class. This means that the elaborated form class A must be used to refer to the class. Such artistry with names can be confusing and is best avoided. —end example]

—end note]

5 A simple-template-id is only a class-name if its template-name names a class template.

11.4 Class members

11.4.1 General

member-specification:
  member-declaration member-specification_opt
access-specifier : member-specification_opt

member-declaration:
  attribute-specifier-seq_opt decl-specifier-seq_opt member-declarator-list_opt ;
  function-definition
  friend-type-declaration
  using-declaration
  using-enumeration-declaration
  static_assert-declaration
  template-declaration
  explicit-specialization
  deduction-guide
  alias-declaration
  opaque-enumeration-declaration
  empty-declaration

member-declarator-list:
  member-declarator
  member-declarator-list , member-declarator

member-declarator:
  declarator virt-specifier-seq_opt pure-specifier_opt
  declarator requires-clause
  declarator brace-or-equal-initializer
  identifier_opt attribute-specifier-seq_opt : constant-expression brace-or-equal-initializer_opt

virt-specifier-seq:
  virt-specifier
  virt-specifier-seq virt-specifier

virt-specifier:
  override
  final

pure-specifier:
  = 0

friend-type-declaration:
  friend friend-type-specifier-list ;

friend-type-specifier-list:
  friend-type-specifier ... opt
  friend-type-specifier-list , friend-type-specifier ... opt
friend-type-specifier:
  simple-type-specifier
  elaborated-type-specifier
  typename-specifier

1 In the absence of a virt-specifier-seq, the token sequence \( = 0 \) is treated as a pure-specifier if the type of the declatory-id (9.3.4.1) is a function type, and is otherwise treated as a brace-or-equal-initializer.

[Note 1: If the member declaration acquires a function type through template instantiation, the program is ill-formed; see 13.9.1. — end note]

2 The member-specification in a class definition declares the full set of members of the class; no member can be added elsewhere. A direct member of a class \( X \) is a member of \( X \) that was first declared within the member-specification of \( X \), including anonymous union members (11.5.2) and direct members thereof. Members of a class are data members, member functions (11.4.2), nested types, enumerators, and member templates (13.7.3) and specializations thereof.

[Note 2: A specialization of a static data member template is a static data member. A specialization of a member function template is a member function. A specialization of a member class template is a nested class. — end note]

3 A member-declaration does not declare new members of the class if it is

(3.1) — a friend declaration (11.8.4),
(3.2) — a deduction-guide (13.7.2.3),
(3.3) — a template-declaration whose declaration is one of the above,
(3.4) — a static_assert-declaration,
(3.5) — a using-declaration (9.9), or
(3.6) — an empty-declaration.

For any other member-declaration, each declared entity that is not an unnamed bit-field (11.4.10) is a member of the class, and each such member-declaration shall either declare at least one member name of the class or declare at least one unnamed bit-field.

4 A data member is a non-function member introduced by a member-declarator. A member function is a member that is a function. Nested types are classes (11.3, 11.4.12) and enumerations (9.7.1) declared in the class and arbitrary types declared as members by use of a typedef declaration (9.2.4) or alias-declaration. The enumerators of an unscoped enumeration (9.7.1) defined in the class are members of the class.

5 A data member or member function may be declared static in its member-declaration, in which case it is a static member (see 11.4.9) (a static data member (11.4.9.3) or static member function (11.4.9.2), respectively) of the class. Any other data member or member function is a non-static member (a non-static data member or non-static member function (11.4.3), respectively).

[Note 3: A non-static data member of non-reference type is a member subobject of a class object (6.7.2). — end note]

6 A member shall not be declared twice in the member-specification, except that

(6.1) — a nested class or member class template can be declared and then later defined, and
(6.2) — an enumeration can be introduced with an opaque Enum-declaration and later redeclared with an enum-specifier.

[Note 4: A single name can denote several member functions provided their types are sufficiently different (6.4.1). — end note]

7 A redeclaration of a class member outside its class definition shall be a definition, an explicit specialization, or an explicit instantiation (13.9.4, 13.9.3). The member shall not be a non-static data member.

8 A complete-class context of a class (template) is a

(8.1) — function body (9.5.1),
(8.2) — default argument (9.3.4.7),
(8.3) — default template argument (13.2),
(8.4) — noexcept-specifier (14.5), or
(8.5) — default member initializer
within the member-specification of the class or class template.
N4986

[Note 5: A complete-class context of a nested class is also a complete-class context of any enclosing class, if the nested class is defined within the member-specification of the enclosing class. — end note]

9 A class \( C \) is complete at a program point \( P \) if the definition of \( C \) is reachable from \( P \) (10.7) or if \( P \) is in a complete-class context of \( C \). Otherwise, \( C \) is incomplete at \( P \).

10 If a member-declaration matches the syntactic requirements of friend-type-declaration, it is a friend-type-declaration.

11 In a member-declarator, an \( = \) immediately following the declarator is interpreted as introducing a pure-specifier if the declarator-id has function type, otherwise it is interpreted as introducing a brace-or-equal-initializer.

[Example 1:

```
struct S {
    using T = void();
    T * p = 0; // OK, brace-or-equal-initializer
    virtual T tf = 0; // OK, pure-specifier
 }
```
—end example]

12 In a member-declarator for a bit-field, the constant-expression is parsed as the longest sequence of tokens that could syntactically form a constant-expression.

[Example 2:

```
int a;
const int b = 0;
struct S {
    int x1 : 8 = 42; // OK, "= 42" is brace-or-equal-initializer
    int x2 : 8 { 42 }; // OK, "{ 42 }" is brace-or-equal-initializer
    int y1 : true ? 8 : a = 42; // OK, brace-or-equal-initializer is absent
    int y2 : true ? 8 : b = 42; // error: cannot assign to const int
    int y3 : (true ? 8 : b) = 42; // OK, "= 42" is brace-or-equal-initializer is absent
    int z : 1 || new int { 0 }; // OK, brace-or-equal-initializer is absent
}
```
—end example]

13 A brace-or-equal-initializer shall appear only in the declaration of a data member. (For static data members, see 11.4.9.3; for non-static data members, see 11.9.3 and 9.4.2). A brace-or-equal-initializer for a non-static data member specifies a default member initializer for the member, and shall not directly or indirectly cause the implicit definition of a defaulted default constructor for the enclosing class or the exception specification of that constructor. An immediate invocation (7.7) that is a potentially-evaluated subexpression (6.9.1) of a default member initializer is neither evaluated nor checked for whether it is a constant expression at the point where the subexpression appears.

14 A member shall not be declared with the extern storage-class-specifier. Within a class definition, a member shall not be declared with the thread_local storage-class-specifier unless also declared static.

15 The decl-specifier-seq may be omitted in constructor, destructor, and conversion function declarations only; when declaring another kind of member the decl-specifier-seq shall contain a type-specifier that is not a cv-qualifier. The member-declarator-list can be omitted only after a class-specifier or an enum-specifier or in a friend declaration (11.8.4). A pure-specifier shall be used only in the declaration of a virtual function (11.7.3) that is not a friend declaration.

16 The optional attribute-specifier-seq in a member-declaration appertains to each of the entities declared by the member-declarators; it shall not appear if the optional member-declarator-list is omitted.

17 A virt-specifier-seq shall contain at most one of each virt-specifier. A virt-specifier-seq shall appear only in the first declaration of a virtual member function (11.7.3).

18 The type of a non-static data member shall not be an incomplete type (6.8.1), an abstract class type (11.7.4), or a (possibly multidimensional) array thereof.

[Note 6: In particular, a class \( C \) cannot contain a non-static member of class \( C \), but it can contain a pointer or reference to an object of class \( C \). — end note]

[Note 7: See 7.5.5 for restrictions on the use of non-static data members and non-static member functions. — end note]
[Note 8: The type of a non-static member function is an ordinary function type, and the type of a non-static data member is an ordinary object type. There are no special member function types or data member types. — end note]

[Example 3: A simple example of a class definition is]

```cpp
struct tnode {
    char tword[20];
    int count;
    tnode* left;
    tnode* right;
};
```

which contains an array of twenty characters, an integer, and two pointers to objects of the same type. Once this definition has been given, the declaration

```cpp
tnode s, *sp;
```

declares s to be a tnode and sp to be a pointer to a tnode. With these declarations, sp->count refers to the count member of the object to which sp points; s.left refers to the left subtree pointer of the object s; and s.right->tword[0] refers to the initial character of the tword member of the right subtree of s. — end example]

[Note 9: Non-variant non-static data members of non-zero size (6.7.2) are allocated so that later members have higher addresses within a class object (7.6.9). Implementation alignment requirements can cause two adjacent members not to be allocated immediately after each other; so can requirements for space for managing virtual functions (11.7.3) and virtual base classes (11.7.2). — end note]

If T is the name of a class, then each of the following shall have a name different from T:

- every static data member of class T;
- every member function of class T;
- every member of class T that is itself a type;
- every member template of class T;
- every enumerator of every member of class T that is an unscoped enumeration type; and
- every member of every anonymous union that is a member of class T.

In addition, if class T has a user-declared constructor (11.4.5), every non-static data member of class T shall have a name different from T.

The common initial sequence of two standard-layout struct (11.2) types is the longest sequence of non-static data members and bit-fields in declaration order, starting with the first such entity in each of the structs, such that

- corresponding entities have layout-compatible types (6.8),
- corresponding entities have the same alignment requirements (6.7.6),
- if a has-attribute-expression (15.2) is not 0 for the no_unique_address attribute, then neither entity is declared with the no_unique_address attribute (9.12.12), and
- either both entities are bit-fields with the same width or neither is a bit-field.

[Example 4:

```cpp
struct A { int a; char b; }
struct B { const int b1; volatile char b2; }
struct C { int c; unsigned : 0; char b; }
struct D { int d; char b : 4; }
struct E { unsigned int e; char b; }
```

The common initial sequence of A and B comprises all members of either class. The common initial sequence of A and C and of A and D comprises the first member in each case. The common initial sequence of A and E is empty. — end example]

Two standard-layout struct (11.2) types are layout-compatible classes if their common initial sequence comprises all members and bit-fields of both classes (6.8).

Two standard-layout unions are layout-compatible if they have the same number of non-static data members and corresponding non-static data members (in any order) have layout-compatible types (6.8.1).
In a standard-layout union with an active member (11.5) of struct type T1, it is permitted to read a non-static data member m of another union member of struct type T2 provided m is part of the common initial sequence of T1 and T2; the behavior is as if the corresponding member of T1 were nominated.

[Example 5:

```c
struct T1 { int a, b; }
struct T2 { int c; double d; }
union U { T1 t1; T2 t2; }
int f() {
    U u = { { 1, 2 } };  // active member is t1
    return u.t2.c;  // OK, as if u.t1.a were nominated
}
```

—end example]

[Note 11: Reading a volatile object through a glvalue of non-volatile type has undefined behavior (9.2.9.2). — end note]

If a standard-layout class object has any non-static data members, its address is the same as the address of its first non-static data member if that member is not a bit-field. Its address is also the same as the address of each of its base class subobjects.

[Note 12: There can therefore be unnamed padding within a standard-layout struct object inserted by an implementation, but not at its beginning, as necessary to achieve appropriate alignment. — end note]

[Note 13: The object and its first subobject are pointer-interconvertible (6.8.4, 7.6.1.9). — end note]

### 11.4.2 Member functions [class.mfct]

1 If a member function is attached to the global module and is defined (9.5) in its class definition, it is inline (9.2.8).

[Note 1: A member function is also inline if it is declared inline, constexpr, or consteval. — end note]

2 [Example 1:

```c
struct X {
    typedef int T;
    static T count;
    void f(T);
};
void X::f(T t = count) { }
```

The definition of the member function f of class X inhabits the global scope; the notation X::f indicates that the function f is a member of class X and in the scope of class X. In the function definition, the parameter type T refers to the typedef member T declared in class X and the default argument count refers to the static data member count declared in class X. — end example]

3 Member functions of a local class shall be defined inline in their class definition, if they are defined at all.

[Note 2: A member function can be declared (but not defined) using a typedef for a function type. The resulting member function has exactly the same type as it would have if the function declarator were provided explicitly, see 9.3.4.6 and 13.4.

[Example 2:

```c
typedef void fv();
typedef void fvc() const;
struct S {
    fv memfunc1;  // equivalent to: void memfunc1();
    void memfunc2();
    fvc memfunc3;  // equivalent to: void memfunc3() const;
};
fv S::* pmfv1 = &S::memfunc1;
fv S::* pmfv2 = &S::memfunc2;
fvc S::* pmfv3 = &S::memfunc3;
— end example]
— end note]
11.4.3 Non-static member functions

A non-static member function may be called for an object of its class type, or for an object of a class derived (11.7) from its class type, using the class member access syntax (7.6.1.5, 12.2.2.2). A non-static member function may also be called directly using the function call syntax (7.6.1.3, 12.2.2.2) from within its class or a class derived from its class, or a member thereof, as described below.

[Note 1: An implicit object member function can be declared with cv-qualifiers, which affect the type of the this pointer (7.5.3), and/or a ref-qualifier (9.3.4.6); both affect overload resolution (12.2.2). —end note]

An implicit object member function may be declared virtual (11.7.3) or pure virtual (11.7.4).

11.4.4 Special member functions

Default constructors (11.4.5.2), copy constructors, move constructors (11.4.5.3), copy assignment operators, move assignment operators (11.4.6), and prospective destructors (11.4.7) are special member functions.

[Note 1: The implementation will implicitly declare these member functions for some class types when the program does not explicitly declare them. The implementation will implicitly define them as needed (9.5.2). —end note]

An implicitly-declared special member function is declared at the closing } of the class-specifier. Programs shall not define implicitly-declared special member functions.

Programs may explicitly refer to implicitly-declared special member functions.

[Example 1: A program may explicitly call or form a pointer to member to an implicitly-declared special member function.]

```c
struct A { }; // implicitly declared A::operator=
struct B : A {
  B& operator=(const B &);
};
B& B::operator=(const B & s) {
  this->A::operator=(s); // well-formed
  return *this;
}
```

[Note 2: The special member functions affect the way objects of class type are created, copied, moved, and destroyed, and how values can be converted to values of other types. Often such special member functions are called implicitly. —end note]

Special member functions obey the usual access rules (11.8).

[Example 2: Declaring a constructor protected ensures that only derived classes and friends can create objects using it. —end example]

Two special member functions are of the same kind if

1. they are both default constructors,
2. they are both copy or move constructors with the same first parameter type, or
3. they are both copy or move assignment operators with the same first parameter type and the same cv-qualifiers and ref-qualifier, if any.

An eligible special member function is a special member function for which:

1. the function is not deleted,
2. the associated constraints (13.5), if any, are satisfied, and
3. no special member function of the same kind whose associated constraints, if any, are satisfied is more constrained (13.5.5).

For a class, its non-static data members, its non-virtual direct base classes, and, if the class is not abstract (11.7.4), its virtual base classes are called its potentially constructed subobjects.

11.4.5 Constructors

11.4.5.1 General

A declarator declares a constructor if it is a function declarator (9.3.4.6) of the form

ptr-declarator ( parameter-declaration-clause ) noexcept-specifier_opt attribute-specifier-seq_opt
where the `ptr-declarator` consists solely of an `id-expression`, an optional `attribute-specifier-seq`, and optional surrounding parentheses, and the `id-expression` has one of the following forms:

1. in a friend declaration (11.8.4), the `id-expression` is a `qualified-id` that names a constructor (6.5.5.2);
2. otherwise, in a member-declaration that belongs to the `member-specification` of a class or class template, the `id-expression` is the injected-class-name (11.1) of the immediately-enclosing entity;
3. otherwise, the `id-expression` is a `qualified-id` whose `unqualified-id` is the injected-class-name of its lookup context.

Constructors do not have names. In a constructor declaration, each `decl-specifier` in the optional `decl-specifier-seq` shall be `friend`, `inline`, `constexpr`, `consteval`, or an `explicit-specifier`.

```
[Example 1:
 struct S {
   S(); // declares the constructor
};
 S::S() { } // defines the constructor
—end example]
```

A constructor is used to initialize objects of its class type.

[Note 1: Because constructors do not have names, they are never found during unqualified name lookup; however an explicit type conversion using the functional notation (7.6.1.4) will cause a constructor to be called to initialize an object. The syntax looks like an explicit call of the constructor. —end note]

```
[Example 2:
 complex zz = complex(1,2.3);
cprint( complex(7.8,1.2) );
—end example]
```

A constructor can be invoked for a `const`, `volatile` or `const volatile` object. `const` and `volatile` semantics (9.2.9.2) are not applied on an object under construction. They come into effect when the constructor for the most derived object (6.7.2) ends.

6 The address of a constructor shall not be taken.

[Note 6: A `return` statement in the body of a constructor cannot specify a return value (8.7.4). —end note]

7 A constructor shall not be a coroutine.

8 A constructor shall not have an explicit object parameter (9.3.4.6).

### 11.4.5.2 Default constructors

A `default constructor` for a class `X` is a constructor of class `X` for which each parameter that is not a function parameter pack has a default argument (including the case of a constructor with no parameters). If there is no user-declared constructor or constructor template for class `X`, a non-explicit constructor having no parameters is implicitly declared as defaulted (9.5). An implicitly-declared default constructor is an inline public member of its class.

2 A defaulted default constructor for class `X` is defined as deleted if

1. any non-static data member with no default member initializer (11.4) is of reference type,
2. any non-variant non-static data member of const-qualified type (or possibly multi-dimensional array thereof) with no `brace-or-equal-initializer` is not const-default-constructible (9.4),
3. `X` is a union and all of its variant members are of const-qualified type (or possibly multi-dimensional array thereof),

—end note]
— \( X \) is a non-union class and all members of any anonymous union member are of const-qualified type (or possibly multi-dimensional array thereof),

— any potentially constructed subobject, except for a non-static data member with a brace-or-equal-initializer or a variant member of a union where another non-static data member has a brace-or-equal-initializer, has class type \( M \) (or possibly multi-dimensional array thereof) and overload resolution (12.2) as applied to find \( M \)'s corresponding constructor either does not result in a usable candidate (12.2.1) or, in the case of a variant member, selects a non-trivial function, or

— any potentially constructed subobject has class type \( M \) (or possibly multi-dimensional array thereof) and \( M \) has a destructor that is deleted or inaccessible from the defaulted default constructor.

A default constructor is trivial if it is not user-provided and if

— its class has no virtual functions (11.7.3) and no virtual base classes (11.7.2), and

— no non-static data member of its class has a default member initializer (11.4), and

— all the direct base classes of its class have trivial default constructors, and

— for all the non-static data members of its class that are of class type (or array thereof), each such class has a trivial default constructor.

Otherwise, the default constructor is non-trivial.

An implicitly-defined (9.5.2) default constructor performs the set of initializations of the class that would be performed by a user-written default constructor for that class with no ctor-initializer (11.9.3) and an empty compound-statement. If that user-written default constructor would be ill-formed, the program is ill-formed. If that user-written default constructor would be constexpr-suitable (9.2.6), the implicitly-defined default constructor is constexpr. Before the defaulted default constructor for a class is implicitly defined, all the non-user-provided default constructors for its base classes and its non-static data members are implicitly defined.

[Note 1: An implicitly-declared default constructor has an exception specification (14.5). An explicitly-defaulted definition might have an implicit exception specification, see 9.5. — end note]

[Note 2: A default constructor is implicitly invoked to initialize a class object when no initializer is specified (9.4.1). Such a default constructor needs to be accessible (11.8). — end note]

[Note 3: 11.9.3 describes the order in which constructors for base classes and non-static data members are called and describes how arguments can be specified for the calls to these constructors. — end note]

11.4.5.3 Copy/move constructors

A non-template constructor for class \( X \) is a copy constructor if its first parameter is of type \( X & \), \( \text{const } X & \), \( \text{volatile } X & \) or \( \text{const volatile } X & \), and either there are no other parameters or else all other parameters have default arguments (9.3.4.7).

[Example 1: \( X::X(\text{const } X &) \) and \( X::X(X &, \text{int} = 1) \) are copy constructors.

```cpp
struct X {
    X(int);
    X(\text{const } X &, \text{int} = 1);
};
X a(1);       // calls X(int);
X b(a, 0);    // calls X(\text{const } X &, \text{int});
X c = b;      // calls X(\text{const } X &, \text{int});
    — end example]
```

A non-template constructor for class \( X \) is a move constructor if its first parameter is of type \( X && \), \( \text{const } X && \), \( \text{volatile } X && \), or \( \text{const volatile } X && \), and either there are no other parameters or else all other parameters have default arguments (9.3.4.7).

[Example 2: \( Y::Y(Y &&) \) is a move constructor.

```cpp
struct Y {
    Y(\text{const } Y &);
    Y(Y &&);
};
extern Y f(int);
Y d(f(1));      // calls Y(Y &&)
Y e = d;        // calls Y(\text{const } Y &)
```

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— end example]

3 [Note 1: All forms of copy/move constructor can be declared for a class.]

[Example 3:

```cpp
struct X {
    X(const X&);  // OK
    X(X&);  // OK, but possibly not sensible
    X(X&&);  // OK
    X(const X&&);  // OK
};
```

— end example]

— end note]

4 [Note 2: If a class X only has a copy constructor with a parameter of type X&, an initializer of type const X or volatile X cannot initialize an object of type cv X.]

[Example 4:

```cpp
struct X {
    X();  // default constructor
    X(X&);  // copy constructor with a non-const parameter
};
const X cx;
X x = cx;  // error: X::X(X&) cannot copy cx into x
```

— end example]

— end note]

5 A declaration of a constructor for a class X is ill-formed if its first parameter is of type cv X and either there are no other parameters or else all other parameters have default arguments. A member function template is never instantiated to produce such a constructor signature.

[Example 5:

```cpp
struct S {
    template<typename T> S(T);
    S();  // does not instantiate the member template to produce S::S<S>(S);
};
S g;
void h() {
    S a(g);  // uses the implicitly declared copy constructor
}
```

— end example]

6 If the class definition does not explicitly declare a copy constructor, a non-explicit one is declared implicitly. If the class definition declares a move constructor or move assignment operator, the implicitly declared copy constructor is defined as deleted; otherwise, it is defaulted (9.5). The latter case is deprecated if the class has a user-declared copy assignment operator or a user-declared destructor (D.7).

7 The implicitly-declared copy constructor for a class X will have the form

```cpp
X::X(const X&)
```

if each potentially constructed subobject of a class type M (or array thereof) has a copy constructor whose first parameter is of type const M& or const volatile M&. If there is no such copy constructor, the implicitly-declared copy constructor will have the form

```cpp
X::X(X&)
```

8 If the definition of a class X does not explicitly declare a move constructor, a non-explicit one will be implicitly declared as defaulted if and only if

(8.1) X does not have a user-declared copy constructor,

---

90] This implies that the reference parameter of the implicitly-declared copy constructor cannot bind to a volatile lvalue; see C.7.7.
— X does not have a user-declared copy assignment operator,
— X does not have a user-declared move assignment operator, and
— X does not have a user-declared destructor.

[Note 3: When the move constructor is not implicitly declared or explicitly supplied, expressions that otherwise would have invoked the move constructor might instead invoke a copy constructor. — end note]

The implicitly-declared move constructor for class X will have the form

\[ X::X(X&&) \]

An implicitly-declared copy/move constructor is an inline public member of its class. A defaulted copy/move constructor for a class X is defined as deleted (9.5.3) if X has:

(10.1) — a potentially constructed subobject of type M (or possibly multi-dimensional array thereof) for which overload resolution (12.2), as applied to find M’s corresponding constructor, either does not result in a usable candidate (12.2.1) or, in the case of a variant member, selects a non-trivial function,

(10.2) — any potentially constructed subobject of class type M (or possibly multi-dimensional array thereof) where M has a destructor that is deleted or inaccessible from the defaulted constructor, or,

(10.3) — for the copy constructor, a non-static data member of rvalue reference type.

[Note 4: A defaulted move constructor that is defined as deleted is ignored by overload resolution (12.2, 12.3). Such a constructor would otherwise interfere with initialization from an rvalue which can use the copy constructor instead. — end note]

A copy/move constructor for class X is trivial if it is not user-provided and if

(11.1) — class X has no virtual functions (11.7.3) and no virtual base classes (11.7.2), and

(11.2) — the constructor selected to copy/move each direct base class subobject is trivial, and

(11.3) — for each non-static data member of X that is of class type (or array thereof), the constructor selected to copy/move that member is trivial; otherwise the copy/move constructor is non-trivial.

[Note 5: The copy/move constructor is implicitly defined even if the implementation elided its odr-use (6.3, 6.7.7). — end note]

If an implicitly-defined (9.5.2) constructor would be constexpr-suitable (9.2.6), the implicitly-defined constructor is constexpr.

Before the defaulted copy/move constructor for a class is implicitly defined, all non-user-provided copy/move constructors for its potentially constructed subobjects are implicitly defined.

[Note 6: An implicitly-declared copy/move constructor has an implied exception specification (14.5). — end note]

The implicitly-defined copy/move constructor for a non-union class X performs a memberwise copy/move of its bases and members.

[Note 7: Default member initializers of non-static data members are ignored. — end note]

The order of initialization is the same as the order of initialization of bases and members in a user-defined constructor (see 11.9.3). Let x be either the parameter of the constructor or, for the move constructor, an xvalue referring to the parameter. Each base or non-static data member is copied/moved in the manner appropriate to its type:

(14.1) — if the member is an array, each element is direct-initialized with the corresponding subobject of x;

(14.2) — if a member m has rvalue reference type T&&, it is direct-initialized with static_cast<T&&>(x.m);

(14.3) — otherwise, the base or member is direct-initialized with the corresponding base or member of x.

Virtual base class subobjects shall be initialized only once by the implicitly-defined copy/move constructor (see 11.9.3).

The implicitly-defined copy/move constructor for a union X copies the object representation (6.8.1) of X. For each object nested within (6.7.2) the object that is the source of the copy, a corresponding object o nested within the destination is identified (if the object is a subobject) or created (otherwise), and the lifetime of o begins before the copy is performed.
11.4.6 Copy/move assignment operator

A user-declared *copy* assignment operator `X::operator=` is a non-static non-template member function of class `X` with exactly one non-object parameter of type `X`, `X&`, `const X&`, `volatile X&`, or `const volatile X&`.  

[Note 1: More than one form of copy assignment operator can be declared for a class. — end note]

[Note 2: If a class `X` only has a copy assignment operator with a non-object parameter of type `X&`, an expression of type `const X` cannot be assigned to an object of type `X`.]

**Example 1:**
```c++
struct X {
  X();
  X& operator=(X&); // error: X::operator=(X&) cannot assign cx into x
};
const X cx;
X x;
void f() {
  x = cx;       
}   // end example]
```

—end example]

—end note]

If the class definition does not explicitly declare a copy assignment operator, one is declared implicitly. If the class definition declares a move constructor or move assignment operator, the implicitly declared copy assignment operator is defined as deleted; otherwise, it is defaulted (9.5). The latter case is deprecated if the class has a user-declared copy constructor or a user-declared destructor (D.7). The implicitly-declared copy assignment operator for a class `X` will have the form

```
X& X::operator=(const X&)
```

3 If the definition of a class `X` does not explicitly declare a move assignment operator, one will be implicitly declared as defaulted if and only if

(4.1) — `X` does not have a user-declared copy constructor,
(4.2) — `X` does not have a user-declared move constructor,
(4.3) — `X` does not have a user-declared copy assignment operator, and
(4.4) — `X` does not have a user-declared destructor.

**Example 2:** The class definition

```c++
struct S {
  int a;
};
```
will not have a default move assignment operator implicitly declared because the copy assignment operator has been
user-declared. The move assignment operator may be explicitly defaulted.

```
struct S {
  int a;
  S& operator=(const S&) = default;
  S& operator=(S&&) = default;
};
```

--- end example]  

5 The implicitly-declared move assignment operator for a class \( X \) will have the form

\[
X& X::operator=(X&&)
\]

6 The implicitly-declared copy/move assignment operator for class \( X \) has the return type \( X\& \). An implicitly-declared copy/move assignment operator is an inline public member of its class.

7 A defaulted copy/move assignment operator for class \( X \) is defined as deleted if \( X \) has:

1. (7.1) a non-static data member of \( \text{const} \) non-class type (or possibly multi-dimensional array thereof), or
2. (7.2) a non-static data member of reference type, or
3. (7.3) a direct non-static data member of class type \( M \) (or possibly multi-dimensional array thereof) or a direct base class \( M \) that cannot be copied/moved because overload resolution (12.2), as applied to find \( M\)'s corresponding assignment operator, either does not result in a usable candidate (12.2.1) or, in the case of a variant member, selects a non-trivial function.

[Note 4: A defaulted move assignment operator that is defined as deleted is ignored by overload resolution (12.2, 12.3). — end note]

8 Because a copy/move assignment operator is implicitly declared for a class if not declared by the user, a base class copy/move assignment operator is always hidden by the corresponding assignment operator of a derived class (12.4.3.2).

[Note 5: A \textit{using-declaration} in a derived class \( C \) that names an assignment operator from a base class never suppresses the implicit declaration of an assignment operator of \( C \), even if the base class assignment operator would be a copy or move assignment operator if declared as a member of \( C \). — end note]

9 A copy/move assignment operator for class \( X \) is trivial if it is not user-provided and if

1. (9.1) class \( X \) has no virtual functions (11.7.3) and no virtual base classes (11.7.2), and
2. (9.2) the assignment operator selected to copy/move each direct base class subobject is trivial, and
3. (9.3) for each non-static data member of \( X \) that is of class type (or array thereof), the assignment operator selected to copy/move that member is trivial;

otherwise the copy/move assignment operator is \textit{non-trivial}.

10 An implicitly-defined (9.5.2) copy/move assignment operator is \texttt{constexpr}.

11 Before the defaulted copy/move assignment operator for a class is implicitly defined, all non-user-provided copy/move assignment operators for its direct base classes and its non-static data members are implicitly defined.

[Note 6: An implicitly-declared copy/move assignment operator has an implied exception specification (14.5). — end note]

12 The implicitly-defined copy/move assignment operator for a non-union class \( X \) performs memberwise copy/move assignment of its subobjects. The direct base classes of \( X \) are assigned first, in the order of their declaration in the \textit{base-specifier-list}, and then the immediate non-static data members of \( X \) are assigned, in the order in which they were declared in the class definition. Let \( x \) be either the parameter of the function or, for the move operator, an xvalue referring to the parameter. Each subobject is assigned in the manner appropriate to its type:

1. (12.1) if the subobjec is of class type, as if by a call to \texttt{operator=} with the subobject as the object expression and the corresponding subobject of \( x \) as a single function argument (as if by explicit qualification; that is, ignoring any possible virtual overriding functions in more derived classes);
2. (12.2) if the subobject is an array, each element is assigned, in the manner appropriate to the element type;
(12.3) if the subobject is of scalar type, the built-in assignment operator is used.

It is unspecified whether subobjects representing virtual base classes are assigned more than once by the implicitly-defined copy/move assignment operator.

[Example 3:
   ```cpp
   struct V { }
   struct A : virtual V { }
   struct B : virtual V { }
   struct C : B, A { }
   ```
   It is unspecified whether the virtual base class subobject V is assigned twice by the implicitly-defined copy/move assignment operator for C. — end example]

The implicitly-defined copy/move assignment operator for a union X copies the object representation (6.8.1) of X. If the source and destination of the assignment are not the same object, then for each object nested within (6.7.2) the object that is the source of the copy, a corresponding object o nested within the destination is created, and the lifetime of o begins before the copy is performed.

The implicitly-defined copy/move assignment operator for a class returns the object for which the assignment operator is invoked, that is, the object assigned to.

### 11.4.7 Destructors

A declaration whose declarator-id has an unqualified-id that begins with a ~ declares a prospective destructor; its declarator shall be a function declarator (9.3.4.6) of the form

```
ptr-declarator ( parameter-declaration-clause ) noexcept-specifier_opt attribute-specifier-seq_opt
```

where the ptr-declarator consists solely of an id-expression, an optional attribute-specifier-seq, and optional surrounding parentheses, and the id-expression has one of the following forms:

- in a member-declaration that belongs to the member-specification of a class or class template but is not a friend declaration (11.8.4), the id-expression is ~class-name and the class-name is the injected-class-name (11.1) of the immediately-enclosing entity or
- otherwise, the id-expression is nested-name-specifier ~class-name and the class-name is the injected-class-name of the class nominated by the nested-name-specifier.

A prospective destructor shall take no arguments (9.3.4.6). Each decl-specifier of the decl-specifier-seq of a prospective destructor declaration (if any) shall be friend, inline, virtual, or constexpr.

If a class has no user-declared prospective destructor, a prospective destructor is implicitly declared as defaulted (9.5). An implicitly-declared prospective destructor is an inline public member of its class.

An implicitly-declared prospective destructor for a class X will have the form

```
~X()
```

At the end of the definition of a class, overload resolution is performed among the prospective destructors declared in that class with an empty argument list to select the destructor for the class, also known as the selected destructor. The program is ill-formed if overload resolution fails. Destructor selection does not constitute a reference to, or odr-use (6.3) of, the selected destructor, and in particular, the selected destructor may be deleted (9.5.3).

The address of a destructor shall not be taken.

[Note 1: A return statement in the body of a destructor cannot specify a return value (8.7.4). — end note]

A destructor can be invoked for a const, volatile or const volatile object. const and volatile semantics (9.2.9.2) are not applied on an object under destruction. They stop being in effect when the destructor for the most derived object (6.7.2) starts.

[Note 2: A declaration of a destructor that does not have a noexcept-specifier has the same exception specification as if it had been implicitly declared (14.5). — end note]

A defaulted destructor for a class X is defined as deleted if

- any potentially constructed subobject has class type M (or possibly multi-dimensional array thereof) and M has a destructor that is deleted or is inaccessible from the defaulted destructor or, in the case of a variant member, is non-trivial,
- or, for a virtual destructor, lookup of the non-array deallocation function results in an ambiguity or in a function that is deleted or inaccessible from the defaulted destructor.
A destructor is trivial if it is not user-provided and if

(8.1) the destructor is not virtual,
(8.2) all of the direct base classes of its class have trivial destructors, and
(8.3) for all of the non-static data members of its class that are of class type (or array thereof), each such class has a trivial destructor.

Otherwise, the destructor is non-trivial.

A defaulted destructor is a constexpr destructor if it is constexpr-suitable (9.2.6).

Before a defaulted destructor for a class is implicitly defined, all the non-user-provided destructors for its base classes and its non-static data members are implicitly defined.

A prospective destructor can be declared virtual (11.7.3) and with a pure-specifier (11.7.4). If the destructor of a class is virtual and any objects of that class or any derived class are created in the program, the destructor shall be defined.

[Note 3: Some language constructs have special semantics when used during destruction; see 11.9.5. — end note]

After executing the body of the destructor and destroying any objects with automatic storage duration allocated within the body, a destructor for class X calls the destructors for X’s direct non-variant non-static data members other than anonymous unions, the destructors for X’s non-virtual direct base classes and, if X is the most derived class (11.9.3), its destructor calls the destructors for X’s virtual base classes. All destructors are called as if they were referenced with a qualified name, that is, ignoring any possible virtual overriding destructors in more derived classes. Bases and members are destroyed in the reverse order of the completion of their constructor (see 11.9.3).

[Note 4: A return statement (8.7.4) in a destructor might not directly return to the caller; before transferring control to the caller, the destructors for the members and bases are called. — end note]

Destructors for elements of an array are called in reverse order of their construction (see 11.9).

A destructor is invoked implicitly

(14.1) for a constructed object with static storage duration (6.7.5.2) at program termination (6.9.3.4),
(14.2) for a constructed object with thread storage duration (6.7.5.3) at thread exit,
(14.3) for a constructed object with automatic storage duration (6.7.5.4) when the block in which an object is created exits (8.8),
(14.4) for a constructed temporary object when its lifetime ends (7.3.5, 6.7.7).

In each case, the context of the invocation is the context of the construction of the object. A destructor may also be invoked implicitly through use of a delete-expression (7.6.2.9) for a constructed object allocated by a new-expression (7.6.2.8); the context of the invocation is the delete-expression.

[Note 5: An array of class type contains several subobjects for each of which the destructor is invoked. — end note]

A destructor can also be invoked explicitly. A destructor is potentially invoked if it is invoked or as specified in 7.6.2.8, 8.7.4, 9.4.2, 11.9.3, and 14.2. A program is ill-formed if a destructor that is potentially invoked is deleted or not accessible from the context of the invocation.

At the point of definition of a virtual destructor (including an implicit definition), the non-array deallocation function is determined as if for the expression delete this appearing in a non-virtual destructor of the destructor’s class (see 7.6.2.9). If the lookup fails or if the deallocation function has a deleted definition (9.5), the program is ill-formed.

[Note 6: This assures that a deallocation function corresponding to the dynamic type of an object is available for the delete-expression (11.4.11). — end note]

In an explicit destructor call, the destructor is specified by a ~ followed by a type-name or computed-type-specifier that denotes the destructor’s class type. The invocation of a destructor is subject to the usual rules for member functions (11.4.2); that is, if the object is not of the destructor’s class type and not of a class derived from the destructor’s class type (including when the destructor is invoked via a null pointer value), the program has undefined behavior.

[Note 7: Invoking delete on a null pointer does not call the destructor; see 7.6.2.9. — end note]

[Example 1:}
struct B {
    virtual ~B() { }
};

struct D : B {
    ~D() { }
};

D D_object;
typedef B B_alias;
B* B_ptr = &D_object;

void f() {
    D_object.B::~B(); // calls B’s destructor
    B_ptr->~B();       // calls D’s destructor
    B_ptr->B_alias::~B(); // calls B’s destructor
    B_ptr->B_alias::~B_alias(); // calls B’s destructor
}

/* end example */

[Note 8: An explicit destructor call must always be written using a member access operator (7.6.1.5) or a qualified-id (7.5.5.3); in particular, the unary-expression ~X() in a member function is not an explicit destructor call (7.6.2.2).

/* end note */

17 [Note 9: Explicit calls of destructors are rarely needed. One use of such calls is for objects placed at specific addresses using a placement new-expression. Such use of explicit placement and destruction of objects can be necessary to cope with dedicated hardware resources and for writing memory management facilities.

/* Example 2: */

void* operator new(std::size_t, void* p) { return p; }
struct X {
    X(int);
    ~X();
};
void f(X* p);

void g() {
    // rare, specialized use:
    char* buf = new char[sizeof(X)];
    X* p = new(buf) X(222); // use buf[] and initialize
    f(p);
    p->X::~X(); // cleanup
}

/* end example */

/* end note */

18 Once a destructor is invoked for an object, the object’s lifetime ends; the behavior is undefined if the destructor is invoked for an object whose lifetime has ended (6.7.3).

/* Example 3: If the destructor for an object with automatic storage duration is explicitly invoked, and the block is subsequently left in a manner that would ordinarily invoke implicit destruction of the object, the behavior is undefined.

/* end example */

19 [Note 10: The notation for explicit call of a destructor can be used for any scalar type name (7.5.5.5). Allowing this makes it possible to write code without having to know if a destructor exists for a given type. For example:

typedef int I;
I* p;
p->I::~I();

/* end note */

20 A destructor shall not be a coroutine.

11.4.8 Conversions

11.4.8.1 General

Type conversions of class objects can be specified by constructors and by conversion functions. These conversions are called user-defined conversions and are used for implicit type conversions (7.3), for initialization.
(9.4), and for explicit type conversions (7.6.1.4, 7.6.3, 7.6.1.9).

2 User-defined conversions are applied only where they are unambiguous (6.5.2, 11.4.8.3). Conversions obey the access control rules (11.8). Access control is applied after ambiguity resolution (6.5).

3 [Note 1: See 12.2 for a discussion of the use of conversions in function calls. —end note]

4 At most one user-defined conversion (constructor or conversion function) is implicitly applied to a single value.

[Example 1:

```c
struct X {
    operator int();
};

struct Y {
    operator X();
};

Y a;
int b = a;  // error: no viable conversion (a.operator X().operator int() not considered)
int c = X(a);  // OK, a.operator X().operator int()
```

—end example]

11.4.8.2 Conversion by constructor

1 A constructor that is not explicit (9.2.3) specifies a conversion from the types of its parameters (if any) to the type of its class. Such a constructor is called a converting constructor.

[Example 1:

```c
struct X {
    X(int);
    X(const char*, int = 0);
    X(int, int);
};

void f(X arg) {
    X a = 1;  // a = X(1)
    X b = "Jessie";  // b = X("Jessie",0)
    a = 2;  // a = X(2)
    f(3);  // f(X(3))
    f({1, 2});  // f(X(1,2))
}
```

—end example]

2 [Note 1: An explicit constructor constructs objects just like non-explicit constructors, but does so only where the direct-initialization syntax (9.4) or where casts (7.6.1.9, 7.6.3) are explicitly used; see also 12.2.2.5. A default constructor can be an explicit constructor; such a constructor will be used to perform default-initialization or value-initialization (9.4).

[Example 2:

```c
struct Z {
    explicit Z();
    explicit Z(int);
    explicit Z(int, int);
};

Z a;  // OK, default-initialization performed
Z b();  // OK, direct initialization syntax used
Z c = {};  // error: copy-list-initialization
Z a1 = 1;  // error: no implicit conversion
Z a3 = Z(1);  // OK, direct initialization syntax used
Z a2(Z);  // OK, direct initialization syntax used
Z* p = new Z(1);  // OK, direct initialization syntax used
Z a4 = (Z)1;  // OK, explicit cast used
Z a5 = static_cast<Z>(1);  // OK, explicit cast used
Z a6 = { 3, 4 };  // error: no implicit conversion
```
3 A non-explicit copy/move constructor (11.4.5.3) is a converting constructor.

[Note 2: An implicitly-declared copy/move constructor is not an explicit constructor; it can be called for implicit type conversions. — end note]

11.4.8.3 Conversion functions

conversion-function-id:
  operator conversion-type-id

conversion-type-id:
  type-specifier-seq conversion-declarator\_opt

conversion-declarator:
  ptr-operator conversion-declarator\_opt

1 A declaration whose declarator\_id has an unqualified\_id that is a conversion-function\_id declares a conversion function; its declarator shall be a function declarator (9.3.4.6) of the form

noptr-declarator parameters-and-qualifiers

where the noptr-declarator consists solely of an id-expression, an optional attribute-specifier-seq, and optional surrounding parentheses, and the id-expression has one of the following forms:

(1.1) — in a member-declaration that belongs to the member-specification of a class or class template but is not a friend declaration (11.8.4), the id-expression is a conversion-function\_id;

(1.2) — otherwise, the id-expression is a qualified\_id whose unqualified\_id is a conversion-function\_id.

2 A conversion function shall have no non-object parameters and shall be a non-static member function of a class or class template X; its declared return type is the conversion-type\_id and it specifies a conversion from X to the type specified by the conversion-type\_id, interpreted as a type\_id (9.3.2). A decl-specifier in the decl-specifier-seq of a conversion function (if any) shall not be a defining-type-specifier.

3 [Note 1: A conversion function is never invoked for implicit or explicit conversions of an object to the same object type (or a reference to it), to a base class of that type (or a reference to it), or to cv void. Even though never directly called to perform a conversion, such conversion functions can be declared and can potentially be reached through a call to a virtual conversion function in a base class. — end note]

[Example 1]:

```c
struct X {
  operator int();
  operator auto() -> short;  // error: trailing return type
};

void f(X a) {
  int i = int(a);
  i = (int)a;
  i = a;
}
```

In all three cases the value assigned will be converted by X::operator int(). — end example]

4 A conversion function may be explicit (9.2.3), in which case it is only considered as a user-defined conversion for direct-initialization (9.4). Otherwise, user-defined conversions are not restricted to use in assignments and initializations.

[Example 2]:

```c
class Y { };  
struct Z {
  explicit operator Y() const;
};

void h(Z z) {
  Y y1(z);  // OK, direct-initialization
  Y y2 = z;  // error: no conversion function candidate for copy-initialization
  Y y3 = Y(z); // OK, cast notation
}
```

§ 11.4.8.3 ©ISO/IEC
void g(X a, X b) {
    int i = (a) ? 1+a : 0;
    int j = (a&&b) ? a+b : i;
    if (a) {
    }
}
—end example

The conversion-type-id shall not represent a function type nor an array type. The conversion-type-id in a conversion-function-id is the longest sequence of tokens that could possibly form a conversion-type-id.

[Note 2: This prevents ambiguities between the declarator operator * and its expression counterparts.]

[Example 3:]
&ac.operator int*; // syntax error:
    // parsed as: &(ac.operator int *)i
    // not as: &ac.operator int*i

The * is the pointer declarator and not the multiplication operator. —end example]

This rule also prevents ambiguities for attributes.

[Example 4:]
operator int [[noreturn]] (); // error: noreturn attribute applied to a type
—end example]
—end note]

[Note 3: A conversion function in a derived class hides only conversion functions in base classes that convert to the same type. A conversion function template with a dependent return type hides only templates in base classes that correspond to it (6.5.2); otherwise, it hides and is hidden as a non-template function. Function overload resolution (12.2.4) selects the best conversion function to perform the conversion.

[Example 5:]
struct X {
    operator int();
};
struct Y : X {
    operator char();
};
void f(Y& a) {
    if (a) {
        // error: ambiguous between X::operator int() and Y::operator char()
    }
}
—end example]
—end note]

Conversion functions can be virtual.

[Note 4: A conversion function template shall not have a deduced return type (9.2.9.7).]

[Example 6:]
struct S {
    operator auto() const { return 10; } // OK
    template<class T>
    operator auto() const { return 1.2; } // error: conversion function template
};
—end example]

11.4.9 Static members [class.static]

11.4.9.1 General [class.static.general]

A static member s of class X may be referred to using the qualified-id expression X::s; it is not necessary to use the class member access syntax (7.6.1.5) to refer to a static member. A static member may be referred to using the class member access syntax, in which case the object expression is evaluated.
Example 1:

```cpp
struct process {
    static void reschedule();
};
process& g();

void f() {
    process::reschedule();  // OK, no object necessary
    g().reschedule();  // g() is called
}
```

—end example

Static members obey the usual class member access rules (11.8). When used in the declaration of a class member, the static specifier shall only be used in the member declarations that appear within the member-specification of the class definition.

[Note 1: It cannot be specified in member declarations that appear in namespace scope. — end note]

11.4.9.2 Static member functions

[Note 1: The rules described in 11.4.2 apply to static member functions. — end note]

11.4.9.3 Static data members

[Note 2: A static member function does not have a this pointer (7.5.3). A static member function cannot be qualified with const, volatile, or virtual (9.3.4.6). — end note]

A static data member is not part of the subobjects of a class. If a static data member is declared thread-local there is one copy of the member per thread. If a static data member is not declared thread_local there is one copy of the data member that is shared by all the objects of the class.

A static data member shall not be mutable (9.2.2). A static data member shall not be a direct member (11.4) of an unnamed (11.1) or local (11.6) class or of a (possibly indirectly) nested class (11.4.12) thereof.

The declaration of a non-inline static data member in its class definition is not a definition and may be of an incomplete type other than cv void.

[Note 1: The initializer in the definition of a static data member is in the scope of its class (6.4.7). — end note]

Example 1:

```cpp
class process {
    static process* run_chain;
    static process* running;
};

process* process::running = get_main();
process* process::run_chain = running;
```

The definition of the static data member run_chain of class process inhabits the global scope; the notation process::run_chain indicates that the member run_chain is a member of class process and in the scope of class process. In the static data member definition, the initializer expression refers to the static data member running of class process. — end example

[Note 2: Once the static data member has been defined, it exists even if no objects of its class have been created.

Example 2: In the example above, run_chain and running exist even if no objects of class process are created by the program. — end example]

The initialization and destruction of static data members is described in 6.9.3.2, 6.9.3.3, and 6.9.3.4. — end note

If a non-volatile non-inline const static data member is of integral or enumeration type, its declaration in the class definition can specify a brace-or-equal-initializer in which every initializer-clause that is an assignment-expression is a constant expression (7.7). The member shall still be defined in a namespace scope if it is odr-used (6.3) in the program and the namespace scope definition shall not contain an initializer. The declaration of an inline static data member (which is a definition) may specify a brace-or-equal-initializer. If the member is declared with the constexpr specifier, it may be redeclared in namespace scope with no initializer (this usage is deprecated; see D.5). Declarations of other static data members shall not specify a brace-or-equal-initializer.

[Note 3: There is exactly one definition of a static data member that is odr-used (6.3) in a valid program. — end note]
11.4.10 Bit-fields

A member-declarator of the form

\[
\text{identifier} \opt \text{attribute-specifier-seq} \opt : \text{constant-expression} \ brace-or-equal-initializer \opt
\]

specifies a bit-field. The optional attribute-specifier-seq appertains to the entity being declared. A bit-field shall not be a static member. A bit-field shall have integral or (possibly cv-qualified) enumeration type; the bit-field semantic property is not part of the type of the class member. The constant-expression shall be an integral constant expression with a value greater than or equal to zero and is called the width of the bit-field. If the width of a bit-field is larger than the width of the bit-field’s type (or, in case of an enumeration type, of its underlying type), the extra bits are padding bits (6.8.1). Allocation of bit-fields within a class object is implementation-defined. Alignment of bit-fields is implementation-defined. Bit-fields are packed into some addressable allocation unit.

[Note 1: Bit-fields straddle allocation units on some machines and not on others. Bit-fields are assigned right-to-left on some machines, left-to-right on others. — end note]

A declaration for a bit-field that omits the identifier declares an unnamed bit-field. Unnamed bit-fields are not members and cannot be initialized. An unnamed bit-field shall not be declared with a cv-qualified type.

[Note 2: An unnamed bit-field is useful for padding to conform to externally-imposed layouts. — end note]

As a special case, an unnamed bit-field with a width of zero specifies alignment of the next bit-field at an allocation unit boundary. Only when declaring an unnamed bit-field may the width be zero.

The address-of operator & shall not be applied to a bit-field, so there are no pointers to bit-fields. A non-const reference shall not bind to a bit-field (9.4.4).

[Note 3: If the initializer for a reference of type const T& is an lvalue that refers to a bit-field, the reference is bound to a temporary initialized to hold the value of the bit-field; the reference is not bound to the bit-field directly. See 9.4.4. — end note]

If a value of integral type (other than bool) is stored into a bit-field of width N and the value would be representable in a hypothetical signed or unsigned integer type with width N and the same signedness as the bit-field’s type, the original value and the value of the bit-field compare equal. If the value true or false is stored into a bit-field of type bool of any size (including a one bit bit-field), the original bool value and the value of the bit-field compare equal. If a value of an enumeration type is stored into a bit-field of the same type and the width is large enough to hold all the values of that enumeration type (9.7.1), the original value and the value of the bit-field compare equal.

[Example 1: enum BOOL { FALSE=0, TRUE=1 }; struct A { BOOL b:1; }; A a; void f() { a.b = TRUE; if (a.b == TRUE) // yields true /* ... */ }]

11.4.11 Allocation and deallocation functions

Any allocation function for a class T is a static member (even if not explicitly declared static).

[Example 1: class Arena; struct B { void* operator new(std::size_t, Arena*); }; struct D1 : B { };]
void foo(int i) {
    new (ap) D1;  // calls B::operator new(std::size_t, Arena*)
    new D1[i];   // calls ::operator new[](std::size_t)
    new D1;     // error: ::operator new(std::size_t) hidden
}
—end example]

3 Any deallocation function for a class \( X \) is a static member (even if not explicitly declared static).

[Example 2:]

```cpp
class X {
    void operator delete(void*);
    void operator delete[](void*, std::size_t);
};

class Y {
    void operator delete(void*, std::size_t);
    void operator delete[](void*);
};
—end example]
```

4 Since member allocation and deallocation functions are static they cannot be virtual.

[Note 1: However, when the cast-expression of a delete-expression refers to an object of class type with a virtual destructor, because the deallocation function is chosen by the destructor of the dynamic type of the object, the effect is the same in that case.

[Example 3:]

```cpp
struct B {
    virtual ~B();
    void operator delete(void*, std::size_t);
};

struct D : B {
    void operator delete(void*);
};

struct E : B {
    void log_deletion();
    void operator delete(E *p, std::destroying_delete_t) {
        p->log_deletion();
        p->~E();
        ::operator delete(p);
    }
};

void f() {
    B* bp = new D;
    delete bp;     // 1: uses D::operator delete(void*)
    bp = new E;
    delete bp;     // 2: uses E::operator delete(E*, std::destroying_delete_t)
}
```

Here, storage for the object of class \( D \) is deallocated by \( D::operator delete() \), and the object of class \( E \) is destroyed and its storage is deallocated by \( E::operator delete() \), due to the virtual destructor. —end example]

—end note]

[Note 2: Virtual destructors have no effect on the deallocation function actually called when the cast-expression of a delete-expression refers to an array of objects of class type.

[Example 4:]

```cpp
struct B {
    virtual ~B();
    void operator delete[](void*, std::size_t);
};
```
struct D : B {
    void operator delete[](void*, std::size_t);
};

void f(int i) {
    D* dp = new D[i];
    delete [] dp; // uses D::operator delete[](void*, std::size_t)
    B* bp = new D[i];
    delete[] bp; // undefined behavior
}

Access to the deallocation function is checked statically, even if a different one is actually executed.

[Example 5: For the call on line “// 1” above, if B::operator delete() had been private, the delete expression would have been ill-formed. — end example]

[Note 3: If a deallocation function has no explicit noexcept-specifier, it has a non-throwing exception specification (14.5). — end note]

11.4.12 Nested class declarations [class.nest]

A class can be declared within another class. A class declared within another is called a nested class.

[Note 1: See 7.5.5 for restrictions on the use of non-static data members and non-static member functions. — end note]

[Example 1:

```cpp
int x;
int y;

struct enclose {
    int x;
    static int s;

    struct inner {
        void f(int i) {
            int a = sizeof(x); // OK, operand of sizeof is an unevaluated operand
            x = i; // error: assign to enclose::x
            s = i; // OK, assign to enclose::s
            ::x = i; // OK, assign to global x
            y = i; // OK, assign to global y
        }
        void g(enclose* p, int i) {
            p->x = i; // OK, assign to enclose::x
        }
    }
};

inner* p = 0; // error: inner not found
```

— end example]

[Note 2: Nested classes can be defined either in the enclosing class or in an enclosing namespace; member functions and static data members of a nested class can be defined either in the nested class or in an enclosing namespace scope.

[Example 2:

```cpp
struct enclose {
    struct inner {
        static int x;
        void f(int i);
    }
;

    int enclose::inner::x = 1;

    void enclose::inner::f(int i) { /* ... */ }
```
A friend function (11.8.4) defined within a nested class has no special access rights to members of an enclosing class.

### 11.5 Unions

#### 11.5.1 General

A **union** is a class defined with the `class-key` `union`.

In a union, a non-static data member is **active** if its name refers to an object whose lifetime has begun and has not ended (6.7.3). At most one of the non-static data members of an object of union type can be active at any time, that is, the value of at most one of the non-static data members can be stored in a union at any time.

**Note 1:** One special guarantee is made in order to simplify the use of unions: If a standard-layout union contains several standard-layout structs that share a common initial sequence (11.4), and if a non-static data member of an object of this standard-layout union type is active and is one of the standard-layout structs, the common initial sequence of any of the standard-layout struct members can be inspected; see 11.4.  — end note]

The size of a union is sufficient to contain the largest of its non-static data members. Each non-static data member is allocated as if it were the sole member of a non-union class.

**Note 2:** A union object and its non-static data members are pointer-interconvertible (6.8.4, 7.6.1.9). As a consequence, all non-static data members of a union object have the same address.  — end note]

A union can have member functions (including constructors and destructors), but it shall not have virtual (11.7.3) functions. A union shall not have base classes. A union shall not be used as a base class. If a union contains a non-static data member of reference type, the program is ill-formed.

**Note 3:** Absent default member initializers (11.4), if any non-static data member of a union has a non-trivial default constructor (11.4.5.2), copy constructor, move constructor (11.4.5.3), copy assignment operator, move assignment operator (11.4.6), or destructor (11.4.7), the corresponding member function of the union must be user-provided or it will be implicitly deleted (9.5.3) for the union.

**Example 1:** Consider the following union:

```cpp
union U {
    int i;
    float f;
    std::string s;
};
```

Since `std::string` (23.4) declares non-trivial versions of all of the special member functions, `U` will have an implicitly deleted default constructor, copy/move constructor, copy/move assignment operator, and destructor. To use `U`, some or all of these member functions must be user-provided.  — end example]

When the left operand of an assignment operator involves a member access expression (7.6.1.5) that nominates a union member, it may begin the lifetime of that union member, as described below. For an expression `E`, define the set `S(E)` of subexpressions of `E` as follows:

- (5.1) If `E` is of the form `A.B`, `S(E)` contains the elements of `S(A)`, and also contains `A.B` if `B` names a union member of a non-class, non-array type, or of a class type with a trivial default constructor that is not deleted, or an array of such types.

- (5.2) If `E` is of the form `A[B]` and is interpreted as a built-in array subscripting operator, `S(E)` is `S(A)` if `A` is of array type, `S(B)` if `B` is of array type, and empty otherwise.

- (5.3) Otherwise, `S(E)` is empty.

In an assignment expression of the form `E1 = E2` that uses either the built-in assignment operator (7.6.19) or a trivial assignment operator (11.4.6), for each element `X` of `S(E1)` and each anonymous union member
X (11.5.2) that is a member of a union and has such an element as an immediate subobject (recursively), if modification of X would have undefined behavior under 6.7.3, an object of the type of X is implicitly created in the nominated storage; no initialization is performed and the beginning of its lifetime is sequenced after the value computation of the left and right operands and before the assignment.

[Note 4: This ends the lifetime of the previously-active member of the union, if any (6.7.3). — end note]

[Example 2:]

```c
union A { int x; int y[4]; }
struct B { A a; }
union C { B b; int k; }
int f() {
    C c;                 // does not start lifetime of any union member
    c.b.a.y[3] = 4;     // OK, S(c.b.a.y[3]) contains c.b and c.b.a.y;
    return c.b.a.y[3]; // OK, c.b.a.y refers to newly created object (see 6.7.3)
}

struct X { const int a; int b; }
union Y { X x; int k; }
void g() {
    Y y = { { 1, 2 } };  // OK, y.x is active union member (11.4)
    int n = y.x.a;
    y.k = 4;             // OK, ends lifetime of y.x, y.k is active member of union
    y.x.b = n;           // undefined behavior: y.x.b modified outside its lifetime,
                          // S(y.x.b) is empty because X’s default constructor is deleted,
                          // so union member y.x’s lifetime does not implicitly start
}
```

—end example]

6 [Note 5: In cases where the above rule does not apply, the active member of a union can only be changed by the use of a placement new-expression. — end note]

[Example 3: Consider an object u of a union type U having non-static data members m of type M and n of type N. If M has a non-trivial destructor and N has a non-trivial constructor (for instance, if they declare or inherit virtual functions), the active member of u can be safely switched from m to n using the destructor and placement new-expression as follows:

```c
u.m.~M();
new (&u.n) N;
```

—end example]

11.5.2 Anonymous unions [class.union.anon]

A union of the form

```c
union { member-specification } ;
```

is called an anonymous union; it defines an unnamed type and an unnamed object of that type called an anonymous union member if it is a non-static data member or an anonymous union variable otherwise. Each member-declaration in the member-specification of an anonymous union shall either define one or more public non-static data members or be a static_assert-declaration. Nested types, anonymous unions, and functions shall not be declared within an anonymous union. The names of the members of an anonymous union are bound in the scope inhabited by the union declaration.

[Example 1:]

```c
void f() {
    union { int a; const char* p; };
    a = 1;
    p = "Jennifer";
}
```

Here a and p are used like ordinary (non-member) variables, but since they are union members they have the same address. — end example]

2 An anonymous union declared in the scope of a namespace with external linkage shall use the storage-class-specifier static. Anonymous unions declared at block scope shall not use a storage-class-specifier that is not
permitted in the declaration of a block variable. An anonymous union declaration at class scope shall not have a storage-class-specifier.

3 [Note 1: A union for which objects, pointers, or references are declared is not an anonymous union.]

[Example 2:

```c
void f() {
    union { int aa; char* p; } obj, *ptr = &obj;
    aa = 1;    // error
    ptr->aa = 1; // OK
}
```

The assignment to plain `aa` is ill-formed since the member name is not visible outside the union, and even if it were visible, it is not associated with any particular object. — end example]

— end note

[Note 2: Initialization of unions with no user-declared constructors is described in 9.4.2. — end note]

4 A union-like class is a union or a class that has an anonymous union as a direct member. A union-like class `X` has a set of variant members. If `X` is a union, a non-static data member of `X` that is not an anonymous union is a variant member of `X`. In addition, a non-static data member of an anonymous union that is a member of `X` is also a variant member of `X`. At most one variant member of a union may have a default member initializer.

[Example 3:

```c
union U {
    int x = 0;
    union {
        int k;
    }
    union {
        int z;
        int y = 1;  // error: initialization for second variant member of U
    }
};
```

— end example]

11.6 Local class declarations [class.local]

1 A class can be declared within a function definition; such a class is called a local class.

[Note 1: A declaration in a local class cannot odr-use (6.3) a local entity from an enclosing scope. — end note]

[Example 1:

```c
int x;
void f() {
    static int s;
    int x;
    const int N = 5;
    extern int q();
    int arr[2];
    auto [y, z] = arr;
    struct local {
        int g() { return x; }  // error: odr-use of non-odr-usable variable x
        int h() { return s; }  // OK
        int k() { return ::x; } // OK
        int l() { return q(); } // OK
        int m() { return N; }  // OK, not an odr-use
        int* n() { return &N; } // error: odr-use of non-odr-usable variable N
        int p() { return y; }  // error: odr-use of non-odr-usable structured binding y
    };
    }
    local* p = 0;        // error: local not found
    — end example]
```
An enclosing function has no special access to members of the local class; it obeys the usual access rules (11.8). Member functions of a local class shall be defined within their class definition, if they are defined at all.

If class \( X \) is a local class, a nested class \( Y \) may be declared in class \( X \) and later defined in the definition of class \( X \) or be later defined in the same scope as the definition of class \( X \). A class nested within a local class is a local class.

[Note 2: A local class cannot have static data members (11.4.9.3). — end note]

### 11.7 Derived classes

#### 11.7.1 General

A list of base classes can be specified in a class definition using the notation:

```plaintext
base-clause:
  : base-specifier-list

base-specifier-list:
  base-specifier \ldots opt
  base-specifier-list , base-specifier \ldots opt

base-specifier:
  attribute-specifier-seq opt class-or-decltype
  attribute-specifier-seq opt virtual access-specifier opt class-or-decltype
  attribute-specifier-seq opt access-specifier virtual opt class-or-decltype

class-or-decltype:
  nested-name-specifier opt type-name
  nested-name-specifier template simple-template-id
  computed-type-specifier

access-specifier:
  private
  protected
  public
```

The optional `attribute-specifier-seq` appertains to the `base-specifier`.

The component names of a `class-or-decltype` are those of its `nested-name-specifier`, `type-name`, and/or `simple-template-id`. A `class-or-decltype` shall denote a (possibly cv-qualified) class type that is not an incompletely defined class (11.4); any cv-qualifiers are ignored. The class denoted by the `class-or-decltype` of a `base-specifier` is called a direct base class for the class being defined. The lookup for the component name of the `type-name` or `simple-template-id` is type-only (6.5). A class \( B \) is a base class of a class \( D \) if it is a direct base class of \( D \) or a direct base class of one of \( D \)'s base classes. A class is an indirect base class of another if it is a base class but not a direct base class. A class is said to be (directly or indirectly) derived from its (direct or indirect) base classes.

[Note 1: See 11.8 for the meaning of `access-specifier`. — end note]

Members of a base class are also members of the derived class.

[Note 2: Constructors of a base class can be explicitly inherited (9.9). Base class members can be referred to in expressions in the same manner as other members of the derived class, unless their names are hidden or ambiguous (6.5.2). The scope resolution operator :: (7.5.5.3) can be used to refer to a direct or indirect base member explicitly, even if it is hidden in the derived class. A derived class can itself serve as a base class subject to access control; see 11.8.3. A pointer to a derived class can be implicitly converted to a pointer to an accessible unambiguous base class (7.3.12). An lvalue of a derived class type can be bound to a reference to an accessible unambiguous base class (9.4.4). — end note]

The `base-specifier-list` specifies the type of the base class subobjects contained in an object of the derived class type.

[Example 1:

```plaintext
struct Base {
  int a, b, c;
};

struct Derived : Base {
  int b;
};
```]
Here, an object of class Derived2 will have a subobject of class Derived which in turn will have a subobject of class Base. — end example

4 A base-specifier followed by an ellipsis is a pack expansion (13.7.4).

5 The order in which the base class subobjects are allocated in the most derived object (6.7.2) is unspecified.

[Note 3: A derived class and its base class subobjects can be represented by a directed acyclic graph (DAG) where an arrow means “directly derived from” (see Figure 3). An arrow need not have a physical representation in memory. A DAG of subobjects is often referred to as a “subobject lattice”. — end note]

Figure 3 — Directed acyclic graph  [fig:class.dag]

6 [Note 4: Initialization of objects representing base classes can be specified in constructors; see 11.9.3. — end note]

7 [Note 5: A base class subobject can have a layout different from the layout of a most derived object of the same type. A base class subobject can have a polymorphic behavior (11.9.5) different from the polymorphic behavior of a most derived object of the same type. A base class subobject can be of zero size; however, two subobjects that have the same class type and that belong to the same most derived object cannot be allocated at the same address (6.7.2). — end note]

11.7.2 Multiple base classes  [class.mi]

1 A class can be derived from any number of base classes.

[Note 1: The use of more than one direct base class is often called multiple inheritance. — end note]

[Example 1:

class A { /* ... */ };  
class B { /* ... */ };  
class C { /* ... */ };  
class D : public A, public B, public C { /* ... */ };  
— end example]

2 [Note 2: The order of derivation is not significant except as specified by the semantics of initialization by constructor (11.9.3), cleanup (11.4.7), and storage layout (11.4, 11.8.2). — end note]

3 A class shall not be specified as a direct base class of a derived class more than once.

[Note 3: A class can be an indirect base class more than once and can be a direct and an indirect base class. There are limited things that can be done with such a class; lookup that finds its non-static data members and member functions in the scope of the derived class will be ambiguous. However, the static members, enumerations and types can be unambiguously referred to. — end note]

[Example 2:

class X { /* ... */ };  
class Y : public X, public X { /* ... */ };  // error  
class L { public: int next;  /* ... */ };  
class A : public L { /* ... */ };  
class B : public L { /* ... */ };  
class C : public A, public B { void f(); /* ... */ };  // well-formed  
class D : public A, public L { void f(); /* ... */ };  // well-formed  
— end example]

4 A base class specifier that does not contain the keyword virtual specifies a non-virtual base class. A base class specifier that contains the keyword virtual specifies a virtual base class. For each distinct occurrence

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of a non-virtual base class in the class lattice of the most derived class, the most derived object (6.7.2) shall contain a corresponding distinct base class subobject of that type. For each distinct base class that is specified virtual, the most derived object shall contain a single base class subobject of that type.

[Note 4: For an object of class type C, each distinct occurrence of a (non-virtual) base class L in the class lattice of C corresponds one-to-one with a distinct L subobject within the object of type C. Given the class C defined above, an object of class C will have two subobjects of class L as shown in Figure 4.]

![Figure 4 — Non-virtual base](fig:class.nonvirt)

In such lattices, explicit qualification can be used to specify which subobject is meant. The body of function C::f can refer to the member next of each L subobject:

```cpp
void C::f() { A::next = B::next; } // well-formed
```

Without the A:: or B:: qualifiers, the definition of C::f above would be ill-formed because of ambiguity (6.5.2).

—end note

[Note 5: In contrast, consider the case with a virtual base class:

```cpp
class V { /* ... */ };  
class A : virtual public V { /* ... */ };  
class B : virtual public V { /* ... */ };  
class C : public A, public B { /* ... */ };  
```

![Figure 5 — Virtual base](fig:class.virt)

For an object c of class type C, a single subobject of type V is shared by every base class subobject of c that has a virtual base class of type V. Given the class C defined above, an object of class C will have one subobject of class V, as shown in Figure 5. —end note]

[Note 6: A class can have both virtual and non-virtual base classes of a given type.

```cpp
class B { /* ... */ };  
class X : virtual public B { /* ... */ };  
class Y : virtual public B { /* ... */ };  
class Z : public B { /* ... */ };  
class AA : public X, public Y, public Z { /* ... */ };  
```

For an object of class AA, all virtual occurrences of base class B in the class lattice of AA correspond to a single B subobject within the object of type AA, and every other occurrence of a (non-virtual) base class B in the class lattice of AA corresponds one-to-one with a distinct B subobject within the object of type AA. Given the class AA defined above, class AA has two subobjects of class B: Z’s B and the virtual B shared by X and Y, as shown in Figure 6.

—end note]

11.7.3 Virtual functions

A non-static member function is a virtual function if it is first declared with the keyword virtual or if it overrides a virtual member function declared in a base class (see below).93

---

93) The use of the virtual specifier in the declaration of an overriding function is valid but redundant (has empty semantics).
A class with a virtual member function is called a polymorphic class.\textsuperscript{94}

If a virtual member function $F$ is declared in a class $B$, and, in a class $D$ derived (directly or indirectly) from $B$, a declaration of a member function $G$ corresponds (6.4.1) to a declaration of $F$, ignoring trailing requires-clauses, then $G$ overrides\textsuperscript{95} $F$. For convenience, we say that any virtual function overrides itself. A virtual member function $V$ of a class object $S$ is a final overrider unless the most derived class (6.7.2) of which $S$ is a base class subobject (if any) has another member function that overrides $V$. In a derived class, if a virtual member function of a base class subobject has more than one final overrider, the program is ill-formed.

\textbf{Example 1:}

\begin{verbatim}
struct A { virtual void f(); }
struct B : virtual A { virtual void f(); }
struct C : B, virtual A { 
  using A::f;
};
void foo() {
  C c;
  c.f(); // calls B::f, the final overrider
  c.C::f(); // calls A::f because of the using-declaration
}
\end{verbatim}

— end example]

\textbf{Example 2:}

\begin{verbatim}
struct A { virtual void f(); }
struct B : A { }
struct C : A { void f(); }
struct D : B, C { }  // OK, A::f and C::f are the final overrides
                             // for the B and C subobjects, respectively
\end{verbatim}

— end example]

\textbf{Note 2:} A virtual member function does not have to be visible to be overridden, for example,

\begin{verbatim}
struct B { virtual void f(); }
struct D : B { void f(int); }
struct D2 : D { void f(); }
\end{verbatim}

\textbf{Note 1:} Virtual functions support dynamic binding and object-oriented programming. — end note]

\textsuperscript{94} If all virtual functions are immediate functions, the class is still polymorphic even if its internal representation does not otherwise require any additions for that polymorphic behavior.

\textsuperscript{95} A function with the same name but a different parameter list (Clause 12) as a virtual function is not necessarily virtual and does not override. Access control (11.8) is not considered in determining overriding.
the function \( f(int) \) in class \( D \) hides the virtual function \( f() \) in its base class \( B \); \( D::f(int) \) is not a virtual function. However, \( f() \) declared in class \( D2 \) has the same name and the same parameter list as \( B::f() \), and therefore is a virtual function that overrides the function \( B::f() \) even though \( B::f() \) is not visible in class \( D2 \). — end note

4 If a virtual function \( f \) in some class \( B \) is marked with the \textit{virt-specifier} \texttt{final} and in a class \( D \) derived from \( B \) a function \( D::f \) overrides \( B::f \), the program is ill-formed.

[Example 3:

```cpp
struct B {
    virtual void f() const final;
};

struct D : B {
    void f() const;   // error: \( D::f \) attempts to override \( final \) \( B::f \n};
```

— end example]

5 If a virtual function is marked with the \textit{virt-specifier} \texttt{override} and does not override a member function of a base class, the program is ill-formed.

[Example 4:

```cpp
struct B {
    virtual void f(int);
};

struct D : B {
    virtual void f(long) override;   // error: wrong signature overriding \( B::f \n    virtual void f(int) override;   // OK
};
```

— end example]

6 A virtual function shall not have a trailing \textit{requires-clause} (9.3).

[Example 5:

```cpp
template<typename T>
struct A {
    virtual void f() requires true;   // error: virtual function cannot be constrained (13.5.3)
};
```

— end example]

7 The \textit{ref-qualifier}, or lack thereof, of an overriding function shall be the same as that of the overridden function.

8 The return type of an overriding function shall be either identical to the return type of the overridden function or \textit{covariant} with the classes of the functions. If a function \( D::f \) overrides a function \( B::f \), the return types of the functions are covariant if they satisfy the following criteria:

- \((8.1)\) both are pointers to classes, both are lvalue references to classes, or both are rvalue references to classes

- \((8.2)\) the class in the return type of \( B::f \) is the same class as the class in the return type of \( D::f \), or is an unambiguous and accessible direct or indirect base class of the class in the return type of \( D::f \)

- \((8.3)\) both pointers or references have the same cv-qualification and the class type in the return type of \( D::f \) has the same cv-qualification as or less cv-qualification than the class type in the return type of \( B::f \).

9 If the class type in the covariant return type of \( D::f \) differs from that of \( B::f \), the class type in the return type of \( D::f \) shall be complete at the locus \((6.4.2)\) of the overriding declaration or shall be the class type \( D \). When the overriding function is called as the final overrider of the overridden function, its result is converted to the type returned by the (statically chosen) overridden function \((7.6.1.3)\).

[Example 6:

```cpp
class B {  
};
class D : private B { friend class Derived;  
};
struct Base { 
    virtual void vf1();

96) Multi-level pointers to classes or references to multi-level pointers to classes are not allowed.
virtual void vf2();
virtual void vf3();
virtual B* vf4();
virtual B* vf5();
void f();

};

struct No_good : public Base {
  D* vf4();  // error: B (base class of D) inaccessible
};

class A;

struct Derived : public Base {
  void vf1();  // virtual and overrides Base::vf1
  void vf2(int);  // not virtual, hides Base::vf2
  char vf3();  // error: invalid difference in return type only
  D* vf4();  // OK, returns pointer to derived class
  A* vf5();  // error: returns pointer to incomplete class
  void f();
};

void g() {
  Derived d;
  Base* bp = &d;  // standard conversion:
                  // Derived* to Base*
  bp->vf1();  // calls Derived::vf1
  bp->vf2();  // calls Base::vf2
  bp->f();  // calls Base::f() (not virtual)
  B* p = bp->vf4();  // calls Derived::vf4() and converts the
                     // result to B*
  Derived* dp = &d;
  D* q = dp->vf4();  // calls Derived::vf4() and does not
                     // convert the result to B*
  dp->vf2();  // error: argument mismatch
}

—end example

[Note 3: The interpretation of the call of a virtual function depends on the type of the object for which it is called
(the dynamic type), whereas the interpretation of a call of a non-virtual member function depends only on the type of
the pointer or reference denoting that object (the static type) (7.6.1.3). —end note]

[Note 4: The virtual specifier implies membership, so a virtual function cannot be a non-member (9.2.3) function.
Nor can a virtual function be a static member, since a virtual function call relies on a specific object for determining
which function to invoke. A virtual function declared in one class can be declared a friend (11.8.4) in another class. —end note]

A virtual function declared in a class shall be defined, or declared pure (11.7.4) in that class, or both; no
diagnostic is required (6.3).

[Example 7: Here are some uses of virtual functions with multiple base classes:

struct A {
  virtual void f();
};

struct B1 : A {
  void f();  // note non-virtual derivation
};

struct B2 : A {
  void f();
};

struct D : B1, B2 {
  // D has two separate A subobjects
};
void foo() {
    D d;
    // A* ap = &d; // would be ill-formed: ambiguous
    B1* b1p = &d;
    A* ap = b1p;
    D* dp = &d;
    ap->f(); // calls D::B1::f
    dp->f(); // error: ambiguous
}

In class D above there are two occurrences of class A and hence two occurrences of the virtual member function A::f. The final overrider of B1::A::f is B1::f and the final overrider of B2::A::f is B2::f. —end example

Example 8: The following example shows a function that does not have a unique final overrider:

struct A {
    virtual void f();
};

struct VB1 : virtual A {
    // note virtual derivation
    void f();
};

struct VB2 : virtual A {
    void f();
};

struct Error : VB1, VB2 {
    // error
};

struct Okay : VB1, VB2 {
    void f();
};

Both VB1::f and VB2::f override A::f but there is no overrider of both of them in class Error. This example is therefore ill-formed. Class Okay is well-formed, however, because Okay::f is a final overrider. —end example

Example 9: The following example uses the well-formed classes from above.

struct VB1a : virtual A {
    // does not declare f
};

struct Da : VB1a, VB2 {
};

void foe() {
    VB1a* vb1ap = new Da;
    vb1ap->f(); // calls VB2::f
}

—end example

Explicit qualification with the scope operator (7.5.5.3) suppresses the virtual call mechanism.

Example 10:

class B { public: virtual void f();
};
class D : public B { public: void f();
};

void D::f() { /* ... */ B::f();
}

Here, the function call in D::f really does call B::f and not D::f. —end example

A deleted function (9.5) shall not override a function that is not deleted. Likewise, a function that is not deleted shall not override a deleted function.

A constexpr virtual function shall not override a virtual function that is not constexpr. A constexpr virtual function shall not be overridden by a virtual function that is not constexpr.

11.7.4 Abstract classes 

[class.abstract]
Note 1: The abstract class mechanism supports the notion of a general concept, such as a shape, of which only more concrete variants, such as circle and square, can actually be used. An abstract class can also be used to define an interface for which derived classes provide a variety of implementations. — end note]

A virtual function is specified as a pure virtual function by using a pure-specifier (11.4) in the function declaration in the class definition.

Note 2: Such a function might be inherited: see below. — end note]

A class is an abstract class if it has at least one pure virtual function.

Note 3: An abstract class can be used only as a base class of some other class; no objects of an abstract class can be created except as subobjects of a class derived from it (6.2, 11.4). — end note]

A pure virtual function need be defined only if called with, or as if with (11.4.7), the qualified-id syntax (7.5.5.3).

Example 1:
```cpp
class point { /* ... */ };  
class shape {  // abstract class
    point center;
    public:
        point where() { return center; }
        void move(point p) { center=p; draw(); }
        virtual void rotate(int) = 0;  // pure virtual
        virtual void draw() = 0;  // pure virtual
    };

    // end example

Note 4: A function declaration cannot provide both a pure-specifier and a definition. — end note]

Example 2:
```cpp
struct C {
    virtual void f() = 0 { };  // error
};

// end example
```

Note 5: An abstract class type cannot be used as a parameter or return type of a function being defined (9.3.4.6) or called (7.6.1.3), except as specified in 9.2.9.3. Further, an abstract class type cannot be used as the type of an explicit type conversion (7.6.1.9, 7.6.1.10, 7.6.1.11), because the resulting prvalue would be of abstract class type (7.2.1). However, pointers and references to abstract class types can appear in such contexts. — end note]

A class is abstract if it has at least one pure virtual function for which the final overrider is pure virtual.

Example 3:
```cpp
class ab_circle : public shape {  
    int radius;
    public:
        void rotate(int) {}  // ab_circle::draw() is a pure virtual
        virtual draw();  // a definition is required somewhere
    };

Since shape::draw() is a pure virtual function ab_circle::draw() is a pure virtual by default. The alternative declaration,
```cpp
class circle : public shape {
    int radius;
    public:
        void rotate(int) {}  
        void draw();  // a definition is required somewhere
    };
```would make class circle non-abstract and a definition of circle::draw() must be provided. — end example]

Note 6: An abstract class can be derived from a class that is not abstract, and a pure virtual function can override a virtual function which is not pure. — end note]

Member functions can be called from a constructor (or destructor) of an abstract class; the effect of making a virtual call (11.7.3) to a pure virtual function directly or indirectly for the object being created (or destroyed) from such a constructor (or destructor) is undefined.
11.8 Member access control

11.8.1 General

A member of a class can be

1. private, that is, it can be named only by members and friends of the class in which it is declared;
2. protected, that is, it can be named only by members and friends of the class in which it is declared, by classes derived from that class, and by their friends (see 11.8.5); or
3. public, that is, it can be named anywhere without access restriction.

[Note 1: A constructor or destructor can be named by an expression (6.3) even though it has no name. — end note]

A member of a class can also access all the members to which the class has access. A local class of a member function may access the same members that the member function itself may access.  

Members of a class defined with the keyword class are private by default. Members of a class defined with the keywords struct or union are public by default.

[Example 1:

```cpp
class X {
    int a; // X::a is private by default
};

struct S {
    int a; // S::a is public by default
};
```

—end example]

Access control is applied uniformly to declarations and expressions.

[Note 2: Access control applies to members nominated by friend declarations (11.8.4) and using-declarations (9.9). — end note]

When a using-declarator is named, access control is applied to it, not to the declarations that replace it. For an overload set, access control is applied only to the function selected by overload resolution.

[Example 2:

```cpp
struct S {
    void f(int);
    private:
    void f(double);
};

g(S* sp) {
    sp->f(2); // OK, access control applied after overload resolution
}
```

—end example]

[Note 3: Because access control applies to the declarations named, if access control is applied to a typedef-name, only the accessibility of the typedef or alias declaration itself is considered. The accessibility of the entity referred to by the typedef-name is not considered.

[Example 3:

```cpp
class A {
    class B { }
    public:
    typedef B BB;
};

void f() {
    A::BB x; // OK, typedef A::BB is public
    A::B y; // access error, A::B is private
}
```

—end example]
[Note 4: Access control does not prevent members from being found by name lookup or implicit conversions to base classes from being considered. — end note]

The interpretation of a given construct is established without regard to access control. If the interpretation established makes use of inaccessible members or base classes, the construct is ill-formed.

All access controls in 11.8 affect the ability to name a class member from the declaration of a particular entity, including parts of the declaration preceding the name of the entity being declared and, if the entity is a class, the definitions of members of the class appearing outside the class’s member-specification.

[Note 5: This access also applies to implicit references to constructors, conversion functions, and destructors. — end note]

[Example 4:

class A {
    typedef int I; // private member
    I f();
    friend I g(I);
    static I x;
    template<int> struct Q;
    template<int> friend struct R;
    protected:
        struct B { };
};

A::I A::f() { return 0; }
A::I g(A::I p = A::x);
A::I g(A::I p) { return 0; }
A::I A::x = 0;
template<A::I> struct A::Q { };
template<A::I> struct R { };

struct D: A::B, A { };
}

Here, all the uses of A::I are well-formed because A::f, A::x, and A::Q are members of class A and g and R are friends of class A. This implies, for example, that access checking on the first use of A::I must be deferred until it is determined that this use of A::I is as the return type of a member of class A. Similarly, the use of A::B as a base-specifier is well-formed because D is derived from A, so checking of base-specifiers must be deferred until the entire base-specifier-list has been seen. — end example]

Access is checked for a default argument (9.3.4.7) at the point of declaration, rather than at any points of use of the default argument. Access checking for default arguments in function templates and in member functions of class templates is performed as described in 13.9.2.

Access for a default template-argument (13.2) is checked in the context in which it appears rather than at any points of use of it.

[Example 5:

class B { };
template <class T> class C {
protected:
    typedef T TT;
};

template <class U, class V = typename U::TT>
class D : public U { };

D <C<B> >> d; // access error, C::TT is protected
— end example]

11.8.2 Access specifiers

Member declarations can be labeled by an access-specifier (11.7):

access-specifier : member-specification_opt

§ 11.8.2 ©ISO/IEC 315
An access-specifier specifies the access rules for members following it until the end of the class or until another access-specifier is encountered.

[Example 1:

```c
class X {
    int a; // X::a is private by default: class used
    public:
        int b; // X::b is public
        int c; // X::c is public
};
```

— end example]}

Any number of access specifiers is allowed and no particular order is required.

[Example 2:

```c
struct S {
    int a; // S::a is public by default: struct used
    protected:
        int b; // S::b is protected
    private:
        int c; // S::c is private
        public:
            int d; // S::d is public
};
```

— end example]}

When a member is redeclared within its class definition, the access specified at its redeclaration shall be the same as at its initial declaration.

[Example 3:

```c
struct S {
    class A;
    enum E : int;
    private:
        class A { }; // error: cannot change access
        enum E : int { e0 }; // error: cannot change access
};
```

— end example]}

[Note 1: In a derived class, the lookup of a base class name will find the injected-class-name instead of the name of the base class in the scope in which it was declared. The injected-class-name might be less accessible than the name of the base class in the scope in which it was declared. — end note]

[Example 4:

```c
class A { }; class B : private A { }; class C : public B {
    A* p; // error: injected-class-name A is inaccessible
    ::A* q; // OK
};
```

— end example]}

11.8.3 Accessibility of base classes and base class members  [class.access.base]

If a class is declared to be a base class (11.7) for another class using the public access specifier, the public members of the base class are accessible as public members of the derived class and protected members of the base class are accessible as protected members of the derived class. If a class is declared to be a base class for another class using the protected access specifier, the public and protected members of the base class are accessible as protected members of the derived class. If a class is declared to be a base class for another class using the private access specifier, the public and protected members of the base class are accessible as private members of the derived class.  

98 As specified previously in 11.8, private members of a base class remain inaccessible even to derived classes unless friend declarations within the base class definition are used to grant access explicitly.
In the absence of an access-specifier for a base class, public is assumed when the derived class is defined with the class-key struct and private is assumed when the class is defined with the class-key class.

[Example 1:

class B { /* ... */ };
class D1 : private B { /* ... */ };
class D2 : public B { /* ... */ };
class D3 : B { /* ... */ };
// B private by default
struct D4 : public B { /* ... */ };
struct D5 : private B { /* ... */ };
struct D6 : B { /* ... */ };
// B public by default
class D7 : protected B { /* ... */ };
struct D8 : protected B { /* ... */ };

Here B is a public base of D2, D4, and D6, a private base of D1, D3, and D5, and a protected base of D7 and D8. — end example]

3 [Note 1: A member of a private base class can be inaccessible as inherited, but accessible directly. Because of the rules on pointer conversions (7.3.12) and explicit casts (7.6.1.4, 7.6.1.9, 7.6.3), a conversion from a pointer to a derived class to a pointer to an inaccessible base class can be ill-formed if an implicit conversion is used, but well-formed if an explicit cast is used.

[Example 2:

class B {
    public:
        int mi; // non-static member
        static int si; // static member
    }
    class D : private B {
    }
    class DD : public D {
        void f();
    }

    void DD::f() {
        mi = 3; // error: mi is private in D
        si = 3; // error: si is private in D
        ::B b;
        b.mi = 3; // OK (b.mi is different from this->mi)
        b.si = 3; // OK (b.si is different from this->si)
        ::B::si = 3; // OK
        ::B* bp1 = this; // error: B is a private base class
        ::B* bp2 = (::B*)this; // OK with cast
        bp2->mi = 3; // OK, access through a pointer to B.
    }
— end example]
— end note]

A base class B of N is accessible at R, if

(4.1) — an invented public member of B would be a public member of N, or
(4.2) — R occurs in a direct member or friend of class N, and an invented public member of B would be a private or protected member of N, or
(4.3) — R occurs in a direct member or friend of a class P derived from N, and an invented public member of B would be a private or protected member of P, or
(4.4) — there exists a class S such that B is a base class of S accessible at R and S is a base class of N accessible at R.

[Example 3:

class B {
    public:
        int m;
    };
class S: private B {
    friend class N;
};

class N: private S {
    void f() {
        B* p = this; // OK because class S satisfies the fourth condition above: B is a base class of N
        // accessible in f() because B is an accessible base class of S and S is an accessible
        // base class of N.
    }
};

—end example

5 If a base class is accessible, one can implicitly convert a pointer to a derived class to a pointer to that base
class (7.3.12, 7.3.13).

[Note 2: It follows that members and friends of a class X can implicitly convert an X* to a pointer to a private or
protected immediate base class of X. — end note]

The access to a member is affected by the class in which the member is named. This naming class is the
class in whose scope name lookup performed a search that found the member.

[Note 3: This class can be explicit, e.g., when a qualified-id is used, or implicit, e.g., when a class member access
operator (7.6.1.5) is used (including cases where an implicit “this->” is added). If both a class member access
operator and a qualified-id are used to name the member (as in p->T::m), the class naming the member is the class
denoted by the nested-name-specifier of the qualified-id (that is, T). — end note]

A member m is accessible at the point R when named in class N if

\[ (5.1) \quad \text{m as a member of N is public, or} \]
\[ (5.2) \quad \text{m as a member of N is private, and R occurs in a direct member or friend of class N, or} \]
\[ (5.3) \quad \text{m as a member of N is protected, and R occurs in a direct member or friend of class N, or in a member
of a class P derived from N, where m as a member of P is public, private, or protected, or} \]
\[ (5.4) \quad \text{there exists a base class B of N that is accessible at R, and m is accessible at R when named in class B.} \]

[Example 4:
    class B;
    class A {
        private:
        int i;
        friend void f(B*);
    }
    class B : public A {
        void f(B* p) {
            p->i = 1; // OK, B* can be implicitly converted to A*, and f has access to i in A
        }
    }
—end example]

6 If a class member access operator, including an implicit “this->”, is used to access a non-static data member
or non-static member function, the reference is ill-formed if the left operand (considered as a pointer in the
“.” operator case) cannot be implicitly converted to a pointer to the naming class of the right operand.

[Note 4: This requirement is in addition to the requirement that the member be accessible as named. — end note]

11.8.4 Friends

1 A friend of a class is a function or class that is given permission to name the private and protected members
of the class. A class specifies its friends, if any, by way of friend declarations. Such declarations give special
access rights to the friends, but they do not make the nominated friends members of the befriending class.

[Example 1: The following example illustrates the differences between members and friends:

    class X {
        int a;
        friend void friend_set(X*, int);
    }
public:
    void member_set(int);
};

void friend_set(X* p, int i) { p->a = i; }
void X::member_set(int i) { a = i; }

void f() {
    X obj;
    friend_set(&obj,10);
    obj.member_set(10);
}

—end example

2 Declaring a class to be a friend implies that private and protected members of the class granting friendship can be named in the base-specifiers and member declarations of the befriended class.

[Example 2:

class A {
    class B { };  // OK, A::B accessible to friend
    friend class X;  // OK, A::B accessible to member of friend
};

struct X : A::B {  // OK, A::B accessible to nested member of friend
    A::B mx;
    class Y {  // OK, A::B accessible to nested member of friend
        A::B my;
    };
};

—end example]

[Example 3:

class X {
    enum { a=100 };  // OK, Y is a friend of X
    friend class Y;
};

class Y {
    int v[X::a];  // OK, Y is a friend of X
};

class Z {
    int v[X::a];  // error: X::a is private
};

—end example]

3 A friend declaration that does not declare a function shall be a friend-type-declaration.

[Note 1: A friend declaration can be the declaration in a template-declaration (13.1, 13.7.5). — end note]

If a friend-type-specifier in a friend declaration designates a (possibly cv-qualified) class type, that class is declared as a friend; otherwise, the friend-type-specifier is ignored.

[Example 4:

class C;
typedef C Ct;
class E;

class X1 {
    friend C;  // OK, class C is a friend
};

class X2 {
    friend Ct;  // OK, class C is a friend
    friend D;  // error: D not found

friend class D;  // OK, elaborated-type-specifier declares new class

template <typename ... Ts> class R {
friend Ts...;
};

template <class... Ts, class... Us>
class R<R<Ts...>, R<Us...>> {
friend Ts::Nested..., Us...;
};

R<C> rc;  // class C is a friend of R<C>
R<C, E> rce;  // classes C and E are friends of R<C, E>
R<int> Ri;  // OK, “friend int;” is ignored

struct E { struct Nested; };

R<R<E>, R<C, int>> rr;  // E::Nested and C are friends of R<R<E>, R<C, int>>
—end example

[Note 2: A friend declaration refers to an entity, not (all overloads of) a name. A member function of a class X can be a friend of a class Y.

[Example 5:

class Y {
friend char* X::foo(int);
friend X::X(char);  // constructors can be friends
friend X::~X();  // destructors can be friends
};
—end example]
—end note]

A function may be defined in a friend declaration of a class if and only if the class is a non-local class (11.6) and the function name is unqualified.

[Example 6:

class M {
friend void f() { }  // definition of global f, a friend of M,
// not the definition of a member function
};
—end example]

Such a function is implicitly an inline (9.2.8) function if it is attached to the global module.

[Note 3: If a friend function is defined outside a class, it is not in the scope of the class. — end note]

No storage-class-specifier shall appear in the decl-specifier-seq of a friend declaration.

A member nominated by a friend declaration shall be accessible in the class containing the friend declaration.
The meaning of the friend declaration is the same whether the friend declaration appears in the private, protected, or public (11.4) portion of the class member-specification.

Friendship is neither inherited nor transitive.

[Example 7:

class A {
friend class B;
int a;
};
class B {
friend class C;
};

§ 11.8.4 ©ISO/IEC 320
class C {
    void f(A* p) {
        p->a++; // error: C is not a friend of A despite being a friend of a friend
    }
};

class D : public B {
    void f(A* p) {
        p->a++; // error: D is not a friend of A despite being derived from a friend
    }
};
—end example]

[Note 4: A friend declaration never binds any names (9.3.4, 9.2.9.5). — end note]

[Example 8:
// Assume f and g have not yet been declared.
void h(int);
template <class T> void f2(T);
namespace A {
    class X {
        friend void f(X); // A::f(X) is a friend
        class Y {
            friend void g(); // A::g is a friend
            friend void h(int); // A::h is a friend
            // ::h not considered
            friend void f2<(int); // ::f2<(int) is a friend
        }
    }

    // A::f, A::g and A::h are not visible here
    X x;
    void g() { f(x); } // definition of A::g
    void f(X) { /* ... */ } // definition of A::f
    void h(int) { /* ... */ } // definition of A::h
    // A::f, A::g and A::h are visible here and known to be friends
}
}

using A::x;

void h() {
    A::f(x);
    A::X::f(x); // error: f is not a member of A::X
    A::X::Y::g(); // error: g is not a member of A::X::Y
}
—end example]

[Example 9:
class X;
void a();
void f() {
    class Y;
    extern void b();
    class A {
        friend class X; // OK, but X is a local class, not ::X
        friend class Y; // OK
        friend class Z; // OK, introduces local class Z
        friend void a(); // error, ::a is not considered
        friend void b(); // OK
        friend void c(); // error
    };
    X* px; // OK, but ::X is found
    Z* pz; // error: no Z is found
}
11.8.5 Protected member access

An additional access check beyond those described earlier in 11.8 is applied when a non-static data member or non-static member function is a protected member of its naming class (11.8.3). As described earlier, access to a protected member is granted because the reference occurs in a friend or direct member of some class C. If the access is to form a pointer to member (7.6.2.2), the nested-name-specifier shall denote C or a class derived from C. All other accesses involve a (possibly implicit) object expression (7.6.1.5). In this case, the class of the object expression shall be C or a class derived from C.

[Example 1:]

```cpp
class B {
  protected:
    int i;
    static int j;
};
class D1 : public B {
};
class D2 : public B {
  friend void fr(B*, D1*, D2*);
  void mem(B*, D1*);
};

void fr(B* pb, D1* p1, D2* p2) {
  pb->i = 1; // error
  p1->i = 2; // error
  p2->i = 3; // OK (access through a D2)
  p2->B::i = 4; // OK (access through B D2, even though naming class is B)
  int B::* pmi_B = &B::i; // error
  int B::* pmi_B2 = &D2::i; // OK (type of &D2::i is int B::*
  B::j = 5; // OK (because refers to static member)
  D2::j = 6; // OK (because refers to static member)
}

void D2::mem(B* pb, D1* p1) {
  pb->i = 1; // error
  p1->i = 2; // error
  i = 3; // OK (access through this)
  B::i = 4; // OK (access through this, qualification ignored)
  int B::* pmi_B = &B::i; // error
  int B::* pmi_B2 = &D2::i; // OK
  j = 5; // OK (because j refers to static member)
  B::j = 6; // OK (because B::j refers to static member)
}

void g(B* pb, D1* p1, D2* p2) {
  pb->i = 1; // error
  p1->i = 2; // error
  p2->i = 3; // error
}
```

— end example]

11.8.6 Access to virtual functions

The access rules (11.8) for a virtual function are determined by its declaration and are not affected by the rules for a function that later overrides it.

---

99) This additional check does not apply to other members, e.g., static data members or enumerator member constants.
Example 1:
```cpp
class B {
    public:
    virtual int f();
};

class D : public B {
    private:
    int f();
};

void f() {
    D d;
    B* pb = &d;
    D* pd = &d;

    pb->f(); // OK, B::f() is public, D::f() is invoked
    pd->f(); // error: D::f() is private
}
```
— end example]

Access is checked at the call point using the type of the expression used to denote the object for which the member function is called (B* in the example above). The access of the member function in the class in which it was defined (D in the example above) is in general not known.

11.8.7 Multiple access [class.paths]

If a declaration can be reached by several paths through a multiple inheritance graph, the access is that of the path that gives most access.

Example 1:
```cpp
class W { public: void f(); }
class A : private virtual W { }
class B : public virtual W { }
class C : public A, public B {
    void f() { W::f(); } // OK
};
```
Since W::f() is available to C::f() along the public path through B, access is allowed. — end example]

11.8.8 Nested classes [class.access.nest]

A nested class is a member and as such has the same access rights as any other member. The members of an enclosing class have no special access to members of a nested class; the usual access rules (11.8) shall be obeyed.

Example 1:
```cpp
class E {
    int x;
    class B { }

class I {
    B b; // OK, E::I can access E::B
    int y;
    void f(E* p, int i) {
        p->x = i; // OK, E::I can access E::x
    }
};

int g(I* p) {
    return p->y; // error: I::y is private
}
```
11.9 Initialization

11.9.1 General

1 When no initializer is specified for an object of (possibly cv-qualified) class type (or array thereof), or the initializer has the form (), the object is initialized as specified in 9.4.

2 An object of class type (or array thereof) can be explicitly initialized; see 11.9.2 and 11.9.3.

3 When an array of class objects is initialized (either explicitly or implicitly) and the elements are initialized by constructor, the constructor shall be called for each element of the array, following the subscript order; see 9.3.4.5.

[Note 1: Destructors for the array elements are called in reverse order of their construction. — end note]

11.9.2 Explicit initialization

1 An object of class type can be initialized with a parenthesized expression-list, where the expression-list is construed as an argument list for a constructor that is called to initialize the object. Alternatively, a single assignment-expression can be specified as an initializer using the = form of initialization. Either direct-initialization semantics or copy-initialization semantics apply; see 9.4.

[Example 1:

struct complex {
    complex();
    complex(double);
    complex(double,double);
};

complex sqrt(complex,complex);

complex a(1); // initialized by calling complex(double) with argument 1
complex b = a; // initialized as a copy of a
complex c = complex(1,2); // initialized by calling complex(double, double) with arguments 1 and 2
complex d = sqrt(b,c); // initialized by calling sqrt(complex, complex) with d as its result object
complex e; // initialized by calling complex()
complex f = 3; // initialized by calling complex(double) with argument 3
complex g = { 1, 2 }; // initialized by calling complex(double, double) with arguments 1 and 2
— end example]

[Note 1: Overloading of the assignment operator (12.4.3.2) has no effect on initialization. — end note]

2 An object of class type can also be initialized by a braced-init-list. List-initialization semantics apply; see 9.4 and 9.4.5.

[Example 2:

complex v[6] = { 1, complex(1,2), complex(), 2 };]

Here, complex::complex(double) is called for the initialization of v[0] and v[3], complex::complex(double, double) is called for the initialization of v[1], complex::complex() is called for the initialization of v[2], v[4], and v[5]. For another example,

struct X {
    int i;
    float f;
    complex c;
} x = { 99, 88.8, 77.7 };

Here, x.i is initialized with 99, x.f is initialized with 88.8, and complex::complex(double) is called for the initialization of x.c. — end example]

[Note 2: Braces can be elided in the initializer-list for any aggregate, even if the aggregate has members of a class type with user-defined type conversions; see 9.4.2. — end note]

3 [Note 3: If T is a class type with no default constructor, any declaration of an object of type T (or array thereof) is ill-formed if no initializer is explicitly specified (see 11.9 and 9.4). — end note]

4 [Note 4: The order in which objects with static or thread storage duration are initialized is described in 6.9.3.3 and 8.8. — end note]
11.9.3 Initializing bases and members

In the definition of a constructor for a class, initializers for direct and virtual base class subobjects and non-static data members can be specified by a `ctor-initializer`, which has the form

```
ctor-initializer:
  : mem-initializer-list

mem-initializer-list:
  mem-initializer ... opt
  mem-initializer-list , mem-initializer ... opt

mem-initializer:
  mem-initializer-id ( expression-list opt )
  mem-initializer-id braced-init-list

mem-initializer-id:
  class-or-decltype identifier
```

1 Lookup for an unqualified name in a `mem-initializer-id` ignores the constructor’s function parameter scope.

[Note 1: If the constructor’s class contains a member with the same name as a direct or virtual base class of the class, a `mem-initializer-id` naming the member or base class and composed of a single identifier refers to the class member. A `mem-initializer-id` for the hidden base class can be specified using a qualified name. — end note]

Unless the `mem-initializer-id` names the constructor’s class, a non-static data member of the constructor’s class, or a direct or virtual base of that class, the `mem-initializer` is ill-formed.

2 A `mem-initializer-list` can initialize a base class using any `class-or-decltype` that denotes that base class type.

[Example 1:
```
struct A { A(); };typedef A global_A;
struct B { };struct C: public A, public B { C(); };C::C(): global_A() { }  // mem-initializer for base A
```
—end example]

3 If a `mem-initializer-id` is ambiguous because it designates both a direct non-virtual base class and an indirect virtual base class, the `mem-initializer` is ill-formed.

[Example 2:
```
struct A { A(); };struct B: public virtual A { };struct C: public A, public B { C(); };C::C(): A() { }  // error: which A?
```
—end example]

4 A `ctor-initializer` may initialize a variant member of the constructor’s class. If a `ctor-initializer` specifies more than one `mem-initializer` for the same member or for the same base class, the `ctor-initializer` is ill-formed.

5 A `mem-initializer-list` can delegate to another constructor of the constructor’s class using any `class-or-decltype` that denotes the constructor’s class itself. If a `mem-initializer-id` designates the constructor’s class, it shall be the only `mem-initializer`; the constructor is a `delegating constructor`, and the constructor selected by the `mem-initializer` is the `target constructor`. The target constructor is selected by overload resolution. Once the target constructor returns, the body of the delegating constructor is executed. If a constructor delegates to itself directly or indirectly, the program is ill-formed, no diagnostic required.

[Example 3:
```
struct C {
  C( int ) { }  // #1: non-delegating constructor
  C(42) { }  // #2: delegates to #1
  C( char c ): C(42.0) { }  // #3: ill-formed due to recursion with #4
  C( double d ): C(‘a’) { }  // #4: ill-formed due to recursion with #3
};
```
—end example]
The expression-list or braced-init-list in a mem-initializer is used to initialize the designated subobject (or, in the case of a delegating constructor, the complete class object) according to the initialization rules of 9.4 for direct-initialization.

[Example 4:

```cpp
struct B1 { B1(int); /* ... */ };  
struct B2 { B2(int); /* ... */ };  
struct D : B1, B2 {
    D(int);
    B1 b;
    const int c;
};

D::D(int a) : B2(a+1), B1(a+2), c(a+3), b(a+4) { /* ... */ }
D d(10);
```

— end example]

[Note 2: The initialization performed by each mem-initializer constitutes a full-expression (6.9.1). Any expression in a mem-initializer is evaluated as part of the full-expression that performs the initialization. — end note]

A mem-initializer where the mem-initializer-id denotes a virtual base class is ignored during execution of a constructor of any class that is not the most derived class.

A temporary expression bound to a reference member in a mem-initializer is ill-formed.

[Example 5:

```cpp
struct A {
    A() : v(42) { }  
    const int& v;
};
```

— end example]

In a non-delegating constructor other than an implicitly-defined copy/move constructor (11.4.5.3), if a given potentially constructed subobject is not designated by a mem-initializer-id (including the case where there is no mem-initializer-list because the constructor has no ctor-initializer), then

9.1 — if the entity is a non-static data member that has a default member initializer (11.4) and either

9.1.1 — the constructor’s class is a union (11.5), and no other variant member of that union is designated by a mem-initializer-id or

9.1.2 — the constructor’s class is not a union, and, if the entity is a member of an anonymous union, no other member of that union is designated by a mem-initializer-id,

the entity is initialized from its default member initializer as specified in 9.4;

9.2 — otherwise, if the entity is an anonymous union or a variant member (11.5.2), no initialization is performed;

9.3 — otherwise, the entity is default-initialized (9.4).

[Note 3: An abstract class (11.7.4) is never a most derived class, thus its constructors never initialize virtual base classes, therefore the corresponding mem-initializers can be omitted. — end note]

An attempt to initialize more than one non-static data member of a union renders the program ill-formed.

[Note 4: After the call to a constructor for class X for an object with automatic or dynamic storage duration has completed, if the constructor was not invoked as part of value-initialization and a member of X is neither initialized nor given a value during execution of the compound-statement of the body of the constructor, the member has an indeterminate or erroneous value (6.7.4). — end note]

[Example 6:

```cpp
struct A {
    A();
};

struct B {
    B(int);
};
```
```cpp
struct C {
    C() {} // initializes members as follows:
    A a;   // OK, calls A::A()
    const B b; // error: B has no default constructor
    int i;  // OK, i has indeterminate or erroneous value
    int j = 5; // OK, j has the value 5
};
```

If a given non-static data member has both a default member initializer and a mem-initializer, the initialization specified by the mem-initializer is performed, and the non-static data member’s default member initializer is ignored.

[Example 7: Given
```cpp
struct A {
    int i = /* some integer expression with side effects */;
    A(int arg) : i(arg) {} // ...
};
```
the A(int) constructor will simply initialize i to the value of arg, and the side effects in i’s default member initializer will not take place. — end example]

A temporary expression bound to a reference member from a default member initializer is ill-formed.

[Example 8:
```cpp
struct A {
    A() = default; // OK
    A(int v) : v(v) {} // OK
    const int& v = 42; // OK
};
A a1;  // error: ill-formed binding of temporary to reference
A a2(1); // OK, unfortunately
```
— end example]

In a non-delegating constructor, the destructor for each potentially constructed subobject of class type is potentially invoked (11.4.7).

[Note 5: This provision ensures that destructors can be called for fully-constructed subobjects in case an exception is thrown (14.3). — end note]

In a non-delegating constructor, initialization proceeds in the following order:

1. First, and only for the constructor of the most derived class (6.7.2), virtual base classes are initialized in the order they appear on a depth-first left-to-right traversal of the directed acyclic graph of base classes, where “left-to-right” is the order of appearance of the base classes in the derived class base-specifier-list.
2. Then, direct base classes are initialized in declaration order as they appear in the base-specifier-list (regardless of the order of the mem-initializers).
3. Then, non-static data members are initialized in the order they were declared in the class definition (again regardless of the order of the mem-initializers).
4. Finally, the compound-statement of the constructor body is executed.

[Note 6: The declaration order is mandated to ensure that base and member subobjects are destroyed in the reverse order of initialization. — end note]
struct B : virtual V {
    B();
    B(int);
};

struct C : A, B, virtual V {
    C();
    C(int);
};

A::A(int i) : V(i) { /* ... */ }
B::B(int i) { /* ... */ }
C::C(int i) { /* ... */ }

V v(1);       // use V(int)
A a(2);       // use V(int)
B b(3);       // use V()
C c(4);       // use V()

—end example

[Note 7: The expression-list or braced-init-list of a mem-initializer is in the function parameter scope of the constructor and can use this to refer to the object being initialized. —end note]

[Example 10:]
class X {
    int a;
    int b;
    int i;
    int j;
    public:
        const int& r;
        X(int i): r(a), b(i), i(i), j(this->i) { }
};

initializes X::r to refer to X::a, initializes X::b with the value of the constructor parameter i, initializes X::i with the value of the constructor parameter i, and initializes X::j with the value of X::i; this takes place each time an object of class X is created. —end example]

15 Member functions (including virtual member functions, 11.7.3) can be called for an object under construction. Similarly, an object under construction can be the operand of the typeid operator (7.6.1.8) or of a dynamic_cast (7.6.1.7). However, if these operations are performed in a ctor-initializer (or in a function called directly or indirectly from a ctor-initializer) before all the mem-initializers for base classes have completed, the program has undefined behavior.

[Example 11:]
class A {
    public:
        A(int);
};

class B : public A {
    int j;
    public:
        int f();
        B() : A(f()), // undefined behavior: calls member function but base A not yet initialized
            j(f()) { } // well-defined: bases are all initialized
    };

class C {
    public:
        C(int);
    };

class D : public B, C {
    int i;

§ 11.9.3 ©ISO/IEC 328
public:
D() : C(f()), // undefined behavior: calls member function but base C not yet initialized
i(f()) {} // well-defined: bases are all initialized
};

[Note 8: 11.9.5 describes the results of virtual function calls, typeid and dynamic_casts during construction for the well-defined cases; that is, describes the polymorphic behavior of an object under construction. — end note]

A mem-initializer followed by an ellipsis is a pack expansion (13.7.4) that initializes the base classes specified by a pack expansion in the base-specifier-list for the class.

[Example 12:

```cpp
template<class... Mixins>
class X : public Mixins... {
public:
    X(const Mixins&... mixins) : Mixins(mixins)... { }
};
```
—end example]

### 11.9.4 Initialization by inherited constructor

When a constructor for type B is invoked to initialize an object of a different type D (that is, when the constructor was inherited (9.9)), initialization proceeds as if a defaulted default constructor were used to initialize the D object and each base class subobject from which the constructor was inherited, except that the B subobject is initialized by the inherited constructor if the base class subobject were to be initialized as part of the D object (11.9.3). The invocation of the inherited constructor, including the evaluation of any arguments, is omitted if the B subobject is not to be initialized as part of the D object. The complete initialization is considered to be a single function call; in particular, unless omitted, the initialization of the inherited constructor’s parameters is sequenced before the initialization of any part of the D object.

[Example 1:

```cpp
struct B1 {
    B1(int, ...) { }
};

struct B2 {
    B2(double) { }
};

int get();

struct D1 : B1 {
    using B1::B1; // inherits B1(int, ...)
    int x;
    int y = get();
};

void test() {
    D1 d2(2, 3, 4); // OK, B1 is initialized by calling B1(2, 3, 4),
                    // then d.x is default-initialized (no initialization is performed),
                    // then d.y is initialized by calling get()
    D1 e; // error: D1 has no default constructor
}

struct D2 : B2 {
    using B2::B2;
    B1 b;
};

D2 f(1.0); // error: B1 has no default constructor
```

struct W { W(int); };
struct X : virtual W { using W::W; X() = delete; };
struct Y : X { using X::X; };
struct Z : Y, virtual W { using Y::Y; };
Z z(0);  // OK, initialization of Y does not invoke default constructor of X

template<class T> struct Log : T {
  using T::T;  // inherits all constructors from class T
  ~Log() { std::clog << "Destroying wrapper" << std::endl; }
};

Class template Log wraps any class and forwards all of its constructors, while writing a message to the standard log whenever an object of class Log is destroyed. — end example

Example 2:
struct V { V() = default; V(int); };
struct Q { Q(); };
struct A : virtual V, Q {
  using V::V;
  A() = delete;
};
int bar() { return 42; }
struct B : A {
  B() : A(bar()) {} // OK
};
struct C : B {};
void foo() { C c;} // bar is not invoked, because the V subobject is not initialized as part of B
— end example

If the constructor was inherited from multiple base class subobjects of type B, the program is ill-formed.

Example 3:
struct A { A(int); };
struct B : A { using A::A; };

struct C1 : B { using B::B; };
struct C2 : B { using B::B; };

struct D1 : C1, C2 {
  using C1::C1;
  using C2::C2;
};

struct V1 : virtual B { using B::B; };
struct V2 : virtual B { using B::B; };

struct D2 : V1, V2 {
  using V1::V1;
  using V2::V2;
};

D1 d1(0); // error: ambiguous
D2 d2(0); // OK, initializes virtual B base class, which initializes the A base class
 // then initializes the V1 and V2 base classes as if by a defaulted default constructor

struct M { M(); M(int); };
struct N : M { using M::M; };
struct O : M {};
struct P : N, O { using N::N; using O::O; };
P p(0); // OK, use M(O) to initialize N’s base class,
 // use M(O) to initialize O’s base class
— end example

When an object is initialized by an inherited constructor, initialization of the object is complete when the initialization of all subobjects is complete.
11.9.5 Construction and destruction

For an object with a non-trivial constructor, referring to any non-static member or base class of the object before the constructor begins execution results in undefined behavior. For an object with a non-trivial destructor, referring to any non-static member or base class of the object after the destructor finishes execution results in undefined behavior.

Example 1:

```c
struct X { int i; };  // non-trivial
struct Y : X { Y(); };  // non-trivial
struct A { int a; };  // non-trivial
struct B : public A { int j; Y y; };  // non-trivial

extern B bobj;
B* pb = &bobj;  // OK
int* p1 = &bobj.a;  // undefined behavior: refers to base class member
int* p2 = &bobj.y.i;  // undefined behavior: refers to member's member

A* pa = &bobj;  // undefined behavior: upcast to a base class type
B bobj;  // definition of bobj

extern X xobj;
int* p3 = &xobj.i;  // OK, X is a trivial class
X xobj;
```

For another example,

```c
struct W { int j; };  // non-trivial
struct X : public virtual W { };  // non-trivial
struct Y {
    int* p;
    X x;
    Y() : p(&x.j) {  // undefined, x is not yet constructed
}
};
```

During the construction of an object, if the value of the object or any of its subobjects is accessed through a glvalue that is not obtained, directly or indirectly, from the constructor's this pointer, the value of the object or subobject thus obtained is unspecified.

Example 2:

```c
struct C;
void no_opt(C*);

struct C {
    int c;
    C() : c(0) { no_opt(this); }
};

const C cobj;

void no_opt(C* cptr) {
    int i = cobj.c * 100;  // value of cobj.c is unspecified
    cptr->c = 1;
    cout << cobj.c * 100  // value of cobj.c is unspecified
        << '\n';
}

extern struct D d;
struct D {
    D(int a) : a(a), b(d.a) {}  // value of d.b is unspecified
    int a, b;
};
D d = D(1);  // value of d.b is unspecified
```
To explicitly or implicitly convert a pointer (a glvalue) referring to an object of class \( \text{X} \) to a pointer (reference) to a direct or indirect base class \( \text{B} \) of \( \text{X} \), the construction of \( \text{X} \) and the construction of all of its direct or indirect bases that directly or indirectly derive from \( \text{B} \) shall have started and the destruction of these classes shall not have completed, otherwise the conversion results in undefined behavior. To form a pointer to (or access the value of) a direct non-static member of an object \( \text{obj} \), the construction of \( \text{obj} \) shall have started and its destruction shall not have completed, otherwise the computation of the pointer value (or accessing the member value) results in undefined behavior.

\[\text{Example 3:}\]

```cpp
struct A { }
struct B : virtual A { }
struct C : B { }
struct D : virtual A { D(A*); }
struct X { X(A*); }

struct E : C, D, X {
    E() : D(this), // undefined behavior: upcast from E* to A* might use path E* \rightarrow D* \rightarrow A*
        // but D is not constructed
    // "D((C*)this)" would be defined: E* \rightarrow C* is defined because E() has started,
    // and C* \rightarrow A* is defined because C is fully constructed
    X(this) {} // defined: upon construction of X, C/B/D/A sublattice is fully constructed
};
```

- end example]

Member functions, including virtual functions (11.7.3), can be called during construction or destruction (11.9.3). When a virtual function is called directly or indirectly from a constructor or from a destructor, including during the construction or destruction of the class’s non-static data members, and the object to which the call applies is the object (call it \( \text{x} \)) under construction or destruction, the function called is the final overrider in the constructor’s or destructor’s class and not one overriding it in a more-derived class. If the virtual function call uses an explicit class member access (7.6.1.5) and the object expression refers to the complete object of \( \text{x} \) or one of that object’s base class subobjects but not \( \text{x} \) or one of its base class subobjects, the behavior is undefined.

\[\text{Example 4:}\]

```cpp
struct V {
    virtual void f();
    virtual void g();
};

struct A : virtual V {
    virtual void f();
};

struct B : virtual V {
    virtual void g();
    B(V*, A*); }

struct D : A, B {
    virtual void f();
    virtual void g();
    D() : B((A*)this, this) {} }

B::B(V* v, A* a) {
    f(); // calls V::f, not A::f
    g(); // calls B::g, not D::g
    v->g(); // v is base of B, the call is well-defined, calls B::g
    a->f(); // undefined behavior: a’s type not a base of B
}
```
The typeid operator (7.6.1.8) can be used during construction or destruction (11.9.3). When typeid is used in a constructor (including the mem-initializer or default member initializer (11.4) for a non-static data member) or in a destructor, or used in a function called (directly or indirectly) from a constructor or destructor, if the operand of typeid refers to the object under construction or destruction, typeid yields the std::type_info object representing the constructor or destructor's class. If the operand of typeid refers to the object under construction or destruction and the static type of the operand is neither the constructor or destructor's class nor one of its bases, the behavior is undefined.

dynamic_casts (7.6.1.7) can be used during construction or destruction (11.9.3). When a dynamic_cast is used in a constructor (including the mem-initializer or default member initializer for a non-static data member) or in a destructor, or used in a function called (directly or indirectly) from a constructor or destructor, if the operand of the dynamic_cast refers to the object under construction or destruction, this object is considered to be a most derived object that has the type of the constructor or destructor's class. If the operand of the dynamic_cast refers to the object under construction or destruction and the static type of the operand is not a pointer to or object of the constructor or destructor's own class or one of its bases, the dynamic_cast results in undefined behavior.

Example 5:

```cpp
struct V {
    virtual void f();
};

struct A : virtual V {
};

struct B : virtual V {
    B(V*, A*);
};

struct D : A, B {
    D() : B((A*)this, this) { }
};

B::B(V* v, A* a) {
    typeid(*this);
    typeid(v);
    typeid(a);
    dynamic_cast<B*>(v);
    dynamic_cast<B*>(a);
}
```

— end example

11.9.6 Copy/move elision

When certain criteria are met, an implementation is allowed to omit the copy/move construction of a class object, even if the constructor selected for the copy/move operation and/or the destructor for the object have side effects. In such cases, the implementation treats the source and target of the omitted copy/move operation as simply two different ways of referring to the same object. If the first parameter of the selected constructor is an rvalue reference to the object's type, the destruction of that object occurs when the target would have been destroyed; otherwise, the destruction occurs at the later of the times when the two objects would have been destroyed without the optimization. This elision of copy/move operations, called copy elision, is permitted in the following circumstances (which may be combined to eliminate multiple copies):

— in a return statement in a function with a class return type, when the expression is the name of a non-volatile object with automatic storage duration (other than a function parameter or a variable introduced by the exception-declaration of a handler (14.4)) with the same type (ignoring cv-qualification) as the function return type, the copy/move operation can be omitted by constructing the object directly into the function call's return object.

100 Because only one object is destroyed instead of two, and one copy/move constructor is not executed, there is still one object destroyed for each one constructed.
— in a throw-expression (7.6.18), when the operand is the name of a non-volatile object with automatic storage duration (other than a function or catch-clause parameter) that belongs to a scope that does not contain the innermost enclosing compound-statement associated with a try-block (if there is one), the copy/move operation can be omitted by constructing the object directly into the exception object

— in a coroutine (9.5.4), a copy of a coroutine parameter can be omitted and references to that copy replaced with references to the corresponding parameter if the meaning of the program will be unchanged except for the execution of a constructor and destructor for the parameter copy object

— when the exception-declaration of a handler (14.4) declares an object of the same type (except for cv-qualification) as the exception object (14.2), the copy operation can be omitted by treating the exception-declaration as an alias for the exception object if the meaning of the program will be unchanged except for the execution of constructors and destructors for the object declared by the exception-declaration.

[Note 1: There cannot be a move from the exception object because it is always an lvalue. — end note]

Copy elision is not permitted where an expression is evaluated in a context requiring a constant expression (7.7) and in constant initialization (6.9.3.2).

[Note 2: It is possible that copy elision is performed if the same expression is evaluated in another context. — end note]

Example 1:

```cpp
class Thing {
public:
  Thing();
  ~Thing();
  Thing(const Thing&);
};

Thing f() {
  Thing t;
  return t;
}

Thing t2 = f();

struct A {
  void *p;
  constexpr A(): p(this) {}
};

constexpr A g() {
  A loc;
  return loc;
}

constexpr A a; // well-formed, a.p points to a
constexpr A b = g(); // error: b.p would be dangling (7.7)

void h() {
  A c = g(); // well-formed, c.p can point to c or be dangling
}
```

Here the criteria for elision can eliminate the copying of the object `t` with automatic storage duration into the result object for the function call `f()`, which is the non-local object `t2`. Effectively, the construction of `t` can be viewed as directly initializing `t2`, and that object’s destruction will occur at program exit. Adding a move constructor to `Thing` has the same effect, but it is the move construction from the object with automatic storage duration to `t2` that is elided. — end example]

Example 2:

```cpp
class Thing {
public:
  Thing();
  ~Thing();
  Thing(Thing&&);
};
```
private:
    Thing(const Thing&);
};

Thing f(bool b) {
    Thing t;
    if (b)
        throw t;  // OK, Thing(Thing&&) used (or elided) to throw t
    return t;  // OK, Thing(Thing&&) used (or elided) to return t
}

Thing t2 = f(false);  // OK, no extra copy/move performed, t2 constructed by call to f

struct Weird {
    Weird();
    Weird(Weird&);
};

Weird g(bool b) {
    static Weird w1;
    Weird w2;
    if (b)
        return w1;  // OK, uses Weird(Weird&)
    else
        return w2;  // error: w2 in this context is an xvalue
}

int& h(bool b, int i) {
    static int s;
    if (b)
        return s;  // OK
    else
        return i;  // error: i is an xvalue
}

decltype(auto) h2(Thing t) {
    return t;  // OK, t is an xvalue and h2's return type is Thing
}

decltype(auto) h3(Thing t) {
    return (t);  // OK, (t) is an xvalue and h3's return type is Thing&&
}

/* end example */

4 [Example 3:
   template<class T> void g(const T&);
   template<class T> void f() {
      T x;
      try {
         T y;
         try { g(x); }
         catch (...) {
            if (/*/...*/)  
                throw x;  // does not move
                throw y;  // moves
         }  
         g(y);
      } catch(...) {
         g(x);
         g(y);  // error: y is not in scope
      }
   }
]
11.10 Comparisons

11.10.1 Defaulted comparison operator functions

A defaulted comparison operator function (12.4.3) shall be a non-template function that

1. is a non-static member or friend of some class `C`,
2. is defined as defaulted in `C` or in a context where `C` is complete, and
3. either has two parameters of type `const C&` or two parameters of type `C`, where the implicit object parameter (if any) is considered to be the first parameter.

Such a comparison operator function is termed a defaulted comparison operator function for class `C`. Name lookups and access checks in the implicit definition (9.5.2) of a comparison operator function are performed from a context equivalent to its function-body. A definition of a comparison operator as defaulted that appears in a class shall be the first declaration of that function.

**Example 1:**
```cpp
struct S;
bool operator==(S, S) = default;  // error: S is not complete
struct S {
    friend bool operator==(S, const S&) = default;  // error: parameters of different types
};
enum E {
};
bool operator==(E, E) = default;  // error: not a member or friend of a class
```

A defaulted `<=` or `==` operator function for class `C` is defined as deleted if any non-static data member of `C` is of reference type or `C` has variant members (11.5.2).

A binary operator expression `a @ b` is usable if either

1. `a` or `b` is of class or enumeration type and overload resolution (12.2) as applied to `a @ b` results in a usable candidate, or
2. neither `a` nor `b` is of class or enumeration type and `a @ b` is a valid expression.

If the member-specification does not explicitly declare any member or friend named `operator==`, an `==` operator function is declared implicitly for each three-way comparison operator function defined as defaulted in the member-specification, with the same access and function-definition and in the same class scope as the respective three-way comparison operator function, except that the return type is replaced with `bool` and the declarator-id is replaced with `operator==`.

[Note 1: Such an implicitly-declared `==` operator for a class `X` is defined as defaulted in the definition of `X` and has the same parameter-declaration-clause and trailing requires-clause as the respective three-way comparison operator. It is declared with `friend`, `virtual`, `constexpr`, or `consteval` if the three-way comparison operator function has no `noexcept-specifier`, the implicitly-declared `==` operator function has an implicit exception specification (14.5) that can differ from the implicit exception specification of the three-way comparison operator function. — end note]

**Example 2:**
```cpp
template<typename T> struct X {
    friend constexpr std::partial_ordering operator<=>(X, X) requires (sizeof(T) != 1) = default;
    // implicitly declares: friend constexpr bool operator==(X, X) requires (sizeof(T) != 1) = default;
    
    [[nodiscard]] virtual std::strong_ordering operator<=>(const X&) const = default;
    // implicitly declares: [[nodiscard]] virtual bool operator==(const X&) const = default;
};
```

[Note 2: The `==` operator function is declared implicitly even if the defaulted three-way comparison operator function is defined as deleted. — end note]

The direct base class subobjects of `C`, in the order of their declaration in the `base-specifier-list` of `C`, followed by the non-static data members of `C`, in the order of their declaration in the `member-specification` of `C`, form a list of subobjects. In that list, any subobject of array type is recursively expanded to the sequence of its elements, in the order of increasing subscript. Let `x_i` be an lvalue denoting the `i`th element in the
expanded list of subobjects for an object \( x \) (of length \( n \)), where \( x_i \) is formed by a sequence of derived-to-base conversions (12.2.4.2), class member access expressions (7.6.1.5), and array subscript expressions (7.6.1.2) applied to \( x \).

### 11.10.2 Equality operator

1. A defaulted equality operator function (12.4.3) shall have a declared return type \( \text{bool} \).
2. A defaulted == operator function for a class \( C \) is defined as deleted unless, for each \( x_i \) in the expanded list of subobjects for an object \( x \) of type \( C \), \( x_i == x_i \) is usable (11.10.1).
3. The return value of a defaulted == operator function with parameters \( x \) and \( y \) is determined by comparing corresponding elements \( x_i \) and \( y_i \) in the expanded lists of subobjects for \( x \) and \( y \) (in increasing index order) until the first index \( i \) where \( x_i == y_i \) yields a result value which, when contextually converted to \( \text{bool} \), yields \text{false}. The return value is \text{false} if such an index exists and \text{true} otherwise.

**Example 1:**

```cpp
struct D {
  int i;
  friend bool operator==(const D& x, const D& y) = default;
  // OK, returns \( x.i == y.i \)
};
```

### 11.10.3 Three-way comparison

1. The synthesized three-way comparison of type \( R \) (17.11.2) of glvalues \( a \) and \( b \) of the same type is defined as follows:

   - If \( a \leftrightarrow b \) is usable (11.10.1) and can be explicitly converted to \( R \) using \texttt{static
cast\langle R \rangle(a \leftrightarrow b)}.
   - Otherwise, if overload resolution for \( a \leftrightarrow b \) is performed and finds at least one viable candidate, the synthesized three-way comparison is not defined.
   - Otherwise, if \( R \) is not a comparison category type, or either the expression \( a == b \) or the expression \( a < b \) is not usable, the synthesized three-way comparison is not defined.
   - Otherwise, if \( R \) is \texttt{strong\_ordering}, then
     ```
     a == b ? strong\_ordering::equal :
     a < b ? strong\_ordering::less :
             strong\_ordering::greater
     ```
   - Otherwise, if \( R \) is \texttt{weak\_ordering}, then
     ```
     a == b ? weak\_ordering::equivalent :
     a < b ? weak\_ordering::less :
             weak\_ordering::greater
     ```
   - Otherwise (when \( R \) is \texttt{partial\_ordering}),
     ```
     a == b ? partial\_ordering::equivalent :
     a < b ? partial\_ordering::less :
     b < a ? partial\_ordering::greater :
             partial\_ordering::unordered
     ```

**Note 1:** A synthesized three-way comparison is ill-formed if overload resolution finds usable candidates that do not otherwise meet the requirements implied by the defined expression. —end note

2. Let \( R \) be the declared return type of a defaulted three-way comparison operator function, and let \( x_i \) be the elements of the expanded list of subobjects for an object \( x \) of type \( C \).

   - If \( R \) is \texttt{auto}, then let \( cv_i \), \( R_i \) be the type of the expression \( x_i \leftrightarrow x_i \). The operator function is defined as deleted if that expression is not usable or if \( R_i \) is not a comparison category type (17.11.2.1) for any \( i \). The return type is deduced as the common comparison type (see below) of \( R_0, R_1, \ldots, R_{n-1} \).
   - Otherwise, \( R \) shall not contain a placeholder type. If the synthesized three-way comparison of type \( R \) between any objects \( x_i \) and \( x_i \) is not defined, the operator function is defined as deleted.

3. The return value of type \( R \) of the defaulted three-way comparison operator function with parameters \( x \) and \( y \) of the same type is determined by comparing corresponding elements \( x_i \) and \( y_i \) in the expanded lists of subobjects.
for \( x \) and \( y \) (in increasing index order) until the first index \( i \) where the synthesized three-way comparison of type \( R \) between \( x_i \) and \( y_i \), yields a result value \( v_i \) where \( v_i \neq 0 \), contextually converted to \texttt{bool}, yields \texttt{true}. The return value is a copy of \( v_i \) if such an index exists and \texttt{static_cast<R>(std::strong_ordering::equal)} otherwise.

The common comparison type \( U \) of a possibly-empty list of \( n \) comparison category types \( T_0, T_1, \ldots, T_{n-1} \) is defined as follows:

(4.1) If at least one \( T_i \) is \texttt{std::partial_ordering}, \( U \) is \texttt{std::partial_ordering} (17.11.2.2).

(4.2) Otherwise, if at least one \( T_i \) is \texttt{std::weak_ordering}, \( U \) is \texttt{std::weak_ordering} (17.11.2.3).

(4.3) Otherwise, \( U \) is \texttt{std::strong_ordering} (17.11.2.4).

[Note 2: In particular, this is the result when \( n \) is 0. — end note]

11.10.4 Secondary comparison operators

A secondary comparison operator is a relational operator (7.6.9) or the \(!=\) operator. A defaulted operator function (12.4.3) for a secondary comparison operator \@ shall have a declared return type \texttt{bool}.

The operator function with parameters \( x \) and \( y \) is defined as deleted if

(2.1) a first overload resolution (12.2), as applied to \( x \@ y \),

(2.1.1) does not result in a usable candidate, or

(2.1.2) the selected candidate is not a rewritten candidate, or

(2.2) a second overload resolution for the expression resulting from the interpretation of \( x \@ y \) using the selected rewritten candidate (12.2.2.3) does not result in a usable candidate (for example, that expression might be \( (x <= y) \@ 0 \)), or

(2.3) \( x \@ y \) cannot be implicitly converted to \texttt{bool}.

In any of the two overload resolutions above, the defaulted operator function is not considered as a candidate for the \@ operator. Otherwise, the operator function yields \( x \@ y \).

[Example 1:

```cpp
struct HasNoLessThan { };

struct C {
    friend HasNoLessThan operator<=>(const C&, const C&);
    bool operator<(const C&) const = default; // OK, function is deleted
};

@end example]
12 Overloading

12.1 Preamble

[Note 1: Each of two or more entities with the same name in the same scope, which must be functions or function templates, is commonly called an “overload”. — end note]

When a function is named in a call, which function declaration is being referenced and the validity of the call are determined by comparing the types of the arguments at the point of use with the types of the parameters in the declarations in the overload set. This function selection process is called overload resolution and is defined in 12.2.

[Example 1:
  double abs(double);
  int abs(int);
  
  abs(1);       // calls abs(int);
  abs(1.0);     // calls abs(double);
  — end example]

12.2 Overload resolution

12.2.1 General

Overload resolution is a mechanism for selecting the best function to call given a list of expressions that are to be the arguments of the call and a set of candidate functions that can be called based on the context of the call. The selection criteria for the best function are the number of arguments, how well the arguments match the parameter-type-list of the candidate function, how well (for non-static member functions) the object matches the object parameter, and certain other properties of the candidate function.

[Note 1: The function selected by overload resolution is not guaranteed to be appropriate for the context. Other restrictions, such as the accessibility of the function, can make its use in the calling context ill-formed. — end note]

Overload resolution selects the function to call in seven distinct contexts within the language:

(2.1) invocation of a function named in the function call syntax (12.2.2.2);
(2.2) invocation of a function call operator, a pointer-to-function conversion function, a reference-to-pointer-to-function conversion function, or a reference-to-function conversion function on a class object named in the function call syntax (12.2.2.3);
(2.3) invocation of the operator referenced in an expression (12.2.2.3);
(2.4) invocation of a constructor for default- or direct-initialization (9.4) of a class object (12.2.2.4);
(2.5) invocation of a user-defined conversion for copy-initialization (9.4) of a class object (12.2.2.5);
(2.6) invocation of a conversion function for initialization of an object of a non-class type from an expression of class type (12.2.2.6); and
(2.7) invocation of a conversion function for conversion in which a reference (9.4.4) will be directly bound (12.2.2.7).

Each of these contexts defines the set of candidate functions and the list of arguments in its own unique way. But, once the candidate functions and argument lists have been identified, the selection of the best function is the same in all cases:

(2.8) First, a subset of the candidate functions (those that have the proper number of arguments and meet certain other conditions) is selected to form a set of viable functions (12.2.3).
(2.9) Then the best viable function is selected based on the implicit conversion sequences (12.2.4.2) needed to match each argument to the corresponding parameter of each viable function.

If a best viable function exists and is unique, overload resolution succeeds and produces it as the result. Otherwise overload resolution fails and the invocation is ill-formed. When overload resolution succeeds, and the best viable function is not accessible (11.8) in the context in which it is used, the program is ill-formed.
Overload resolution results in a usable candidate if overload resolution succeeds and the selected candidate is either not a function (12.5), or is a function that is not deleted and is accessible from the context in which overload resolution was performed.

12.2.2 Candidate functions and argument lists

12.2.2.1 General

The subclauses of 12.2.2 describe the set of candidate functions and the argument list submitted to overload resolution in each context in which overload resolution is used. The source transformations and constructions defined in these subclauses are only for the purpose of describing the overload resolution process. An implementation is not required to use such transformations and constructions.

2 The set of candidate functions can contain both member and non-member functions to be resolved against the same argument list. If a member function is

(2.1) an implicit object member function that is not a constructor, or

(2.2) a static member function and the argument list includes an implied object argument, it is considered to have an extra first parameter, called the implicit object parameter, which represents the object for which the member function has been called.

3 Similarly, when appropriate, the context can construct an argument list that contains an implied object argument as the first argument in the list to denote the object to be operated on.

4 For implicit object member functions, the type of the implicit object parameter is

(4.1) “lvalue reference to cv X” for functions declared without a ref-qualifier or with the & ref-qualifier

(4.2) “rvalue reference to cv X” for functions declared with the && ref-qualifier where X is the class of which the function is a direct member and cv is the cv-qualification on the member function declaration.

[Example 1: For a const member function of class X, the extra parameter is assumed to have type “lvalue reference to const X”. — end example]

For conversion functions that are implicit object member functions, the function is considered to be a member of the class of the implied object argument for the purpose of defining the type of the implicit object parameter. For non-conversion functions that are implicit object member functions nominated by a using-declaration in a derived class, the function is considered to be a member of the derived class for the purpose of defining the type of the implicit object parameter. For static member functions, the implicit object parameter is considered to match any object (since if the function is selected, the object is discarded).

[Note 1: No actual type is established for the implicit object parameter of a static member function, and no attempt will be made to determine a conversion sequence for that parameter (12.2.4). — end note]

5 During overload resolution, the implied object argument is indistinguishable from other arguments. The implicit object parameter, however, retains its identity since no user-defined conversions can be applied to achieve a type match with it. For implicit object member functions declared without a ref-qualifier, even if the implicit object parameter is not const-qualified, an rvalue can be bound to the parameter as long as in all other respects the argument can be converted to the type of the implicit object parameter.

[Note 2: The fact that such an argument is an rvalue does not affect the ranking of implicit conversion sequences (12.2.4.3). — end note]

6 Because other than in list-initialization only one user-defined conversion is allowed in an implicit conversion sequence, special rules apply when selecting the best user-defined conversion (12.2.4, 12.2.4.2).

[Example 2:

class T {
    public:
    T();
};

class C : T {
    public:
    C(int);
};
T a = 1; // error: no viable conversion (T(C(1)) not considered)
In each case where conversion functions of a class \( S \) are considered for initializing an object or reference of type \( T \), the candidate functions include the result of a search for the conversion-function-id operator \( T \) in \( S \).

[Note 3: This search can find a specialization of a conversion function template (6.5). — end note]

Each such case also defines sets of permissible types for explicit and non-explicit conversion functions; each (non-template) conversion function that

(7.1) — is a non-hidden member of \( S \),

(7.2) — yields a permissible type, and,

(7.3) — for the former set, is non-explicit

is also a candidate function. If initializing an object, for any permissible type \( cv \ U \), any \( cv2 \ U \), \( cv2 \ U \& \) or \( cv2 \ U \&& \) is also a permissible type. If the set of permissible types for explicit conversion functions is empty, any candidates that are explicit are discarded.

In each case where a candidate is a function template, candidate function template specializations are generated using template argument deduction (13.10.4, 13.10.3). If a constructor template or conversion function template has an explicit-specifier whose constant-expression is value-dependent (13.8.3), template argument deduction is performed first and then, if the context admits only candidates that are not explicit and the generated specialization is explicit (9.2.3), it will be removed from the candidate set. Those candidates are then handled as candidate functions in the usual way. A given name can refer to, or a conversion can consider, one or more function templates as well as a set of non-template functions. In such a case, the candidate functions generated from each function template are combined with the set of non-template candidate functions.

A defaulted move special member function (11.4.5.3, 11.4.6) that is defined as deleted is excluded from the set of candidate functions in all contexts. A constructor inherited from class type \( C \) (11.9.4) that has a first parameter of type “reference to \( cv1 \ P \)” (including such a constructor instantiated from a template) is excluded from the set of candidate functions when constructing an object of type \( cv2 \ D \) if the argument list has exactly one argument and \( C \) is reference-related to \( P \) and \( P \) is reference-related to \( D \).

[Example 3:

```c
struct A {
    A(); // #1
    A(A &&); // #2
    template<typename T> A(T &&); // #3
};
struct B : A {
    using A::A;
    B(const B &); // #4
    B(B &&) = default; // #5, implicitly deleted
}
struct X { X(X &&) = delete; } x;
};
extern B b1;
B b2 = static_cast<B&&>(b1); // calls #4: #1 is not viable, #2, #3, and #5 are not candidates
struct C { operator B&&(); }; // calls #4
```

— end example]
if the *postfix-expression* names at least one function or function template, overload resolution is applied as specified in 12.2.2.2.2. If the *postfix-expression* denotes an object of class type, overload resolution is applied as specified in 12.2.2.2.3.

2 If the *postfix-expression* is the address of an overload set, overload resolution is applied using that set as described above.

[Note 1: No implied object argument is added in this case. — end note]

If the function selected by overload resolution is an implicit object member function, the program is ill-formed.

[Note 2: The resolution of the address of an overload set in other contexts is described in 12.3. — end note]

12.2.2.2.2 Call to named function

Of interest in 12.2.2.2.2 are only those function calls in which the *postfix-expression* ultimately contains an *id-expression* that denotes one or more functions. Such a *postfix-expression*, perhaps nested arbitrarily deep in parentheses, has one of the following forms:

*postfix-expression:*

  *postfix-expression* . *id-expression*

  *postfix-expression* -> *id-expression*

  *primary-expression*

These represent two syntactic subcategories of function calls: qualified function calls and unqualified function calls.

2 In qualified function calls, the function is named by an *id-expression* preceded by an *->* or . operator. Since the construct *A*->*B* is generally equivalent to (*A*) . *B*, the rest of Clause 12 assumes, without loss of generality, that all member function calls have been normalized to the form that uses an object and the . operator. Furthermore, Clause 12 assumes that the *postfix-expression* that is the left operand of the . operator has type “cv T” where T denotes a class. The function declarations found by name lookup (6.5.2) constitute the set of candidate functions. The argument list is the *expression-list* in the call augmented by the addition of the left operand of the . operator in the normalized member function call as the implied object argument (12.2.2). In unqualified function calls, the function is named by a *primary-expression*. The function declarations found by name lookup (6.5) constitute the set of candidate functions. Because of the rules for name lookup, the set of candidate functions consists either entirely of non-member functions or entirely of member functions of some class T. In the former case or if the *primary-expression* is the address of an overload set, the argument list is the same as the *expression-list* in the call. Otherwise, the argument list is the *expression-list* in the call augmented by the addition of an implied object argument as in a qualified function call. If the current class is, or is derived from, T, and the keyword this (7.5.3) refers to it, then the implied object argument is (*this). Otherwise, a contrived object of type T becomes the implied object argument; if overload resolution selects a non-static member function, the call is ill-formed.

[Example 1:]

```c
struct C {
    void a();
    void b() {
        a();           // OK, (*this).a()
    }

    void c(this const C&); // #1
    void c() &;            // #2
    static void c(int = 0); // #3

    void d() {
        c();            // error: ambiguous between #2 and #3
        (C::c)();       // error: as above
        (&(C::c))();    // error: cannot resolve address of overloaded this->C::c (12.3)
        (&(C::c)(C{})); // selects #1
        (&(C::c)(*this)); // error: selects #2, and is ill-formed (12.2.2.2.1)
        (&(C::c)());    // selects #3
    }
}
```

102) Note that cv-qualifiers on the type of objects are significant in overload resolution for both glvalue and class prvalue objects.

103) An implied object argument is contrived to correspond to the implicit object parameter attributed to member functions during overload resolution. It is not used in the call to the selected function. Since the member functions all have the same implicit object parameter, the contrived object will not be the cause to select or reject a function.
void f(this const C&);
void g() const {
    f(); // OK, (*this).f()
    f(*this); // error: no viable candidate for (*this).f(*this)
    this->f(); // OK
}

static void h() {
    f(); // error: contrived object argument, but overload resolution
    // picked a non-static member function
    f(C()); // error: no viable candidate
    C().f(); // OK
}

void k(this int);
operator int() const;
void m(this const C& c) {
    c.k(); // OK
}

—end example

12.2.2.2.3 Call to object of class type [over.call.object]

1 If the postfix-expression E in the function call syntax evaluates to a class object of type “cv T”, then the set of
candidate functions includes at least the function call operators of T. The function call operators of T are the
results of a search for the name operator() in the scope of T.

2 In addition, for each non-explicit conversion function declared in T of the form

    operator conversion-type-id () cv-qualifier-seq_opt ref-qualifier_opt noexcept-specifier_opt attribute-specifier-seq_opt;

where the optional cv-qualifier-seq is the same cv-qualification as, or a greater cv-qualification than, cv,
and where conversion-type-id denotes the type “pointer to function of (P_1, ..., P_n) returning R”, or the type
“reference to pointer to function of (P_1, ..., P_n) returning R”, or the type “reference to function of (P_1, ..., P_n)
returning R”, a surrogate call function with the unique name call-function and having the form

    R call-function ( conversion-type-id F, P_1 a_1, ..., P_n a_n ) { return F(a_1, ..., a_n); }

is also considered as a candidate function. Similarly, surrogate call functions are added to the set of candidate
functions for each non-explicit conversion function declared in a base class of T provided the function is not
hidden within T by another intervening declaration.104

3 The argument list submitted to overload resolution consists of the argument expressions present in the
function call syntax preceded by the implied object argument (E).

[Note 1: When comparing the call against the function call operators, the implied object argument is compared
against the object parameter of the function call operator. When comparing the call against a surrogate call function,
the implied object argument is compared against the first parameter of the surrogate call function. — end note]

[Example 1:]

    int f1(int);
    int f2(float);
    typedef int (*fp1)(int);
    typedef int (*fp2)(float);
    struct A {
        operator fp1() { return f1; }
        operator fp2() { return f2; }
    } a;
    int i = a(1); // calls f1 via pointer returned from conversion function

—end example

104) Note that this construction can yield candidate call functions that cannot be differentiated one from the other by overload
resolution because they have identical declarations or differ only in their return type. The call will be ambiguous if overload
resolution cannot select a match to the call that is uniquely better than such undifferentiable functions.
12.2.2.3 Operators in expressions [over.match.oper]

1 If no operand of an operator in an expression has a type that is a class or an enumeration, the operator is assumed to be a built-in operator and interpreted according to 7.6.

[Note 1: Because ..*, .*, and :: cannot be overloaded, these operators are always built-in operators interpreted according to 7.6. ?: cannot be overloaded, but the rules in this subclause are used to determine the conversions to be applied to the second and third operands when they have class or enumeration type (7.6.16). — end note]

[Example 1:]

```cpp
struct String {
    String (const String&);
    String (const char*);
    operator const char* () const;
};
String operator + (const String&, const String&);

void f() {
    const char* p= "one" + "two"; // error: cannot add two pointers; overloaded operator+ not considered
    // because neither operand has class or enumeration type
    int I = 1 + 1; // always evaluates to 2 even if class or enumeration types exist
    // that would perform the operation.
}
—end example]
```

2 If either operand has a type that is a class or an enumeration, a user-defined operator function can be declared that implements this operator or a user-defined conversion can be necessary to convert the operand to a type that is appropriate for a built-in operator. In this case, overload resolution is used to determine which operator function or built-in operator is to be invoked to implement the operator. Therefore, the operator notation is first transformed to the equivalent function-call notation as summarized in Table 18 (where @ denotes one of the operators covered in the specified subclause). However, the operands are sequenced in the order prescribed for the built-in operator (7.6).

Table 18 — Relationship between operator and function call notation [tab:over.match.oper]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Expression</th>
<th>As member function</th>
<th>As non-member function</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4.2</td>
<td>@a</td>
<td>(a).operator@ ()</td>
<td>operator@ (a)</td>
</tr>
<tr>
<td>12.4.3</td>
<td>a@b</td>
<td>(a).operator@ (b)</td>
<td>operator@ (a, b)</td>
</tr>
<tr>
<td>12.4.3.2</td>
<td>a = b</td>
<td>(a).operator= (b)</td>
<td></td>
</tr>
<tr>
<td>12.4.5</td>
<td>a[b]</td>
<td>(a).operator[] (b)</td>
<td></td>
</tr>
<tr>
<td>12.4.6</td>
<td>a-&gt;</td>
<td>(a).operator-&gt;()</td>
<td></td>
</tr>
<tr>
<td>12.4.7</td>
<td>a@</td>
<td>(a).operator@ (0)</td>
<td>operator@ (a, 0)</td>
</tr>
</tbody>
</table>

3 For a unary operator @ with an operand of type cv1 T1, and for a binary operator @ with a left operand of type cv1 T1 and a right operand of type cv2 T2, four sets of candidate functions, designated member candidates, non-member candidates, built-in candidates, and rewritten candidates, are constructed as follows:

(3.1) — If T1 is a complete class type or a class currently being defined, the set of member candidates is the result of a search for operator@ in the scope of T1; otherwise, the set of member candidates is empty.

(3.2) — For the operators =, [], or ->, the set of non-member candidates is empty; otherwise, it includes the result of unqualified lookup for operator@ in the rewritten function call (6.5.3, 6.5.4), ignoring all member functions. However, if no operand has a class type, only those non-member functions in the lookup set that have a first parameter of type T1 or “reference to cv T1”, when T1 is an enumeration type, or (if there is a right operand) a second parameter of type T2 or “reference to cv T2”, when T2 is an enumeration type, are candidate functions.

(3.3) — For the operator ., the unary operator &, or the operator ->, the built-in candidates set is empty. For all other operators, the built-in candidates include all of the candidate operator functions defined in 12.5 that, compared to the given operator,

(3.3.1) — have the same operator name, and

(3.3.2) — accept the same number of operands, and
accept operand types to which the given operand or operands can be converted according to 12.2.4.2, and
— do not have the same parameter-type-list as any non-member candidate or rewritten non-member candidate that is not a function template specialization.

The rewritten candidate set is determined as follows:

— For the relational (7.6.9) operators, the rewritten candidates include all non-rewritten candidates for the expression $x \leftrightarrow y$.

— For the relational (7.6.9) and three-way comparison (7.6.8) operators, the rewritten candidates also include a synthesized candidate, with the order of the two parameters reversed, for each non-rewritten candidate for the expression $y \leftrightarrow x$.

— For the $!=\text{ operator}$ (7.6.10), the rewritten candidates include all non-rewritten candidates for the expression $x == y$ that are rewrite targets with first operand $x$ (see below).

— For the equality operators, the rewritten candidates also include a synthesized candidate, with the order of the two parameters reversed, for each non-rewritten candidate for the expression $y == x$ that is a rewrite target with first operand $y$.

— For all other operators, the rewritten candidate set is empty.

[Note 2: A candidate synthesized from a member candidate has its object parameter as the second parameter, thus implicit conversions are considered for the first, but not for the second, parameter. — end note]

A non-template function or function template $F$ named operator$==$ is a rewrite target with first operand $o$ unless a search for the name operator$!=$ in the scope $S$ from the instantiation context of the operator expression finds a function or function template that would correspond (6.4.1) to $F$ if its name were operator$==$,

where $S$ is the scope of the class type of $o$ if $F$ is a class member, and the namespace scope of which $F$ is a member otherwise. A function template specialization named operator$==$ is a rewrite target if its function template is a rewrite target.

[Example 2:]
```cpp
struct A {
    template<typename T> bool operator==(A, T); // #1
    bool a1 = 0 == A(); // OK, calls reversed #1
    template<typename T> bool operator!=(A, T); // #4
    inline namespace N {
        template<typename T> bool operator!=(D, T); // #5
    }
    bool a2 = 0 == A(); // error, #1 is not a rewrite target
};

struct B {
    bool operator==(const B&); // #2
};
struct C : B {
    C();
    C(B);
    bool operator!=(const B&); // #3
};
bool c1 = B() == C(); // OK, calls #2; reversed #2 is not a candidate
// because search for operator!= in C finds #3
bool c2 = C() == B(); // error: ambiguous between #2 found when searching C and
// reversed #2 found when searching B
```

For the first parameter of the built-in assignment operators, only standard conversion sequences (12.2.4.2.2) are considered.

For all other operators, no such restrictions apply.
The set of candidate functions for overload resolution for some operator `@` is the union of the member candidates, the non-member candidates, the built-in candidates, and the rewritten candidates for that operator `@`.

The argument list contains all of the operands of the operator. The best function from the set of candidate functions is selected according to 12.2.3 and 12.2.4.105

Example 3:

```c
struct A {
    operator int();
};
A operator+(const A &, const A &);
void m() {
    A a, b;
    a + b;    // operator+(a, b) chosen over int(a) + int(b)
}
@end example
```

If a rewritten `operator<=>` candidate is selected by overload resolution for an operator `@`, `x @ y` is interpreted as `0 @ (y <=> x)` if the selected candidate is a synthesized candidate with reversed order of parameters, or `(x <=> y) @ 0` otherwise, using the selected rewritten `operator<=>` candidate. Rewritten candidates for the operator `@` are not considered in the context of the resulting expression.

If a rewritten `operator==` candidate is selected by overload resolution for an operator `@`, its return type shall be `cv bool`, and `x @ y` is interpreted as:

1. If `@` is `!=` and the selected candidate is a synthesized candidate with reversed order of parameters, `!(y == x)`,
2. otherwise, if `@` is `!=`, `!(x == y)`,
3. otherwise (when `@` is `==`), `y == x`,

in each case using the selected rewritten `operator==` candidate.

If a built-in candidate is selected by overload resolution, the operands of class type are converted to the types of the corresponding parameters of the selected operation function, except that the second standard conversion sequence of a user-defined conversion sequence (12.2.4.2.3) is not applied. Then the operator is treated as the corresponding built-in operator and interpreted according to 7.6.

Example 4:

```c
struct X {
    operator double();
};
struct Y {
    operator int*();
};

int *a = Y() + 100.0;       // error: pointer arithmetic requires integral operand
int *b = Y() + X();        // error: pointer arithmetic requires integral operand
@end example
```

The second operand of operator `->` is ignored in selecting an `operator->` function, and is not an argument when the `operator->` function is called. When `operator->` returns, the operator `->` is applied to the value returned, with the original second operand.106

If the operator is the operator `.`, the unary operator `&`, or the operator `->`, and there are no viable functions, then the operator is assumed to be the built-in operator and interpreted according to 7.6.

Note 3: The lookup rules for operators in expressions are different than the lookup rules for operator function names in a function call, as shown in the following example:

```c
struct A {
};
void operator + (A, A);
```

105) If the set of candidate functions is empty, overload resolution is unsuccessful.
106) If the value returned by the `operator->` function has class type, this can result in selecting and calling another `operator->` function. The process repeats until an `operator->` function returns a value of non-class type.
struct B {
    void operator + (B);
    void f ();
};

A a;

void B::f() {
    operator+ (a,a); // error: global operator hidden by member
    a + a; // OK, calls global operator+
}
— end note]

12.2.2.4 Initialization by constructor [over.match.ctor]

When objects of class type are direct-initialized (9.4), copy-initialized from an expression of the same or a derived class type (9.4), or default-initialized (9.4), overload resolution selects the constructor. For direct-initialization or default-initialization (including default-initialization in the context of copy-list-initialization), the candidate functions are all the constructors of the class of the object being initialized. Otherwise, the candidate functions are all the converting constructors (11.4.8.2) of that class. The argument list is the expression-list or assignment-expression of the initializer. For default-initialization in the context of copy-list-initialization, if an explicit constructor is chosen, the initialization is ill-formed.

12.2.2.5 Copy-initialization of class by user-defined conversion [over.match.copy]

Under the conditions specified in 9.4, as part of a copy-initialization of an object of class type, a user-defined conversion can be invoked to convert an initializer expression to the type of the object being initialized. Overload resolution is used to select the user-defined conversion to be invoked.

[Note 1: The conversion performed for indirect binding to a reference to a possibly cv-qualified class type is determined in terms of a corresponding non-reference copy-initialization. — end note]

Assuming that “cv1 T” is the type of the object being initialized, with T a class type, the candidate functions are selected as follows:

(1.1) — The converting constructors (11.4.8.2) of T are candidate functions.

(1.2) — When the type of the initializer expression is a class type “cv S”, conversion functions are considered. The permissible types for non-explicit conversion functions are T and any class derived from T. When initializing a temporary object (11.4) to be bound to the first parameter of a constructor where the parameter is of type “reference to cv2 T” and the constructor is called with a single argument in the context of direct-initialization of an object of type “cv3 T”, the permissible types for explicit conversion functions are the same; otherwise there are none.

2 In both cases, the argument list has one argument, which is the initializer expression.

[Note 2: This argument will be compared against the first parameter of the constructors and against the object parameter of the conversion functions. — end note]

12.2.2.6 Initialization by conversion function [over.match.conv]

Under the conditions specified in 9.4, as part of an initialization of an object of non-class type, a conversion function can be invoked to convert an initializer expression of class type to the type of the object being initialized. Overload resolution is used to select the conversion function to be invoked. Assuming that “cv T” is the type of the object being initialized, the candidate functions are selected as follows:

(1.1) — The permissible types for non-explicit conversion functions are those that can be converted to type T via a standard conversion sequence (12.2.4.2.2). For direct-initialization, the permissible types for explicit conversion functions are those that can be converted to type T with a (possibly trivial) qualification conversion (7.3.6); otherwise there are none.

2 The argument list has one argument, which is the initializer expression.

[Note 1: This argument will be compared against the object parameter of the conversion functions. — end note]

12.2.2.7 Initialization by conversion function for direct reference binding [over.match.ref]

Under the conditions specified in 9.4.4, a reference can be bound directly to the result of applying a conversion function to an initializer expression. Overload resolution is used to select the conversion function to be
invoked. Assuming that “reference to cv1 T” is the type of the reference being initialized, the candidate functions are selected as follows:

(1.1) — Let $R$ be a set of types including

(1.1.1) — “lvalue reference to cv2 T2” (when initializing an lvalue reference or an rvalue reference to function) and

(1.1.2) — “cv2 T2” and “rvalue reference to cv2 T2” (when initializing an rvalue reference or an lvalue reference to function)

for any T2. The permissible types for non-explicit conversion functions are the members of $R$ where “cv1 T” is reference-compatible (9.4.4) with “cv2 T2”. For direct-initialization, the permissible types for explicit conversion functions are the members of $R$ where T2 can be converted to type T with a (possibly trivial) qualification conversion (7.3.6); otherwise there are none.

2 The argument list has one argument, which is the initializer expression.

[Note 1: This argument will be compared against the object parameter of the conversion functions. — end note]

### 12.2.2.8 Initialization by list-initialization

When objects of non-aggregate class type T are list-initialized such that 9.4.5 specifies that overload resolution is performed according to the rules in this subclause or when forming a list-initialization sequence according to 12.2.4.2.6, overload resolution selects the constructor in two phases:

(1.1) — If the initializer list is not empty or T has no default constructor, overload resolution is first performed where the candidate functions are the initializer-list constructors (9.4.5) of the class T and the argument list consists of the initializer list as a single argument.

(1.2) — Otherwise, or if no viable initializer-list constructor is found, overload resolution is performed again, where the candidate functions are all the constructors of the class T and the argument list consists of the elements of the initializer list.

In copy-list-initialization, if an explicit constructor is chosen, the initialization is ill-formed.

[Note 1: This differs from other situations (12.2.2.4, 12.2.2.5), where only converting constructors are considered for copy-initialization. This restriction only applies if this initialization is part of the final result of overload resolution. — end note]

### 12.2.2.9 Class template argument deduction

When resolving a placeholder for a deduced class type (9.2.9.8) where the template-name names a primary class template C, a set of functions and function templates, called the guides of C, is formed comprising:

(1.1) — If C is defined, for each constructor of C, a function template with the following properties:

(1.1.1) — The template parameters are the template parameters of C followed by the template parameters (including default template arguments) of the constructor, if any.

(1.1.2) — The associated constraints (13.5.3) are the conjunction of the associated constraints of C and the associated constraints of the constructor, if any.

[Note 1: A constraint-expression in the template-head of C is checked for satisfaction before any constraints from the template-head or trailing requires-clause of the constructor. — end note]

(1.1.3) — The parameter-declaration-clause is that of the constructor.

(1.1.4) — The return type is the class template specialization designated by C and template arguments corresponding to the template parameters of C.

(1.2) — If C is not defined or does not declare any constructors, an additional function template derived as above from a hypothetical constructor C().

(1.3) — An additional function template derived as above from a hypothetical constructor C(C), called the copy deduction candidate.

(1.4) — For each deduction-guide, a function or function template with the following properties:

(1.4.1) — The template-head, if any, and parameter-declaration-clause are those of the deduction-guide.

(1.4.2) — The return type is the simple-template-id of the deduction-guide.

In addition, if C is defined and its definition satisfies the conditions for an aggregate class (9.4.2) with the assumption that any dependent base class has no virtual functions and no virtual base classes, and the
initializer is a non-empty braced-init-list or parenthesized expression-list, and there are no deduction-guides for C, the set contains an additional function template, called the aggregate deduction candidate, defined as follows. Let \( x_1, \ldots, x_n \) be the elements of the initializer-list or designated-initializer-list of the braced-init-list, or of the expression-list. For each \( x_i \), let \( e_i \) be the corresponding aggregate element of C or of one of its (possibly recursive) subaggregates that would be initialized by \( x_i \) (9.4.2) if

(1.5) — brace elision is not considered for any aggregate element that has

(1.5.1) — a dependent non-array type,

(1.5.2) — an array type with a value-dependent bound, or

(1.5.3) — an array type with a dependent array element type and \( x_i \) is a string literal; and

(1.6) — each non-trailing aggregate element that is a pack expansion is assumed to correspond to no elements of the initializer list, and

(1.7) — a trailing aggregate element that is a pack expansion is assumed to correspond to all remaining elements of the initializer list (if any).

If there is no such aggregate element \( e_i \) for any \( x_i \), the aggregate deduction candidate is not added to the set. The aggregate deduction candidate is derived as above from a hypothetical constructor \( C(T_1, \ldots, T_n) \), where

(1.8) — if \( e_i \) is of array type and \( x_i \) is a braced-init-list, \( T_i \) is an rvalue reference to the declared type of \( e_i \), and

(1.9) — if \( e_i \) is of array type and \( x_i \) is a string-literal, \( T_i \) is an lvalue reference to the const-qualified declared type of \( e_i \), and

(1.10) — otherwise, \( T_i \) is the declared type of \( e_i \),

except that additional parameter packs of the form \( P_j \ldots \) are inserted into the parameter list in their original aggregate element position corresponding to each non-trailing aggregate element of type \( P_j \) that was skipped because it was a parameter pack, and the trailing sequence of parameters corresponding to a trailing aggregate element that is a pack expansion (if any) is replaced by a single parameter of the form \( T_n \ldots \). In addition, if \( C \) is defined and inherits constructors (9.9) from a direct base class denoted in the base-specifier-list by a class-or-decltype \( B \), let \( A \) be an alias template whose template parameter list is that of \( C \) and whose defining-type-id is \( B \). If \( A \) is a deducible template (9.2.9.3), the set contains the guides of \( A \) with the return type \( R \) of each guide replaced with \texttt{typename CC\lt R\gt::type} given a class template

\[
\text{template <typename> class CC;}
\]

whose primary template is not defined and with a single partial specialization whose template parameter list is that of \( A \) and whose template argument list is a specialization of \( A \) with the template argument list of \( A \) (13.8.3.2) having a member typedef \texttt{type} designating a template specialization with the template argument list of \( A \) but with \( C \) as the template.

\[\text{[Note 2: Equivalently, the template parameter list of the specialization is that of } C, \text{ the template argument list of the specialization is } B, \text{ and the member typedef names } C \text{ with the template argument list of } C. \text{ — end note]}\]

2 \[\text{[Example 1:}\]

\[
\text{template <typename T> struct B {}
    B(T);
};
\]

\[
\text{template <typename T> struct C : public B\lt T\gt {}
    using B\lt T\gt::B;
};
\]

\[
\text{template <typename T> struct D : public B\lt T\gt {}}
\]

\[
\text{C c(42); // OK, deduces } \text{C\lt int\gt}
\]

\[
\text{D d(42); // error: deduction failed, no inherited deduction guides}
\]

\[
\text{B\lt int\gt -> B\lt char\gt;}
\]

\[
\text{C c2(42); // OK, deduces } \text{C\lt char\gt}
\]

\[
\text{template <typename T> struct E : public B\lt int\gt {}
    using B\lt int\gt::B;
};
\]

\[
\text{E e(42); // error: deduction failed, arguments of } E \text{ cannot be deduced from introduced guides}
\]
template <typename T, typename U, typename V> struct F {
    F(T, U, V);
};
template <typename T, typename U> struct G : F<U, T, int> {
    using G::F::F;
}
G g(true, 'a', 1);  // OK, deduces G<char, bool>

template<class T, std::size_t N>
struct H {
    T array[N];
};
template<class T, std::size_t N>
struct I {
    volatile T array[N];
};
template<std::size_t N>
struct J {
    unsigned char array[N];
};
H h = { "abc" };  // OK, deduces H<char, 4> /not T = const char
I i = { "def" };  // OK, deduces I<char, 4>
J j = { "ghi" };  // error: cannot bind reference to array of unsigned char to array of char in deduction

end example

3 When resolving a placeholder for a deduced class type (9.2.9.3) where the template-name names an alias template A, the defining-type-id of A must be of the form

```
typename_opt nested-name-specifier_opt template_opt simple-template-id
```
as specified in 9.2.9.3. The guides of A are the set of functions or function templates formed as follows. For each function or function template f in the guides of the template named by the simple-template-id of the defining-type-id, the template arguments of the return type of f are deduced from the defining-type-id of A according to the process in 13.10.3.6 with the exception that deduction does not fail if not all template arguments are deduced. If deduction fails for another reason, proceed with an empty set of deduced template arguments. Let g denote the result of substituting these deductions into f. If substitution succeeds, form a function or function template f' with the following properties and add it to the set of guides of A:

(3.1) — The function type of f' is the function type of g.
(3.2) — If f is a function template, f' is a function template whose template parameter list consists of all the template parameters of A (including their default template arguments) that appear in the above deductions or (recursively) in their default template arguments, followed by the template parameters of f that were not deduced (including their default template arguments), otherwise f' is not a function template.
(3.3) — The associated constraints (13.5.3) are the conjunction of the associated constraints of g and a constraint that is satisfied if and only if the arguments of A are deducible (see below) from the return type.
(3.4) — If f is a copy deduction candidate, then f' is considered to be so as well.
(3.5) — If f was generated from a deduction-guide (13.7.2.3), then f' is considered to be so as well.
(3.6) — The explicit-specifier of f' is the explicit-specifier of g (if any).

4 The arguments of a template A are said to be deducible from a type T if, given a class template

```
template <typename> class AA;
```
with a single partial specialization whose template parameter list is that of A and whose template argument list is a specialization of A with the template argument list of A (13.8.3.2), AA<T> matches the partial specialization.

5 Initialization and overload resolution are performed as described in 9.4 and 12.2.2.4, 12.2.2.5, or 12.2.2.8 (as appropriate for the type of initialization performed) for an object of a hypothetical class type, where the guides of the template named by the placeholder are considered to be the constructors of that class type for
the purpose of forming an overload set, and the initializer is provided by the context in which class template argument deduction was performed. The following exceptions apply:

(5.1) The first phase in 12.2.2.8 (considering initializer-list constructors) is omitted if the initializer list consists of a single expression of type \( cv \) \( U \), where \( U \) is, or is derived from, a specialization of the class template directly or indirectly named by the placeholder.

(5.2) During template argument deduction for the aggregate deduction candidate, the number of elements in a trailing parameter pack is only deduced from the number of remaining function arguments if it is not otherwise deduced.

If the function or function template was generated from a constructor or deduction-guide that had an explicit-specifier, each such notional constructor is considered to have that same explicit-specifier. All such notional constructors are considered to be public members of the hypothetical class type.

6 [Example 2:

```cpp
template <class T> struct A {
    explicit A(const T&, ...) noexcept; // #1
    A(T&&, ...); // #2
};

int i;
A a1 = { i, i }; // error: explicit constructor #1 selected in copy-list-initialization during deduction,
// cannot deduce from non-forwarding rvalue reference in #2

A a2{i, i}; // OK, #1 deduces to A<int> and also initializes
A a3{0, i}; // OK, #2 deduces to A<int> and also initializes
A a4 = {0, i}; // OK, #2 deduces to A<int> and also initializes

template <class T> A(const T&, const T&) -> A<T&>; // #3

template <class T> explicit A(T&&, T&&) -> A<T>; // #4

A a5 = {0, 1}; // error: explicit deduction guide #4 selected in copy-list-initialization during deduction
A a6(0,1); // OK, #4 deduces to A<int> and #2 initializes
A a7 = {0, i}; // error: #3 deduces to A<int&>, #1 and #2 declare same constructor
A a8(0,i); // error: #3 deduces to A<int&>, #1 and #2 declare same constructor

template <class T> struct B {
    template <class U> using TA = T;
    template <class U> B(U, TA<U>);
};

B b{(int*)0, (char*)0}; // OK, deduces B<char>

template <typename T>
struct S {
    T x;
    T y;
};

template <typename T>
struct C {
    S<T> s;
    T t;
};

template <typename T>
struct D {
    S<int> s;
    T t;
};

C c1 = {1, 2}; // error: deduction failed
C c2 = {1, 2, 3}; // error: deduction failed
C c3 = {{1u, 2u}, 3}; // OK, deduces C<int>
```
D d1 = {1, 2};          // error: deduction failed
D d2 = {1, 2, 3};       // OK, braces elided, deduces D<int>

template <typename T>
struct E {
    T t;
    decltype(t) t2;
};

E e1 = {1, 2};          // OK, deduces E<int>

// Example 3:

// The following concept ensures a specialization of A is deduced.
template <class> class AA;
template <class V> class AA<A<V>> { };

template <class T> concept deduces_A = requires { sizeof(AA<T>); };

// f1 is formed from the constructor #1 of C, generating the following function template
template<class T, class U> auto f1(T, U) -> C<T, U>;

// Deducing arguments for C<T, U> from C<V *, V *> deduces T as V * and U as V *;
// f1' is obtained by transforming f1 as described by the above procedure.
template<class V> requires deduces_A C<V *, V *>
    auto f1_prime(V *, V *) -> C<V *, V *>;

// f2 is formed from the deduction-guide #2 of C
template<class T, class U> auto f2(T, U) -> C<T, std::type_identity_t<U>>;
Deducing arguments for `C<T, std::type_identity_t<U>>` from `C<V *, V*>` deduces `T` as `V *`;

```cpp
// f2' is obtained by transforming f2 as described by the above procedure.
template<class V, class U>
  requires deduces_A<C<V *, std::type_identity_t<U>>>
  auto f2_prime(V *, U) -> C<V *, std::type_identity_t<U>>;
```

The following concept ensures a specialization of `B` is deduced.
```cpp
template <class> class BB;
template <class V> class BB<V> { };
template <class T> concept deduces_B = requires { sizeof(BB<T>); };
```

The guides for `B` derived from the above `f1'` and `f2'` for `A` are as follows:
```cpp
template<std::integral W>
  requires deduces_A<C<W *, W *>> && deduces_B<C<W *, W *>>
  auto f1_prime_for_B(W *, W *) -> C<W *, W *>; 
```

```cpp
template<std::integral W, class U>
  requires deduces_A<C<W *, std::type_identity_t<U>>> &&
  deduces_B<C<W *, std::type_identity_t<U>>> 
  auto f2_prime_for_B(W *, U) -> C<W *, std::type_identity_t<U>>;
```

---

12.2.3 Viable functions

From the set of candidate functions constructed for a given context (12.2.2), a set of viable functions is chosen, from which the best function will be selected by comparing argument conversion sequences and associated constraints (13.5.3) for the best fit (12.2.4). The selection of viable functions considers associated constraints, if any, and relationships between arguments and function parameters other than the ranking of conversion sequences.

First, to be a viable function, a candidate function shall have enough parameters to agree in number with the arguments in the list.

1. If there are `m` arguments in the list, all candidate functions having exactly `m` parameters are viable.
2. A candidate function having fewer than `m` parameters is viable only if it has an ellipsis in its parameter list (9.3.4.6). For the purposes of overload resolution, any argument for which there is no corresponding parameter is considered to “match the ellipsis” (12.2.4.2.4).
3. A candidate function having more than `m` parameters is viable only if all parameters following the `m`th have default arguments (9.3.4.7). For the purposes of overload resolution, the parameter list is truncated on the right, so that there are exactly `m` parameters.

Second, for a function to be viable, if it has associated constraints (13.5.3), those constraints shall be satisfied (13.5.2).

Third, for `F` to be a viable function, there shall exist for each argument an implicit conversion sequence (12.2.4.2) that converts that argument to the corresponding parameter of `F`. If the parameter has reference type, the implicit conversion sequence includes the operation of binding the reference, and the fact that an lvalue reference to non-`const` cannot bind to an rvalue and that an rvalue reference cannot bind to an lvalue can affect the viability of the function (see 12.2.4.2.5).

12.2.4 Best viable function

Define `ICS_i(F)` as the implicit conversion sequence that converts the `i`th argument in the list to the type of the `i`th parameter of viable function `F`. 12.2.4.2 defines the implicit conversion sequences and 12.2.4.3 defines what it means for one implicit conversion sequence to be a better conversion sequence or worse conversion sequence than another.

Given these definitions, a viable function `F_1` is defined to be a better function than another viable function `F_2` if for all arguments `i`, `ICS_i(F_1)` is not a worse conversion sequence than `ICS_i(F_2)`, and then

1. for some argument `j`, `ICS_j(F_1)` is a better conversion sequence than `ICS_j(F_2)`, or, if not that,
2. the context is an initialization by user-defined conversion (see 9.4, 12.2.2.6, and 12.2.2.7) and the standard conversion sequence from the result of `F_1` to the destination type (i.e., the type of the entity

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being initialized) is a better conversion sequence than the standard conversion sequence from the result of \( F_2 \) to the destination type

**Example 1:**

```c
struct A {
    A();
    operator int();
    operator double();
} a;
int i = a;  // a.operator int() followed by no conversion is better than
            // a.operator double() followed by a conversion to int
float x = a; // ambiguous: both possibilities require conversions,
              // and neither is better than the other
```

— end example

or, if not that,

(2.3) — the context is an initialization by conversion function for direct reference binding (12.2.2.7) of a reference to function type, the return type of \( F_1 \) is the same kind of reference (lvalue or rvalue) as the reference being initialized, and the return type of \( F_2 \) is not

**Example 2:**

```c
template <class T> struct A {
    operator T&();  // #1
    operator T&&(); // #2
};
typedef int Fn();
A<Fn> a;
Fn& lf = a;  // calls #1
Fn&& rf = a; // calls #2
```

— end example

or, if not that,

(2.4) — \( F_1 \) is not a function template specialization and \( F_2 \) is a function template specialization, or, if not that,

(2.5) — \( F_1 \) and \( F_2 \) are function template specializations, and the function template for \( F_1 \) is more specialized than the template for \( F_2 \) according to the partial ordering rules described in 13.7.7.3, or, if not that,

(2.6) — \( F_1 \) and \( F_2 \) are non-template functions and

(2.6.1) — they have the same non-object-parameter-type-lists (9.3.4.6), and

(2.6.2) — if they are member functions, both are direct members of the same class, and

(2.6.3) — if both are non-static member functions, they have the same types for their object parameters, and

(2.6.4) — \( F_1 \) is more constrained than \( F_2 \) according to the partial ordering of constraints described in 13.5.5, or if not that,

**Example 3:**

```c
template <typename T = int>
struct S {
    constexpr void f();  // #1
    constexpr void f(this S&) requires true; // #2
};

void test() {
    S<> s;
    s.f();  // calls #2
}
```

— end example

(2.7) — \( F_1 \) is a constructor for a class \( D \), \( F_2 \) is a constructor for a base class \( B \) of \( D \), and for all arguments the corresponding parameters of \( F_1 \) and \( F_2 \) have the same type

**Example 4:**
struct A {
    A(int = 0);
};

struct B: A {
    using A::A;
    B();
};

int main() {
    B b;    // OK, B::B()
} — end example]
or, if not that,

(2.8) — F2 is a rewritten candidate (12.2.2.3) and F1 is not

[Example 5:
struct S {
    friend auto operator<=>(const S&, const S&) = default;    // #1
    friend bool operator<(const S&, const S&);    // #2
};
bool b = S() < S();    // calls #2
— end example]
or, if not that,

(2.9) — F1 and F2 are rewritten candidates, and F2 is a synthesized candidate with reversed order of parameters and F1 is not

[Example 6:
struct S {
    friend std::weak_ordering operator<=>(const S&, int);    // #1
    friend std::weak_ordering operator<=>(int, const S&);    // #2
};
bool b = 1 < S();    // calls #2
— end example]
or, if not that,

(2.10) — F1 and F2 are generated from class template argument deduction (12.2.2.9) for a class D, and F2 is generated from inheriting constructors from a base class of D while F1 is not, and for each explicit function argument, the corresponding parameters of F1 and F2 are either both ellipses or have the same type, or, if not that,

(2.11) — F1 is generated from a deduction-guide (12.2.2.9) and F2 is not, or, if not that,

(2.12) — F1 is the copy deduction candidate (12.2.2.9) and F2 is not, or, if not that,

(2.13) — F1 is generated from a non-template constructor and F2 is generated from a constructor template.

[Example 7:
template <class T> struct A {
    using value_type = T;
    A(value_type);
    // #1
    A(const A&);    // #2
    A(T, T, int);    // #3
    template<class U>
    A(T, T, U);    // #4
    // #5 is the copy deduction candidate, A(A)
};
A x(1, 2, 3);    // uses #3, generated from a non-template constructor

template <class T>
A(T) -> A<T>;    // #6, less specialized than #5

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A a(42);  // uses #6 to deduce A<int> and #1 to initialize
A b = a;  // uses #5 to deduce A<int> and #2 to initialize

template <class T>
A(A<T>) -> A<A<T>>;  // #7, as specialized as #5

A b2 = a;  // uses #7 to deduce A<A<int>> and #1 to initialize

—end example]  

3 If there is exactly one viable function that is a better function than all other viable functions, then it is the one selected by overload resolution; otherwise the call is ill-formed.107

[Example 8:

void Fcn(const int*, short);
void Fcn(int*, int);

int i;
short s = 0;

void f() {
    Fcn(&i, s);  // is ambiguous because &i → int* is better than &i → const int*
    // but s → short is also better than s → int
    Fcn(&i, 1L);  // calls Fcn(int*, int), because &i → int* is better than &i → const int*
    // and 1L → short and 1L → int are indistinguishable
    Fcn(&i, 'c');  // calls Fcn(int*, int), because &i → int* is better than &i → const int*
    // and 'c' → int is better than 'c' → short
}

—end example]

4 If the best viable function resolves to a function for which multiple declarations were found, and if any two of these declarations inhabit different scopes and specify a default argument that made the function viable, the program is ill-formed.

[Example 9:

namespace A {
    extern "C" void f(int = 5);
}
namespace B {
    extern "C" void f(int = 5);
}

using A::f;
using B::f;

void use() {
    f(3);  // OK, default argument was not used for viability
    f();  // error: found default argument twice
}

—end example]

12.2.4.2 Implicit conversion sequences

12.2.4.2.1 General

An implicit conversion sequence is a sequence of conversions used to convert an argument in a function call to the type of the corresponding parameter of the function being called. The sequence of conversions is an implicit conversion as defined in 7.3, which means it is governed by the rules for initialization of an object or reference by a single expression (9.4, 9.4.4).

107) The algorithm for selecting the best viable function is linear in the number of viable functions. Run a simple tournament to find a function \( W \) that is not worse than any opponent it faced. Although it is possible that another function \( F \) that \( W \) did not face is at least as good as \( W \), \( F \) cannot be the best function because at some point in the tournament \( F \) encountered another function \( G \) such that \( F \) was not better than \( G \). Hence, either \( W \) is the best function or there is no best function. So, make a second pass over the viable functions to verify that \( W \) is better than all other functions.
Implicit conversion sequences are concerned only with the type, cv-qualification, and value category of the argument and how these are converted to match the corresponding properties of the parameter.

[Note 1: Other properties, such as the lifetime, storage duration, linkage, alignment, accessibility of the argument, whether the argument is a bit-field, and whether a function is deleted (9.5.3), are ignored. So, although an implicit conversion sequence can be defined for a given argument-parameter pair, the conversion from the argument to the parameter might still be ill-formed in the final analysis. — end note]

A well-formed implicit conversion sequence is one of the following forms:

1. a standard conversion sequence (12.2.4.2.2),
2. a user-defined conversion sequence (12.2.4.2.3), or
3. an ellipsis conversion sequence (12.2.4.2.4).

However, if the target is

1. the first parameter of a constructor or
2. the object parameter of a user-defined conversion function

and the constructor or user-defined conversion function is a candidate by

1. 12.2.2.4, when the argument is the temporary in the second step of a class copy-initialization,
2. 12.2.2.5, 12.2.2.6, or 12.2.2.7 (in all cases), or
3. the second phase of 12.2.2.8 when the initializer list has exactly one element that is itself an initializer list, and the target is the first parameter of a constructor of class X, and the conversion is to X or reference to cv X,

user-defined conversion sequences are not considered.

[Note 2: These rules prevent more than one user-defined conversion from being applied during overload resolution, thereby avoiding infinite recursion. — end note]

Example 1:

```cpp
struct Y { Y(int); };  
struct A { operator int(); };  
Y y1 = A();  // error: A::operator int() is not a candidate

struct X { X(); };  
struct B { operator X(); };  
B b;  
X x{b};  // error: B::operator X() is not a candidate
```

—end example

For the case where the parameter type is a reference, see 12.2.4.2.5.

When the parameter type is not a reference, the implicit conversion sequence models a copy-initialization of the parameter from the argument expression. The implicit conversion sequence is the one required to convert the argument expression to a prvalue of the type of the parameter.

[Note 3: When the parameter has a class type, this is a conceptual conversion defined for the purposes of Clause 12; the actual initialization is defined in terms of constructors and is not a conversion. — end note]

Any difference in top-level cv-qualification is subsumed by the initialization itself and does not constitute a conversion.

Example 2: A parameter of type A can be initialized from an argument of type const A. The implicit conversion sequence for that case is the identity sequence; it contains no “conversion” from const A to A. — end example]

When the parameter has a class type and the argument expression has the same type, the implicit conversion sequence is an identity conversion. When the parameter has a class type and the argument expression has a derived class type, the implicit conversion sequence is a derived-to-base conversion from the derived class to the base class. A derived-to-base conversion has Conversion rank (12.2.4.2.2).

[Note 4: There is no such standard conversion; this derived-to-base conversion exists only in the description of implicit conversion sequences. — end note]

When the parameter is the implicit object parameter of a static member function, the implicit conversion sequence is a standard conversion sequence that is neither better nor worse than any other standard conversion sequence.

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In all contexts, when converting to the implicit object parameter or when converting to the left operand of an assignment operation only standard conversion sequences are allowed.

[Note 5: When a conversion to the explicit object parameter occurs, it can include user-defined conversion sequences. —end note]

If no conversions are required to match an argument to a parameter type, the implicit conversion sequence is the standard conversion sequence consisting of the identity conversion (12.2.4.2.2).

If no sequence of conversions can be found to convert an argument to a parameter type, an implicit conversion sequence cannot be formed.

If there are multiple well-formed implicit conversion sequences converting the argument to the parameter type, the implicit conversion sequence associated with the parameter is defined to be the unique conversion sequence designated the ambiguous conversion sequence. For the purpose of ranking implicit conversion sequences as described in 12.2.4.3, the ambiguous conversion sequence is treated as a user-defined conversion sequence that is indistinguishable from any other user-defined conversion sequence.

[Note 6: This rule prevents a function from becoming non-viable because of an ambiguous conversion sequence for one of its parameters.]

If a function that uses the ambiguous conversion sequence is selected as the best viable function, the call will be ill-formed because the conversion of one of the arguments in the call is ambiguous.

The three forms of implicit conversion sequences mentioned above are defined in the following subclauses.

12.2.4.2.2 Standard conversion sequences

Table 19 summarizes the conversions defined in 7.3 and partitions them into four disjoint categories: Lvalue Transformation, Qualification Adjustment, Promotion, and Conversion.

[Note 1: These categories are orthogonal with respect to value category, cv-qualification, and data representation: the Lvalue Transformations do not change the cv-qualification or data representation of the type; the Qualification Adjustments do not change the value category or data representation of the type; and the Promotions and Conversions do not change the value category or cv-qualification of the type. —end note]

[Note 2: As described in 7.3, a standard conversion sequence either is the Identity conversion by itself (that is, no conversion) or consists of one to three conversions from the other four categories. If there are two or more conversions in the sequence, the conversions are applied in the canonical order: Lvalue Transformation, Promotion or Conversion, Qualification Adjustment. —end note]

Each conversion in Table 19 also has an associated rank (Exact Match, Promotion, or Conversion). These are used to rank standard conversion sequences (12.2.4.3). The rank of a conversion sequence is determined by considering the rank of each conversion in the sequence and the rank of any reference binding (12.2.4.2.5). If any of those has Conversion rank, the sequence has Conversion rank; otherwise, if any of those has Promotion rank, the sequence has Promotion rank; otherwise, the sequence has Exact Match rank.

12.2.4.2.3 User-defined conversion sequences

A user-defined conversion sequence consists of an initial standard conversion sequence followed by a user-defined conversion (11.4.8) followed by a second standard conversion sequence. If the user-defined conversion is specified by a constructor (11.4.8.2), the initial standard conversion sequence converts the source type to the type of the first parameter of that constructor. If the user-defined conversion is specified by a conversion
Table 19 — Conversions

<table>
<thead>
<tr>
<th>Conversion</th>
<th>Category</th>
<th>Rank</th>
<th>Subclause</th>
</tr>
</thead>
<tbody>
<tr>
<td>No conversions required</td>
<td>Identity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lvalue-to-rvalue conversion</td>
<td>Lvalue Transformation</td>
<td>Exact Match</td>
<td>7.3.2</td>
</tr>
<tr>
<td>Array-to-pointer conversion</td>
<td>Lvalue Transformation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function-to-pointer conversion</td>
<td>Exact Match</td>
<td></td>
<td>7.3.4</td>
</tr>
<tr>
<td>Qualification conversions</td>
<td>Qualification Adjustment</td>
<td></td>
<td>7.3.6</td>
</tr>
<tr>
<td>Function pointer conversion</td>
<td>Qualification Adjustment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integral promotions</td>
<td>Promotion</td>
<td>Promotion</td>
<td>7.3.7</td>
</tr>
<tr>
<td>Floating-point promotion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integral conversions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floating-point conversions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floating-integral conversions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pointer conversions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pointer-to-member conversions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boolean conversions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

function (11.4.8.3), the initial standard conversion sequence converts the source type to the type of the object parameter of that conversion function.

2 The second standard conversion sequence converts the result of the user-defined conversion to the target type for the sequence; any reference binding is included in the second standard conversion sequence. Since an implicit conversion sequence is an initialization, the special rules for initialization by user-defined conversion apply when selecting the best user-defined conversion for a user-defined conversion sequence (see 12.2.4 and 12.2.4.2).

3 If the user-defined conversion is specified by a specialization of a conversion function template, the second standard conversion sequence shall have exact match rank.

4 A conversion of an expression of class type to the same class type is given Exact Match rank, and a conversion of an expression of class type to a base class of that type is given Conversion rank, in spite of the fact that a constructor (i.e., a user-defined conversion function) is called for those cases.

12.2.4.2.4 Ellipsis conversion sequences

An ellipsis conversion sequence occurs when an argument in a function call is matched with the ellipsis parameter specification of the function called (see 7.6.1.3).

12.2.4.2.5 Reference binding

When a parameter of type “reference to cvT” binds directly (9.4.4) to an argument expression:

(1.1) — If the argument expression has a type that is a derived class of the parameter type, the implicit conversion sequence is a derived-to-base conversion (12.2.4.2).

(1.2) — Otherwise, if T is a function type, or if the type of the argument is possibly cv-qualified T, or if T is an array type of unknown bound with element type U and the argument has an array type of known bound whose element type is possibly cv-qualified U, the implicit conversion sequence is the identity conversion.

[Note 1: When T is a function type, the type of the argument can differ only by the presence of noexcept.]

(1.3) — Otherwise, the implicit conversion sequence is a qualification conversion.

[Example 1:

```c
struct A {}
struct B : public A {} b;
int f(A&);
int f(B&);
int i = f(b); // calls f(B&), an exact match, rather than f(A&), a conversion
```

— end example]
If the parameter binds directly to the result of applying a conversion function to the argument expression, the implicit conversion sequence is a user-defined conversion sequence (12.2.4.2.3) whose second standard conversion sequence is determined by the above rules.

When a parameter of reference type is not bound directly to an argument expression, the conversion sequence is the one required to convert the argument expression to the referenced type according to 12.2.4.2. Conceptually, this conversion sequence corresponds to copy-initializing a temporary of the referenced type with the argument expression. Any difference in top-level cv-qualification is subsumed by the initialization itself and does not constitute a conversion.

Except for an implicit object parameter, for which see 12.2.2, an implicit conversion sequence cannot be formed if it requires binding an lvalue reference other than a reference to a non-volatile const type to an rvalue or binding an rvalue reference to an lvalue of object type.

[Note 2: This means, for example, that a candidate function cannot be a viable function if it has a non-const lvalue reference parameter (other than the implicit object parameter) and the corresponding argument would require a temporary to be created to initialize the lvalue reference (see 9.4.4). — end note]

Other restrictions on binding a reference to a particular argument that are not based on the types of the reference and the argument do not affect the formation of an implicit conversion sequence, however.

[Example 2: A function with an “lvalue reference to int” parameter can be a viable candidate even if the corresponding argument is an int bit-field. The formation of implicit conversion sequences treats the int bit-field as an int lvalue and finds an exact match with the parameter. If the function is selected by overload resolution, the call will nonetheless be ill-formed because of the prohibition on binding a non-const lvalue reference to a bit-field (9.4.4). — end example]

12.2.4.2.6 List-initialization sequence

When an argument is an initializer list (9.4.5), it is not an expression and special rules apply for converting it to a parameter type.

If the initializer list is a designated-initializer-list and the parameter is not a reference, a conversion is only possible if the parameter has an aggregate type that can be initialized from the initializer list according to the rules for aggregate initialization (9.4.2), in which case the implicit conversion sequence is a user-defined conversion sequence whose second standard conversion sequence is an identity conversion.

[Note 1: Aggregate initialization does not require that the members are declared in designation order. If, after overload resolution, the order does not match for the selected overload, the initialization of the parameter will be ill-formed (9.4.5).]

[Example 1:

```c
struct A { int x, y; };
struct B { int y, x; };
void f(A a, int);    // #1
void f(B b, ...);   // #2
void g(A a);        // #3
void g(B b);        // #4
void h() {
    f({.x = 1, .y = 2}, 0);    // OK; calls #1
    f({.y = 2, .x = 1}, 0);    // error: selects #1, initialization of a fails
                            // due to non-matching member order (9.4.5)
    g({.x = 1, .y = 2});       // error: ambiguous between #3 and #4
}
```

— end example]

— end note]

Otherwise, if the parameter type is an aggregate class X and the initializer list has a single element of type cv U, where U is X or a class derived from X, the implicit conversion sequence is the one required to convert the element to the parameter type.

Otherwise, if the parameter type is a character array and the initializer list has a single element that is an appropriately-typed string-literal (9.4.3), the implicit conversion sequence is the identity conversion.

Otherwise, if the parameter type is std::initializer_list<X> and all the elements of the initializer list can be implicitly converted to X, the implicit conversion sequence is the worst conversion necessary to convert

---

108) Since there are no parameters of array type, this will only occur as the referenced type of a reference parameter.
an element of the list to \( X \), or if the initializer list has no elements, the identity conversion. This conversion can be a user-defined conversion even in the context of a call to an initializer-list constructor.

[Example 2:

```cpp
void f(const std::initializer_list<int>&);  
f({});  // OK, f(const initializer_list<int>&) identity conversion  
f({1, 2, 3});  // OK, f(const initializer_list<int>&) identity conversion  
f({'a', 'b'});  // OK, f(const initializer_list<int>&) integral promotion  
f({1.0});  // error: narrowing
```

struct A {
    A(const std::initializer_list<double>&);  // #1  
    A(const std::initializer_list<std::complex<double>>&);  // #2  
    A(const std::initializer_list<std::string>&);  // #3
};
A a{1.0, 2.0};  // OK, uses #1

void g(A);
g({'foo', "bar"});  // OK, uses #3

typedef int IA[3];
void h(const IA&);
h({1, 2, 3});  // OK, identity conversion
— end example]

6 Otherwise, if the parameter type is “array of \( N \) \( X \)” or “array of unknown bound of \( X \)”, if there exists an implicit conversion sequence from each element of the initializer list (and from {} in the former case if \( N \) exceeds the number of elements in the initializer list) to \( X \), the implicit conversion sequence is the worst such implicit conversion sequence.

7 Otherwise, if the parameter is a non-aggregate class \( X \) and overload resolution per 12.2.2.8 chooses a single best constructor \( C \) of \( X \) to perform the initialization of an object of type \( X \) from the argument initializer list:

(7.1) — If \( C \) is not an initializer-list constructor and the initializer list has a single element of type \( cv U \), where \( U \) is \( X \) or a class derived from \( X \), the implicit conversion sequence has Exact Match rank if \( U \) is \( X \), or Conversion rank if \( U \) is derived from \( X \).

(7.2) — Otherwise, the implicit conversion sequence is a user-defined conversion sequence whose second standard conversion sequence is an identity conversion.

If multiple constructors are viable but none is better than the others, the implicit conversion sequence is the ambiguous conversion sequence. User-defined conversions are allowed for conversion of the initializer list elements to the constructor parameter types except as noted in 12.2.4.2.

[Example 3:

```cpp
struct A {
    A(const std::initializer_list<int>&);
};
void f(A);
f({'a', 'b'});  // OK, f(A(const initializer_list<int>&)) user-defined conversion

struct B {
    B(int, double);
};
void g(B);
g({'a', 'b'});  // OK, g(B(int, double)) user-defined conversion  
g({1.0, 1.0});  // error: narrowing

void f(B);
f({'a', 'b'});  // error: ambiguous f(A) or f(B)

struct C {
    C(const std::string&);
};
void h(C);
```
h({"foo"}); // OK, h(C::string("foo")))

struct D {
    D(A, C);
};
void i(D);
i({ {1,2}, {"bar"} }); // OK, i(D(A::initializer_list<int>{1,2}), C::string("bar")))
— end example

8 Otherwise, if the parameter has an aggregate type which can be initialized from the initializer list according to the rules for aggregate initialization (9.4.2), the implicit conversion sequence is a user-defined conversion sequence whose second standard conversion sequence is an identity conversion.

[Example 4:
    struct A {
        int m1;
        double m2;
    };
    void f(A);
f( { 'a', 'b' } ); // OK, f(A(int,double)) user-defined conversion
f( {1.0} ); // error: narrowing
— end example]

9 Otherwise, if the parameter is a reference, see 12.2.4.2.5.

[Note 2: The rules in this subclause will apply for initializing the underlying temporary for the reference. — end note]

[Example 5:
    struct A {
        int m1;
        double m2;
    };
    void f(const A&);
f( { 'a', 'b' } ); // OK, f(A(int,double)) user-defined conversion
f( {1.0} ); // error: narrowing
void g(const double &);
g({1}); // same conversion as int to double
— end example]

10 Otherwise, if the parameter type is not a class:

    — if the initializer list has one element that is not itself an initializer list, the implicit conversion sequence is the one required to convert the element to the parameter type;

    [Example 6:
        void f(int);
f( {'a'} ); // OK, same conversion as char to int
f( {1.0} ); // error: narrowing
— end example]

    — if the initializer list has no elements, the implicit conversion sequence is the identity conversion.

    [Example 7:
        void f(int);
f( {} ); // OK, identity conversion
— end example]

11 In all cases other than those enumerated above, no conversion is possible.

12.2.4.3 Ranking implicit conversion sequences [over.ics.rank]

This subclause defines a partial ordering of implicit conversion sequences based on the relationships better conversion sequence and better conversion. If an implicit conversion sequence S1 is defined by these rules to be a better conversion sequence than S2, then it is also the case that S2 is a worse conversion sequence than
S1. If conversion sequence S1 is neither better than nor worse than conversion sequence S2, S1 and S2 are said to be indistinguishable conversion sequences.

2 When comparing the basic forms of implicit conversion sequences (as defined in 12.2.4.2)

(2.1) — a standard conversion sequence (12.2.4.2.2) is a better conversion sequence than a user-defined conversion sequence or an ellipsis conversion sequence, and

(2.2) — a user-defined conversion sequence (12.2.4.2.3) is a better conversion sequence than an ellipsis conversion sequence (12.2.4.2.4).

3 Two implicit conversion sequences of the same form are indistinguishable conversion sequences unless one of the following rules applies:

(3.1) — List-initialization sequence L1 is a better conversion sequence than list-initialization sequence L2 if

(3.1.1) — L1 converts to `std::initializer_list<X>` for some X and L2 does not, or, if not that,

(3.1.2) — L1 and L2 convert to arrays of the same element type, and either the number of elements n1 initialized by L1 is less than the number of elements n2 initialized by L2, or n1 = n2 and L2 converts to an array of unknown bound and L1 does not,

even if one of the other rules in this paragraph would otherwise apply.

[Example 1:

void f1(int);
void f1(std::initializer_list<long>); // #1
void g1() { f1({42}); } // #2
void f2(std::initializer_list<long>*); // #3
void f2(std::initializer_list<std::string>); // #4
void g2() { f2({"foo","bar"}); } // #4
— end example]

[Example 2:

void f(int (&&)[3]); // #1
void f(double (&&)[3]); // #2
void f(int (&&)[2]); // #3

f( {1} ); // Calls #1: Better than #2 due to conversion, better than #3 due to bounds
f( {1.0} ); // Calls #2: Identity conversion is better than floating-integral conversion
f( {1.0, 2.0} ); // Calls #2: Identity conversion is better than floating-integral conversion
f( {1, 2} ); // Calls #3: Converting to array of known bound is better than to unknown bound,
// and an identity conversion is better than floating-integral conversion
— end example]

(3.2) — Standard conversion sequence S1 is a better conversion sequence than standard conversion sequence S2 if

(3.2.1) — S1 is a proper subsequence of S2 (comparing the conversion sequences in the canonical form defined by 12.2.4.2.2, excluding any Lvalue Transformation; the identity conversion sequence is considered to be a subsequence of any non-identity conversion sequence) or, if not that,

(3.2.2) — the rank of S1 is better than the rank of S2, or S1 and S2 have the same rank and are distinguishable by the rules in the paragraph below, or, if not that,

(3.2.3) — S1 and S2 include reference bindings (9.4.4) and neither refers to an implicit object parameter of a non-static member function declared without a ref-qualifier, and S1 binds an rvalue reference to an rvalue and S2 binds an lvalue reference

[Example 3:

int i;
int f1();
int&& f2();
int g(const int&);
int g(const int&&);
int j = g(i); // calls g(const int)
int k = g(f1()); // calls g(const int&&)
int l = g(f2()); // calls g(const int&&)
struct A {
    A& operator<<(int);
    void p() &;
    void p() &&;
};
A& operator<<(A&&, char);
A() << 1;       // calls A::operator<<(int)
a << 1;         // calls A::operator<<(int)
a().p();        // calls A::p()&
a.p();          // calls A::p()&
—end example]  
or, if not that,

(3.2.4)
— S1 and S2 include reference bindings (9.4.4) and S1 binds an lvalue reference to an lvalue of function type and S2 binds an rvalue reference to an lvalue of function type

[Example 4:
int f(void(&)());   // #1
int f(void(&&)());  // #2
void g();
int i1 = f(g);      // calls #1
—end example]
or, if not that,

(3.2.5)
— S1 and S2 differ only in their qualification conversion (7.3.6) and yield similar types T1 and T2, respectively (where a standard conversion sequence that is a reference binding is considered to yield the cv-unqualified referenced type), where T1 and T2 are not the same type, and const T2 is reference-compatible with T1 (9.4.4)

[Example 5:
int f(const volatile int*);
int f(const int*);
int i;
int j = f(&i);       // calls f(const int*)
g(const int*);
g(const volatile int* const&);
int* p;
int k = g(p);        // calls g(const int*)
—end example]
or, if not that,

(3.2.6)
— S1 and S2 bind “reference to T1” and “reference to T2”, respectively (9.4.4), where T1 and T2 are not the same type, and T2 is reference-compatible with T1

[Example 6:
int f(const int &);
int f(int &);
g(const int &);
g(int);

int i;
int j = f(i);        // calls f(int &)
k = g(i);            // ambiguous

struct X {
    void f() const;
    void f();
};
g(const X& a, X b) {
    a.f();            // calls X::f() const
}
b.f(); // calls X::f()
}

int h1(int (&)[1]);
int h1(int (&)[1]);
int h2(void (&)());
int h2(void (&)() noexcept);
void g2() {
    int a[1];
    h1(a); // calls h1(int (&)[1])
    extern void f2() noexcept;
    h2(f2); // calls h2(void (&)() noexcept)
}

— end example

or, if not that,

(3.2.7) — S1 and S2 bind the same reference type “reference to T” and have source types V1 and V2, respectively, where the standard conversion sequence from V1* to T* is better than the standard conversion sequence from V2* to T*.

[Example 7:

struct Z {};

struct A {
    operator Z&();
    operator const Z&(); // #1
};

struct B {
    operator Z();
    operator const Z&&(); // #2
};

const Z& r1 = A(); // OK, uses #1
const Z&& r2 = B(); // OK, uses #2
— end example]

(3.3) — User-defined conversion sequence U1 is a better conversion sequence than another user-defined conversion sequence U2 if they contain the same user-defined conversion function or constructor or they initialize the same class in an aggregate initialization and in either case the second standard conversion sequence of U1 is better than the second standard conversion sequence of U2.

[Example 8:

struct A {
    operator short();
} a;
int f(int);
int f(float);
int i = f(a); // calls f(int), because short → int is // better than short → float.
— end example]

4 Standard conversion sequences are ordered by their ranks: an Exact Match is a better conversion than a Promotion, which is a better conversion than a Conversion. Two conversion sequences with the same rank are indistinguishable unless one of the following rules applies:

(4.1) — A conversion that does not convert a pointer or a pointer to member to bool is better than one that does.

(4.2) — A conversion that promotes an enumeration whose underlying type is fixed to its underlying type is better than one that promotes to the promoted underlying type, if the two are different.

(4.3) — A conversion in either direction between floating-point type FP1 and floating-point type FP2 is better than a conversion in the same direction between FP1 and arithmetic type T3 if
— the floating-point conversion rank (6.8.6) of FP1 is equal to the rank of FP2, and

— T3 is not a floating-point type, or T3 is a floating-point type whose rank is not equal to the rank of FP1, or the floating-point conversion subrank (6.8.6) of FP2 is greater than the subrank of T3.

[Example 9:

```c
int f(std::float32_t);
int f(std::float64_t);
int f(long long);
float x;
std::float16_t y;
int i = f(x); // calls f(std::float32_t) on implementations where
// float and std::float32_t have equal conversion ranks
int j = f(y); // error: ambiguous, no equal conversion rank
```

— end example]

— (4.4) If class B is derived directly or indirectly from class A, conversion of B* to A* is better than conversion of B* to void*, and conversion of A* to void* is better than conversion of B* to void*.

— (4.5) If class B is derived directly or indirectly from class A and class C is derived directly or indirectly from B,

— (4.5.1) conversion of C* to B* is better than conversion of C* to A*,

[Example 10:

```c
struct A {};
struct B : public A {};
struct C : public B {};
C* pc;
int f(A*);
int f(B*);
int i = f(pc); // calls f(B*)
```

— end example]

— (4.5.2) binding of an expression of type C to a reference to type B is better than binding an expression of type C to a reference to type A,

— (4.5.3) conversion of A::* to B::* is better than conversion of A::* to C::*,

— (4.5.4) conversion of C to B is better than conversion of C to A,

— (4.5.5) conversion of B* to A* is better than conversion of C* to A*,

— (4.5.6) binding of an expression of type B to a reference to type A is better than binding an expression of type C to a reference to type A,

— (4.5.7) conversion of B::* to C::* is better than conversion of A::* to C::* and

— (4.5.8) conversion of B to A is better than conversion of C to A.

[Note 1: Compared conversion sequences will have different source types only in the context of comparing the second standard conversion sequence of an initialization by user-defined conversion (see 12.2.4); in all other contexts, the source types will be the same and the target types will be different. — end note]

12.3 Address of an overload set

An id-expression whose terminal name refers to an overload set S and that appears without arguments is resolved to a function, a pointer to function, or a pointer to member function for a specific function that is chosen from a set of functions selected from S determined based on the target type required in the context (if any), as described below. The target can be

(1.1) — an object or reference being initialized (9.4, 9.4.4, 9.4.5),

(1.2) — the left side of an assignment (7.6.19),

(1.3) — a parameter of a function (7.6.1.3),

(1.4) — a parameter of a user-defined operator (12.4),

(1.5) — the return value of a function, operator function, or conversion (8.7.4),

(1.6) — an explicit type conversion (7.6.1.4, 7.6.1.9, 7.6.3), or

(1.7) — a non-type template-parameter (13.4.3).
The *id-expression* can be preceded by the `&` operator.

*Note 1*: Any redundant set of parentheses surrounding the function name is ignored (7.5.4). — *end note*

2 If there is no target, all non-template functions named are selected. Otherwise, a non-template function with type F is selected for the function type FT of the target type if F (after possibly applying the function pointer conversion (7.3.14)) is identical to FT.

*Note 2*: That is, the class of which the function is a member is ignored when matching a pointer-to-member-function type. — *end note*

3 The specialization, if any, generated by template argument deduction (13.10.4, 13.10.3.3, 13.10.2) for each function template named is added to the set of selected functions considered.

4 Non-member functions, static member functions, and explicit object member functions match targets of function pointer type or reference to function type. Implicit object member functions match targets of pointer-to-member-function type.

*Note 3*: If an implicit object member function is chosen, the result can be used only to form a pointer to member (7.6.2.2). — *end note*

5 All functions with associated constraints that are not satisfied (13.5.3) are eliminated from the set of selected functions. If more than one function in the set remains, all function template specializations in the set are eliminated if the set also contains a function that is not a function template specialization. Any given non-template function F0 is eliminated if the set contains a second non-template function that is more constrained than F0 according to the partial ordering rules of 13.5.5. Any given function template specialization F1 is eliminated if the set contains a second function template specialization whose function template is more specialized than the function template of F1 according to the partial ordering rules of 13.7.7.3. After such eliminations, if any, there shall remain exactly one selected function.

6 *Example 1:*

```c
int f(double);
int f(int);
int (*pfd)(double) = &f; // selects f(double)
int (*pfi)(int) = &f; // selects f(int)
int (*pfe)(...) = &f; // error: type mismatch
int (&rfi)(int) = f; // selects f(int)
int (&rfd)(double) = f; // selects f(double)
void g() {
    (int (*)(int))&f; // cast expression as selector
}
```

The initialization of `pfe` is ill-formed because no `f()` with type `int(...)` has been declared, and not because of any ambiguity. For another example,

```c
struct X {
    int f(int);
    static int f(long);
};

int (X::*p1)(int) = &X::f; // OK
int (X::*p2)(int) = &X::f; // error: mismatch
int (X::*p3)(long) = &X::f; // OK
int (X::*p4)(long) = &X::f; // error: mismatch
int (X::*p5)(int) = &X:f; // error: wrong syntax for
                        // pointer to member
int (X::*p6)(long) = &X:f; // OK
```

*end example*

*Note 4*: If f and g are both overload sets, the Cartesian product of possibilities is considered to resolve `f(&g)`, or the equivalent expression `f(g)`. — *end note*

*Note 5*: Even if B is a public base of D, we have

```c
D* f();
B* (*p1)() = &f; // error
void g(D*);
void (*p2)(B*) = &g; // error
```

§ 12.3 ©ISO/IEC 367
12.4 Overloaded operators

12.4.1 General

A declaration whose declarator-id is an operator-function-id shall declare a function or function template or an explicit instantiation or specialization of a function template. A function so declared is an operator function. A function template so declared is an operator function template. A specialization of an operator function template is also an operator function. An operator function is said to implement the operator named in its operator-function-id:

```
operator-function-id:
   operator operator
```

Example 1:
```
complex z = a.operator+(b);  // complex z = a+b;
void* p = operator new(sizeof(int)*n);
```

Both the unary and binary forms of
```
+ - * &
```
can be overloaded.

2 [Note 2: The following operators cannot be overloaded:]
```
.* :: ?:
```
nor can the preprocessing symbols # (15.6.3) and ## (15.6.4). — end note]

4 Operator functions are usually not called directly; instead they are invoked to evaluate the operators they implement (12.4.2 – 12.4.7). They can be explicitly called, however, using the operator-function-id as the name of the function in the function call syntax (7.6.1.3).

Example 1:
```
complex z = a.operator+(b);  // complex z = a+b;
void* p = operator new(sizeof(int)*n);
```

The allocation and deallocation functions, operator new, operator new[], operator delete, and operator delete[], are described completely in 6.7.5.5. The attributes and restrictions found in the rest of 12.4 do not apply to them unless explicitly stated in 6.7.5.5.

5 The co_await operator is described completely in 7.6.2.4. The attributes and restrictions found in the rest of 12.4 do not apply to it unless explicitly stated in 7.6.2.4.

7 An operator function shall either

(7.1) — be a member function or
(7.2) — be a non-member function that has at least one non-object parameter whose type is a class, a reference to a class, an enumeration, or a reference to an enumeration.

It is not possible to change the precedence, grouping, or number of operands of operators. The meaning of the operators =, (unary) &, and , (comma), predefined for each type, can be changed for specific class types by defining operator functions that implement these operators. Likewise, the meaning of the operators (unary) & and , (comma) can be changed for specific enumeration types. Operator functions are inherited in the same manner as other base class functions.

8 An operator function shall be a prefix unary, binary, function call, subscripting, class member access, increment, or decrement operator function.

9 [Note 3: The identities among certain predefined operators applied to basic types (for example, ++a ≡ a+=1) need not hold for operator functions. Some predefined operators, such as *, require an operand to be an lvalue when applied to basic types; this is not required by operator functions. — end note]
An operator function cannot have default arguments (9.3.4.7), except where explicitly stated below. Operator functions cannot have more or fewer parameters than the number required for the corresponding operator, as described in the rest of 12.4.

Operators not mentioned explicitly in subclauses 12.4.3.2 through 12.4.7 act as ordinary unary and binary operators obeying the rules of 12.4.2 or 12.4.3.

12.4.2 Unary operators

A prefix unary operator function is a function named `operator@` for a prefix unary-operator `@` (7.6.2.2) that is either a non-static member function (11.4.2) with no non-object parameters or a non-member function with one parameter. For a unary-expression of the form `@` cast-expression, the operator function is selected by overload resolution (12.2.2.3). If a member function is selected, the expression is interpreted as

```
cast-expression . operator @ ()
```

Otherwise, if a non-member function is selected, the expression is interpreted as

```
operator @ ( cast-expression )
```

[Note 1: The operators `++` and `--` (7.6.2.3) are described in 12.4.7. — end note]

12.4.3 Binary operators

12.4.3.1 General

A binary operator function is a function named `operator@` for a binary operator `@` that is either a non-static member function (11.4.2) with one non-object parameter or a non-member function with two parameters. For an expression `x @ y` with subexpressions `x` and `y`, the operator function is selected by overload resolution (12.2.2.3). If a member function is selected, the expression is interpreted as

```
x . operator @ ( y )
```

Otherwise, if a non-member function is selected, the expression is interpreted as

```
operator @ ( x , y )
```

2 An equality operator function is an operator function for an equality operator (7.6.10). A relational operator function is an operator function for a relational operator (7.6.9). A three-way comparison operator function is an operator function for the three-way comparison operator (7.6.8). A comparison operator function is an equality operator function, a relational operator function, or a three-way comparison operator function.

12.4.3.2 Simple assignment

A simple assignment operator function is a binary operator function named `operator=`. A simple assignment operator function shall be a non-static member function.

[Note 1: Because only standard conversion sequences are considered when converting to the left operand of an assignment operation (12.2.4.2), an expression `x = y` with a subexpression `x` of class type is always interpreted as `x . operator= (y)`. — end note]

2 [Note 2: Since a copy assignment operator is implicitly declared for a class if not declared by the user (11.4.6), a base class assignment operator function is always hidden by the copy assignment operator function of the derived class. — end note]

3 [Note 3: Any assignment operator function, even the copy and move assignment operators, can be virtual. For a derived class `D` with a base class `B` for which a virtual copy/move assignment has been declared, the copy/move assignment operator function in `D` does not override `B`’s virtual copy/move assignment operator.

[Example 1:]

```
struct B {
    virtual int operator= (int);
    virtual B& operator= (const B&);
};
struct D : B {
    virtual int operator= (int);
    virtual D& operator= (const B&);
};
```
D dobj1;
D dobj2;
B* bptr = &dobj1;

void f() {
    bptr->operator=(99); // calls D::operator=(int)
    *bptr = 99; // ditto
    bptr->operator=(dobj2); // calls D::operator=(const B&)
    *bptr = dobj2; // ditto
    dobj1 = dobj2; // calls implicitly-declared D::operator=(const D&)
}

—end example]
—end note]

12.4.4 Function call 

A function call operator function is a function named `operator()` that is a member function with an arbitrary number of parameters. It may have default arguments. For an expression of the form

\[
\text{postfix-expression (expression-list_opt )}
\]

where the postfix-expression is of class type, the operator function is selected by overload resolution (12.2.2.2.3). If a surrogate call function is selected, let \( e \) be the result of invoking the corresponding conversion operator function on the postfix-expression; the expression is interpreted as

\[
e (\text{expression-list_opt })
\]

Otherwise, the expression is interpreted as

\[
\text{postfix-expression . operator () (expression-list_opt )}
\]

12.4.5 Subscripting

A subscripting operator function is a member function named `operator[]` with an arbitrary number of parameters. It may have default arguments. For an expression of the form

\[
\text{postfix-expression [expression-list_opt ]}
\]

the operator function is selected by overload resolution (12.2.2.3). If a member function is selected, the expression is interpreted as

\[
\text{postfix-expression . operator [] (expression-list_opt )}
\]

[Example 1:

\[
\begin{align*}
\text{struct X 
{ &
\begin{array}{l}
\text{Z operator[](std::initializer_list<int>);}
\text{Z operator[](auto...);}
\end{array}
};
\text{X x;}
\text{x[{1,2,3}] = 7;} & \quad \text{// OK, meaning x.operator[](\{1,2,3\})}
\text{x[1,2,3] = 7;} & \quad \text{// OK, meaning x.operator[](1,2,3)}
\text{int a[10];}
\text{a[{1,2,3}] = 7;} & \quad \text{// error: built-in subscript operator}
\text{a[1,2,3] = 7;} & \quad \text{// error: built-in subscript operator}
\end{align*}
\]

—end example]

12.4.6 Class member access

A class member access operator function is a function named `operator->` that is a non-static member function taking no non-object parameters. For an expression of the form

\[
\text{postfix-expression -> template_opt id-expression}
\]

the operator function is selected by overload resolution (12.2.2.3), and the expression is interpreted as

\[
(\text{postfix-expression . operator -> () }) \rightarrow \text{template_opt id-expression}
\]

12.4.7 Increment and decrement

An increment operator function is a function named `operator++`. If this function is a non-static member function with no non-object parameters, or a non-member function with one parameter, it defines the prefix

§ 12.4.7 ©ISO/IEC 370
increment operator ++ for objects of that type. If the function is a non-static member function with one non-object parameter (which shall be of type int) or a non-member function with two parameters (the second of which shall be of type int), it defines the postfix increment operator ++ for objects of that type. When the postfix increment is called as a result of using the ++ operator, the int argument will have value zero.\footnote{Calling \texttt{operator++} explicitly, as in expressions like \texttt{a.operator++(2)}, has no special properties: The argument to \texttt{operator++} is 2.}

[Example 1:

```c
struct X {
    X& operator++();    // prefix ++a
    X operator++(int);  // postfix a++
};

struct Y {
    Y& operator++(Y&);  // prefix ++b
    Y operator++(Y&, int);  // postfix b++
}

void f(X a, Y b) {
    ++a;  // a.operator++();
    a++;  // a.operator++(0);
    ++b;  // operator++(b);
    b++;  // operator++(b, 0);

    a.operator++();  // explicit call: like ++a;
    a.operator++(0);  // explicit call: like a++;
    operator++(b);  // explicit call: like ++b;
    operator++(b, 0);  // explicit call: like b++;
}
```

---end example---]

A decrement operator function is a function named \texttt{operator--} and is handled analogously to an increment operator function.

12.5 Built-in operators \([\text{over.built}]\)

The candidate operator functions that represent the built-in operators defined in 7.6 are specified in this subclause. These candidate functions participate in the operator overload resolution process as described in 12.2.2.3 and are used for no other purpose.

[Note 1: Because built-in operators take only operands with non-class type, and operator overload resolution occurs only when an operand expression originally has class or enumeration type, operator overload resolution can resolve to a built-in operator only when an operand has a class type that has a user-defined conversion to a non-class type appropriate for the operator, or when an operand has an enumeration type that can be converted to a type appropriate for the operator. Also note that some of the candidate operator functions given in this subclause are more permissive than the built-in operators themselves. As described in 12.2.2.3, after a built-in operator is selected by overload resolution the expression is subject to the requirements for the built-in operator given in 7.6, and therefore to any additional semantic constraints given there. In some cases, user-written candidates with the same name and parameter types as a built-in candidate operator function cause the built-in operator function to not be included in the set of candidate functions. ---end note---]

In this subclause, the term \textit{promoted integral type} is used to refer to those cv-unqualified integral types which are preserved by integral promotion (7.3.7) (including e.g. \texttt{int} and \texttt{long} but excluding e.g. \texttt{char}).

[Note 2: In all cases where a promoted integral type is required, an operand of unscoped enumeration type will be acceptable by way of the integral promotions. ---end note---]

In the remainder of this subclause, \texttt{vq} represents either \texttt{volatile} or no cv-qualifier.

For every pair \((T, vq)\), where \(T\) is a cv-unqualified arithmetic type other than \texttt{bool} or a cv-unqualified pointer to (possibly cv-qualified) object type, there exist candidate operator functions of the form

\begin{verbatim}
  vq T& operator++(vq T&);
  T operator++(vq T&, int);
  vq T& operator--(vq T&);
  T operator--(vq T&, int);
\end{verbatim}
For every (possibly cv-qualified) object type \( T \) and for every function type \( T \) that has neither cv-qualifiers nor a ref-qualifier, there exist candidate operator functions of the form

\[
T^* \quad \text{operator}*(T^*);
\]

For every type \( T \) there exist candidate operator functions of the form

\[
T^* \quad \text{operator}*(T^*);
\]

For every cv-unqualified floating-point or promoted integral type \( T \), there exist candidate operator functions of the form

\[
T \quad \text{operator}+T(T);
\]

\[
T \quad \text{operator}-T(T);
\]

For every cv-unqualified floating-point or promoted integral type \( T \), there exist candidate operator functions of the form

\[
T \quad \text{operator}+T(T);
\]

\[
T \quad \text{operator}-T(T);
\]

For every quintuple \((C1, C2, T, cv1, cv2)\), where \( C2 \) is a class type, \( C1 \) is the same type as \( C2 \) or is a derived class of \( C2 \), and \( T \) is an object type or a function type, there exist candidate operator functions of the form

\[
cv12 \quad T^* \quad \text{operator}->* (cv1 C1^*, cv2 T C2::*);
\]

where \( cv12 \) is the union of \( cv1 \) and \( cv2 \). The return type is shown for exposition only; see 7.6.4 for the determination of the operator’s result type.

For every pair of types \( L \) and \( R \), where each of \( L \) and \( R \) is a floating-point or promoted integral type, there exist candidate operator functions of the form

\[
LR \quad \text{operator}*(L, R);
\]

\[
LR \quad \text{operator}/(L, R);
\]

\[
LR \quad \text{operator}+(L, R);
\]

\[
LR \quad \text{operator}-(L, R);
\]

\[
\text{bool} \quad \text{operator}==(L, R);
\]

\[
\text{bool} \quad \text{operator]!=L, R);
\]

\[
\text{bool} \quad \text{operator}<L, R);
\]

\[
\text{bool} \quad \text{operator}>(L, R);
\]

\[
\text{bool} \quad \text{operator}<=(L, R);
\]

\[
\text{bool} \quad \text{operator}>=L, R);
\]

where \( LR \) is the result of the usual arithmetic conversions (7.4) between types \( L \) and \( R \).

For every integral type \( T \) there exists a candidate operator function of the form

\[
\text{std::strong_ordering} \quad \text{operator}<>(T, T);
\]

For every pair of floating-point types \( L \) and \( R \), there exists a candidate operator function of the form

\[
\text{std::partial_ordering} \quad \text{operator}<>(L, R);
\]

For every cv-qualified or cv-unqualified object type \( T \) there exist candidate operator functions of the form

\[
T^* \quad \text{operator}+(T^*, \text{std::ptrdiff_t});
\]

\[
T^* \quad \text{operator}[] (T^*, \text{std::ptrdiff_t});
\]

\[
T^* \quad \text{operator}-(T^*, \text{std::ptrdiff_t});
\]

\[
T^* \quad \text{operator}+(\text{std::ptrdiff_t}, T^*);
\]

\[
T^* \quad \text{operator}[] (\text{std::ptrdiff_t}, T^*);
\]

For every \( T \), where \( T \) is a pointer to object type, there exist candidate operator functions of the form

\[
\text{std::ptrdiff_t} \quad \text{operator}-(T, T);
\]

For every \( T \), where \( T \) is an enumeration type or a pointer type, there exist candidate operator functions of the form

\[
\text{bool} \quad \text{operator}==(T, T);
\]

\[
\text{bool} \quad \text{operator]!=T, T);
\]

\[
\text{bool} \quad \text{operator}<T, T);
\]

\[
\text{bool} \quad \text{operator}>(T, T);
\]

\[
\text{bool} \quad \text{operator}<(T, T);
\]

\[
\text{bool} \quad \text{operator}>=T, T);
\]

\[
R \quad \text{operator}<>(T, T);
\]

where \( R \) is the result type specified in 7.6.8.
For every \( T \), where \( T \) is a pointer-to-member type or \std::nullptr_t, there exist candidate operator functions of the form

\[
\begin{align*}
\text{bool} & \quad \text{operator}==(T, T); \\
\text{bool} & \quad \text{operator}!=(T, T);
\end{align*}
\]

For every pair of promoted integral types \( L \) and \( R \), there exist candidate operator functions of the form

\[
\begin{align*}
\text{LR} & \quad \text{operator}%(L, R); \\
\text{LR} & \quad \text{operator}%(L, R); \\
\text{LR} & \quad \text{operator}%(L, R); \\
\text{LR} & \quad \text{operator}%(L, R); \\
\text{L} & \quad \text{operator}<<(L, R); \\
\text{L} & \quad \text{operator}>>(L, R);
\end{align*}
\]

where \( LR \) is the result of the usual arithmetic conversions (7.4) between types \( L \) and \( R \).

For every triple \( (L, vq, R) \), where \( L \) is an arithmetic type, and \( R \) is a floating-point or promoted integral type, there exist candidate operator functions of the form

\[
\begin{align*}
vq Lk & \quad \text{operator}=(vq Lk, R); \\
vq Lk & \quad \text{operator}==(vq Lk, R); \\
vq Lk & \quad \text{operator}!=(vq Lk, R); \\
vq Lk & \quad \text{operator}=(vq Lk, R); \\
vq Lk & \quad \text{operator}+=(vq Lk, R); \\
vq Lk & \quad \text{operator}-=(vq Lk, R);
\end{align*}
\]

For every pair \( (T, vq) \), where \( T \) is any type, there exist candidate operator functions of the form

\[
\begin{align*}
T*vqk & \quad \text{operator}=((T*vqk, T*); \\
T*vqk & \quad \text{operator}+=(T*vqk, std::ptrdiff_t); \\
T*vqk & \quad \text{operator}-=(T*vqk, std::ptrdiff_t);
\end{align*}
\]

For every pair \( (T, vq) \), where \( T \) is an enumeration or pointer-to-member type, there exist candidate operator functions of the form

\[
\begin{align*}
vq Tk & \quad \text{operator}=(vq Tk, T); \\
vq Tk & \quad \text{operator}+=(vq Tk, T); \\
vq Tk & \quad \text{operator}+=(vq Tk, T);
\end{align*}
\]

For every pair \( (T, vq) \), where \( T \) is a cv-qualified or cv-unqualified object type, there exist candidate operator functions of the form

\[
\begin{align*}
T*vqk & \quad \text{operator}+=(T*vqk, std::ptrdiff_t); \\
T*vqk & \quad \text{operator}-=(T*vqk, std::ptrdiff_t);
\end{align*}
\]

For every triple \( (L, vq, R) \), where \( L \) is an integral type, and \( R \) is a promoted integral type, there exist candidate operator functions of the form

\[
\begin{align*}
vq Lk & \quad \text{operator}%(vq Lk, R); \\
vq Lk & \quad \text{operator}<<(vq Lk, R); \\
vq Lk & \quad \text{operator}>>(vq Lk, R); \\
vq Lk & \quad \text{operator}%(vq Lk, R); \\
vq Lk & \quad \text{operator}+=(vq Lk, R); \\
vq Lk & \quad \text{operator}-=(vq Lk, R);
\end{align*}
\]

There also exist candidate operator functions of the form

\[
\begin{align*}
\text{bool} & \quad \text{operator}!(bool); \\
\text{bool} & \quad \text{operator}&&=(bool, bool); \\
\text{bool} & \quad \text{operator}||=(bool, bool);
\end{align*}
\]

For every pair of types \( L \) and \( R \), where each of \( L \) and \( R \) is a floating-point or promoted integral type, there exist candidate operator functions of the form

\[
\begin{align*}
\text{LR} & \quad \text{operator}?:((bool, L, R); \\
\text{LR} & \quad \text{operator}?:((bool, L, R); \\
\text{LR} & \quad \text{operator}?:((bool, L, R);
\end{align*}
\]

where \( LR \) is the result of the usual arithmetic conversions (7.4) between types \( L \) and \( R \).

[Note 3: As with all these descriptions of candidate functions, this declaration serves only to describe the built-in operator for purposes of overload resolution. The operator “?:” cannot be overloaded. — end note]

For every type \( T \), where \( T \) is a pointer, pointer-to-member, or scoped enumeration type, there exist candidate operator functions of the form

\[
\begin{align*}
T & \quad \text{operator}?:((bool, T, T); \\
T & \quad \text{operator}?:((bool, T, T); \\
T & \quad \text{operator}?:((bool, T, T);
\end{align*}
\]

12.6 User-defined literals

[over.literal]
literal-operator-id:
  operator unevaluated-string identifier
  operator user-defined-string-literal

1 The user-defined-string-literal in a literal-operator-id shall have no encoding-prefix. The unevaluated-string or user-defined-string-literal shall be empty. The ud-suffix of the user-defined-string-literal or the identifier in a literal-operator-id is called a literal suffix identifier. The first form of literal-operator-id is deprecated (D.8). Some literal suffix identifiers are reserved for future standardization; see 16.4.5.3.6. A declaration whose literal-operator-id uses such a literal suffix identifier is ill-formed, no diagnostic required.

2 A declaration whose declarator-id is a literal-operator-id shall declare a function or function template that belongs to a namespace (it could be a friend function (11.8.4)) or an explicit instantiation or specialization of a function template. A function declared with a literal-operator-id is a literal operator. A function template declared with a literal-operator-id is a literal operator template.

3 The declaration of a literal operator shall have a parameter-declaration-clause equivalent to one of the following:
   - const char*
   - unsigned long long int
   - long double
   - wchar_t
   - char8_t
   - char16_t
   - char32_t
   - const char*, std::size_t
   - const wchar_t*, std::size_t
   - const char8_t*, std::size_t
   - const char16_t*, std::size_t
   - const char32_t*, std::size_t

   If a parameter has a default argument (9.3.4.7), the program is ill-formed.

4 A raw literal operator is a literal operator with a single parameter whose type is const char*.

5 A numeric literal operator template is a literal operator template whose template-parameter-list has a single template-parameter that is a non-type template parameter pack (13.7.4) with element type char. A string literal operator template is a literal operator template whose template-parameter-list comprises a single non-type template-parameter of class type. The declaration of a literal operator template shall have an empty parameter-declaration-clause and shall declare either a numeric literal operator template or a string literal operator template.

6 Literal operators and literal operator templates shall not have C language linkage.

7 [Note 1: Literal operators and literal operator templates are usually invoked implicitly through user-defined literals (5.13.9). However, except for the constraints described above, they are ordinary namespace-scope functions and function templates. In particular, they are looked up like ordinary functions and function templates and they follow the same overload resolution rules. Also, they can be declared inline or constexpr, they can have internal, module, or external linkage, they can be called explicitly, their addresses can be taken, etc. —end note]

8 [Example 1:

   void operator "+"_km(long double);         // OK
   string operator "+"_i18n(const char*, std::size_t); // OK, deprecated
   template <char...> double operator "+"_u6300(); // OK, UCN for lowercase pi
   float operator "+"_e(const char*);           // OK
   float operator "+"_E(const char*);           // ill-formed, no diagnostic required:
                                              // reserved literal suffix (16.4.5.3.6, 5.13.9)
   double operator "+"_Bq(long double);        // OK, does not use the reserved identifier _Bq (5.10)
   double operator "+"_Bq(long double);        // ill-formed, no diagnostic required:
                                              // uses the reserved identifier _Bq (5.10)
   float operator "B(const char*);             // error: non-empty string-literal
   string operator "S5X(const char*, std::size_t); // error: invalid literal suffix identifier
   double operator "_miles(double);            // error: invalid parameter-declaration-clause
   template <char...> int operator "_j(const char*); // error: invalid parameter-declaration-clause
   extern "C" void operator "+"_m(long double); // error: C language linkage

   —end example]
13 Templates

13.1 Preamble

A template defines a family of classes, functions, or variables, an alias for a family of types, or a concept.

\[
\text{template-declaration:} \\
\text{template-head declaration} \\
\text{template-head concept-definition}
\]

\[
\text{template-head:} \\
\text{template < template-parameter-list > requires-clause}_{opt}
\]

\[
\text{template-parameter-list:} \\
\text{template-parameter} \\
\text{template-parameter-list , template-parameter}
\]

\[
\text{requires-clause:} \\
\text{requires constraint-logical-or-expression}
\]

\[
\text{constraint-logical-or-expression:} \\
\text{constraint-logical-and-expression} \\
\text{constraint-logical-or-expression} \lor \text{constraint-logical-and-expression}
\]

\[
\text{constraint-logical-and-expression:} \\
\text{primary-expression} \\
\text{constraint-logical-and-expression} \&\& \text{primary-expression}
\]

[Note 1: The > token following the template-parameter-list of a template-declaration can be the product of replacing a >> token by two consecutive > tokens (13.3). — end note]

2 The declaration in a template-declaration (if any) shall

- (2.1) declare or define a function, a class, or a variable, or
- (2.2) define a member function, a member class, a member enumeration, or a static data member of a class template or of a class nested within a class template, or
- (2.3) define a member template of a class or class template, or
- (2.4) be a friend-type-declaration, or
- (2.5) be a deduction-guide, or
- (2.6) be an alias-declaration.

3 A template-declaration is a declaration. A declaration introduced by a template declaration of a variable is a variable template. A variable template at class scope is a static data member template.

\[
\text{template<class T>}
\text{constexpr T pi = T(3.1415926535897932385L);}
\text{template<class T>
T circular_area(T r) {
return pi<T> * r * r;
}
\]

\[
\text{struct matrix_constants {}
\text{template<class T>
using pauli = hermitian_matrix<T, 2>;
\text{template<class T>
constexpr static pauli<T> sigma1 = {{0, 1}, {1, 0}};}
\text{template<class T>
constexpr static pauli<T> sigma2 = {{0, -1i}, {1i, 0}};}
\text{template<class T>
constexpr static pauli<T> sigma3 = {{1, 0}, {0, -1}};}
\}
\]

[Note 2: A template-declaration can appear only as a namespace scope or class scope declaration. — end note]

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Its declaration shall not be an **export-declaration**. In a function template declaration, the **unqualified-id** of the **declarator-id** shall be a name.

[Note 3: A class or variable template declaration of a **simple-template-id** declares a partial specialization (13.7.6). — end note]

5 In a **template-declaration**, explicit specialization, or explicit instantiation, the **init-declarator-list** in the declaration shall contain at most one declarator. When such a declaration is used to declare a class template, no declarator is permitted.

6 A specialization (explicit or implicit) of one template is distinct from all specializations of any other template. A template, an explicit specialization (13.9.4), and a partial specialization shall not have C language linkage.

[Note 4: Default arguments for function templates and for member functions of class templates are considered definitions for the purpose of template instantiation (13.7) and must obey the one-definition rule (6.3). — end note]

7 [Note 5: A template cannot have the same name as any other name bound in the same scope (6.4.1), except that a function template can share a name with non-template functions (9.3.4.6) and/or function templates (13.10.4). Specializations, including partial specializations (13.7.6), do not reintroduce or bind names. Their target scope is the target scope of the primary template, so all specializations of a template belong to the same scope as it does. — end note]

8 An entity is **templated** if it is

(8.1) a template,
(8.2) an entity defined (6.2) or created (6.7.7) in a templated entity,
(8.3) a member of a templated entity,
(8.4) an enumerator for an enumeration that is a templated entity, or
(8.5) the closure type of a **lambda-expression** (7.5.6.2) appearing in the declaration of a templated entity.

[Note 6: A local class, a local or block variable, or a friend function defined in a templated entity is a templated entity. — end note]

A **templated function** is a function template or a function that is templated. A **templated class** is a class template or a class that is templated. A **templated variable** is a variable template or a variable that is templated.

9 A **template-declaration** is written in terms of its template parameters. The optional **requires-clause** following a **template-parameter-list** allows the specification of constraints (13.5.3) on template arguments (13.4). The **requires-clause** introduces the **constraint-expression** that results from interpreting the **constraint-logical-or-expression** as a constraint-expression. The **constraint-logical-or-expression** of a **requires-clause** is an unevaluated operand (7.2.3).

[Note 7: The expression in a **requires-clause** uses a restricted grammar to avoid ambiguities. Parentheses can be used to specify arbitrary expressions in a **requires-clause**.

[Example 2:
```c
    template<int N> requires N == sizeof new unsigned short
    int f(); // error: parentheses required around == expression
```]

— end example]

— end note]

10 A definition of a function template, member function of a class template, variable template, or static data member of a class template shall be reachable from the end of every definition domain (6.3) in which it is implicitly instantiated (13.9.2) unless the corresponding specialization is explicitly instantiated (13.9.3) in some translation unit; no diagnostic is required.

### 13.2 Template parameters

1 The syntax for **template-parameters** is:

```
template-parameter:
  type-parameter
  parameter-declaration
```
type-parameter:
  type-parameter-key ... opt identifier opt
type-parameter-key identifier opt = type-id
type-constraint ... opt identifier opt
type-constraint identifier opt = type-id
template-head type-parameter-key ... opt identifier opt
template-head type-parameter-key identifier opt = id-expression

type-parameter-key:
  class
typename
type-constraint:
  nested-name-specifier opt concept-name
  nested-name-specifier opt concept-name < template-argument-list opt >

The component names of a type-constraint are its concept-name and those of its nested-name-specifier (if any).

[Note 1: The > token following the template-parameter-list of a type-parameter can be the product of replacing a >> token by two consecutive > tokens (13.3). — end note]

2 There is no semantic difference between class and typename in a type-parameter-key. typename followed by an unqualified-id names a template type parameter. typename followed by a qualified-id denotes the type in a non-type parameter-declaration. A template-parameter of the form class identifier is a type-parameter.

[Example 1]:
  class T { /* ... */ };  // class T
  int i;

  template<class T, T i> void f(T t) {
    T t1 = i;  // template-parameters T and i
    ::T t2 = ::i;  // global namespace members T and i
  }

Here, the template f has a type-parameter called T, rather than an unnamed non-type template-parameter of class T. — end example]

A template-parameter declaration shall not have a storage-class-specifier. Types shall not be defined in a template-parameter declaration.

3 The identifier in a type-parameter is not looked up. A type-parameter whose identifier does not follow an ellipsis defines its identifier to be a typedef-name (if declared without template) or template-name (if declared with template) in the scope of the template declaration.

[Note 2: A template argument can be a class template or alias template. For example,

  template<class T> class myarray { /* ... */ };  // class template
  template<class K, class V, template<class T> class C = myarray>  // alias template
    class Map {
      C<K> key;
      C<V> value;
    };

— end note]

4 A type-constraint Q that designates a concept C can be used to constrain a contextually-determined type or template type parameter pack T with a constraint-expression E defined as follows. If Q is of the form C<A_1, · · · , A_n>, then let E' be C<T, A_1, · · · , A_n>. Otherwise, let E' be C<T>. If T is not a pack, then E is E', otherwise E is (E' && ...). This constraint-expression E is called the immediately-declared constraint of Q for T. The concept designated by a type-constraint shall be a type concept (13.7.9).

5 A type-parameter that starts with a type-constraint introduces the immediately-declared constraint of the type-constraint for the parameter.

[Example 2]:
  template<typename T> concept C1 = true;
  template<typename... Ts> concept C2 = true;

110) Since template template-parameters and template template-arguments are treated as types for descriptive purposes, the terms non-type parameter and non-type argument are used to refer to non-type, non-template parameters and arguments.
template<typename T, typename U> concept C3 = true;

template<C1 T> struct s1;    // associates C1<T>
template<C1... T> struct s2; // associates (C1<T> && ...)
template<C2... T> struct s3; // associates (C2<T> && ...)
template<C3<int> T> struct s4; // associates C3<T, int>
template<C3<int>... T> struct s5; // associates (C3<T, int> && ...)

— end example

6 A non-type template-parameter shall have one of the following (possibly cv-qualified) types:

(6.1) — a structural type (see below),
(6.2) — a type that contains a placeholder type (9.2.9.7), or
(6.3) — a placeholder for a deduced class type (9.2.9.8).

The top-level cv-qualifiers on the template-parameter are ignored when determining its type.

7 A structural type is one of the following:

(7.1) — a scalar type, or
(7.2) — an lvalue reference type, or
(7.3) — a literal class type with the following properties:

(7.3.1) — all base classes and non-static data members are public and non-mutable and
(7.3.2) — the types of all base classes and non-static data members are structural types or (possibly multidimensional) array thereof.

8 An id-expression naming a non-type template-parameter of class type T denotes a static storage duration object of type const T, known as a template parameter object, which is template-argument-equivalent (13.6) to the corresponding template argument after it has been converted to the type of the template-parameter (13.4.3). No two template parameter objects are template-argument-equivalent.

[Note 3: If an id-expression names a non-type non-reference template-parameter, then it is a prvalue if it has non-class type. Otherwise, if it is of class type T, it is an lvalue and has type const T (7.5.5.2). — end note]

[Example 3:

using X = int;
struct A {}

template<const X& x, int i, A a> void f() {
    int ri = i;
    const int& cri = i;
    const A& ra = a;
    // error: change of template-parameter value
    ++i;
    // OK
    &x;
    // OK
    &i;
    // error: address of non-reference template-parameter
    &a;
    // OK
    int& ri = i;
    // error: attempt to bind non-const reference to temporary
    const int& cri = i;
    // OK, const reference binds to temporary
    const A& ra = a;
    // OK, const reference binds to a template parameter object
}
— end example]

[Note 4: A non-type template-parameter cannot be declared to have type cv void.

[Example 4:

template<void v> class X; // error
template<void* pv> class Y; // OK
— end example]
— end note]

10 A non-type template-parameter of type “array of T” or of function type T is adjusted to be of type “pointer to T”.

[Example 5:

template<int* a> struct R { /* ... */};
template<int b[5]> struct S { /* ... */};
int p;
A non-type template parameter declared with a type that contains a placeholder type with a *type-constraint* introduces the immediately-declared constraint of the *type-constraint* for the invented type corresponding to the placeholder (9.3.4.6).

A *default template argument* is a template argument (13.4) specified after `=` in a *template-parameter*. A default template argument may be specified for any kind of *template-parameter* (type, non-type, template) that is not a template parameter pack (13.7.4). A default template argument may be specified in a template declaration. A default template argument shall not be specified in the *template-parameter-lists* of the definition of a member of a class template that appears outside of the member’s class. A default template argument shall not be specified in a friend class template declaration. If a friend function template declaration `D` specifies a default template argument, that declaration shall be a definition and there shall be no other declaration of the function template which is reachable from `D` or from which `D` is reachable.

The set of default template arguments available for use is obtained by merging the default arguments from all prior declarations of the template in the same way default function arguments are (9.3.4.7).

[Example 6]:
```
template<class T1, class T2 = int> class A;
```

is equivalent to
```
template<class T1 = int, class T2 = int> class A;
```

—end example[

If a *template-parameter* of a class template, variable template, or alias template has a default template argument, each subsequent *template-parameter* shall either have a default template argument supplied or be a template parameter pack. If a *template-parameter* of a primary class template, primary variable template, or alias template is a template parameter pack, it shall be the last *template-parameter*. A template parameter pack of a function template shall not be followed by another template parameter unless that template parameter can be deduced from the parameter-type-list (9.3.4.6) of the function template or has a default argument (13.10.3). A template parameter of a deduction guide template (13.7.2.3) that does not have a default argument shall be deducible from the parameter-type-list of the deduction guide template.

[Example 7]:
```
template<class T1 = int, class T2> class B; // error
```

```
// U can be neither deduced from the parameter-type-list nor specified
```
```
template<class... T, class... U> void f() { } // error
```
```
template<class... T, class U> void g() { } // error
```

—end example[

When parsing a default template argument for a non-type *template-parameter*, the first non-nested `>` is taken as the end of the *template-parameter-list* rather than a greater-than operator.

[Example 8]:
```
template<int i = 3 > 4 > class X { /* ... */ }; // syntax error
```
```
template<int i = (3 > 4) > class Y { /* ... */ }; // OK
```

—end example[

A *template-parameter* of a template *template-parameter* is permitted to have a default template argument. When such default arguments are specified, they apply to the template *template-parameter* in the scope of the template *template-parameter*.

[Example 9]:

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template <template <class TT = float> class T> struct A {
    inline void f();
    inline void g();
};

template <template <class TT> class T> void A<T>::f() {
    T<> t; // error: TT has no default template argument
}

template <template <class TT = char> class T> void A<T>::g() {
    T<> t; // OK, T<char>
}

—end example

17 If a template-parameter is a type-parameter with an ellipsis prior to its optional identifier or is a parameter-declaration that declares a pack (9.3.4.6), then the template-parameter is a template parameter pack (13.7.4). A template parameter pack that is a parameter-declaration whose type contains one or more unexpanded packs is a pack expansion. Similarly, a template parameter pack that is a type-parameter with a template-parameter-list containing one or more unexpanded packs is a pack expansion. A type parameter pack with a type-constraint that contains an unexpanded parameter pack is a pack expansion. A template parameter pack that is a pack expansion shall not expand a template parameter pack declared in the same template-parameter-list.

[Example 10:

    template <class... Types> // Types is a template type parameter pack
        class Tuple;
    // but not a pack expansion

    template <class T, int... Dims> // Dims is a non-type template parameter pack
        struct multi_array;
    // but not a pack expansion

    template <class... T> // Values is a non-type template parameter pack
        struct value_holder {
            template <T... Values> struct apply { }; // and a pack expansion
        };

    template <class... T, T... Values> // error: Values expands template type parameter
        struct static_array; // pack T within the same template parameter list

—end example]

13.3 Names of template specializations [temp.names]

1 A template specialization (13.9) can be referred to by a template-id:

    simple-template-id:
        template-name < template-argument-list_opt >

    template-id:
        simple-template-id
        operator-function-id < template-argument-list_opt >
        literal-operator-id < template-argument-list_opt >

    template-name:
        identifier

    template-argument-list:
        template-argument ...opt
        template-argument-list_opt , template-argument ...opt

    template-argument:
        constant-expression
        type-id
        id-expression
        braced-init-list

2 The component name of a simple-template-id, template-id, or template-name is the first name in it.

3 A < is interpreted as the delimiter of a template-argument-list if it follows a name that is not a conversion-function-id and

(3.1) — that follows the keyword template or a - after a nested-name-specifier or in a class member access expression, or

§ 13.3
for which name lookup finds the injected-class-name of a class template or finds any declaration of a
template, or
that is an unqualified name for which name lookup either finds one or more functions or finds nothing,
or
that is a terminal name in a using-declarator (9.9), in a declarator-id (9.3.4), or in a type-only context
other than a nested-name-specifier (13.8).

[Note 1: If the name is an identifier, it is then interpreted as a template-name. The keyword template is used to
indicate that a dependent qualified name (13.8.3.2) denotes a template where an expression might appear. — end
note]

[Example 1:

```c
struct X {
    template<std::size_t> X* alloc();
    template<std::size_t> static X* adjust();
};
```

```c
template<class T> void f(T* p) {
    T* p1 = p->alloc<200>(); // error: < means less than
    T* p2 = p->template alloc<200>(); // OK, < starts template argument list
    T::adjust<100>(); // error: < means less than
    T::template adjust<100>(); // OK, < starts template argument list
}
```

— end example]

4 When parsing a template-argument-list, the first non-nested >111 is taken as the ending delimiter rather than
a greater-than operator. Similarly, the first non-nested >> is treated as two consecutive but distinct > tokens,
the first of which is taken as the end of the template-argument-list and completes the template-id.

[Note 2: The second > token produced by this replacement rule can terminate an enclosing template-id construct or it
can be part of a different construct (e.g., a cast). — end note]

[Example 2:

```c
template<int i> class X { /* ... */ };
```

```c
X<1>2 > x1; // syntax error
X<1>2> x2; // OK
```

```c
template<class T> class Y { /* ... */ };
```

```c
Y<X<1>> x3; // OK, same as Y<X<1> > x3;
Y<X<6>1>> x4; // syntax error
Y<X<6>1>> x5; // OK
```

— end example]

5 The keyword template shall not appear immediately after a declarative nested-name-specifier (7.5.5.3).

6 A name prefixed by the keyword template shall be followed by a template argument list or refer to a class
template or an alias template. The latter case is deprecated (D.9). The keyword template shall not appear
immediately before a ~ token (as to name a destructor).

[Note 3: The keyword template cannot be applied to non-template members of class templates. — end note]

[Note 4: As is the case with the typename prefix, the template prefix is well-formed even when lookup for the name
would already find a template. — end note]

[Example 3:

```c
template <class T> struct A {
    void f(int);
    template <class U> void f(U);
};
```

```c
template <class T> void f(T t) {
    A<T> a;
    a.template f<(t); // OK, calls template
```
a.template f(t); // error: not a template-id
}

template <class T> struct B {
    template <class T2> struct C {
    }
    
    // deprecated: T::C is assumed to name a class template:
    template <class T, template <class X> class TT = T::template C> struct D {
    }
    D<B<int>> > db;
    — end example
}

7 A template-id is valid if
(7.1) — there are at most as many arguments as there are parameters or a parameter is a template parameter

(7.2) — there is an argument for each non-deducible non-pack parameter that does not have a default template-

(7.3) — each template-argument matches the corresponding template-parameter (13.4),

(7.4) — substitution of each template argument into the following template parameters (if any) succeeds, and

(7.5) — if the template-id is non-dependent, the associated constraints are satisfied as specified in the next

A simple-template-id shall be valid unless it names a function template specialization (13.10.3).

Example 4:

```cpp
template<class T, T::type n = 0> class X;
struct S {
    using type = int;
};
using T1 = X<S, int, int>;
    // error: too many arguments
using T2 = X<>;
    // error: no default argument for first template parameter
using T3 = X<int>;
    // error: value 1 does not match type-parameter
using T4 = X<int>;
    // error: substitution failure for second template parameter
using T5 = X<S>;
    // OK
— end example
```

8 When the template-name of a simple-template-id names a constrained non-function template or a constrained

template template-parameter, and all template-arguments in the simple-template-id are non-dependent (13.8.3.5),

the associated constraints (13.5.3) of the constrained template shall be satisfied (13.5.2).

Example 5:

```cpp
template<typename T> concept C1 = sizeof(T) != sizeof(int);

template<C1 T> struct S1 {}

template<C1 T> using Ptr = T*;

S1<int>* p;
    // error: constraints not satisfied
Ptr<int> p;
    // error: constraints not satisfied

template<typename T>
struct S2 { Ptr<int> x; }
    // ill-formed, no diagnostic required

template<typename T>
struct S3 { Ptr<T> x; }
    // OK, satisfaction is not required

S3<int> x;
    // error: constraints not satisfied

template<template<C1 T> class X>
struct S4 {
    X<int> x;
    // ill-formed, no diagnostic required
};
```

§ 13.3

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382
template<typename T> concept C2 = sizeof(T) == 1;

template<C2 T> struct S { }; // error: constraints not satisfied

template struct S<char[2]>; // error: constraints not satisfied

—end example

9 A concept-id is a simple-template-id where the template-name is a concept-name. A concept-id is a prvalue of type bool, and does not name a template specialization. A concept-id evaluates to true if the concept’s normalized constraint-expression (13.5.3) is satisfied (13.5.2) by the specified template arguments and false otherwise.

[Note 5: Since a constraint-expression is an unevaluated operand, a concept-id appearing in a constraint-expression is not evaluated except as necessary to determine whether the normalized constraints are satisfied. —end note]

[Example 6:
    template<typename T> concept C = true;
    static_assert(C<int>); // OK
—end example]

13.4 Template arguments

13.4.1 General

There are three forms of template-argument, corresponding to the three forms of template-parameter: type, non-type and template. The type and form of each template-argument specified in a template-id shall match the type and form specified for the corresponding parameter declared by the template in its template-parameter-list. When the parameter declared by the template is a template parameter pack (13.7.4), it will correspond to zero or more template-arguments.

[Example 1:
    template<class T> class Array {
    T* v;
    int sz;
    public:
      explicit Array(int);
      T& operator[](int);
      T& elem(int i) { return v[i]; }
    };
    Array<int> v1(20);
    typedef std::complex<double> dcomplex; // std::complex is a standard library template
    Array<dcomplex> v2(30);
    Array<dcomplex> v3(40);
    void bar() {
      v1[3] = 7;
      v2[3] = v3.elem(4) = dcomplex(7,8);
    }
—end example]

2 The template argument list of a template-head is a template argument list in which the nth template argument has the value of the nth template parameter of the template-head. If the nth template parameter is a template parameter pack (13.7.4), the nth template argument is a pack expansion whose pattern is the name of the template parameter pack.

3 In a template-argument, an ambiguity between a type-id and an expression is resolved to a type-id, regardless of the form of the corresponding template-parameter.\(^{112}\)

[Example 2:
    template<class T> void f();
    template<int I> void f();

\(^{112}\)There is no such ambiguity in a default template-argument because the form of the template-parameter determines the allowable forms of the template-argument.]
void g() {
    f<int>(); // int() is a type-id: call the first f()
}
—end example

[Note 1: Names used in a template-argument are subject to access control where they appear. Because a template-parameter is not a class member, no access control applies. —end note]

[Example 3:

template<class T> class X {
    static T t;
};

class Y {
private:
    struct S { /* ... */
        X<S> x; // OK, S is accessible
        X<Y::S> y; // error: S not accessible
    };
    X<Y::S> y; // error: S not accessible
—end example]

For a template argument that is a class type or a class template, the template definition has no special access rights to the members of the template argument.

[Example 4:

template <template <class TT> class T> class A {
    typename T<int>::S s;
};
template <class U> class B {
private:
    struct S { /* ... */
    };
    A<B> b; // error: A has no access to B::S
—end example]

5 When template argument packs or default template arguments are used, a template-argument list can be empty. In that case the empty <> brackets shall still be used as the template-argument-list.

[Example 5:

template<class T = char> class String;
String<>* p; // OK, String<char>
String* q; // syntax error

template<class ... Elements> class Tuple;
Tuple<>* t; // OK, Elements is empty
Tuple* u; // syntax error
—end example]

6 An explicit destructor call (11.4.7) for an object that has a type that is a class template specialization may explicitly specify the template-arguments.

[Example 6:

template<class T> struct A {
    ~A();
};
void f(A<int>** p, A<int>** q) {
    p->A<int>::~A(); // OK, destructor call
    q->A<int>::~A<int>(); // OK, destructor call
}
—end example]
If the use of a template argument gives rise to an ill-formed construct in the instantiation of a template specialization, the program is ill-formed.

When name lookup for the component name of a template-id finds an overload set, both non-template functions in the overload set and function templates in the overload set for which the template-arguments do not match the template-parameters are ignored.

[Note 2: If none of the function templates have matching template-parameters, the program is ill-formed. — end note]

When a simple-template-id does not name a function, a default template-argument is implicitly instantiated (13.9.2) when the value of that default argument is needed.

[Example 7:

```cpp
template<
    typename T, typename U = int
>
struct S { };
S<bool>* p; // the type of p is S<bool, int>*
```

The default argument for U is instantiated to form the type S<bool, int>*. — end example]

A template-argument followed by an ellipsis is a pack expansion (13.7.4).

13.4.2 Template type arguments

A template-argument for a template-parameter which is a type shall be a type-id.

[Example 1:

```cpp
template <class T> class X { };
template <class T> void f(T t) { }
struct { } unnamed_obj;

void f() {
    struct A { };
    enum { e1 };
typedef struct { } B;
    B b;
    X<A> x1;     // OK
    X<A> x2;     // OK
    X<B> x3;     // OK
    f(e1);
    f(unnamed_obj); // OK
    f(b);        // OK
}
```

— end example]

[Note 1: A template type argument can be an incomplete type (6.8.1). — end note]

13.4.3 Template non-type arguments

If the type T of a template-parameter (13.2) contains a placeholder type (9.2.9.7) or a placeholder for a deduced class type (9.2.9.8), the type of the parameter is the type deduced for the variable \( x \) in the invented declaration

\[
T \ x = E
\]

where E is the template argument provided for the parameter.

[Note 1: \( E \) is a template-argument or (for a default template argument) an initializer-clause. — end note]

If a deduced parameter type is not permitted for a template-parameter declaration (13.2), the program is ill-formed.

The value of a non-type template-parameter \( P \) of (possibly deduced) type \( T \) is determined from its template argument \( A \) as follows. If \( T \) is not a class type and \( A \) is not a braced-init-list, \( A \) shall be a converted constant expression (7.7) of type \( T \); the value of \( P \) is \( A \) (as converted).

Otherwise, a temporary variable

```cpp
constexpr T v = A;
```

is introduced. The lifetime of \( v \) ends immediately after initializing it and any template parameter object (see below). For each such variable, the id-expression \( v \) is termed a candidate initializer.
If \( T \) is a class type, a template parameter object (13.2) exists that is constructed so as to be template-argument-equivalent to \( v \). \( P \) denotes that template parameter object. \( P \) is copy-initialized from an unspecified candidate initializer that is template-argument-equivalent to \( v \). If, for the initialization from any candidate initializer,

1. the initialization would be ill-formed, or
2. the full-expression of an invented \textit{init-declarator} for the initialization would not be a constant expression when interpreted as a \textit{constant-expression} (7.7), or
3. the initialization would cause \( P \) to not be template-argument-equivalent (13.6) to \( v \), the program is ill-formed.

Otherwise, the value of \( P \) is that of \( v \).

For a non-type \textit{template-parameter} of reference or pointer type, or for each non-static data member of reference or pointer type in a non-type \textit{template-parameter} of class type or subobject thereof, the reference or pointer value shall not refer to or be the address of (respectively):

1. a temporary object (6.7.7),
2. a string literal object (5.13.5),
3. the result of a \texttt{typeid} expression (7.6.1.8),
4. a predefined \texttt{__func__} variable (9.5.1), or
5. a subobject (6.7.2) of one of the above.

[Example 1:]

```cpp
template<const int* pci> struct X { /* ... */ }; int ai[10]; X<ai> xi; // array to pointer and qualification conversions

struct Y { /* ... */ }; template<const Y& b> struct Z { /* ... */ }; Y y; Z<y> z; // no conversion, but note extra cv-qualification

template<int (&pa)[5]> struct W { /* ... */ }; int b[5]; W<b> w; // no conversion

void f(char); void f(int);

template<void (*pf)(int)> struct A { /* ... */ }; A<&f> a; // selects f(int)

template<auto n> struct B { /* ... */ }; B<5> b1; // OK, template parameter type is int B<'a'> b2; // OK, template parameter type is char B<2.5> b3; // OK, template parameter type is double B<void(0)> b4; // error: template parameter type cannot be void

template<int i> struct C { /* ... */ }; C<42> c1; // OK

struct J1 { J1 *self = this; }; B<J1*> j1; // error: initialization of template parameter object is not a constant expression

struct J2 { J2 *self = this; constexpr J2() {} }
```

§ 13.4.3
constexpr J2(const J2&) {}

B<J2{}> j2; // error: template parameter object not template-argument-equivalent to introduced temporary
— end example]

8 [Note 2: A string-literal (5.13.5) is not an acceptable template-argument for a template-parameter of non-class type.

[Example 2:

template<class T, T p> class X {
    /* ... */
};

X<const char*, "Studebaker"> x; // error: string literal object as template-argument
X<const char*, "Knope" + 1> x2; // error: subobject of string literal object as template-argument

const char p[] = "Vivisectionist";
X<const char*, p> y; // OK

struct A {
    constexpr A(const char*) {}
};

X<A, "Pyrophoricity"> z; // OK, string-literal is a constructor argument to A
— end example]
— end note]

9 [Note 3: A temporary object is not an acceptable template-argument when the corresponding template-parameter has reference type.

[Example 3:

template<const int& CRI> struct B { /* ... */ };  

B<1> b1; // error: temporary would be required for template argument
int c = 1;
B<c> b2; // OK

struct X { int n; };
struct Y { const int &x; };
template<Y y> struct C { /* ... */ };  
C<Y{X{1}.n}> c; // error: subobject of temporary object used to initialize
// reference member of template parameter
— end example]
— end note]

13.4.4 Template template arguments [temp.arg.template]

A template-argument for a template template-parameter shall be the name of a class template or an alias template, expressed as id-expression. Only primary templates are considered when matching the template template argument with the corresponding parameter; partial specializations are not considered even if their parameter lists match that of the template template parameter.

Any partial specializations (13.7.6) associated with the primary template are considered when a specialization based on the template template-parameter is instantiated. If a specialization is not reachable from the point of instantiation, and it would have been selected had it been reachable, the program is ill-formed, no diagnostic required.

[Example 1:

template<class T> class A { // primary template
    int x;
};
template<class T> class A<T*> { // partial specialization
    long x;
};

§ 13.4.4 ©ISO/IEC 387
template<template<class U> class V> class C {
  V<int> y;
  V<int*> z;
};
C<A> c; // V<int> within C<A> uses the primary template, so c.y.x has type int
          // V<int*> within C<A> uses the partial specialization, so c.z.x has type long

—end example

A template-argument matches a template template-parameter P when P is at least as specialized as the template-argument A. In this comparison, if P is unconstrained, the constraints on A are not considered. If P contains a template parameter pack, then A also matches P if each of A’s template parameters matches the corresponding template parameter in the template-head of P. Two template parameters match if they are of the same kind (type, non-type, template), for non-type template-parameters, their types are equivalent (13.7.7.2), and for template template-parameters, each of their corresponding template-parameters matches, recursively. When P’s template-head contains a template parameter pack (13.7.4), the template parameter pack will match zero or more template parameters or template parameter packs in the template-head of A with the same type and form as the template parameter pack in P (ignoring whether those template parameters are template parameter packs).

[Example 2:]

    template<class T> class A { /* ... */ }
    template<class T, class U = T> class B { /* ... */ }
    template<class ... Types> class C { /* ... */ }
    template<auto n> class D { /* ... */ }
    template<template<class> class P> class X { /* ... */ }
    template<template<class ...> class Q> class Y { /* ... */ }
    template<template<int> class R> class Z { /* ... */ }
    X<A> xa; // OK
    X<B> xb; // OK
    X<C> xc; // OK
    Y<A> ya; // OK
    Y<B> yb; // OK
    Y<C> yc; // OK
    Z<D> zd; // OK

—end example

[Example 3:]

    template <class T> struct eval;
    template <template <class, class...> class TT, class T1, class... Rest>
    struct eval<TT<T1, Rest...>> { };
    template <class T1> struct A;
    template <class T1, class T2> struct B;
    template <int N> struct C;
    template <class T1, int N> struct D;
    template <class T1, class T2, int N = 17> struct E;
    eval<A<int>> eA; // OK, matches partial specialization of eval
    eval<A<int, float>> eB; // OK, matches partial specialization of eval
    eval<C<int>> eC; // error: C does not match TT in partial specialization
    eval<C<int, float>> eD; // error: D does not match TT in partial specialization
    eval<C<int, float>> eE; // error: E does not match TT in partial specialization

—end example

[Example 4:]

    template<typename T> concept C = requires (T t) { t.f(); };
    template<typename T> concept D = C<T> && requires (T t) { t.g(); };
    template<template<C> class P> struct S { };

§ 13.4.4
A template `template-parameter P` is at least as specialized as a template `template-argument A` if, given the following rewrite to two function templates, the function template corresponding to `P` is at least as specialized as the function template corresponding to `A` according to the partial ordering rules for function templates (13.7.7.3). Given an invented class template `X` with the `template-head` of `A` (including default arguments and `requires-clause`, if any):

(4.1) — Each of the two function templates has the same template parameters and `requires-clause` (if any), respectively, as `P` or `A`.

(4.2) — Each function template has a single function parameter whose type is a specialization of `X` with template arguments corresponding to the template parameters from the respective function template where, for each template parameter `PP` in the `template-head` of the function template, a corresponding template argument `AA` is formed. If `PP` declares a template parameter pack, then `AA` is the pack expansion `PP...` (13.7.4); otherwise, `AA` is the `id-expression` `PP`.

If the rewrite produces an invalid type, then `P` is not at least as specialized as `A`.

### 13.5 Template constraints

#### 13.5.1 General

A `constraint` is a sequence of logical operations and operands that specifies requirements on template arguments. The operands of a logical operation are constraints. There are four different kinds of constraints:

1. **conjunctions** `(13.5.2.2),`
2. **disjunctions** `(13.5.2.2),`
3. **atomic constraints** `(13.5.2.3),` and
4. **fold expanded constraints** `(13.5.2.4).`

In order for a constrained template to be instantiated (13.9), its associated constraints (13.5.3) shall be satisfied as described in the following subclauses.

[Note 1: Forming the name of a specialization of a class template, a variable template, or an alias template (13.3) requires the satisfaction of its constraints. Overload resolution (12.2.3) requires the satisfaction of constraints on functions and function templates. — end note]

#### 13.5.2.2 Logical operations

There are two binary logical operations on constraints: conjunction and disjunction.

[Note 1: These logical operations have no corresponding C++ syntax. For the purpose of exposition, conjunction is spelled using the symbol `∧` and disjunction is spelled using the symbol `∨`. The operands of these operations are called the left and right operands. In the constraint `A ∧ B`, `A` is the left operand, and `B` is the right operand. — end note]

A **conjunction** is a constraint taking two operands. To determine if a conjunction is `satisfied`, the satisfaction of the first operand is checked. If that is not satisfied, the conjunction is not satisfied. Otherwise, the conjunction is satisfied if and only if the second operand is satisfied.

A **disjunction** is a constraint taking two operands. To determine if a disjunction is `satisfied`, the satisfaction of the first operand is checked. If that is satisfied, the disjunction is satisfied. Otherwise, the disjunction is satisfied if and only if the second operand is satisfied.
template<typename T>
constexpr bool get_value() { return T::value; }

template<typename T>
requires (sizeof(T) > 1) && (get_value<T>())
void f(T);  // has associated constraint sizeof(T) > 1 \&\& get_value<T>()

void f(int);  // OK, calls f(int)

In the satisfaction of the associated constraints (13.5.3) of f, the constraint sizeof(char) > 1 is not satisfied; the second operand is not checked for satisfaction. —end example

Example 2:

template <class T> concept sad = false;

template <class T> int f1(T) requires (!sad<T>);

// ambiguous, !sad<T> atomic constraint expressions (13.5.2.3)
int i1 = f1(42);  // are not formed from the same expression

template <class T> int f2(T) requires not_sad<T> && true;
int i2 = f2(42);  // OK, !sad<T> atomic constraint expressions both come from not_sad

template <class T> int f3(T) requires (!sad<typename T::type>);
int i3 = f3(42);  // error: associated constraints not satisfied due to substitution failure

template <class T> concept sad_nested_type = sad<typename T::type>;

template <class T> int f4(T) requires (!sad_nested_type<T>);
int i4 = f4(42);  // OK, substitution failure contained within sad_nested_type

Here, requires (1sadtypename T::type>) requires that there is a nested type that is not sad, whereas requires (1sad_nested_type<T>) requires that there is no sad nested type. —end example

—end note

13.5.2.3 Atomic constraints [temp.constr.atomic]

An atomic constraint is formed from an expression E and a mapping from the template parameters that appear within E to template arguments that are formed via substitution during constraint normalization in the declaration of a constrained entity (and, therefore, can involve the unsubstituted template parameters of the constrained entity), called the parameter mapping (13.5.3).

[Note 1: Atomic constraints are formed by constraint normalization (13.5.4). E is never a logical AND expression (7.6.14) nor a logical OR expression (7.6.15). —end note]

Two atomic constraints, e1 and e2, are identical if they are formed from the same appearance of the same expression and if, given a hypothetical template A whose template-parameter-list consists of template-parameters corresponding and equivalent (13.7.7.2) to those mapped by the parameter mappings of the expression, a template-id naming A whose template-arguments are the targets of the parameter mapping of e1 is the same (13.6) as a template-id naming A whose template-arguments are the targets of the parameter mapping of e2.

[Note 2: The comparison of parameter mappings of atomic constraints operates in a manner similar to that of declaration matching with alias template substitution (13.7.8).

[Example 1:

template <unsigned N> constexpr bool Atomic = true;

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390
template <unsigned N> concept C = Atomic<N>;

int x = f<0>();    // OK, the atomic constraints from concept C in both f's are Atomic<N>
with mapping similar to N → 2 * M + 1

As specified in 13.7.7.2, if the validity or meaning of the program depends on whether two constructs are equivalent, and they are functionally equivalent but not equivalent, the program is ill-formed, no diagnostic required.

Example 2:

template <unsigned N> void f2()
  requires Add1<2 * N>;

template <unsigned N> int f2()
  requires Add1<2 * N> && true;

void h2() {
  f2<0>();    // ill-formed, no diagnostic required:
  // requires determination of subsumption between atomic constraints that are
  // functionally equivalent but not equivalent
}

—end example
—end note

To determine if an atomic constraint is satisfied, the parameter mapping and template arguments are first substituted into its expression. If substitution results in an invalid type or expression in the immediate context of the atomic constraint (13.10.3.1), the constraint is not satisfied. Otherwise, the lvalue-to-rvalue conversion (7.3.2) is performed if necessary, and \( \text{E} \) shall be a constant expression of type bool. The constraint is satisfied if and only if evaluation of \( \text{E} \) results in true. If, at different points in the program, the satisfaction result is different for identical atomic constraints and template arguments, the program is ill-formed, no diagnostic required.

Example 3:

```cpp
template<typename T> concept C =
  sizeof(T) == 4 && !true;

template<typename T> struct S {
  constexpr operator bool() const { return true; }
};

template<typename T> requires (S<T>{})
  void f(T);
  // #1
  void f(int);    // #2

void g() {
  f(0);    // error: expression S<int>{} does not have type bool
  // while checking satisfaction of deduced arguments of #1;
  // call is ill-formed even though #2 is a better match
}
```

—end example
13.5.2.4 Fold expanded constraint

A fold expanded constraint is formed from a constraint \( C \) and a fold-operator which can either be && or ||. A fold expanded constraint is a pack expansion (13.7.4). Let \( N \) be the number of elements in the pack expansion parameters (13.7.4).

A fold expanded constraint whose fold-operator is && is satisfied if it is a valid pack expansion and if \( N = 0 \) or if for each \( i \) where \( 0 \leq i < N \) in increasing order, \( C \) is satisfied when replacing each pack expansion parameter with the corresponding \( i \)th element. No substitution takes place for any \( i \) greater than the smallest \( i \) for which the constraint is not satisfied.

A fold expanded constraint whose fold-operator is || is satisfied if it is a valid pack expansion, \( N > 0 \), and if for \( i \) where \( 0 \leq i < N \) in increasing order, there is a smallest \( i \) for which \( C \) is satisfied when replacing each pack expansion parameter with the corresponding \( i \)th element. No substitution takes place for any \( i \) greater than the smallest \( i \) for which the constraint is satisfied.

Note 1: If the pack expansion expands packs of different size, then it is invalid and the fold expanded constraint is not satisfied. — end note

Two fold expanded constraints are compatible for subsumption if their respective constraints both contain an equivalent unexpanded pack (13.7.7.2).

13.5.3 Constrained declarations

A template declaration (13.1) or templated function declaration (9.3.4.6) can be constrained by the use of a requires-clause. This allows the specification of constraints for that declaration as an expression:

\[
\text{constraint-expression} = \text{logical-or-expression}
\]

Constraints can also be associated with a declaration through the use of type-constraints in a template-parameter-list or parameter-type-list. Each of these forms introduces additional constraint-expressions that are used to constrain the declaration.

A declaration’s associated constraints are defined as follows:

(3.1) — If there are no introduced constraint-expressions, the declaration has no associated constraints.

(3.2) — Otherwise, if there is a single introduced constraint-expression, the associated constraints are the normal form (13.5.4) of that expression.

(3.3) — Otherwise, the associated constraints are the normal form of a logical AND expression (7.6.14) whose operands are in the following order:

(3.3.1) — the constraint-expression introduced by each type-constraint (13.2) in the declaration’s template-parameter-list, in order of appearance, and

(3.3.2) — the constraint-expression introduced by a requires-clause following a template-parameter-list (13.1), and

(3.3.3) — the constraint-expression introduced by each type-constraint in the parameter-type-list of a function declaration, and

(3.3.4) — the constraint-expression introduced by a trailing requires-clause (9.3) of a function declaration (9.3.4.6).

The formation of the associated constraints establishes the order in which constraints are instantiated when checking for satisfaction (13.5.2).

Example 1:

```cpp
template<typename T> concept C = true;

template<C T> void f1(T);
template<typename T> requires C<T> void f2(T);
template<typename T> void f3(T) requires C<T>;
```

The functions f1, f2, and f3 have the associated constraint C<T>.

```cpp
template<typename T> concept C1 = true;
template<typename T> concept C2 = sizeof(T) > 0;

template<C1 T> void f4(T) requires C2<T>;
template<typename T> requires C1<T> && C2<T> void f5(T);
```
The associated constraints of \( f_4 \) and \( f_5 \) are \( C_1 < T > \land C_2 < T > \).

\[
\text{template}<C_1 T> \text{ requires } C_2<T> \text{ void } f_6(); \\
\text{template}<C_2 T> \text{ requires } C_1<T> \text{ void } f_7();
\]

The associated constraints of \( f_6 \) are \( C_1 < T > \land C_2 < T > \), and those of \( f_7 \) are \( C_2 < T > \land C_1 < T > \). — end example

When determining whether a given introduced constraint-expression \( C_1 \) of a declaration in an instantiated specialization of a templated class is equivalent (13.7.7.2) to the corresponding constraint-expression \( C_2 \) of a declaration outside the class body, \( C_1 \) is instantiated. If the instantiation results in an invalid expression, the constraint-expressions are not equivalent.

Note 1: This can happen when determining which member template is specialized by an explicit specialization declaration. — end note

Example 2:

```cpp
template<class T> concept C = true;
template<class T> struct A {
    template<class U> U f(U) requires C<typename T::type>; // #1
    template<class U> U f(U) requires C<T>; // #2
};
```

```cpp
template<> template<class U>
U A<int>::f(U u) requires C<int> { return u; } // OK, specializes #2
```

Substituting \( \text{int} \) for \( T \) in \( C<\text{typename } T::\text{type}> \) produces an invalid expression, so the specialization does not match \#1. Substituting \( \text{int} \) for \( T \) in \( C<T> \) produces \( C<\text{int}> \), which is equivalent to the constraint-expression for the specialization, so it does match \#2. — end example

13.5.4 Constraint normalization [temp.constr.normal]

1 The normal form of an expression \( E \) is a constraint (13.5.2) that is defined as follows:

1.1 The normal form of an expression \( (E) \) is the normal form of \( E \).
1.2 The normal form of an expression \( E_1 \land E_2 \) is the disjunction (13.5.2.2) of the normal forms of \( E_1 \) and \( E_2 \).
1.3 The normal form of an expression \( E_1 \land E_2 \) is the conjunction of the normal forms of \( E_1 \) and \( E_2 \).
1.4 The normal form of a concept-id \( C<A_1, A_2, \ldots, A_n> \) is the normal form of the constraint-expression of \( C \), after substituting \( A_1, A_2, \ldots, A_n \) for \( C \)'s respective template parameters in the parameter mappings in each atomic constraint. If any such substitution results in an invalid type or expression, the program is ill-formed; no diagnostic is required.

Example 1:

```cpp
template<typename T> concept A = T::value \| true;
template<typename U> concept B = A<U*>; // #1
template<typename V> concept C = B<V&>; // #2
```

Normalization of \( B \)'s constraint-expression is valid and results in \( T::value \) (with the mapping \( T \rightarrow U^* \)) \lor true (with an empty mapping), despite the expression \( T::value \) being ill-formed for a pointer type \( T \). Normalization of \( C \)'s constraint-expression results in the program being ill-formed, because it would form the invalid type \( V^* \) in the parameter mapping. — end example

1.5 For a fold-operator (7.5.7) that is either \&\& or \|\|, the normal form of an expression \( (\ldots \text{ fold-operator } E \ldots) \) is the normal form of \( (E \text{ fold-operator } \ldots) \).
1.6 For a fold-operator that is either \&\& or \|\|, the normal form of an expression \( (E_1 \text{ fold-operator } \ldots) \) \( \text{ fold-operator } E_2 \) \( \ldots \) is the normal form of

1.6.1 \( (E_1 \text{ fold-operator } \ldots) \) fold-operator \( E_2 \) if \( E_1 \) contains an unexpanded pack, or
1.6.2 \( E_1 \text{ fold-operator } (E_2 \text{ fold-operator } \ldots) \) otherwise.

1.7 The normal form of \( (E \&\& \ldots) \) is a fold expanded constraint (13.5.2.4) whose constraint is the normal form of \( E \) and whose fold-operator is \&\&.

1.8 The normal form of \( (E \|\| \ldots) \) is a fold expanded constraint whose constraint is the normal form of \( E \) and whose fold-operator is \|\|.

1.9 The normal form of any other expression \( E \) is the atomic constraint whose expression is \( E \) and whose parameter mapping is the identity mapping.
The process of obtaining the normal form of a constraint-expression is called normalization.

[Note 1: Normalization of constraint-expressions is performed when determining the associated constraints (13.5.2) of a declaration and when evaluating the value of an id-expression that names a concept specialization (7.5.5). — end note]

[Example 2:

```cpp
template<typename T> concept C1 = sizeof(T) == 1;
template<typename T> concept C2 = C1<T> && 1 == 2;
template<typename T> concept C3 = requires { typename T::type; };
template<typename T> concept C4 = requires (T x) { ++x; };
```

The associated constraints of #1 are `sizeof(T) == 1` (with mapping T → U) ∧ 1 == 2.
The associated constraints of #2 are `requires { typename T::type; }` (with mapping T → U).
The associated constraints of #3 are `requires (T x) { ++x; }` (with mapping T → U). — end example]

### 13.5.5 Partial ordering by constraints

A constraint $P$ subsumes a constraint $Q$ if and only if, for every disjunctive clause $P_i$ in the disjunctive normal form\(^{113}\) of $P$, $P_i$ subsumes every conjunctive clause $Q_j$ in the conjunctive normal form\(^{114}\) of $Q$, where

1. a disjunctive clause $P_i$ subsumes a conjunctive clause $Q_j$ if and only if there exists an atomic constraint $P_{ia}$ in $P_i$ for which there exists an atomic constraint $Q_{jb}$ in $Q_j$ such that $P_{ia}$ subsumes $Q_{jb}$.
2. an atomic constraint $A$ subsumes another atomic constraint $B$ if and only if $A$ and $B$ are identical using the rules described in 13.5.2.3, and
3. a fold expanded constraint $A$ subsumes another fold expanded constraint $B$ if they are compatible for subsumption, have the same fold-operator, and the constraint of $A$ subsumes that of $B$.

[Example 1: Let $A$ and $B$ be atomic constraints (13.5.2.3). The constraint $A ∧ B$ subsumes $A$, but $A$ does not subsume $A ∧ B$. The constraint $A$ subsumes $A ∨ B$, but $A ∨ B$ does not subsume $A$. Also note that every constraint subsumes itself. — end example]

[Note 1: The subsumption relation defines a partial ordering on constraints. This partial ordering is used to determine

1. the best viable candidate of non-template functions (12.2.4),
2. the address of a non-template function (12.3),
3. the matching of template template arguments (13.4.4),
4. the partial ordering of class template specializations (13.7.6.3), and
5. the partial ordering of function templates (13.7.7.3). — end note]

A declaration $D1$ is at least as constrained as a declaration $D2$ if

1. $D1$ and $D2$ are both constrained declarations and $D1$’s associated constraints subsume those of $D2$; or
2. $D2$ has no associated constraints.

A declaration $D1$ is more constrained than another declaration $D2$ when $D1$ is at least as constrained as $D2$, and $D2$ is not at least as constrained as $D1$.

[Example 2:

```cpp
template<typename T> concept C1 = requires(T t) { --t; };
template<typename T> concept C2 = C1<T> & & requires(T t) { *t; };
```

The associated constraints of #1 are `requires(T t) { --t; }`.
The associated constraints of #2 are `requires(T t) { *t; }`.

---

\(^{113}\) A constraint is in disjunctive normal form when it is a disjunction of clauses where each clause is a conjunction of atomic constraints. For atomic constraints $A$, $B$, and $C$, the disjunctive normal form of the constraint $A ∧ (B ∨ C)$ is $(A ∧ B) ∨ (A ∧ C)$. Its disjunctive clauses are $(A ∧ B)$ and $(A ∧ C)$.

\(^{114}\) A constraint is in conjunctive normal form when it is a conjunction of clauses where each clause is a disjunction of atomic constraints. For atomic constraints $A$, $B$, and $C$, the constraint $A ∨ (B ∧ C)$ is in conjunctive normal form. Its conjunctive clauses are $A$ and $(B ∧ C)$.
13.6 Type equivalence

Two template-ids are the same if

1. Their template-names, operator-function-ids, or literal-operator-ids refer to the same template, and
2. Their corresponding type template-arguments are the same type, and
3. The template parameter values determined by their corresponding non-type template arguments (13.4.3) are template-argument-equivalent (see below), and
4. Their corresponding template template-arguments refer to the same template.

Two template-ids that are the same refer to the same class, function, or variable.

Two values are template-argument-equivalent if they are of the same type and

1. They are of integral type and their values are the same, or
2. They are of floating-point type and their values are identical, or
3. They are of type std::nullptr_t, or
4. They are of enumeration type and their values are the same, or
5. They are of pointer type and they have the same pointer value, or
6. They are of pointer-to-member type and they refer to the same class member or are both the null member pointer value, or
7. They are of reference type and they refer to the same object or function, or
8. They are of array type and their corresponding elements are template-argument-equivalent, or
9. They are of union type and either they both have no active member or they have the same active member and their active members are template-argument-equivalent, or
10. They are of a closure type (7.5.6.2), or
11. They are of class type and their corresponding direct subobjects and reference members are template-argument-equivalent.

Example 1:

```cpp
template<class E, int size> class buffer { /* ... */ };  
buffer<char,2*512> x;    
buffer<char,1024> y;    
declares x and y to be of the same type, and

template<class T, void(*err_fct)()> class list { /* ... */ };  
list<int,&error_handler1> x1;    
list<int,&error_handler2> x2;    
list<int,&error_handler2> x3;    
list<char,&error_handler2> x4;    
declares x2 and x3 to be of the same type. Their type differs from the types of x1 and x4.

template<class T> struct X { };  
template<class> struct Y { };  
template<class T> using Z = Y<T>;  
X<Y<int>> > y;    
X<Z<int>> > z;    
declares y and z to be of the same type. — end example]
```

Example 2:

```cpp
f(0);  // selects #1  
f((int*)0);  // selects #2  
g(true);  // selects #3 because C1<bool> is not satisfied  
g(0);  // selects #4
```

115) The identity of enumerators is not preserved.
116) An array as a template-parameter decays to a pointer.
[Note 1: However, such a type might be aliased, e.g., by a typedef-name. — end note]

For a type template parameter pack T, T... [constant-expression] denotes a unique dependent type.

If the constant-expression of a pack-index-specifier is value-dependent, two such pack-index-specifiers refer to the same type only if their constant-expressions are equivalent (13.7.7.2). Otherwise, two such pack-index-specifiers refer to the same type only if their indexes have the same value.

13.7 Template declarations

13.7.1 General

1 The template parameters of a template are specified in the angle bracket enclosed list that immediately follows the keyword template.

2 A primary template declaration is one in which the name of the template is not followed by a template-argument-list. The template argument list of a primary template is the template argument list of its template-head (13.4). A template declaration in which the name of the template is followed by a template-argument-list is a partial specialization (13.7.6) of the template named in the declaration, which shall be a class or variable template.

3 For purposes of name lookup and instantiation, default arguments, type-constraints, requires-clause(s) (13.1), and noexcept-specifiers of function templates and of member functions of class templates are considered definitions; each default argument, type-constraint, requires-clause, or noexcept-specifier is a separate definition which is unrelated to the templated function definition or to any other default arguments, type-constraints, requires-clause(s), or noexcept-specifiers. For the purpose of instantiation, the substatements of a constexpr if statement (8.5.2) are considered definitions.

4 Because an alias-declaration cannot declare a template-id, it is not possible to partially or explicitly specialize an alias template.

13.7.2 Class templates

13.7.2.1 General

1 A class template defines the layout and operations for an unbounded set of related types.

2 [Example 1: It is possible for a single class template List to provide an unbounded set of class definitions: one class List<T> for every type T, each describing a linked list of elements of type T. Similarly, a class template Array describing a contiguous, dynamic array can be defined like this:

```
template<class T> class Array {
  T* v;
  int sz;
  public:
    explicit Array(int);
    T& operator[](int);
    T& elem(int i) { return v[i]; }
};
```

The prefix template<class T> specifies that a template is being declared and that a type-name T can be used in the declaration. In other words, Array is a parameterized type with T as its parameter. — end example]

3 [Note 1: When a member of a class template is defined outside of the class template definition, the member definition is defined as a template definition with the template-head equivalent to that of the class template. The names of the template parameters used in the definition of the member can differ from the template parameter names used in the class template definition. The class template name in the member definition is followed by the template argument list of the template-head (13.4).

[Example 2:

```
template<class T1, class T2> struct A {
  void f1();
  void f2();
};

template<class T2, class T1> void A<T2,T1>::f1() { } // OK
template<class T2, class T1> void A<T1,T2>::f2() { } // error

template<class ... Types> struct B {
  void f3();
  void f4();
};
```
template<class ... Types> void B<Types ...>::f3() { } // OK

// OK

// error

// error: no matching declaration for S<T>

// OK

// OK, template-heads match

// ill-formed, no diagnostic required: template-heads are functionally equivalent but not equivalent

—in end example]

—in end note]

4 In a partial specialization, explicit specialization or explicit instantiation of a class template, the class-key shall agree in kind with the original class template declaration (9.2.9.5).

13.7.2.2 Member functions of class templates [temp.mem.func]

A member function of a class template may be defined outside of the class template definition in which it is declared.

[Example 1:

template<class T> class Array {
  T* v;
  int sz;
public:
  explicit Array(int);
  T& operator[](int i) { return v[i]; }
};

declares three member functions of a class template. The subscript function can be defined like this:

template<class T> T& Array<T>::operator[](int i) {
  if (i<0 || sz<=i) error("Array: range error");
  return v[i];
}

A constrained member function can be defined out of line:

template<typename T> concept C = requires {
  typename T::type;
};

template<typename T> struct S {
  void f() requires C<T>;
  void g() requires C<T>;
};

template<typename T>
  void S<T>::f() requires C<T> { } // OK

// error: no matching function in S<T>

—in end example]
The template-arguments for a member function of a class template are determined by the template-arguments of the type of the object for which the member function is called.

Example 2: The template-argument for Array<T>::operator[] will be determined by the Array to which the subscripting operation is applied.

```cpp
Array<int> v1(20);
Array<dcomplex> v2(30);

v1[3] = 7;         // Array<int>::operator[]
v2[3] = dcomplex(7,8); // Array<dcomplex>::operator[]
```

13.7.2.3 Deduction guides

Deduction guides are used when a template-name appears as a type specifier for a deduced class type (9.2.9.8). Deduction guides are not found by name lookup. Instead, when performing class template argument deduction (12.2.2.9), all reachable deduction guides declared for the class template are considered.

```
deduction-guide:
  explicit-specifier_opt template-name ( parameter-declaration-clause ) requires-clause_opt -> simple-template-id;
```

Example 1:

```cpp
template<class T, class D = int>
struct S {
  T data;
};
template<class U>
S(U) -> S<typename U::type>;

struct A {
  using type = short;
  operator type();
};
S x(A());       // x is of type S<short, int>
```

The same restrictions apply to the parameter-declaration-clause of a deduction guide as in a function declaration (9.3.4.6), except that a generic parameter type placeholder (9.2.9.7) shall not appear in the parameter-declaration-clause of a deduction guide. The simple-template-id shall name a class template specialization. The template-name shall be the same identifier as the template-name of the simple-template-id. A deduction-guide shall inhabit the scope to which the corresponding class template belongs and, for a member class template, have the same access. Two deduction guide declarations for the same class template shall not have equivalent parameter-declaration-clauses if either is reachable from the other.

13.7.2.4 Member classes of class templates

A member class of a class template may be defined outside the class template definition in which it is declared.

Note 1: The member class must be defined before its first use that requires an instantiation (13.9.2). For example,

```cpp
template<class T> struct A {
  class B;
};
A<int>::B* b1;         // OK, requires A to be defined but not A::B
```

13.7.2.5 Static data members of class templates

A definition for a static data member or static data member template may be provided in a namespace scope enclosing the definition of the static member’s class template.

Example 1:

```cpp
template<class T> class X {
  static T s;
};
```
template<class T> T X<T>::s = 0;

struct limits {
    template<class T>
        static const T min;  // declaration
};

template<class T>
    const T limits::min = { };  // definition
— end example]

2 An explicit specialization of a static data member declared as an array of unknown bound can have a different
bound from its definition, if any.

[Example 2:
    template <class T> struct A {
        static int i[];
    };
    template <class T> int A<T>::i[4];  // 4 elements
    template <> int A<int>::i[] = { 1 };  // OK, 1 element
— end example]

13.7.2.6 Enumeration members of class templates

An enumeration member of a class template may be defined outside the class template definition.

[Example 1:
    template<class T> struct A {
        enum E : T;
    };
    A<int> a;
    template<class T> enum A<T>::E : T { e1, e2 };
    A<int>::E e = A<int>::e1;
— end example]

13.7.3 Member templates

A template can be declared within a class or class template; such a template is called a member template. A
member template can be defined within or outside its class definition or class template definition. A member
template of a class template that is defined outside of its class template definition shall be specified with a
template-head equivalent to that of the class template followed by a template-head equivalent to that of the
member template (13.7.7.2).

[Example 1:
    template<class T> struct string {
        template<class T2> int compare(const T2&);
        template<class T2> string(const string<T2>& s) { /* ... */ }
    };
    template<class T> template<class T2> int string<T>::compare(const T2& s) {
    }
— end example]

[Example 2:
    template<typename T> concept C1 = true;
    template<typename T> concept C2 = sizeof(T) <= 4;

    template<C1 T> struct S {
        template<C2 U> void f(U);
        template<C2 U> void g(U);
    };

    template<C1 T> template<C2 U>
        void S<T>::f(U) { }  // OK

§ 13.7.3 ©ISO/IEC 399
A local class of non-closure type shall not have member templates. Access control rules (11.8) apply to member template names. A destructor shall not be a member template. A non-template member function (9.3.4.6) with a given name and type and a member function template of the same name, which could be used to generate a specialization of the same type, can both be declared in a class. When both exist, a use of that name and type refers to the non-template member unless an explicit template argument list is supplied.

[Example 3:]

```cpp
template <class T> struct A {
   void f(int);
   template <class T2> void f(T2);
};

template <> void A<int>::f(int) { } // non-template member function
template <> template <> void A<int>::f<>(int) { } // member function template specialization

int main() {
   A<char> ac;
   ac.f(1);      // non-template
   ac.f('c');   // template
   ac.f<>(1);   // template
}
```

A member function template shall not be declared virtual.

[Example 4:]

```cpp
template <class T> struct AA {
   template <class C> virtual void g(C); // error
   virtual void f();                     // OK
};
```

A specialization of a member function template does not override a virtual function from a base class.

[Example 5:]

```cpp
class B {
   virtual void f(int);
};

class D : public B {
   template <class T> void f(T); // does not override B::f(int)
   void f(int i) { f<>(i); } // overriding function that calls the function template specialization
};
```

[Note 1: A specialization of a conversion function template is referenced in the same way as a non-template conversion function that converts to the same type (11.4.8.3).]

[Example 6:]

```cpp
struct A {
   template <class T> operator T*();
};

template <class T> A::operator T*() { return 0; }
template <> A::operator char*() { return 0; } // specialization
template A::operator void*(); // explicit instantiation

int main() {
   A a;
   int* ip;
   ip = a.operator int*(); // explicit call to template operator A::operator int*()
}
```
There is no syntax to form a template-id (13.3) by providing an explicit template argument list (13.10.2) for a conversion function template. —end note

13.7.4 Variadic templates

A template parameter pack is a template parameter that accepts zero or more template arguments.

[Example 1:

```cpp
template<class ... Types> struct Tuple { }

Tuple<> t0; // Types contains no arguments
Tuple<int> t1; // Types contains one argument: int
Tuple<int, float> t2; // Types contains two arguments: int and float
Tuple<0> error; // error: 0 is not a type
```

—end example]

A function parameter pack is a function parameter that accepts zero or more function arguments.

[Example 2:

```cpp
template<class ... Types> void f(Types ... args);

f(); // args contains no arguments
f(1); // args contains one argument: int
f(2, 1.0); // args contains two arguments: int and double
```

—end example]

An init-capture pack is a lambda capture that introduces an init-capture for each of the elements in the pack expansion of its initializer.

[Example 3:

```cpp
template <typename... Args>
void foo(Args... args) {
    [...]xs=args{
        bar(xs...); // xs is an init-capture pack
    }
}  // xs contains one init-capture
```

—end example]

A pack is a template parameter pack, a function parameter pack, or an init-capture pack. The number of elements of a template parameter pack or a function parameter pack is the number of arguments provided for the parameter pack. The number of elements of an init-capture pack is the number of elements in the pack expansion of its initializer.

A pack expansion consists of a pattern and an ellipsis, the instantiation of which produces zero or more instantiations of the pattern in a list (described below). The form of the pattern depends on the context in which the expansion occurs. Pack expansions can occur in the following contexts:

- In a function parameter pack (9.3.4.6); the pattern is the parameter-declaration without the ellipsis.
- In a using-declaration (9.9); the pattern is a using-declarator.
- In a friend-type-declaration (11.4.1); the pattern is a friend-type-specifier.
- In a template parameter pack that is a pack expansion (13.2):
  - if the template parameter pack is a parameter-declaration; the pattern is the parameter-declaration without the ellipsis;
  - if the template parameter pack is a type-parameter; the pattern is the corresponding type-parameter without the ellipsis.
- In an initializer-list (9.4); the pattern is an initializer-clause.
- In a base-specifier-list (11.7); the pattern is a base-specifier.
In a `mem-initializer-list` (11.9.3) for a `mem-initializer` whose `mem-initializer-id` denotes a base class; the pattern is the `mem-initializer`.

In a `template-argument-list` (13.4); the pattern is a `template-argument`.

In an `attribute-list` (9.12.1); the pattern is an `attribute`.

In an `alignment-specifier` (9.12.2); the pattern is the `alignment-specifier` without the ellipsis.

In a `capture-list` (7.5.6.3); the pattern is the `capture` without the ellipsis.

In a `sizeof...` expression (7.6.2.5); the pattern is an `identifier`.

In a `pack-index-expression`; the pattern is an `identifier`.

In a `pack-index-specifier`; the pattern is a `typedef-name`.

In a `fold-expression` (7.5.7); the pattern is the `cast-expression` that contains an unexpanded pack.

In a `fold expanded constraint` (13.5.4.4); the pattern is the constraint of that fold expanded constraint.

```cpp
[Example 4:
  template<class ... Types> void f(Types ... rest);
  template<class ... Types> void g(Types ... rest) {
    f(&rest ...); // "&rest ..." is a pack expansion; "&rest" is its pattern
  }
  
  — end example]
```

For the purpose of determining whether a pack satisfies a rule regarding entities other than packs, the pack is considered to be the entity that would result from an instantiation of the pattern in which it appears.

A pack whose name appears within the pattern of a pack expansion is expanded by that pack expansion. An appearance of the name of a pack is only expanded by the innermost enclosing pack expansion. The pattern of a pack expansion shall name one or more packs that are not expanded by a nested pack expansion; such packs are called unexpanded packs in the pattern. All of the packs expanded by a pack expansion shall have the same number of arguments specified. An appearance of a name of a pack that is not expanded is ill-formed.

```cpp
[Example 5:
  template<
    typename...> struct Tuple {};
  template<
    typename T1, typename T2> struct Pair {};

  template<class ... Args1> struct zip {
    template<class ... Args2> struct with {
      typedef Tuple<Pair<Args1, Args2> ... > type;
    };
  };

  typedef zip<
    short, int>::with<
    unsigned short, unsigned>::type T1; // T1 is Tuple<Pair<short, unsigned short>, Pair<int, unsigned>>
  typedef zip<
    short>::with<
    unsigned short, unsigned>::type T2; // error: different number of arguments specified for Args1 and Args2

template<class ... Args>
  void g(Args ... args) {
    f(const_cast<const Args*>(&args)...); // OK, Args is expanded by the function parameter pack args
    f(5 ...); // error: pattern does not contain any packs
    f(args);
    f(b(args ...) + args ...); // OK, first "args" expanded within b,
    // second "args" expanded within f
  }
  
  — end example]
```

The instantiation of a pack expansion considers items $E_1, E_2, \ldots, E_N$, where $N$ is the number of elements in the pack expansion parameters. Each $E_i$ is generated by instantiating the pattern and replacing each pack expansion parameter with its $i^{th}$ element. Such an element, in the context of the instantiation, is interpreted as follows:
— if the pack is a template parameter pack, the element is an id-expression (for a non-type template parameter pack), a typedef-name (for a type template parameter pack declared without template), or a template-name (for a type template parameter pack declared with template), designating the i\(^{th}\) corresponding type or value template argument;

— if the pack is a function parameter pack, the element is an id-expression designating the i\(^{th}\) function parameter that resulted from instantiation of the function parameter pack declaration; otherwise

— if the pack is an init-capture pack, the element is an id-expression designating the variable introduced by the i\(^{th}\) init-capture that resulted from instantiation of the init-capture pack declaration.

When \(N\) is zero, the instantiation of a pack expansion does not alter the syntactic interpretation of the enclosing construct, even in cases where omitting the pack expansion entirely would otherwise be ill-formed or would result in an ambiguity in the grammar.

The instantiation of a sizeof... expression (7.6.2.5) produces an integral constant with value \(N\).

When instantiating a pack-index-expression \(P\), let \(K\) be the index of \(P\). The instantiation of \(P\) is the id-expression \(E_{K}\).

When instantiating a pack-index-specifier \(P\), let \(K\) be the index of \(P\). The instantiation of \(P\) is the typedef-name \(E_{K}\).

The instantiation of an alignment-specifier with an ellipsis produces \(E_{1} E_{2} \ldots E_{N}\).

The instantiation of a fold-expression (7.5.7) produces:

1. For a unary left fold:
   - \(((E_{1} op E_{2}) op \cdots) op E_{N})\)
2. For a unary right fold:
   - \((E_{1} op (\cdots op (E_{N−1} op E_{N})))\)
3. For a binary left fold:
   - \(((E_{1} op E_{2}) op \cdots) op E_{N})\)
4. For a binary right fold:
   - \((E_{1} op (\cdots op (E_{N−1} op (E_{N} op E))))\)

In each case, \(op\) is the fold-operator. For a binary fold, \(E\) is generated by instantiating the cast-expression that did not contain an unexpanded pack.

**Table 20 — Value of folding empty sequences**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Value when pack is empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;&amp;</td>
<td>true</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>,</td>
<td>void()</td>
</tr>
</tbody>
</table>

A fold expanded constraint is not instantiated (13.5.2.4).

The instantiation of any other pack expansion produces a list of elements \(E_{1}, E_{2}, \ldots, E_{N}\).

When \(N\) is zero, the instantiation of the expansion produces an empty list.

**Example 6:**

```cpp
template<typename ...Args>
bool all(Args ...args) { return (... && args); }

bool b = all(true, true, true, false);
```

Within the instantiation of all, the returned expression expands to \(((true \&\& true) \&\& true) \&\& false\), which evaluates to false. —end example]

If \(N\) is zero for a unary fold, the value of the expression is shown in Table 20; if the operator is not listed in Table 20, the instantiation is ill-formed.
template void f<>();  // OK, X<> has no base classes
// x is a variable of type X<> that is value-initialized

— end example]

13.7.5 Friends

A friend of a class or class template can be a function template or class template, a specialization of a function template or class template, or a non-template function or class.

[Example 1:

template<class T> class task;
template<class T> task<T> * preempt(task<T> *);

template<class T> class task {
friend void next_time();
friend void process(task<T> *);
friend task<T> * preempt<T>(task<T> *);
template<class C> friend int func(C);

friend class task<int>;
template<class P> friend class frd;
};

Here, each specialization of the task class template has the function next_time as a friend; because process does not have explicit template-arguments, each specialization of the task class template has an appropriately typed function process as a friend, and this friend is not a function template specialization; because the friend preempt has an explicit template-argument T, each specialization of the task class template has the appropriate specialization of the function template preempt as a friend; and each specialization of the task class template has all specializations of the function template func as friends. Similarly, each specialization of the task class template has the class template specialization task<int> as a friend, and has all specializations of the class template frd as friends. — end example]

2 Friend classes, class templates, functions, or function templates can be declared within a class template. When a template is instantiated, its friend declarations are found by name lookup as if the specialization had been explicitly declared at its point of instantiation.

[Note 1: They can introduce entities that belong to an enclosing namespace scope (9.3.4), in which case they are attached to the same module as the class template (10.1). — end note]

3 A friend template may be declared within a class or class template. A friend function template may be defined within a class or class template, but a friend class template may not be defined in a class or class template. In these cases, all specializations of the friend class or friend function template are friends of the class or class template granting friendship.

[Example 2:

class A {
    template<class T> friend class B;  // OK
    template<class T> friend void f(T) { /* ... */ }  // OK
};

— end example]

4 A template friend declaration specifies that all specializations of that template, whether they are implicitly instantiated (13.9.2), partially specialized (13.7.6) or explicitly specialized (13.9.4), are friends of the class containing the template friend declaration.

[Example 3:

class X {
    template<class T> friend struct A;
    class Y { }
};

template<class T> struct A { X::Y ab; };  // OK
template<class T> struct A<T> { X::Y ab; };  // OK

— end example]

5 A template friend declaration may declare a member of a dependent type to be a friend. The friend declaration shall declare a function or specify a type with an elaborated-type-specifier, in either case with a

§ 13.7.5 ©ISO/IEC 404
nested-name-specifier ending with a simple-template-id, \( C \), whose template-name names a class template. The template parameters of the template friend declaration shall be deducible from \( C \) (13.10.3.6). In this case, a member of a specialization \( S \) of the class template is a friend of the class granting friendship if deduction of the template parameters of \( C \) from \( S \) succeeds, and substituting the deduced template arguments into the friend declaration produces a declaration that corresponds to the member of the specialization.

[Example 4:

```cpp
template<class T> struct A {
    struct B { }
    void f();
    struct D {
        void g();
    }
    T h();
    template<T U> T i();
};
template<> struct A<int> {
    struct B { }
    int f();
    struct D {
        void g();
    }
    template<int U> int i();
};
template<> struct A<float*> {
    int *h();
};
class C {
    template<class T> friend struct A<T>::B; // grants friendship to A<int>::B even though
    template<class T> friend void A<T>::f(); // it is not a specialization of A<T>::B
    template<class T> friend void A<T>::D::g(); // does not grant friendship to A<int>::f()
    template<class T> friend int *A<T>::h(); // because its return type does not match
    template<class T> template<T U>
        friend T A<T>::i();
};
```—end example]

6 A friend template shall not be declared in a local class.
7 Friend declarations shall not declare partial specializations.

[Example 5:

```cpp
template<class T> class A { }
class X {
    template<class T> friend class A<T*>; // error
}
```—end example]

8 When a friend declaration refers to a specialization of a function template, the function parameter declarations shall not include default arguments, nor shall the `inline`, `constexpr`, or `consteval` specifiers be used in such a declaration.
9 A non-template friend declaration with a `requires-clause` shall be a definition. A friend function template with a constraint that depends on a template parameter from an enclosing template shall be a definition. Such a constrained friend function or function template declaration does not declare the same function or function template as a declaration in any other scope.

13.7.6 Partial specialization

13.7.6.1 General

A partial specialization of a template provides an alternative definition of the template that is used instead of the primary definition when the arguments in a specialization match those given in the partial specialization
A declaration of the primary template shall precede any partial specialization of that template. A partial specialization shall be reachable from any use of a template specialization that would make use of the partial specialization as the result of an implicit or explicit instantiation; no diagnostic is required.

Two partial specialization declarations declare the same entity if they are partial specializations of the same template and have equivalent template-heads and template argument lists (13.7.7.2). Each partial specialization is a distinct template.

[Example 1:

```cpp
template<class T1, class T2, int I> class A { };  
template<class T, int I> class A<T, T*, I> { };  
template<class T1, class T2, int I> class A<T1*, T2, I> { };  
template<class T> class A<int, T*, 5> { };  
template<class T1, class T2, int I> class A<T1, T2*, I> { };  
```

The first declaration declares the primary (unspecialized) class template. The second and subsequent declarations declare partial specializations of the primary template. —end example]

A partial specialization may be constrained (13.5).

[Example 2:

```cpp
template<typename T> concept C = true;  
template<typename T> struct X { };  
template<typename T> struct X<T*> { };  // #1  
template<C T> struct X<T> { };  // #2  
```

Both partial specializations are more specialized than the primary template. #1 is more specialized because the deduction of its template arguments from the template argument list of the class template specialization succeeds, while the reverse does not. #2 is more specialized because the template arguments are equivalent, but the partial specialization is more constrained (13.5.5). —end example]

The template argument list of a partial specialization is the template-argument-list following the name of the template.

A partial specialization may be declared in any scope in which the corresponding primary template may be defined (9.3.4, 11.4, 13.7.3).

[Example 3:

```cpp
namespace N {  
    template<class T1, class T2> class A { }; // primary template  
}  
using N::A; // refers to the primary template  
```

—end example]

Partial specialization declarations do not introduce a name. Instead, when the primary template name is used, any reachable partial specializations of the primary template are also considered.

[Note 1: One consequence is that a using-declaration which refers to a class template does not restrict the set of partial specializations that are found through the using-declaration. —end note]


namespace N {
    template<class T> class A<T, T*> { }; // partial specialization
}

A<int,int*> a; // uses the partial specialization, which is found through the using-declaration
    // which refers to the primary template

— end example]

8 A non-type argument is non-specialized if it is the name of a non-type parameter. All other non-type arguments are specialized.

9 Within the argument list of a partial specialization, the following restrictions apply:

(9.1) — The type of a template parameter corresponding to a specialized non-type argument shall not be dependent on a parameter of the partial specialization.

[Example 5:]
    template <class T, T t> struct C {};  
    template <class T> struct C<T, 1>;     // error

    template< int X, int (*array_ptr)[X] > class A {};  
    int array[5];  
    template< int X > class A<X,&array> { };  // error

— end example]

(9.2) — The partial specialization shall be more specialized than the primary template (13.7.6.3).

(9.3) — The template parameter list of a partial specialization shall not contain default template argument values.117

(9.4) — An argument shall not contain an unexpanded pack. If an argument is a pack expansion (13.7.4), it shall be the last argument in the template argument list.

10 The usual access checking rules do not apply to non-dependent names used to specify template arguments of the simple-template-id of the partial specialization.

[Note 2: The template arguments can be private types or objects that would normally not be accessible. Dependent names cannot be checked when declaring the partial specialization, but will be checked when substituting into the partial specialization. — end note]

13.7.6.2 Matching of partial specializations [temp.spec.partial.match]

1 When a template is used in a context that requires an instantiation of the template, it is necessary to determine whether the instantiation is to be generated using the primary template or one of the partial specializations. This is done by matching the template arguments of the template specialization with the template argument lists of the partial specializations.

(1.1) — If exactly one matching partial specialization is found, the instantiation is generated from that partial specialization.

(1.2) — If more than one matching partial specialization is found, the partial order rules (13.7.6.3) are used to determine whether one of the partial specializations is more specialized than the others. If such a partial specialization exists, the instantiation is generated from that partial specialization; otherwise, the use of the template is ambiguous and the program is ill-formed.

(1.3) — If no matches are found, the instantiation is generated from the primary template.

2 A partial specialization matches a given actual template argument list if the template arguments of the partial specialization can be deduced from the actual template argument list (13.10.3), and the deduced template arguments satisfy the associated constraints of the partial specialization, if any (13.5.3).

[Example 1:]
    template<class T1, class T2, int I> class A  { };  // #1
    template<class T, int I>         class A<T, T*, I>  { };  // #2
    template<class T1, class T2, int I> class A<T1*, T2, I> { };  // #3
    template<class T>                class A<int, T*, 5> { };  // #4
    template<class T1, class T2, int I> class A<T1, T2*, I> { };  // #5

117) There is no context in which they would be used.
A<int, int, 1> a1; // uses #1
A<int, int*, 1> a2; // uses #2, T is int, I is 1
A<int, char*, 5> a3; // uses #4, T is char
A<int, char*, 1> a4; // uses #5, T1 is int, T2 is char, I is 1
A<int*, int*, 2> a5; // ambiguous: matches #3 and #5

— end example]  

Example 2:

```cpp
template<typename T> concept C = requires (T t) { t.f(); };

template<typename T> struct S { };
// #1

template<C T> struct S<T> { };
// #2

struct Arg { void f(); };
S<int> s1; // uses #1; the constraints of #2 are not satisfied
S<Arg> s2; // uses #2; both constraints are satisfied but #2 is more specialized

— end example
```

3 If the template arguments of a partial specialization cannot be deduced because of the structure of its template-parameter-list and the template-id, the program is ill-formed.

Example 3:

```cpp
template <int I, int J> struct A {};  
template <int I> struct A<I+5, I*2> {}; // error

template <int I> struct A<I, I> {};  // OK

template <int I, int J, int K> struct B {};  
template <int I> struct B<I, I*2, 2> {}; // OK

— end example
```

4 In a name that refers to a specialization of a class or variable template (e.g., A<int, int, 1>), the argument list shall match the template parameter list of the primary template. The template arguments of a partial specialization are deduced from the arguments of the primary template.

13.7.6.3 Partial ordering of partial specializations [temp.spec.partial.order]

For two partial specializations, the first is more specialized than the second if, given the following rewrite to two function templates, the first function template is more specialized than the second according to the ordering rules for function templates (13.7.7.3):

(1.1) Each of the two function templates has the same template parameters and associated constraints (13.5.3) as the corresponding partial specialization.

(1.2) Each function template has a single function parameter whose type is a class template specialization where the template arguments are the corresponding template parameters from the function template for each template argument in the template-argument-list of the simple-template-id of the partial specialization.

Example 1:

```cpp
template<int I, int J, class T> class X { };

template<int I> class X<I, J> { };
// #1

template<int I> class X<I, I> { };  // #2

template<int I0, int J0> void f(X<I0, J0, int>);  // A

template<int I0> void f(X<I0, I0, int>);  // B

template <auto v> class Y { };

template <auto* p> class Y<p> { };
// #3

template <auto** pp> class Y<pp> { };  // #4

template <auto* p0> void g(Y<p0>);  // C

template <auto** pp0> void g(Y<pp0>);  // D
```
According to the ordering rules for function templates, the function template \( B \) is more specialized than the function template \( A \) and the function template \( D \) is more specialized than the function template \( C \). Therefore, the partial specialization \#2 is more specialized than the partial specialization \#1 and the partial specialization \#4 is more specialized than the partial specialization \#3. — end example

[Example 2:

```cpp
template<typename T> concept C = requires (T t) { t.f(); };  
template<typename T> concept D = C<T> && requires (T t) { t.f(); };  

template<typename T> class S { };  
template<C T> class S<T> { }; // #1  
template<D T> class S<T> { }; // #2  

template<C T> void f(S<T>); // A  
template<D T> void f(S<T>); // B  
```

The partial specialization \#2 is more specialized than \#1 because \( B \) is more specialized than \( A \). — end example]

13.7.6.4 Members of class template partial specializations [temp.spec.partial.member]

1 The members of the class template partial specialization are unrelated to the members of the primary template. Class template partial specialization members that are used in a way that requires a definition shall be defined; the definitions of members of the primary template are never used as definitions for members of a class template partial specialization. An explicit specialization of a member of a class template partial specialization is declared in the same way as an explicit specialization of a member of the primary template.

[Example 1:

```cpp
// primary class template  
template<class T, int I> struct A {  
    void f();  
};  

// member of primary class template  
template<class T, int I> void A<T,I>::f() { }  

// class template partial specialization  
template<class T> struct A<T,2> {  
    void f();  
    void g();  
    void h();  
};  

// member of class template partial specialization  
template<class T> void A<T,2>::g() { }  

// explicit specialization  
template<> void A<char,2>::h() { }  
```

```cpp
int main() {  
    A<char,0> a0;  
    A<char,2> a2;  
    a0.f(); // OK, uses definition of primary template's member  
    a2.f(); // OK, uses definition of partial specialization's member  
    a2.h(); // OK, uses definition of explicit specialization's member  
    a2.f(); // error: no definition of f for A<T,2>; the primary template is not used here  
}
```

— end example]

2 If a member template of a class template is partially specialized, the member template partial specializations are member templates of the enclosing class template; if the enclosing class template is instantiated (13.9.2, 13.9.3), a declaration for every member template partial specialization is also instantiated as part of creating the members of the class template specialization. If the primary member template is explicitly specialized for a given (implicit) specialization of the enclosing class template, the partial specializations of the member template are ignored for this specialization of the enclosing class template. If a partial specialization of the member template is explicitly specialized for a given (implicit) specialization of the enclosing class template,
the primary member template and its other partial specializations are still considered for this specialization
of the enclosing class template.

[Example 2:

```cpp
template<class T> struct A {
  template<class T2> struct B {};
  template<class T2> struct B<T2*> {};
};

template<> template<class T2> struct A<short>::B {};
A<char>::B<int*> abcip; // uses #2
A<short>::B<int*> absip; // uses #3
A<char>::B<int> abci; // uses #1

-- end example]
```

13.7.7 Function templates
13.7.7.1 General

A function template defines an unbounded set of related functions.

[Example 1: A family of sort functions can be declared like this:

```cpp
template<class T> class Array {
  template<class T> void sort(Array<T>&);
}
```

-- end example]

2 [Note 1: A function template can have the same name as other function templates and non-template functions (9.3.4.6) in the same scope. -- end note]

A non-template function is not related to a function template (i.e., it is never considered to be a specialization), even if it has the same name and type as a potentially generated function template specialization.\(^{118}\)

13.7.7.2 Function template overloading

It is possible to overload function templates so that two different function template specializations have the same type.

[Example 1:

```cpp
// translation unit 1:
template<class T>
void f(T*);
void g(int* p) {
  f(p); // calls f<int*>(int*)
}

// translation unit 2:
template<class T>
void f(T);
void h(int* p) {
  f(p); // calls f<int*>(int*)
}
```

-- end example]

2 Such specializations are distinct functions and do not violate the one-definition rule (6.3).

3 The signature of a function template is defined in Clause 3. The names of the template parameters are significant only for establishing the relationship between the template parameters and the rest of the signature.

[Note 1: Two distinct function templates can have identical function return types and function parameter lists, even if overload resolution alone cannot distinguish them.

```cpp
template<class T> void f();
template<int I> void f(); // OK, overloads the first template
// distinguishable with an explicit template argument list
```

-- end note]

4 When an expression that references a template parameter is used in the function parameter list or the return type in the declaration of a function template, the expression that references the template parameter is part of the signature of the function template. This is necessary to permit a declaration of a function template in one translation unit to be linked with another declaration of the function template in another translation

\(^{118}\) That is, declarations of non-template functions do not merely guide overload resolution of function template specializations with the same name. If such a non-template function is odr-used (6.3) in a program, it must be defined; it will not be implicitly instantiated using the function template definition.
unit and, conversely, to ensure that function templates that are intended to be distinct are not linked with one another.

[Example 2:

```cpp
template <int I, int J> A<I+J> f(A<I>, A<J>); // #1
template <int K, int L> A<K+L> f(A<K>, A<L>); // same as #1
template <int I, int J> A<I-J> f(A<I>, A<J>); // different from #1
```

—end example]

[Note 2: Most expressions that use template parameters use non-type template parameters, but it is possible for an expression to reference a type parameter. For example, a template type parameter can be used in the `sizeof` operator. —end note]

Two expressions involving template parameters are considered equivalent if two function definitions containing the expressions would satisfy the one-definition rule (6.3), except that the tokens used to name the template parameters may differ as long as a token used to name a template parameter in one expression is replaced by another token that names the same template parameter in the other expression. Two unevaluated operands that do not involve template parameters are considered equivalent if two function definitions containing the expressions would satisfy the one-definition rule, except that the tokens used to name types and declarations may differ as long as they name the same entities, and the tokens used to form concept-ids (13.3) may differ as long as the two template-ids are the same (13.6).

[Note 3: For instance, `A<42>` and `A<40+2>` name the same type. —end note]

Two lambda-expressions are never considered equivalent.

[Note 4: The intent is to avoid lambda-expressions appearing in the signature of a function template with external linkage. —end note]

For determining whether two dependent names (13.8.3) are equivalent, only the name itself is considered, not the result of name lookup.

[Note 5: If such a dependent name is unqualified, it is looked up from a first declaration of the function template (13.8.1). —end note]

[Example 3:

```cpp
template <int I, int J> void f(A<I>J>); // #1
template <int K, int L> void f(A<K>L>); // same as #1

template <class T> decltype(g(T())) h();
int g(int);
template <class T> decltype(g(T())) h() // redeclaration of h() uses the earlier lookup...
  { return g(T()); } // ...although the lookup here does find g(int)
int i = h<int>(); // template argument substitution fails; g(int)
// not considered at the first declaration of h()
```

// ill-formed, no diagnostic required: the two expressions are functionally equivalent but not equivalent
template <int N> void foo(const char (*)[N]);
template <int N> void foo(const char (*)[N]);

// two different declarations because the non-dependent portions are not considered equivalent
template <class T> void spam(decltype([N]{}) (*s)[sizeof(T)]);
template <class T> void spam(decltype([N]{}) (*s)[sizeof(T)]);

—end example]

Two potentially-evaluated expressions involving template parameters that are not equivalent are functionally equivalent if, for any given set of template arguments, the evaluation of the expression results in the same value. Two unevaluated operands that are not equivalent are functionally equivalent if, for any given set of template arguments, the expressions perform the same operations in the same order with the same entities.

[Note 6: For instance, one could have redundant parentheses. —end note]

[Example 4:

```cpp
template<int I> concept C = true;
template<typename T> struct A {
  void f() requires C<42>; // #1
  void f() requires true; // OK, different functions
};
```

§ 13.7.7.2 © ISO/IEC
Two template-heads are equivalent if their template-parameter-lists have the same length, corresponding template-parameters are equivalent and are both declared with type-constraints that are equivalent if either template-parameter is declared with a type-constraint, and if either template-head has a requires-clause, they both have requires-clauses and the corresponding constraint-expressions are equivalent. Two template-parameters are equivalent under the following conditions:

1. they declare template parameters of the same kind,
2. if either declares a template parameter pack, they both do,
3. if they declare non-type template parameters, they have equivalent types ignoring the use of type-constraints for placeholder types, and
4. if they declare template template parameters, their template parameters are equivalent.

When determining whether types or type-constraints are equivalent, the rules above are used to compare expressions involving template parameters. Two template-heads are functionally equivalent if they accept and are satisfied by (13.5.2) the same set of template argument lists.

If the validity or meaning of the program depends on whether two constructs are equivalent, and they are functionally equivalent but not equivalent, the program is ill-formed, no diagnostic required. Furthermore, if two function templates that do not correspond

1. have the same name,
2. have corresponding signatures (6.4.1),
3. would declare the same entity (6.6) considering them to correspond, and
4. accept and are satisfied by the same set of template argument lists,

the program is ill-formed, no diagnostic required.

[Note 7: This rule guarantees that equivalent declarations will be linked with one another, while not requiring implementations to use heroic efforts to guarantee that functionally equivalent declarations will be treated as distinct. For example, the last two declarations are functionally equivalent and would cause a program to be ill-formed:]

```cpp
// guaranteed to be the same
template <int I> void f(A<I>, A<I+10>);
template <int I> void f(A<I>, A<I+10>);

// guaranteed to be different
template <int I> void f(A<I>, A<I+10>);
template <int I> void f(A<I>, A<I+11>);

// ill-formed, no diagnostic required
template <int I> void f(A<I>, A<I+10>);
template <int I> void f(A<I>, A<I+1+2+3+4>);
```

— end note

13.7.7.3 Partial ordering of function templates

If multiple function templates share a name, the use of that name can be ambiguous because template argument deduction (13.10.3) may identify a specialization for more than one function template. Partial ordering of overloaded function template declarations is used in the following contexts to select the function template to which a function template specialization refers:

1. during overload resolution for a call to a function template specialization (12.2.4);
2. when the address of a function template specialization is taken;
3. when a placement operator delete that is a function template specialization is selected to match a placement operator new (6.7.5.5.3, 7.6.2.8);
4. when a friend function declaration (13.7.5), an explicit instantiation (13.9.3) or an explicit specialization (13.9.4) refers to a function template specialization.

Partial ordering selects which of two function templates is more specialized than the other by transforming each template in turn (see next paragraph) and performing template argument deduction using the function type. The deduction process determines whether one of the templates is more specialized than the other.
If so, the more specialized template is the one chosen by the partial ordering process. If both deductions succeed, the partial ordering selects the more constrained template (if one exists) as determined below.

3 To produce the transformed template, for each type, non-type, or template template parameter (including template parameter packs (13.7.4) thereof) synthesize a unique type, value, or class template respectively and substitute it for each occurrence of that parameter in the function type of the template.

[Note 1: The type replacing the placeholder in the type of the value synthesized for a non-type template parameter is also a unique synthesized type. —end note]

Each function template M that is a member function is considered to have a new first parameter of type X(M), described below, inserted in its function parameter list. If exactly one of the function templates was considered by overload resolution via a rewritten candidate (12.2.2.3) with a reversed order of parameters, then the order of the function parameters in its transformed template is reversed. For a function template M with cv-qualifiers cv that is a member of a class A:

(3.1) — The type X(M) is “rvalue reference to cv A” if the optional ref-qualifier of M is && or if M has no ref-qualifier and the positionally-corresponding parameter of the other transformed template has rvalue reference type; if this determination depends recursively upon whether X(M) is an rvalue reference type, it is not considered to have rvalue reference type.

(3.2) — Otherwise, X(M) is “lvalue reference to cv A”.

[Note 2: This allows a non-static member to be ordered with respect to a non-member function and for the results to be equivalent to the ordering of two equivalent non-members. —end note]

[Example 1:

```c++
struct A { }

template<class T> struct B {
    template<class R> int operator*(R&); // #1
};

template<class T, class R> int operator*(T&, R&); // #2

// The declaration of B::operator* is transformed into the equivalent of
// template<class R> int operator*(B<A>&, R&); // #1a

int main() {
    A a;
    B<A> b;
    b * a; // calls #1
}
```

—end example]

4 Using the transformed function template’s function type, perform type deduction against the other template as described in 13.10.3.5.

[Example 2:

```c++
template<class T> struct A { A(); }

template<class T> void f(T);
template<class T> void f(T*);
template<class T> void f(const T*);

template<class T> void g(T);
template<class T> void g(T&);
template<class T> void g(const T&);

template<class T> void h(const T&);
template<class T> void h(A<T>&);

void m() {
    const int* p;
    f(p); // f(const T*) is more specialized than f(T) or f(T*)
    float x;
    g(x); // ambiguous: g(T) or g(T&)
    A<int> z;
    h(z); // overload resolution selects h(A<T>&)
```
const A<int> z2;

h(z2); // h(const T&) is called because h(A<T&>) is not callable

— end example |

5 [Note 3: Since, in a call context, such type deduction considers only parameters for which there are explicit call arguments, some parameters are ignored (namely, function parameter packs, parameters with default arguments, and ellipses).]

[Example 3:]

template<class T> void f(T); // #1
template<class T> void f(T*, int=1); // #2

template<class T> void g(T); // #3
template<class T> void g(T*, ...); // #4

int main() {
    int* ip;
    f(ip); // calls #2
    g(ip); // calls #4
}

— end example |

[Example 4:]

template<class T, class U> struct A { };

template<class T, class U> void f(U, A<U, T>* p = 0); // #1

template<class T, class U> void f(U, A<U, T>* p = 0); // #2

template<class T> void g(T, T = T()); // #3

template<class T, class... U> void g(T, U ...); // #4

void h() {
    f<int>(42, (A<int, int>*)0); // calls #2
    f<int>(42); // error: ambiguous
    g(42); // error: ambiguous
}

— end example |

[Example 5:]

template<class T, class... U> void f(T, U...); // #1

template<class T> void f(T); // #2

template<class T, class... U> void g(T*, U...); // #3

template<class T> void g(T); // #4

void h(int i) {
    f(&i); // OK, calls #2
    g(&i); // OK, calls #3
}

— end example |

— end note |

6 If deduction against the other template succeeds for both transformed templates, constraints can be considered as follows:

(6.1) — If their template-parameter-lists (possibly including template-parameters invented for an abbreviated function template (9.3.4.6)) or function parameter lists differ in length, neither template is more specialized than the other.

(6.2) — Otherwise:

(6.2.1) — If exactly one of the templates was considered by overload resolution via a rewritten candidate with reversed order of parameters:

(6.2.1.1) — If, for either template, some of the template parameters are not deducible from their function parameters, neither template is more specialized than the other.
If there is either no reordering or more than one reordering of the associated
template-parameter-list such that

- the corresponding template-parameters of the template-parameter-lists are equivalent and
- the function parameters that positionally correspond between the two templates are of
  the same type,

neither template is more specialized than the other.

Otherwise, if the corresponding template-parameters of the template-parameter-lists are not equivalent (13.7.7.2) or if the function parameters that positionally correspond between the two templates are not of the same type, neither template is more specialized than the other.

Otherwise, if the context in which the partial ordering is done is that of a call to a conversion function and the return types of the templates are not the same, then neither template is more specialized than the other.

Otherwise, if one template is more constrained than the other (13.5.5), the more constrained template is more specialized than the other.

Otherwise, neither template is more specialized than the other.

[Example 6:

```cpp
template <typename> constexpr bool True = true;
template <typename T> concept C = True<T>;

void f(C auto &a, auto &b) = delete;
template <C Q> void f(Q &a, C auto &b);

void g(struct A *ap, struct B *bp) {
    f(*ap, *bp); // OK, can use different methods to produce template parameters
}

template <typename T, typename U> struct X {};

template <typename T, C U, typename V> bool operator==(X<T, U>, V) = delete;
template <C T, C U, C V> bool operator==(T, X<U, V>);

void h() {
    X<void *, int>{0} == 0; // OK, correspondence of [T, U, V] and [U, V, T]
}
```

—end example]

13.7.8 Alias templates

A template-declaration in which the declaration is an alias-declaration (9.1) declares the identifier to be an alias template. An alias template is a name for a family of types. The name of the alias template is a template-name.

When a template-id refers to the specialization of an alias template, it is equivalent to the associated type obtained by substitution of its template-arguments for the template-parameters in the defining-type-id of the alias template.

[Note 1: An alias template name is never deduced. —end note]

[Example 1:

```cpp
template<class T> struct Alloc { /* ... */);
template<class T> using Vec = vector<T, Alloc<T>>;
Vec<int> v; // same as vector<int, Alloc<int>> v;

template<class T>
    void process(Vec<T>& v) {
        /* ... */
    }

template<class T>
    void process(vector<T, Alloc<T>>& w) {
        /* ... */ // error: redefinition
```
template<template<class> class TT>
void f(TT<int>);

f(v); // error: Vec not deduced

template<template<class,class> class TT>
void g(TT<int, Alloc<int>>);
g(v); // OK, TT = vector
— end example]

3 However, if the template-id is dependent, subsequent template argument substitution still applies to the template-id.

[Example 2:
template<typename...> using void_t = void;
template<typename T> void_t<typename T::foo> f();
f<int>(); // error: int does not have a nested type foo
— end example]

4 The defining-type-id in an alias template declaration shall not refer to the alias template being declared. The type produced by an alias template specialization shall not directly or indirectly make use of that specialization.

[Example 3:
template <class T> struct A;
template <class T> using B = typename A<T>::U;
template <class T> struct A {
  typedef B<T> U;
};
B<short> b; // error: instantiation of B<short> uses own type via A<short>::U
— end example]

5 The type of a lambda-expression appearing in an alias template declaration is different between instantiations of that template, even when the lambda-expression is not dependent.

[Example 4:
template <class T>
using A = decltype([] { }); // A<int> and A<char> refer to different closure types
— end example]

13.7.9 Concept definitions [temp.concept]

A concept is a template that defines constraints on its template arguments.

concept-definition:
  concept concept-name attribute-specifier-seq_opt = constraint-expression;

concept-name:
  identifier

A concept-definition declares a concept. Its identifier becomes a concept-name referring to that concept within its scope. The optional attribute-specifier-seq appertains to the concept.

[Example 1:
template<typename T>
concept C = requires(T x) {
  { x == x } -> std::convertible_to<bool>;
};
template<typename T>
requires C<T> // C constrains f1(T) in constraint-expression
T f1(T x) { return x; }

template<C T> // C, as a type-constraint, constrains f2(T)
T f2(T x) { return x; }
— end example]

§ 13.7.9 ©ISO/IEC
416
A concept-definition shall inhabit a namespace scope (6.4.6).

A concept shall not have associated constraints (13.5.3).

A concept is not instantiated (13.9).

[Note 1: A concept-id (13.3) is evaluated as an expression. A concept cannot be explicitly instantiated (13.9.3), explicitly specialized (13.9.4), or partially specialized (13.7.6). — end note]

The constraint-expression of a concept-definition is an unevaluated operand (7.2.3).

The first declared template parameter of a concept definition is its prototype parameter. A type concept is a concept whose prototype parameter is a type template-parameter.

13.8 Name resolution [temp.res]

13.8.1 General [temp.res.general]

A name that appears in a declaration D of a template T is looked up from where it appears in an unspecified declaration of T that either is D itself or is reachable from D and from which no other declaration of T that contains the usage of the name is reachable. If the name is dependent (as specified in 13.8.3), it is looked up for each specialization (after substitution) because the lookup depends on a template parameter.

[Note 1: Some dependent names are also looked up during parsing to determine that they are dependent or to interpret following < tokens. Uses of other names might be type-dependent or value-dependent (13.8.3.3, 13.8.3.4). A using-declarator is never dependent in a specialization and is therefore replaced during lookup for that specialization (6.5). — end note]

[Example 1:

```cpp
struct A { operator int(); };
template<class B, class T>
struct D : B {
    T get() { return operator T(); }  // conversion-function-id is dependent
};
int f(D<A, int> d) { return d.get(); }  // OK, lookup finds A::operator int
```

—end example]

[Example 2:

```cpp
void f(char);
template<class T> void g(T t) {
    f(1);                       // f(char)
    f(T(1));                    // dependent
    f(t);                       // dependent
    dd++;                       // not dependent; error: declaration for dd not found
}
```

enum E { e };  
void f(E);

doab;  
void h() {
    g(e);                     // will cause one call of f(char) followed by two calls of f(E)
    g('a');                   // will cause three calls of f(char)
}

—end example]

[Example 3:

```cpp
struct A {
    struct B { /* ... */ };
    int a;
    int Y;
};

```

int a;

```cpp
template<class T> struct Y : T {
    struct B { /* ... */ };
```
The members A::B, A::a, and A::Y of the template argument A do not affect the binding of names in Y<A>. — end example]

If the validity or meaning of the program would be changed by considering a default argument or default template argument introduced in a declaration that is reachable from the point of instantiation of a specialization (13.8.4.1) but is not found by lookup for the specialization, the program is ill-formed, no diagnostic required.

The component names of a typename-specifier are its identifier (if any) and those of its nested-name-specifier and simple-template-id (if any). A typename-specifier denotes the type or class template denoted by the simple-type-specifier (9.2.9.3) formed by omitting the keyword typename.

[Note 2: The usual qualified name lookup (6.5.5) applies even in the presence of typename. — end note]

[Example 4:

```cpp
struct A {
    struct X { }
    int X;
};
struct B {
    struct X { }
};
template<class T> void f(T t) {
    typename T::X x;
}
void foo() {
    A a;
    B b;
    f(b);    // OK, T::X refers to B::X
    f(a);    // error: T::X refers to the data member A::X not the struct A::X
}
— end example]

A qualified or unqualified name is said to be in a type-only context if it is the terminal name of

(4.1) — a typename-specifier, type-requirement, nested-name-specifier, elaborated-type-specifier, class-or-decltype, or

(4.2) — a simple-type-specifier of a friend-type-specifier, or

(4.3) — a type-specifier of a

(4.3.1) — new-type-id,

(4.3.2) — defining-type-id,

(4.3.3) — conversion-type-id,

(4.3.4) — trailing-return-type,

(4.3.5) — default argument of a type-parameter, or

(4.3.6) — type-id of a static_cast, const_cast, reinterpret_cast, or dynamic_cast, or

(4.4) — a decl-specifier of the decl-specifier-seq of a

(4.4.1) — simple-declaration or function-definition in namespace scope,

(4.4.2) — member-declaration,

(4.4.3) — parameter-declaration in a member-declaration, unless that parameter-declaration appears in a

119) This includes friend function declarations.
default argument,

— parameter-declaration in a declarator of a function or function template declaration whose declarator-id is qualified, unless that parameter-declaration appears in a default argument,

— parameter-declaration in a lambda-declarator or requirement-parameter-list, unless that parameter-declaration appears in a default argument, or

— parameter-declaration of a (non-type) template-parameter.

[Example 5:]
```
template<class T> T::R f(); // OK, return type of a function declaration at global scope
template<class T> void f(T::R); // ill-formed, no diagnostic required: attempt to declare // a void variable template
template<class T> struct S {
  using Ptr = PtrTraits<T>::Ptr;
  T::R f(T::P p) {
    return static_cast<T::R>(p);
  }
  auto g() -> S<T>::Ptr; // OK, trailing-return-type
};
template<typename T> void f() {
  void (*pf)(T::X);
  // variable pf of type void* initialized with T::X
  void g(T::X);
  // error: T::X at block scope does not denote a type
  // (attempt to declare a void variable)
}
```
— end example]

5 A qualified-id whose terminal name is dependent and that is in a type-only context is considered to denote a type. A name that refers to a using-declarator whose terminal name is dependent is interpreted as a typedef-name if the using-declarator uses the keyword typename.

[Example 6:]
```
template <class T> void f(int i) {
  T::x * i;
  // expression, not the declaration of a variable i
}
```
```
struct Foo {
  typedef int x;
};

struct Bar {
  static int const x = 5;
};

int main() {
  f<Bar>(1);  // OK
  f<Foo>(1);  // error: Foo::x is a type
}
```
— end example]

6 The validity of a templated entity may be checked prior to any instantiation.

[Note 3: Knowing which names are type names allows the syntax of every template to be checked in this way. — end note]

The program is ill-formed, no diagnostic required, if

— no valid specialization, ignoring static_assert-declarations that fail (9.1), can be generated for a templated entity or a substatement of a constexpr if statement (8.5.2) within a templated entity and the innermost enclosing template is not instantiated, or

— no valid specialization, ignoring static_assert-declarations that fail, can be generated for a default template-argument and the default template-argument is not used in any instantiation, or

— no specialization of an alias template (13.7.8) is valid and no specialization of the alias template is named in the program, or
— any constraint-expression in the program, introduced or otherwise, has (in its normal form) an atomic
constraint \( A \) where no satisfaction check of \( A \) could be well-formed and no satisfaction check of \( A \) is
performed, or

— every valid specialization of a variadic template requires an empty template parameter pack, or

— a hypothetical instantiation of a templated entity immediately following its definition would be ill-formed
due to a construct (other than a static_assert-declaration that fails) that does not depend on a template
parameter, or

— the interpretation of such a construct in the hypothetical instantiation is different from the interpretation
of the corresponding construct in any actual instantiation of the templated entity.

[Note 4: This can happen in situations including the following:

— a type used in a non-dependent name is incomplete at the point at which a template is defined but is complete
at the point at which an instantiation is performed, or

— lookup for a name in the template definition found a using-declaration, but the lookup in the corresponding
scope in the instantiation does not find any declarations because the using-declaration was a pack expansion and
the corresponding pack is empty, or

— an instantiation uses a default argument or default template argument that had not been defined at the point
at which the template was defined, or

— constant expression evaluation (7.7) within the template instantiation uses

  — the value of a const object of integral or unscoped enumeration type or

  — the value of a constexpr object or

  — the value of a reference or

  — the definition of a constexpr function,

and that entity was not defined when the template was defined, or

— a class template specialization or variable template specialization that is specified by a non-dependent simple-
template-id is used by the template, and either it is instantiated from a partial specialization that was not
defined when the template was defined or it names an explicit specialization that was not declared when the
template was defined.

—end note]

[Note 5: If a template is instantiated, errors will be diagnosed according to the other rules in this document. Exactly
when these errors are diagnosed is a quality of implementation issue. — end note]

[Example 7:

```cpp
int j;
template<class T> class X {
    void f(T t, int i, char* p) {
        t = i; // diagnosed if X::f is instantiated, and the assignment to t is an error
        p = i; // may be diagnosed even if X::f is not instantiated
        p = j; // may be diagnosed even if X::f is not instantiated
        X<T>::g(t); // OK
        X<T>::h(); // may be diagnosed even if X::f is not instantiated
    }
    void g(T t) {
        // may be diagnosed even if X::g is not instantiated
    }
};

template<class... T> struct A {
    void operator++(int, T... t); // error: too many parameters
};
template<class... T> union X : T... { }; // error: union with base class
-template<class... T> struct A : T..., T... { }; // error: duplicate base class
–end example]

7 [Note 6: For purposes of name lookup, default arguments and noexcept-specifiers of function templates and default
arguments and noexcept-specifiers of member functions of class templates are considered definitions (13.7). — end
note]
13.8.2 Locally declared names

Like normal (non-template) classes, class templates have an injected-class-name (11.1). The injected-class-name can be used as a template-name or a type-name. When it is used with a template-argument-list, as a template-argument for a template template-parameter, or as the final identifier in the elaborated-type-specifier of a friend class template declaration, it is a template-name that refers to the class template itself. Otherwise, it is a type-name equivalent to the template-name followed by the template argument list (13.7.1, 13.4.1) of the class template enclosed in <>. When the injected-class-name of a class template specialization or partial specialization is used as a type-name, it is equivalent to the template-name followed by the template-arguments of the class template specialization or partial specialization enclosed in <>. The injected-class-name of a class template or class template specialization can be used as either a template-name or a type-name wherever it is named.

Example 1:
```
template<template<class> class T> class A { }
template<class T> class Y;
template< class Y<int> { 
    Y* p;        // meaning Y<int>
    Y<char>* q;  // meaning Y<char>
    A<Y>* a;     // meaning A<::Y>
    class B { 
        template<class> friend class Y;  // meaning ::Y
    };
}
—end example—
```

Example 2:
```
template <class T> struct Base { 
    Base* p;
};
template <class T> struct Derived: public Base<T> { 
    typename Derived::Base* p;  // meaning Derived::Base<T>
};
template<class T, template<class> class U = T::Base> struct Third { 
}; Third<Derived<int> > t;  // OK, default argument uses injected-class-name as a template
—end example—
```

A lookup that finds an injected-class-name (6.5.2) can result in an ambiguity in certain cases (for example, if it is found in more than one base class). If all of the injected-class-names that are found refer to specializations of the same class template, and if the name is used as a template-name, the reference refers to the class template itself and not a specialization thereof, and is not ambiguous.

Example 3:
```
template <class T> struct Base { }
template <class T> struct Derived: Base<int>, Base<char> { 
    typename Derived::Base b;  // error: ambiguous
    typename Derived::Base<double> d;  // OK
};
—end example—
```

When the normal name of the template (i.e., the name from the enclosing scope, not the injected-class-name) is used, it always refers to the class template itself and not a specialization of the template.

Example 4:
```
template<class T> class X { 
    X* p;     // meaning X<T>
    X<T>* p2;
    X<int>* p3;
    ::X* p4;  // error: missing template argument list
```
The name of a `template-parameter` shall not be bound to any following declaration whose locus is contained by the scope to which the template-parameter belongs.

Example 5:

```cpp
template<class T, int i> class Y {
  int T; // error: template-parameter hidden
  void f() {
    char T; // error: template-parameter hidden
  }
  friend void T(); // OK, no name bound
};

// error: hidden by template-parameter

template<class X> class X;
// error: hidden by template-parameter
```

Unqualified name lookup considers the template parameter scope of a `template-declaration` immediately after the outermost scope associated with the template declared (even if its parent scope does not contain the `template-parameter-list`).

Note 1: The scope of a class template, including its non-dependent base classes (13.8.3.2, 6.5.2), is searched before its template parameter scope.

Example 6:

```cpp
struct B { };
namespace N {
typedef void V;
template<class T> struct A : B {
typedef void C;
void f();
template<class U> void g(U);
};
}
template<class V> void N::A<V>::f() { // N::V not considered here
  V v; // V is still the template parameter, not N::V
}

template<class B> template<class C> void N::A<B>::g(C) {
  B b; // B is the base class, not the template parameter
  C c; // C is the template parameter, not A's C
}
```

13.8.3 Dependent names

13.8.3.1 General

Inside a template, some constructs have semantics which may differ from one instantiation to another. Such a construct depends on the template parameters. In particular, types and expressions may depend on the type and/or value of template parameters (as determined by the template arguments) and this determines the context for name lookup for certain names. An expression may be type-dependent (that is, its type may depend on a template parameter) or value-dependent (that is, its value when evaluated as a constant expression (7.7) may depend on a template parameter) as described below.

A dependent call is an expression, possibly formed as a non-member candidate for an operator (12.2.2.3), of the form:

```cpp
postfix-expression ( expression-list_opt )
```

where the postfix-expression is an unqualified-id and

(2.1) any of the expressions in the expression-list is a pack expansion (13.7.4), or

(2.2) any of the expressions or braced-init-lists in the expression-list is type-dependent (13.8.3.3), or
The component name of an unqualified-id (7.5.5.2) is dependent if

(2.4) — it is a conversion-function-id whose conversion-type-id is dependent, or
(2.5) — it is operator= and the current class is a templated entity, or
(2.6) — the unqualified-id is the postfix-expression in a dependent call.

[Note 1: Such names are looked up only at the point of the template instantiation (13.8.4.1) in both the context of the template definition and the context of the point of instantiation (13.8.4.2). — end note]

3 [Example 1:

```cpp
template<class T> struct X : B<T> {
    typename T::A* pa;
    void f(B<T>* pb) {
        static int i = B<T>::i;
        pb->j++;
    }
};
```

The base class name `B<T>`, the type name `T::A`, the names `B<T>::i` and `pb->j` explicitly depend on the template parameter. — end example]

### 13.8.3.2 Dependent types

(temp.dep.type)

1 A name or template-id refers to the current instantiation if it is

(1.1) — in the definition of a class template, a nested class of a class template, a member of a class template, or a member of a nested class of a class template, the injected-class-name (11.1) of the class template or nested class,
(1.2) — in the definition of a primary class template or a member of a primary class template, the name of the class template followed by the template argument list of its template-head (13.4) enclosed in <> (or an equivalent template alias specialization),
(1.3) — in the definition of a nested class of a class template, the name of the nested class referenced as a member of the current instantiation, or
(1.4) — in the definition of a class template partial specialization or a member of a class template partial specialization, the name of the class template followed by a template argument list equivalent to that of the partial specialization (13.7.6) enclosed in <> (or an equivalent template alias specialization).

2 A template argument that is equivalent to a template parameter can be used in place of that template parameter in a reference to the current instantiation. For a template type-parameter, a template argument is equivalent to a template parameter if it denotes the same type. For a non-type template parameter, a template argument is equivalent to a template parameter if it is an identifier that names a variable that is equivalent to the template parameter. A variable is equivalent to a template parameter if

(2.1) — it has the same type as the template parameter (ignoring cv-qualification) and
(2.2) — its initializer consists of a single identifier that names the template parameter or, recursively, such a variable.

[Note 1: Using a parenthesized variable name breaks the equivalence. — end note]

[Example 1:

```cpp
template <class T> class A {
    A* p1; // A is the current instantiation
    A<T>* p2; // A<T> is the current instantiation
    A<T>* p3; // A<T> is not the current instantiation
    ::A<T>* p4; // ::A<T> is the current instantiation
}
class B {
    B* p1; // B is the current instantiation
    A<T>::B* p2; // A<T>::B is the current instantiation
    A<T>::B* p3; // A<T>::B is not the current instantiation
};
```

]
template <class T> class A<T*> {
    A<T*>* p1;    // A<T*> is the current instantiation
    A<T>* p2;     // A<T> is not the current instantiation
};

template <class T1, class T2, int I> struct B {
    B<T1, T2, I>* b1;    // refers to the current instantiation
    B<T2, T1, I>* b2;    // not the current instantiation
    typedef T1 my_T1;
    static const int my_I = I;
    static const int my_I2 = I+0;
    static const int my_I3 = my_I;
    static const long my_I4 = I;
    static const int my_I5 = (I);
    B<my_T1, T2, my_I2>* b3;    // refers to the current instantiation
    B<my_T1, T2, my_I3>* b4;    // not the current instantiation
    B<my_T1, T2, my_I4>* b5;    // not the current instantiation
    B<my_T1, T2, my_I5>* b6;    // not the current instantiation
    B<my_T1, T2, my_I5>* b7;    // not the current instantiation
};

— end example

3 A dependent base class is a base class that is a dependent type and is not the current instantiation.

[Note 2: A base class can be the current instantiation in the case of a nested class naming an enclosing class as a base.]

[Example 2:]

    template<class T> struct A {
    typedef int M;
    struct B {
        typedef void M;
        struct C;
    };
    };

    template<class T> struct A<T>::B::C : A<T> {
        M m;
        // OK, A<T>::M
    };

— end example

— end note

4 A qualified (6.5.5) or unqualified name is a member of the current instantiation if

(4.1) — its lookup context, if it is a qualified name, is the current instantiation, and

(4.2) — lookup for it finds any member of a class that is the current instantiation

[Example 3:]

    template <class T> class A {
    static const int i = 5;
    int n1[i];       // i refers to a member of the current instantiation
    int n2[A::i];    // A::i refers to a member of the current instantiation
    int n3[A<T>::i]; // A<T>::i refers to a member of the current instantiation
    int f();
    };

    template <class T> int A<T>::f() {
        return i;      // i refers to a member of the current instantiation
    }

— end example

A qualified or unqualified name names a dependent member of the current instantiation if it is a member of the current instantiation that, when looked up, refers to at least one member declaration (including a using-declarator whose terminal name is dependent) of a class that is the current instantiation.

5 A qualified name (6.5.5) is dependent if
it is a conversion-function-id whose conversion-type-id is dependent, or
— its lookup context is dependent and is not the current instantiation, or
— its lookup context is the current instantiation and it is operator=, or
— its lookup context is the current instantiation and has at least one dependent base class, and qualified name lookup for the name finds nothing.

[Example 4:

```cpp
struct A {
    using B = int;
    A f();
};
struct C : A {};
template<class T>
void g(T t) {
    decltype(t.A::f()):B i;  // error: typename needed to interpret B as a type
}
template void g(C);  // ...even though A is ::A here
end example]

If, for a given set of template arguments, a specialization of a template is instantiated that refers to a member of the current instantiation with a qualified name, the name is looked up in the template instantiation context. If the result of this lookup differs from the result of name lookup in the template definition context, name lookup is ambiguous.

[Example 5:

```cpp
struct A {
    int m;
};
struct B {
    int m;
};
template<typename T>
struct C : A, T {
    int f() { return this->m; }  // finds A::m in the template definition context
    int g() { return m; }  // finds A::m in the template definition context
};
template int C<B>::f();  // error: finds both A::m and B::m
template int C<B>::g();  // OK, transformation to class member access syntax
// does not occur in the template definition context; see 7.5.5.1
end example]

An initializer is dependent if any constituent expression (6.9.1) of the initializer is type-dependent. A placeholder type (9.2.9.7.1) is dependent if it designates a type deduced from a dependent initializer.

A placeholder for a deduced class type (9.2.9.8) is dependent if
— it has a dependent initializer, or
— it refers to an alias template that is a member of the current instantiation and whose defining-type-id is dependent after class template argument deduction (12.2.2.9) and substitution (13.7.8).

[Example 6:

```cpp
template<class T, class V>
struct S { S(T); }

template<class U>
struct A {
    template<class T> using X = S<T, U>;
    template<class T> using Y = S<T, int>;
}
```

Every instantiation of a class template declares a different set of assignment operators.
void f() {
    new X(1);    // dependent
    new Y(1);    // not dependent
}

A type is dependent if it is

(10.1) a template parameter,
(10.2) denoted by a dependent (qualified) name,
(10.3) a nested class or enumeration that is a direct member of a class that is the current instantiation,
(10.4) a cv-qualified type where the cv-unqualified type is dependent,
(10.5) a compound type constructed from any dependent type,
(10.6) an array type whose element type is dependent or whose bound (if any) is value-dependent,
(10.7) a function type whose parameters include one or more function parameter packs,
(10.8) a function type whose exception specification is value-dependent,
(10.9) denoted by a dependent placeholder type,
(10.10) denoted by a dependent placeholder for a deduced class type,
(10.11) denoted by a `simple-template-id` in which either the template name is a template parameter or any of the template arguments is a dependent type or an expression that is type-dependent or value-dependent
or is a pack expansion,\(^{(121)}\)
(10.12) a `pack-index-specifier`, or
(10.13) denoted by \texttt{decltype(expression)}, where \texttt{expression} is type-dependent (13.8.3.3).

\(^{11}\)[Note 3: Because typedefs do not introduce new types, but instead simply refer to other types, a name that refers to a typedef that is a member of the current instantiation is dependent only if the type referred to is dependent. — end note]

13.8.3.3 Type-dependent expressions

Except as described below, an expression is type-dependent if any subexpression is type-dependent.

\(^{1}\) this is type-dependent if the current class (7.5.3) is dependent (13.8.3.2).

\(^{2}\) An \textit{id-expression} is type-dependent if it is a \texttt{template-id} that is not a concept-id and is dependent; or if its terminal name is

(3.1) associated by name lookup with one or more declarations declared with a dependent type,
(3.2) associated by name lookup with a non-type \texttt{template-parameter} declared with a type that contains a placeholder type (9.2.9.7),
(3.3) associated by name lookup with a variable declared with a type that contains a placeholder type (9.2.9.7) where the initializer is type-dependent,
(3.4) associated by name lookup with one or more declarations of member functions of a class that is the current instantiation declared with a return type that contains a placeholder type,
(3.5) associated by name lookup with a structured binding declaration (9.6) whose \texttt{brace-or-equal-initializer} is type-dependent,
(3.6) associated by name lookup with an entity captured by copy (7.5.6.3) in a \textit{lambda-expression} that has an explicit object parameter whose type is dependent (9.3.4.6),
(3.7) the \texttt{identifier \_\_func\_} (9.5.1), where any enclosing function is a template, a member of a class template, or a generic lambda,
(3.8) a \texttt{conversion-function-id} that specifies a dependent type, or
(3.9) dependent

or if it names a dependent member of the current instantiation that is a static data member of type “array of unknown bound of T” for some T (13.7.2.5). Expressions of the following forms are type-dependent only if

\(^{(121)}\) This includes an injected-class-name (11.1) of a class template used without a \texttt{template-argument-list}.
the type specified by the type-id, simple-type-specifier, typename-specifier, or new-type-id is dependent, even if any subexpression is type-dependent:

```
  simple-type-specifier ( expression-list_opt )
  simple-type-specifier braced-init-list
  typename-specifier ( expression-list_opt )
  typename-specifier braced-init-list
  :: opt new new-placement_opt new-type-id new-initializer_opt
  :: opt new new-placement_opt ( type-id ) new-initializer_opt
  dynamic_cast < type-id > ( expression )
  static_cast < type-id > ( expression )
  const_cast < type-id > ( expression )
  reinterpret_cast < type-id > ( expression )
```

Expressions of the following forms are never type-dependent (because the type of the expression cannot be dependent):

```
literal
sizeof unary-expression
sizeof ( type-id )
sizeof ... ( identifier )
alignof ( type-id )
typeid ( expression )
typeid ( type-id )
:: opt delete cast-expression
:: opt delete [ ] cast-expression
throw assignment-expression_opt
requires ( expression )
requires-expression
```

[Note 1: For the standard library macro offsetof, see 17.2. — end note]

5 A class member access expression (7.6.1.5) is type-dependent if the terminal name of its id-expression, if any, is dependent or the expression refers to a member of the current instantiation and the type of the referenced member is dependent.

[Note 2: In an expression of the form x.y or xp->y the type of the expression is usually the type of the member y of the class of x (or the class pointed to by xp). However, if x or xp refers to a dependent type that is not the current instantiation, the type of y is always dependent. — end note]

6 A braced-init-list is type-dependent if any element is type-dependent or is a pack expansion.

7 A fold-expression is type-dependent.

8 A pack-index-expression is type-dependent if its id-expression is type-dependent.

### 13.8.3.4 Value-dependent expressions

Except as described below, an expression used in a context where a constant expression is required is value-dependent if any subexpression is value-dependent.

An id-expression is value-dependent if

1. it is a concept-id and any of its arguments are dependent,
2. it is type-dependent,
3. it is the name of a non-type template parameter,
4. it names a static data member that is a dependent member of the current instantiation and is not initialized in a member-declarator,
5. it names a static member function that is a dependent member of the current instantiation, or
6. it names a potentially-constant variable (7.7) that is initialized with an expression that is value-dependent.

Expressions of the following form are value-dependent if the unary-expression or expression is type-dependent or the type-id is dependent:
Expressions of the following form are value-dependent if either the type-id or simple-type-specifier is dependent or the expression or cast-expression is value-dependent:

- sizeof (type-id)
- typeid (expression)
- typeid (type-id)
- alignof (type-id)
- noexcept (expression)

[Note 1: For the standard library macro offsetof, see 17.2. — end note]

Expressions of the following form are value-dependent if the type-id or simple-type-specifier is dependent:

- simple-type-specifier (expression-list)
- static_cast <type-id> (expression)
- const_cast <type-id> (expression)
- reinterpret_cast <type-id> (expression)
- (type-id) cast-expression

Expressions of the following form are value-dependent:

- sizeof ... (identifier)
- fold-expression

An expression of the form &qualified-id where the qualified-id names a dependent member of the current instantiation is value-dependent. An expression of the form &cast-expression is also value-dependent if evaluating cast-expression as a core constant expression (7.7) succeeds and the result of the evaluation refers to a templated entity that is an object with static or thread storage duration or a member function.

13.8.3.5 Dependent template arguments

A type template-argument is dependent if the type it specifies is dependent.

A non-type template-argument is dependent if its type is dependent or the constant expression it specifies is value-dependent.

Furthermore, a non-type template-argument is dependent if the corresponding non-type template-parameter is of reference or pointer type and the template-argument designates or points to a member of the current instantiation or a member of a dependent type.

A template template-parameter is dependent if it names a template-parameter or its terminal name is dependent.

13.8.4 Dependent name resolution

13.8.4.1 Point of instantiation

For a function template specialization, a member function template specialization, or a specialization for a member function or static data member of a class template, if the specialization is implicitly instantiated because it is referenced from within another template specialization and the context from which it is referenced depends on a template parameter, the point of instantiation of the specialization is the point of instantiation of the enclosing specialization. Otherwise, the point of instantiation for such a specialization immediately follows the namespace scope declaration or definition that refers to the specialization.

If a function template or member function of a class template is called in a way which uses the definition of a default argument of that function template or member function, the point of instantiation of the default argument is the point of instantiation of the function template or member function specialization.

For a noexcept-specifier of a function template specialization or specialization of a member function of a class template, if the noexcept-specifier is implicitly instantiated because it is needed by another template specialization and the context that requires it depends on a template parameter, the point of instantiation of the specialization is the point of instantiation of the enclosing specialization. Otherwise, the point of instantiation for such a specialization immediately follows the namespace scope declaration or definition that requires the noexcept-specifier.

For a class template specialization, a class member template specialization, or a specialization for a class member of a class template, if the specialization is implicitly instantiated because it is referenced from within another template specialization, if the context from which the specialization is referenced depends on a template parameter, and if the specialization is not instantiated previous to the instantiation of the enclosing template, the point of instantiation is immediately before the point of instantiation of the enclosing template. Otherwise, the point of instantiation for such a specialization immediately precedes the namespace scope declaration or definition that refers to the specialization.

§ 13.8.4.1 ©ISO/IEC 428
If a virtual function is implicitly instantiated, its point of instantiation is immediately following the point of instantiation of its enclosing class template specialization.

An explicit instantiation definition is an instantiation point for the specialization or specializations specified by the explicit instantiation.

A specialization for a function template, a member function template, or of a member function or static data member of a class template may have multiple points of instantiations within a translation unit, and in addition to the points of instantiation described above,

(7.1) — for any such specialization that has a point of instantiation within the declaration-seq of the translation-unit, prior to the private-module-fragment (if any), the point after the declaration-seq of the translation-unit is also considered a point of instantiation, and

(7.2) — for any such specialization that has a point of instantiation within the private-module-fragment, the end of the translation unit is also considered a point of instantiation.

A specialization for a class template has at most one point of instantiation within a translation unit. A specialization for any template may have points of instantiation in multiple translation units. If two different points of instantiation give a template specialization different meanings according to the one-definition rule (6.3), the program is ill-formed, no diagnostic required.

13.8.4.2 Candidate functions

If a dependent call (13.8.3) would be ill-formed or would find a better match had the lookup for its dependent name considered all the function declarations with external linkage introduced in the associated namespaces in all translation units, not just considering those declarations found in the template definition and template instantiation contexts (6.5.4), then the program is ill-formed, no diagnostic required.

[Example 1:

Source file "X.h":

```cpp
namespace Q {

struct X { };
}
```

Source file "G.h":

```cpp
namespace Q {

void g_impl(X, X);
}
```

Module interface unit of M1:

```cpp
module;
#include "X.h"
#include "G.h"
export module M1;
export template<typename T>
void g(T t) {
    g_impl(t, Q::X{}); // ADL in definition context finds Q::g_impl, g_impl not discarded
}
```

Module interface unit of M2:

```cpp
module;
#include "X.h"
export module M2;
import M1;
void h(Q::X x) {
    g(x); // OK
}
```

— end example]

3 [Example 2:

Module interface unit of Std:

```cpp
export module Std;
```

§ 13.8.4.2 ©ISO/IEC 429
export template<typename Iter>
void indirect_swap(Iter lhs, Iter rhs)
{
    swap(*lhs, *rhs); // swap not found by unqualified lookup, can be found only via ADL
}

Module interface unit of M:

export module M;
import Std;

struct S { /* ... */};
void swap(S& p, S& q); // #1

void f(S* p, S* q)
{
    indirect_swap(p, q); // finds #1 via ADL in instantiation context
}

—end example

4 [Example 3:

Source file "X.h":

struct X { /* ... */};
X operator+(X, X);

Module interface unit of F:

export module F;
export template<typename T>
void f(T t) {
    t + t;
}

Module interface unit of M:

module;
#include "X.h"
export module M;
import F;
void g(X x) {
    f(x); // OK, instantiates f from F, operator+ is visible in instantiation context
}

—end example

5 [Example 4:

Module interface unit of A:

export module A;
export template<typename T>
void f(T t) {
    cat(t, t); // #1
    dog(t, t); // #2
}

Module interface unit of B:

export module B;
import A;
export template<typename T, typename U>
void g(T t, U u) {
    f(t);
}

Source file "foo.h", not an importable header:

§ 13.8.4.2 ©ISO/IEC 430
struct foo {
    friend int cat(foo, foo);
};
int dog(foo, foo);

Module interface unit of C1:

module;
#include "foo.h"    // dog not referenced, discarded
export module C1;
import B;
export template<typename T>
void h(T t) {
    g(foo{ }, t);
}

Translation unit:

import C1;
void i() {
    h(0);       // error: dog not found at #2
}

Importable header "bar.h":

struct bar {
    friend int cat(bar, bar);
};
int dog(bar, bar);

Module interface unit of C2:

module;
#include "bar.h"    // imports header unit "bar.h"
export module C2;
import B;
export template<typename T>
void j(T t) {
    g(bar{ }, t);
}

Translation unit:

import C2;
void k() {
    j(0);           // OK, dog found in instantiation context:
    // visible at end of module interface unit of C2
}

--- end example ---

13.9 Template instantiation and specialization [temp.spec]

13.9.1 General [temp.spec.general]

1 The act of instantiating a function, a variable, a class, a member of a class template, or a member template is referred to as template instantiation.

2 A function instantiated from a function template is called an instantiated function. A class instantiated from a class template is called an instantiated class. A member function, a member class, a member enumeration, or a static data member of a class template instantiated from the member definition of the class template is called, respectively, an instantiated member function, member class, member enumeration, or static data member. A member function instantiated from a member function template is called an instantiated member function. A member class instantiated from a member class template is called an instantiated member class. A variable instantiated from a variable template is called an instantiated variable. A static data member instantiated from a static data member template is called an instantiated static data member.

3 An explicit specialization may be declared for a function template, a variable template, a class template, a member of a class template, or a member template. An explicit specialization declaration is introduced by template<>. In an explicit specialization declaration for a variable template, a class template, a member
of a class template, or a class member template, the variable or class that is explicitly specialized shall be specified with a simple-template-id. In the explicit specialization declaration for a function template or a member function template, the function or member function explicitly specialized may be specified using a template-id.

[Example 1:

```c
template<class T = int> struct A {
    static int x;
};
template<class U> void g(U) { }
template<> struct A<double> { }; // specialize for T == double
template<> struct A<> { }; // specialize for T == int
// U is deduced from the parameter type
template<> void g<int>(int) { } // specialize for U == int
template<> int A<char>::x = 0; // specialize for T == char

// Example 2:

template<class T> class X {
    static T s;
};
template<class T> T X<T>::s = 0;
X<int> aa;
X<char*> bb;
// X<int> has a static member s of type int and X<char*> has a static member s of type char.*

Note 1: In particular, the template arguments and names used in the function declarator (including parameter types, return types and exception specifications) can be private types or objects that would normally not be accessible.

— end example
```

— end example

4 An instantiated template specialization can be either implicitly instantiated (13.9.2) for a given argument list or be explicitly instantiated (13.9.3). A specialization is a class, variable, function, or class member that is either instantiated (13.9.2) from a templated entity or is an explicit specialization (13.9.4) of a templated entity.

5 For a given template and a given set of template-arguments,

(5.1) — an explicit instantiation definition shall appear at most once in a program,
(5.2) — an explicit specialization shall be defined at most once in a program, as specified in 6.3, and
(5.3) — both an explicit instantiation and a declaration of an explicit specialization shall not appear in a program unless the explicit specialization is reachable from the explicit instantiation.

An implementation is not required to diagnose a violation of this rule if neither declaration is reachable from the other.

6 The usual access checking rules do not apply to names in a declaration of an explicit instantiation or explicit specialization, with the exception of names appearing in a function body, default argument, base-clause, member-specification, enumerator-list, or static data member or variable template initializer.

[Note 1: In particular, the template arguments and names used in the function declarator (including parameter types, return types and exception specifications) can be private types or objects that would normally not be accessible.

— end note]

7 Each class template specialization instantiated from a template has its own copy of any static members.

[Example 2:

```c
template<class T> class X {
    static T s;
};
template<class T> T X<T>::s = 0;
X<int> aa;
X<char*> bb;

X<int> has a static member s of type int and X<char*> has a static member s of type char*. — end example
```

8 If a function declaration acquired its function type through a dependent type (13.8.3.2) without using the syntactic form of a function declarator, the program is ill-formed.

[Example 3:

```c
template<class T> struct A {
    static T t;
};
typedef int function();
```

— end example

§ 13.9.1 ©ISO/IEC 432
A\textless \text{function}\textgreater \ a; \quad \text{// error: would declare A\textless \text{function}\textgreater::t as a static member function}

— end example]

13.9.2 Implicit instantiation

A template specialization $E$ is a declared specialization if there is a reachable explicit instantiation definition (13.9.3) or explicit specialization declaration (13.9.4) for $E$, or if there is a reachable explicit instantiation declaration for $E$ and $E$ is not

(1.1) — an inline function,

(1.2) — declared with a type deduced from its initializer or return value (9.2.9.7),

(1.3) — a potentially-constant variable (7.7), or

(1.4) — a specialization of a templated class.

[Note 1: An implicit instantiation in an importing translation unit cannot use names with internal linkage from an imported translation unit (6.6). — end note]

2 Unless a class template specialization is a declared specialization, the class template specialization is implicitly instantiated when the specialization is referenced in a context that requires a completely-defined object type or when the completeness of the class type affects the semantics of the program.

[Note 2: In particular, if the semantics of an expression depend on the member or base class lists of a class template specialization, the class template specialization is implicitly generated. For instance, deleting a pointer to class type depends on whether or not the class declares a destructor, and a conversion between pointers to class type depends on the inheritance relationship between the two classes involved. — end note]

[Example 1:

\begin{verbatim}
\template<class T> class B { /* ... */ };  
\template<class T> class D : public B<T> { /* ... */ };  

void f(void*);
void f(B<int>*);

void g(D<int>* p, D<char>* pp, D<double>* ppp) {
  f(p); \quad \text{// instantiation of D<int> required: call f(B<int>*)}
  B<char>* q = pp; \quad \text{// instantiation of D<char> required: convert D<char> to B<char>}
  delete ppp; \quad \text{// instantiation of D<double> required}
}
\end{verbatim}

— end example]

If the template selected for the specialization (13.7.6.2) has been declared, but not defined, at the point of instantiation (13.8.4.1), the instantiation yields an incomplete class type (6.8.1).

[Example 2:

\begin{verbatim}
\template<class T> class X;
X<char> ch; \quad \text{// error: incomplete type X<char>}
\end{verbatim}

— end example]

[Note 3: Within a template declaration, a local class (11.6) or enumeration and the members of a local class are never considered to be entities that can be separately instantiated (this includes their default arguments, \texttt{noexcept-specifiers}, and non-static data member initializers, if any, but not their \textit{type-constraints} or \textit{requires-clauses}). As a result, the dependent names are looked up, the semantic constraints are checked, and any templates used are instantiated as part of the instantiation of the entity within which the local class or enumeration is declared. — end note]

3 The implicit instantiation of a class template specialization causes

(3.1) — the implicit instantiation of the declarations, but not of the definitions, of the non-deleted class member functions, member classes, scoped member enumerations, static data members, member templates, and friends; and

(3.2) — the implicit instantiation of the definitions of deleted member functions, unscoped member enumerations, and member anonymous unions.

The implicit instantiation of a class template specialization does not cause the implicit instantiation of default arguments or \texttt{noexcept-specifiers} of the class member functions.
Example 3:

```cpp
template<class T>
struct C {
    void f() { T x; }
    void g() = delete;
};
C<void> c; // OK, definition of C<void>::f is not instantiated at this point
```

However, for the purpose of determining whether an instantiated redeclaration is valid according to 6.3 and 11.4, an instantiated declaration that corresponds to a definition in the template is considered to be a definition.

Example 4:

```cpp
template<class T, class U>
struct Outer {
    template<class X, class Y> struct Inner;
    template<class Y> struct Inner<T, Y>; // #1a
    template<class Y> struct Inner<T, Y> { }; // #1b; OK, valid redeclaration of #1a
    template<class Y> struct Inner<U, Y> { }; // #2
};
Outer<int, int> outer; // error at #2
```

Outer<int, int>::Inner<int, Y> is redeclared at #1b. (It is not defined but noted as being associated with a definition in Outer<T, U>.) #2 is also a redeclaration of #1a. It is noted as associated with a definition, so it is an invalid redeclaration of the same partial specialization.

```cpp
template<typename T> struct Friendly {
    template<typename U> friend int f(U) { return sizeof(T); }
};
Friendly<char> fc;
Friendly<float> ff; // error: produces second definition of f(U)
```

Example 5:

```cpp
template<class T> struct Z {
    void f();
    void g();
};
```

```cpp
void h() {
    Z<int> a; // instantiation of class Z<int> required
    Z<char>* p; // instantiation of class Z<char> not required
}
```

4 Unless a member of a templated class is a declared specialization, the specialization of the member is implicitly instantiated when the specialization is referenced in a context that requires the member definition to exist or if the existence of the definition of the member affects the semantics of the program; in particular, the initialization (and any associated side effects) of a static data member does not occur unless the static data member is itself used in a way that requires the definition of the static data member to exist.

5 Unless a function template specialization is a declared specialization, the function template specialization is implicitly instantiated when the specialization is referenced in a context that requires a function definition to exist or if the existence of the definition affects the semantics of the program. A function whose declaration was instantiated from a friend function definition is implicitly instantiated when it is referenced in a context that requires a function definition to exist or if the existence of the definition affects the semantics of the program. Unless a call is to a function template explicit specialization or to a member function of an explicitly specialized class template, a default argument for a function template or a member function of a class template is implicitly instantiated when the function is called in a context that requires the value of the default argument.

Note 4: An inline function that is the subject of an explicit instantiation declaration is not a declared specialization; the intent is that it still be implicitly instantiated when odr-used (6.3) so that the body can be considered for inlining, but that no out-of-line copy of it be generated in the translation unit. — end note]

6 [Example 5:

```cpp
template<class T> struct Z {
    void f();
    void g();
};
```

```cpp
void h() {
    Z<int> a; // instantiation of class Z<int> required
    Z<char>* p; // instantiation of class Z<char> not required
}
```
Z<double>* q; // instantiation of class Z<double> not required

a.f(); // instantiation of Z<int>::f() required
p->g(); // instantiation of class Z<char> required, and
        // instantiation of Z<char>::g() required
}

Nothing in this example requires class Z<double>, Z<int>::g(), or Z<char>::f() to be implicitly instantiated.
—end example

Unless a variable template specialization is a declared specialization, the variable template specialization is implicitly instantiated when it is referenced in a context that requires a variable definition to exist or if the existence of the definition affects the semantics of the program. A default template argument for a variable template is implicitly instantiated when the variable template is referenced in a context that requires the value of the default argument.

The existence of a definition of a variable or function is considered to affect the semantics of the program if the variable or function is needed for constant evaluation by an expression (7.7), even if constant evaluation of the expression is not required or if constant expression evaluation does not use the definition.

[Example 6]:

    template<typename T> constexpr int f() { return T::value; } // instantiation of template
    template<bool B, typename T> void g(decltype(B ? f<T>() : 0));
    template<bool B, typename T> void g(...);
    template<bool B, typename T> void h(decltype(int{B ? f<T>() : 0}));
    template<bool B, typename T> void h(...);
    void x() {
        g<false, int>(0); // OK, B ? f<T>() : 0 is not potentially constant evaluated
        h<false, int>(0); // error, instantiates f<int> even though B evaluates to false and
                         // list-initialization of int from int cannot be narrowing
    }
—end example

If the function selected by overload resolution (12.2) can be determined without instantiating a class template definition, it is unspecified whether that instantiation actually takes place.

[Example 7]:

    template <class T> struct S {
        operator int();
    };
    void f(int);
    void f(S<int>&);
    void f(S<float>);
    void g(S<int>& sr) {
        f(sr); // instantiation of S<int> allowed but not required
        h(sr); // instantiation of S<float> allowed but not required
    }
—end example

If a function template or a member function template specialization is used in a way that involves overload resolution, a declaration of the specialization is implicitly instantiated (13.10.4).

An implementation shall not implicitly instantiate a function template, a variable template, a member template, a non-virtual member function, a member class or static data member of a templated class, or a substatement of a constexpr if statement (8.5.2), unless such instantiation is required.

[Note 5: The instantiation of a generic lambda does not require instantiation of substatements of a constexpr if statement within its compound-statement unless the call operator template is instantiated. —end note]

It is unspecified whether or not an implementation implicitly instantiates a virtual member function of a class template if the virtual member function would not otherwise be instantiated. The use of a template specialization in a default argument or default member initializer shall not cause the template to be implicitly instantiated except where needed to determine the correctness of the default argument or default member initializer. The use of a default argument in a function call causes specializations in the default argument to
be implicitly instantiated. Similarly, the use of a default member initializer in a constructor definition or an aggregate initialization causes specializations in the default member initializer to be instantiated.

If a templated function \( f \) is called in a way that requires a default argument to be used, the dependent names are looked up, the semantics constraints are checked, and the instantiation of any template used in the default argument is done as if the default argument had been an initializer used in a function template specialization with the same scope, the same template parameters and the same access as that of the function template \( f \) used at that point, except that the scope in which a closure type is declared (7.5.6.2) — and therefore its associated namespaces — remain as determined from the context of the definition for the default argument. This analysis is called default argument instantiation. The instantiated default argument is then used as the argument of \( f \).

Each default argument is instantiated independently.

*Example 8:*
```cpp
template<class T> void f(T x, T y = ydef(T())), T z = zdef(T()));

class A { };
A zdef(A);

void g(A a, A b, A c) {
  f(a, b, c); // no default argument instantiation
  f(a, b); // default argument \( z = zdef(T()) \) instantiated
  f(a); // error: ydef is not declared
}
```

— end example —

The noexcept-specifier of a function template specialization is not instantiated along with the function declaration; it is instantiated when needed (14.5). If such a noexcept-specifier is needed but has not yet been instantiated, the dependent names are looked up, the semantics constraints are checked, and the instantiation of any template used in the noexcept-specifier is done as if it were being done as part of instantiating the declaration of the specialization at that point.

*Note 6: 13.8.4.1 defines the point of instantiation of a template specialization. — end note*

There is an implementation-defined quantity that specifies the limit on the total depth of recursive instantiations (Annex B), which could involve more than one template. The result of an infinite recursion in instantiation is undefined.

*Example 9:*
```cpp
template<class T> class X {
  X<T>* p; // OK
  X<T*>* a; // implicit generation of \( X<T> \) requires
            // the implicit instantiation of \( X<T*> \) which requires
            // the implicit instantiation of \( X<T**> \) which ...
};
```

— end example —

The type-constraints and requires-clause of a template specialization or member function are not instantiated along with the specialization or function itself, even for a member function of a local class; substitution into the atomic constraints formed from them is instead performed as specified in 13.5.3 and 13.5.2.3 when determining whether the constraints are satisfied or as specified in 13.5.3 when comparing declarations.

*Note 7: The satisfaction of constraints is determined during template argument deduction (13.10.3) and overload resolution (12.2). — end note*

*Example 10:*
```cpp
template<typename T> concept C = sizeof(T) > 2;
template<typename T> concept D = C<T> && sizeof(T) > 4;
template<typename T> struct S {
  S() requires C<T> { } // #1
  S() requires D<T> { } // #2
};
```
When `S<char>` is instantiated, both constructors are part of the specialization. Their constraints are not satisfied, and they suppress the implicit declaration of a default constructor for `S<char>` (11.4.5.2), so there is no viable constructor for `s1`. —end example

Example 11:

```cpp
template<typename T> struct S1 {
    template<typename U>
    requires false
    struct Inner1; // ill-formed, no diagnostic required
};

template<typename T> struct S2 {
    template<typename U>
    requires (sizeof(T[-(int)sizeof(T)]) > 1)
    struct Inner2; // ill-formed, no diagnostic required
};
```

The class `S1<T>::Inner1` is ill-formed, no diagnostic required, because it has no valid specializations. `S2` is ill-formed, no diagnostic required, since no substitution into the constraints of its `Inner2` template would result in a valid expression. —end example

13.9.3 Explicit instantiation

A class, function, variable, or member template specialization can be explicitly instantiated from its template. A member function, member class or static data member of a class template can be explicitly instantiated from the member definition associated with its class template.

The syntax for explicit instantiation is:

```
explicit-instantiation:
        extern_opt template declaration
```

There are two forms of explicit instantiation: an explicit instantiation definition and an explicit instantiation declaration. An explicit instantiation declaration begins with the `extern` keyword.

An explicit instantiation shall not use a `storage-class-specifier` (9.2.2) other than `thread_local`. An explicit instantiation of a function template, member function of a class template, or variable template shall not use the `inline`, `constexpr`, or `consteval` specifiers. No `attribute-specifier-seq` (9.12.1) shall appertain to an explicit instantiation.

If the explicit instantiation is for a class or member class, the `elaborated-type-specifier` in the `declaration` shall include a `simple-template-id`; otherwise, the `declaration` shall be a `simple-declaration` whose `init-declarator-list` comprises a single `init-declarator` that does not have an `initializer`. If the explicit instantiation is for a variable template specialization, the `unqualified-id` in the `declarator` shall be a `simple-template-id`.

Example 1:

```
template<class T> class Array { void mf(); }

template class Array<char>;

template void Array<int>::mf();

template<class T> void sort(Array<T>& v) { /* ... */ }  
template void sort(Array<char>&);            // argument is deduced here (13.10.2)

namespace N {
    template<class T> void f(T&); 
}

template void N::f<int>(int&);
```

An explicit instantiation does not introduce a name (6.4.1). A declaration of a function template, a variable template, a member function or static data member of a class template, or a member function template of a class or class template shall be reachable from any explicit instantiation of that entity. A definition of a class template, a member class of a class template, or a member class template of a class or class template shall be reachable from any explicit instantiation of that entity unless an explicit specialization of the entity with the
same template arguments is reachable therefrom. If the declaration of the explicit instantiation names an implicitly-declared special member function (11.4.4), the program is ill-formed.

The declaration in an explicit-instantiation and the declaration produced by the corresponding substitution into the templated function, variable, or class are two declarations of the same entity.

[Note 1: These declarations need to have matching types as specified in 6.6, except as specified in 14.5.]

[Example 2:]

```cpp
template<typename T> T var = {};  // OK, instantiated variable has type T
template float var<float>;        // OK, absence of major array bound is permitted
template int var<int[16]>[];      // error: instantiated variable has type int

template<typename T> T var = T(); // OK, instantiated variable has type T
template int av<int>;            // error: instantiated variable can be redeclared with type auto

template<typename T> auto av = T();
template auto av<int>;           // OK, variable with type int can be redeclared with type auto

template<typename T> auto f() {} // error: function with deduced return type
template void f<int>();          // redeclared with non-deduced return type (9.2.9.7)
```

— end example

— end note

Despite its syntactic form, the declaration in an explicit-instantiation for a variable is not itself a definition and does not conflict with the definition instantiated by an explicit instantiation definition for that variable.

For a given set of template arguments, if an explicit instantiation of a template appears after a declaration of an explicit specialization for that template, the explicit instantiation has no effect. Otherwise, for an explicit instantiation definition, the definition of a function template, a variable template, a member function template, or a member function or static data member of a class template shall be present in every translation unit in which it is explicitly instantiated.

[Note 2: An explicit instantiation of a constrained template needs to satisfy that template’s associated constraints (13.5.3). The satisfaction of constraints is determined when forming the template name of an explicit instantiation in which all template arguments are specified (13.3), or, for explicit instantiations of function templates, during template argument deduction (13.10.3.7) when one or more trailing template arguments are left unspecified. — end note]

An explicit instantiation that names a class template specialization is also an explicit instantiation of the same kind (declaration or definition) of each of its direct non-template members that has not been previously explicitly specialized in the translation unit containing the explicit instantiation, provided that the associated constraints, if any, of that member are satisfied by the template arguments of the explicit instantiation (13.5.3, 13.5.2), except as described below.

[Note 3: In addition, it will typically be an explicit instantiation of certain implementation-dependent data about the class. — end note]

An explicit instantiation definition that names a class template specialization explicitly instantiates the class template specialization and is an explicit instantiation definition of only those members that have been defined at the point of instantiation.

An explicit instantiation of a prospective destructor (11.4.7) shall correspond to the selected destructor of the class.

If an entity is the subject of both an explicit instantiation declaration and an explicit instantiation definition in the same translation unit, the definition shall follow the declaration. An entity that is the subject of an explicit instantiation declaration and that is also used in a way that would otherwise cause an explicit instantiation (13.9.2) in the translation unit shall be the subject of an explicit instantiation definition somewhere in the program; otherwise the program is ill-formed, no diagnostic required.

[Note 4: This rule does apply to inline functions even though an explicit instantiation declaration of such an entity has no other normative effect. This is needed to ensure that if the address of an inline function is taken in a translation unit in which the implementation chose to suppress the out-of-line body, another translation unit will supply the body. — end note]

An explicit instantiation declaration shall not name a specialization of a template with internal linkage.

An explicit instantiation does not constitute a use of a default argument, so default argument instantiation is not done.
Example 3:

```c
char* p = 0;
template<class T> T g(T x = &p) { return x; }
template int g<int>(int); // OK even though &p isn't an int.
@end example
```

13.9.4 Explicit specialization

An explicit specialization of any of the following:

1. function template
2. class template
3. variable template
4. member function of a class template
5. static data member of a class template
6. member class of a class template
7. member enumeration of a class template
8. member class template of a class or class template
9. member function template of a class or class template

can be declared by a declaration introduced by `template<>`; that is:

```c
explicit-specialization:
template <> declaration
```

Example 1:

```c
template<class T> class stream;
template<> class stream<char> { /* ... */ }; // #1
template<class T> class Array { /* ... */ };
template<class T> void sort(Array<T>& v) { /* ... */ }
template<> void sort<int>(Array<int>&); // #2
template<> void sort(Array<char*>&); // #3 template argument is deduced (13.10.2)
```

Given these declarations, #1 will be used as the definition of streams of `char`s; other streams will be handled by class template specializations instantiated from the class template. Similarly, #2 will be used as the sort function for arguments of type `Array<int>` and #3 will be used for arguments of type `Array<char*>`; other `Array` types will be sorted by functions generated from the function template. —end example

The `declaration` in an `explicit-specialization` shall not be an `export-declaration`. An explicit specialization shall not use a `storage-class-specifier` (9.2.2) other than `thread_local`.

An explicit specialization may be declared in any `scope` in which the corresponding primary template may be defined (9.3.4, 11.4, 13.7.3).

An explicit specialization does not introduce a name (6.4.1). A declaration of a function template, class template, or variable template being explicitly specialized shall be reachable from the declaration of the explicit specialization.

[Note 1: A declaration, but not a definition of the template is needed. —end note]

The definition of a class or class template shall be reachable from the declaration of an explicit specialization for a member template of the class or class template.

Example 2:

```c
template<> class X<int> { /* ... */ }; // error: X not a template
template<class T> class X;
template<> class X<char*> { /* ... */ }; // OK, X is a template
@end example
```
A member function, a member function template, a member class, a member enumeration, a member class template, a static data member, or a static data member template of a class template may be explicitly specialized for a class specialization that is implicitly instantiated; in this case, the definition of the class template shall be reachable from the explicit specialization for the member of the class template. If such an explicit specialization for the member of a class template names an implicitly-declared special member function (11.4.4), the program is ill-formed.

A member of an explicitly specialized class is not implicitly instantiated from the member declaration of the class template; instead, the member of the class template specialization shall itself be explicitly defined if its definition is required. The definition of the class template explicit specialization shall be reachable from the definition of any member of it. The definition of an explicitly specialized class is unrelated to the definition of a generated specialization. That is, its members need not have the same names, types, etc. as the members of a generated specialization. Members of an explicitly specialized class template are defined in the same manner as members of normal classes, and not using the `template<>` syntax. The same is true when defining a member of an explicitly specialized member class. However, `template<>` is used in defining a member of an explicitly specialized member class template that is specialized as a class template.

[Example 3:]

```cpp
template<class T> struct A {
    struct B { }
    template<class U> struct C { }
};

template<> struct A<int> {
    void f(int);
};

void h() {
    A<int> a;
    a.f(16); // A<int>::f must be defined somewhere
}

// template<> not used for a member of an explicitly specialized class template
void A<int>::f(int) { /* ... */ }

template<> struct A<char>::B {
    void f();
}; // template<> also not used when defining a member of an explicitly specialized member class
void A<char>::B::f() { /* ... */ }

template<> template<class U> struct A<char>::C {
    void f();
}; // template<> is used when defining a member of an explicitly specialized member class template
// specialized as a class template

template<> template<class U> void A<char>::C<U>::f() { /* ... */ }

template<> struct A<short>::B {
    void f();
};
template<> void A<short>::B::f() { /* ... */ } // error: template<> not permitted

template<> template<class U> struct A<short>::C {
    void f();
};
template<class U> void A<short>::C<U>::f() { /* ... */ } // error: template<> required
```

—end example

If a template, a member template or a member of a class template is explicitly specialized, a declaration of that specialization shall be reachable from every use of that specialization that would cause an implicit instantiation to take place, in every translation unit in which such a use occurs; no diagnostic is required. If
the program does not provide a definition for an explicit specialization and either the specialization is used in a way that would cause an implicit instantiation to take place or the member is a virtual member function, the program is ill-formed, no diagnostic required. An implicit instantiation is never generated for an explicit specialization that is declared but not defined.

[Example 4:

```cpp
class String {};  
template<class T> class Array { /* ... */ };  
template<class T> void sort(Array<T>& v) { /* ... */ }

void f(Array<String>& v) {
    sort(v);  // use primary template sort(Array<T>&), T is String
}

template<> void sort<String>(Array<String>& v);  // error: specialization after use of primary template
template<> void sort<>(Array<char*>& v);  // OK, sort<char*> not yet used

template<class T> struct A {
    enum E : T;
    enum class S : T;
};

template<> enum A<int>::E : int { eint };  // OK
template<> enum class A<int>::S : int { sint };  // OK
template<class T> struct A<T> {  
    enum E : T { eT };  
};

template<class T> struct A<T> {  
    enum E : T { eT };  
};

template<> enum class A<char>::S : char { schar };  // OK
```

—end example]

8 The placement of explicit specialization declarations for function templates, class templates, variable templates, member functions of class templates, static data members of class templates, member classes of class templates, member enumerations of class templates, member class templates of class templates, member function templates of class templates, static data member templates of class templates, member functions of member templates of class templates, member functions of member templates of non-template classes, static data member templates of non-template classes, member function templates of member classes of class templates, etc., and the placement of partial specialization declarations of class templates, variable templates, member class templates of non-template classes, static data member templates of non-template classes, member function templates of member classes of class templates, etc., can affect whether a program is well-formed according to the relative positioning of the explicit specialization declarations and their points of instantiation in the translation unit as specified above and below. When writing a specialization, be careful about its location; or to make it compile will be such a trial as to kindle its self-immolation.

9 A simple-template-id that names a class template explicit specialization that has been declared but not defined can be used exactly like the names of other incompletely-defined classes (6.8).

[Example 5:

```cpp
template<class T> class X;  // X is a class template

template<> class X<int>;

X<int> * p;  // OK, pointer to declared class X<int>
X<int> x;  // error: object of incomplete class X<int>
```

—end example]

10 [Note 2: An explicit specialization of a constrained template needs to satisfy that template’s associated constraints (13.3.5.3). The satisfaction of constraints is determined when forming the template name of an explicit specialization in which all template arguments are specified (13.3), or, for explicit specializations of function templates, during template argument deduction (13.10.3.7) when one or more trailing template arguments are left unspecified. —end note]

11 A function with the same name as a template and a type that exactly matches that of a template specialization is not an explicit specialization (13.7.7).

12 Whether an explicit specialization of a function or variable template is inline, constexpr, constinit, or consteval is determined by the explicit specialization and is independent of those properties of the template. Similarly,
attributes appearing in the declaration of a template have no effect on an explicit specialization of that template.

[Example 6:]
```cpp
template<class T> void f(T) { /* ... */ }
template<class T> inline T g(T) { /* ... */ }

template<> inline void f<>(int) { /* ... */ } // OK, inline
template<> int g<>(int) { /* ... */ } // OK, not inline

template<typename> [[noreturn]] void h([[maybe_unused]] int i);
template<> void h<int>(int i) { // Implementations are expected not to warn that the function returns
    // but can warn about the unused parameter.
}
```

—end example]

An explicit specialization of a static data member of a template or an explicit specialization of a static data member template is a definition if the declaration includes an initializer; otherwise, it is a declaration.

[Note 3: The definition of a static data member of a template for which default-initialization is desired can use functional cast notation (7.6.1.4):]
```cpp
template<> X Q<int>::x; // declaration
template<> X Q<int>::x(); // error: declares a function
template<> X Q<int>::x = X(); // definition
```

—end note]

A member or a member template of a class template may be explicitly specialized for a given implicit instantiation of the class template, even if the member or member template is defined in the class template definition. An explicit specialization of a member or member template is specified using the syntax for explicit specialization.

[Example 7:]
```cpp
template<class T> struct A {
    void f(T);
    template<class X1> void g1(T, X1);
    template<class X2> void g2(T, X2);
    void h(T) { }
};

// specialization
template<> void A<int>::f(int);

// out of class member template definition
template<class T> template<class X1> void A<T>::g1(T, X1) { }

// member template specialization
template<class T> template<class X1> void A<T>::g1(int, X1);

// member template specialization
template<> template<> void A<int>::g1(int, char); // X1 deduced as char
template<> template<> void A<int>::g2<int,char>(int, char); // X2 specified as char

// member specialization even if defined in class definition
template<> void A<int>::h(int) { }
```

—end example]

A member or a member template may be nested within many enclosing class templates. In an explicit specialization for such a member, the member declaration shall be preceded by a `template<>` for each enclosing class template that is explicitly specialized.

[Example 8:]
```cpp
```
template<class T1> class A {
    template<class T2> class B {
        void mf();
    };
};
template<> template<> class A<int>::B<double>;
template<> template<> void A<char>::B<char>::mf();

— end example

In an explicit specialization declaration for a member of a class template or a member template that appears in namespace scope, the member template and some of its enclosing class templates may remain unspecialized, except that the declaration shall not explicitly specialize a class member template if its enclosing class templates are not explicitly specialized as well. In such an explicit specialization declaration, the keyword `template` followed by a `template-parameter-list` shall be provided instead of the `template<>` preceding the explicit specialization declaration of the member. The types of the `template-parameters` in the `template-parameter-list` shall be the same as those specified in the primary template definition.

[Example 9:]

```cpp
template <class T1> class A {
    template<class T2> class B {
        template<class T3> void mf1(T3);
        void mf2();
    };
};
template <> template <class X>
    class A<int>::B {
        template <class T> void mf1(T);
    };
template <> template <> template<class T>
    void A<int>::B<double>::mf1(T t) { }
    template <class Y> template <>
    void A<Y>::B<double>::mf2() { } // error: B<double> is specialized but
    // its enclosing class template A is not

— end example
```

A specialization of a member function template, member class template, or static data member template of a non-specialized class template is itself a template.

An explicit specialization declaration shall not be a friend declaration.

Default function arguments shall not be specified in a declaration or a definition for one of the following explicit specializations:

(19.1) — the explicit specialization of a function template;

(19.2) — the explicit specialization of a member function template;

(19.3) — the explicit specialization of a member function of a class template where the class template specialization to which the member function specialization belongs is implicitly instantiated.

[Note 4: Default function arguments can be specified in the declaration or definition of a member function of a class template specialization that is explicitly specialized. — end note]

13.10 Function template specializations [temp.fct.spec]

13.10.1 General [temp.fct.spec.general]

1 A function instantiated from a function template is called a function template specialization; so is an explicit specialization of a function template. Template arguments can be explicitly specified when naming the function template specialization, deduced from the context (e.g., deduced from the function arguments in a call to the function template specialization, see 13.10.3), or obtained from default template arguments.

2 Each function template specialization instantiated from a template has its own copy of any static variable.

[Example 1:]

```cpp
    template<class T> void f(T* p) {
        static T s;
    };
```
void g(int a, char* b) {
    f(&a); // calls f<int>(int*)
    f(&b); // calls f<char*>(char**)
}

Here f<int>(int*) has a static variable s of type int and f<char*>(char**) has a static variable s of type char*.
—end example

13.10.2 Explicit template argument specification [temp.arg.explicit]

Template arguments can be specified when referring to a function template specialization that is not a specialization of a constructor template by qualifying the function template name with the list of template-arguments in the same way as template-arguments are specified in uses of a class template specialization.

[Example 1]

```cpp
template<class T> void sort(Array<T>& v);
void f(Array<dcomplex>& cv, Array<int>& ci) {
    sort<dcomplex>(cv); // sort(Array<dcomplex>&)
    sort<int>(ci);    // sort(Array<int>&)
}
```

and

```cpp
template<class U, class V> U convert(V v);
void g(double d) {
    int i = convert<int,double>(d);  // int convert(double)
    char c = convert<char,double>(d); // char convert(double)
}
```
—end example

1 Template arguments shall not be specified when referring to a specialization of a constructor template (11.4.5, 6.5.5.2).

2 A template argument list may be specified when referring to a specialization of a function template

(1.1) when a function is called,
(1.2) when the address of a function is taken, when a function initializes a reference to function, or when a pointer to member function is formed,
(1.3) in an explicit specialization,
(1.4) in an explicit instantiation, or
(1.5) in a friend declaration.

3 Trailing template arguments that can be deduced (13.10.3) or obtained from default template-arguments may be omitted from the list of explicit template-arguments.

[Note 1: A trailing template parameter pack (13.7.4) not otherwise deduced will be deduced as an empty sequence of template arguments. —end note]

If all of the template arguments can be deduced or obtained from default template-arguments, they may all be omitted; in this case, the empty template argument list <> itself may also be omitted.

[Example 2]

```cpp
template<class X, class Y> X f(Y);
template<class X, class Y, class ... Z> X g(Y);
void h() {
    int i = f<int>(5.6);       // Y deduced as double
    int j = f(5.6);           // error: X cannot be deduced
    f<void>(f<int, bool>);    // error: f<int> does not denote a single function template specialization
    f<void>(f<int>);          // error: f<int> does not denote a single function template specialization
    int k = g<int>(5.6);      // Y deduced as double; Z deduced as an empty sequence
    f<void>(g<int, bool>);    // error: f<int> does not denote a single function template specialization
    // Z deduced as an empty sequence
}
```
—end example

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[Note 2: An empty template argument list can be used to indicate that a given use refers to a specialization of a function template even when a non-template function (9.3.4.6) is visible that would otherwise be used. For example:

```cpp
template <class T> int f(T);  // #1
int f(int);  // #2
int k = f(1);  // uses #2
int l = f<>();  // uses #1
— end note]
```

Template arguments that are present shall be specified in the declaration order of their corresponding template-parameters. The template argument list shall not specify more template-arguments than there are corresponding template-parameters unless one of the template-parameters is a template parameter pack.

[Example 3:

```cpp
template<class X, class Y, class Z> X f(Y,Z);
template<class ... Args> void f2();
void g() {
    f<int, const char*, double>("aa",3.0);  // Z deduced as double
    f<int>("aa",3.0);  // Y deduced as const char*; Z deduced as double
    f("aa",3.0);  // error: X cannot be deduced
    f2<char, short, int, long>();  // OK
}
— end example]
```

Implicit conversions (7.3) will be performed on a function argument to convert it to the type of the corresponding function parameter if the parameter type contains no template-parameters that participate in template argument deduction.

[Note 3: Template parameters do not participate in template argument deduction if they are explicitly specified. For example,

```cpp
template<class T> void f(T);

class Complex {
    Complex(double);
};

void g() {
    f<Complex>(1);  // OK, means f<Complex>(Complex(1))
}
— end note]
```

[Note 4: Because the explicit template argument list follows the function template name, and because constructor templates (11.4.5) are named without using a function name (6.5.5.2), there is no way to provide an explicit template argument list for these function templates. — end note]

Template argument deduction can extend the sequence of template arguments corresponding to a template parameter pack, even when the sequence contains explicitly specified template arguments.

[Example 4:

```cpp
template<class ... Types> void f(Types ... values);

void g() {
    f<int*, float*>(0, 0, 0);  // Types deduced as the sequence int*, float*, int
}
— end example]
```

13.10.3 Template argument deduction [temp.deduct]

13.10.3.1 General [temp.deduct.general]

When a function template specialization is referenced, all of the template arguments shall have values. The values can be explicitly specified or, in some cases, be deduced from the use or obtained from default template-arguments.
Example 1:

```cpp
void f(Array<dcomplex>& cv, Array<int>& ci) {
    sort(cv);    // calls sort(Array<dcomplex>&)
    sort(ci);    // calls sort(Array<int>&)
}
```

and

```cpp
void g(double d) {
    int i = convert<int>(d);    // calls convert<int,double>(double)
    int c = convert<char>(d);    // calls convert<char,double>(double)
}
```

—end example

When an explicit template argument list is specified, if the given template-id is not valid (13.3), type deduction fails. Otherwise, the specified template argument values are substituted for the corresponding template parameters as specified below.

After this substitution is performed, the function parameter type adjustments described in 9.3.4.6 are performed.

Example 2: A parameter type of “void (const int, int[5])” becomes “void(*)(int,int*)”. —end example

Note 1: A top-level qualifier in a function parameter declaration does not affect the function type but still affects the type of the function parameter variable within the function. —end note

Example 3:

```cpp
template <class T> void f(T t);
template <class X> void g(const X x);
template <class Z> void h(Z, Z*);

int main() {
    // #1: function type is f(int), t is non const
    f<int>(1);

    // #2: function type is f(int), t is const
    f<const int>(1);

    // #3: function type is g(int), x is const
    g<int>(1);

    // #4: function type is g(int), x is const
    g<const int>(1);

    // #5: function type is h(int, const int*)
    h<const int>(1,0);
}
```

—end example

Note 2: f<int>(1) and f<const int>(1) call distinct functions even though both of the functions called have the same function type. —end note

The resulting substituted and adjusted function type is used as the type of the function template for template argument deduction. If a template argument has not been deduced and its corresponding template parameter has a default argument, the template argument is determined by substituting the template arguments determined for preceding template parameters into the default argument. If the substitution results in an invalid type, as described above, type deduction fails.

Example 4:

```cpp
template <class T, class U = double>
void f(T t = 0, U u = 0);

void g() {
    f(1, 'c');    // f<int,char>(1,'c')
    f(1);        // f<int,double>(1,0)
    f();         // error: T cannot be deduced
    f<int>();    // f<int,double>(0,0)
}
When all template arguments have been deduced or obtained from default template arguments, all uses of template parameters in the template parameter list of the template are replaced with the corresponding deduced or default argument values. If the substitution results in an invalid type, as described above, type deduction fails. If the function template has associated constraints (13.5.3), those constraints are checked for satisfaction (13.5.2). If the constraints are not satisfied, type deduction fails. In the context of a function call, if type deduction has not yet failed, then for those function parameters for which the function call has arguments, each function parameter with a type that was non-dependent before substitution of any explicitly-specified template arguments is checked against its corresponding argument; if the corresponding argument cannot be implicitly converted to the parameter type, type deduction fails.

[Note 3: Overload resolution will check the other parameters, including parameters with dependent types in which no template parameters participate in template argument deduction and parameters that became non-dependent due to substitution of explicitly-specified template arguments. —end note]

If type deduction has not yet failed, then all uses of template parameters in the function type are replaced with the corresponding deduced or default argument values. If the substitution results in an invalid type, as described above, type deduction fails.

[Example 5:

```cpp
template <class T> struct Z {
    typedef typename T::x xx;
};

template <class T> concept C = requires { typename T::A; };

template <C T> typename Z<T>::xx f(void *, T);  // #1

// #2

struct A {} a;
struct ZZ {
    template <class T, class = typename Z<T>::xx> operator T *();
    operator int();
};

int main() {
    ZZ zz;
    f(1, a);  // OK, deduction fails for #1 because there is no conversion from int to void*
    f(zz, 42);  // OK, deduction fails for #1 because C<int> is not satisfied
}

—end example]

At certain points in the template argument deduction process it is necessary to take a function type that makes use of template parameters and replace those template parameters with the corresponding template arguments. This is done at the beginning of template argument deduction when any explicitly specified template arguments are substituted into the function type, and again at the end of template argument deduction when any template arguments that were deduced or obtained from default arguments are substituted.

The deduction substitution loci are

1. the function type outside of the noexcept-specifier,
2. the explicit-specifier,
3. the template parameter declarations, and
4. the template argument list of a partial specialization (13.7.6.1).

The substitution occurs in all types and expressions that are used in the deduction substitution loci. The expressions include not only constant expressions such as those that appear in array bounds or as nontype template arguments but also general expressions (i.e., non-constant expressions) inside sizeof, decltype, and other contexts that allow non-constant expressions. The substitution proceeds in lexical order and stops when a condition that causes deduction to fail is encountered. If substitution into different declarations of the same function template would cause template instantiations to occur in a different order or not at all, the program is ill-formed; no diagnostic required.
Note 4: The equivalent substitution in exception specifications is done only when the noexcept-specifier is instantiated, at which point a program is ill-formed if the substitution results in an invalid type or expression. — end note

Example 6:

```cpp
template <class T> struct A { using X = typename T::X; };
template <class T> typename T::X f(typename A<T>::X);
template <class T> void f(...) { }
template <class T> auto g(typename A<T>::X) -> typename T::X;
template <class T> void g(...) { }
template <class T> typename T::X h(typename A<T>::X);
template <class T> auto h(typename A<T>::X) -> typename T::X; // redeclaration
```

```cpp
void x() {
    f<int>(0); // OK, substituting return type causes deduction to fail
    g<int>(0); // error, substituting parameter type instantiates A<int>
    h<int>(0); // ill-formed, no diagnostic required
}
— end example]
```

If a substitution results in an invalid type or expression, type deduction fails. An invalid type or expression is one that would be ill-formed, with a diagnostic required, if written in the same context using the substituted arguments.

Note 5: If no diagnostic is required, the program is still ill-formed. Access checking is done as part of the substitution process. — end note

Invalid types and expressions can result in a deduction failure only in the immediate context of the deduction substitution loci.

Note 6: The substitution into types and expressions can result in effects such as the instantiation of class template specializations and/or function template specializations, the generation of implicitly-defined functions, etc. Such effects are not in the “immediate context” and can result in the program being ill-formed. — end note

When substituting into a lambda-expression, substitution into its body is not in the immediate context.

Note 7: The intent is to avoid requiring implementations to deal with substitution failure involving arbitrary statements.

Example 7:

```cpp
template <class T>
    auto f(T) -> decltype([]() { T::invalid; } ());
void f(...);
```

```cpp
f(0); // error: invalid expression not part of the immediate context
```

```cpp
template <class T, std::size_t = sizeof([]() { T::invalid; })>
    void g(T);
void g(...);
g(0); // error: invalid expression not part of the immediate context
```

```cpp
template <class T>
    auto h(T) -> decltype([]() { T::invalid; })
void h(...);
h(0); // error: invalid expression not part of the immediate context
```

```cpp
template <class T>
    auto i(T) -> typename T::invalid
void i(...);
i(0); // error: invalid expression not part of the immediate context
```

```cpp
template <class T>
    auto j(T t) -> decltype([](auto x) -> decltype(x.invalid) { } (t)); // #1
void j(...); // #2
j(0); // deduction fails on #1, calls #2
— end example]
— end note]
Example 8:

```cpp
struct X { }
struct Y {
    Y(X) {}
};

template <class T> auto f(T t1, T t2) -> decltype(t1 + t2);  // #1
X f(Y, Y);                                                   // #2

X x1, x2;
X x3 = f(x1, x2);  // deduction fails on #1 (cannot add X+X), calls #2
```

Note 8: Type deduction can fail for the following reasons:

11.1 Attempting to instantiate a pack expansion containing multiple packs of differing lengths.

11.2 Attempting to create an array with an element type that is void, a function type, or a reference type, or attempting to create an array with a size that is zero or negative.

Example 9:

```cpp
template <class T> int f(T[5]);
int I = f<int>(0);
int j = f<void>(0);  // invalid array
```

11.3 Attempting to use a type that is not a class or enumeration type in a qualified name.

Example 10:

```cpp
template <class T> int f(typename T::B*);
int i = f<int>(0);
```

11.4 Attempting to use a type in a nested-name-specifier of a qualified-id when that type does not contain the specified member, or

11.4.1 the specified member is not a type where a type is required, or

11.4.2 the specified member is not a template where a template is required, or

11.4.3 the specified member is not a non-type where a non-type is required.

Example 11:

```cpp
template <int I> struct X { }
template <template <class T> class> struct Z { }
template <class T> void f(typename T::Y*) {}
template <class T> void g(X<T::N>**) {}
template <class T> void h(Z<T::TT>**) {}
struct A {};
struct B { int Y; };
struct C {
    typedef int N;
};
struct D {
    typedef int TT;
};

int main() {
    // Deduction fails in each of these cases:
    f<A>(0);       // A does not contain a member Y
    f<B>(0);       // The Y member of B is not a type
    g<C>(0);       // The N member of C is not a non-type
    h<D>(0);       // The TT member of D is not a template
}
```

11.5 Attempting to create a pointer to reference type.

11.6 Attempting to create a reference to void.
— Attempting to create “pointer to member of T” when T is not a class type.

[Example 12:
  template <class T> int f(int T::*);
  int i = f<int>(0);
— end example]

— Attempting to give an invalid type to a non-type template parameter.

[Example 13:
  template <class T, T> struct S {}
  template <class T> int f(S&lt;T, T*>*)
  class X {
    int m;
  };
  int i0 = f&lt;X&gt;(0);  // #1 uses a value of non-structural type X as a non-type template argument
— end example]

— Attempting to perform an invalid conversion in either a template argument expression, or an expression used in the function declaration.

[Example 14:
  template &lt;class T, T*&gt; int f(int);
  int i2 = f&lt;int,1&gt;(0); // can’t convert 1 to int*
— end example]

— Attempting to create a function type in which a parameter has a type of void, or in which the return type is a function type or array type.

— Attempting to give to an explicit object parameter of a lambda’s function call operator a type not permitted for such (7.5.6.2).

12 [Example 15: In the following example, assuming a signed char cannot represent the value 1000, a narrowing conversion (9.4.5) would be required to convert the template-argument of type int to signed char, therefore substitution fails for the second template (13.4.3).

  template &lt;int&gt; int f(int);
  template &lt;signed char&gt; int f(int);
  int i1 = f&lt;1000&gt;(0); // OK
  int i2 = f&lt;1&gt;(0);    // ambiguous; not narrowing
— end example]

13.10.3.2 Deducing template arguments from a function call [temp.deduct.call]

Template argument deduction is done by comparing each function template parameter type (call it P) that contains template-parameter that participate in template argument deduction with the type of the corresponding argument of the call (call it A) as described below. If removing references and cv-qualifiers from P gives std::initializer_list&lt;P’&gt; or P’[N] for some P’ and N and the argument is a non-empty initializer list (9.4.5), then deduction is performed instead for each element of the initializer list independently, taking P’ as separate function template parameter types P’i and the i-th initializer element as the corresponding argument. In the P’[N] case, if N is a non-type template parameter, N is deduced from the length of the initializer list. Otherwise, an initializer list argument causes the parameter to be considered a non-deduced context (13.10.3.6).

[Example 1:
  template&lt;class T&gt; void f(std::initializer_list&lt;T&gt;);
  f({1,2,3});     // T deduced as int
  f({1,"asdf"});  // error: T deduced as both int and const char*

  template&lt;class T&gt; void g(T);
  g({1,2,3});     // error: no argument deduced for T

  template&lt;class T, int N&gt; void h(T const(&amp;) [N]);
  h({1,2,3});     // T deduced as int; N deduced as 3

§ 13.10.3.2 ©ISO/IEC
template<class T> void j(T const(&)[3]);
j({42});  // T deduced as int; array bound not considered

struct Aggr { int i; int j; };
template<class N> void k(Aggr const(&)[N]);
k({1,2,3});  // error: deduction fails, no conversion from int to Aggr
k({{1}, {2}, {3}});  // OK, N deduced as 3

template<class T, int N> void n(T const(&)[N], T);
n({{1}, {2}, {3}}, Aggr());  // OK, T is Aggr, N is 3

For a function parameter pack that occurs at the end of the parameter-declaration-list, deduction is performed for each remaining argument of the call, taking the type P of the declarator-id of the function parameter pack as the corresponding function template parameter type. Each deduction deduces template arguments for subsequent positions in the template parameter packs expanded by the function parameter pack. When a function parameter pack appears in a non-deduced context (13.10.3.6), the type of that pack is never deduced.

[Example 2]:

```cpp
template<class ... Types> void f(Types& ...);
template<class T1, class ... Types> void g(T1, Types ...);
template<class T1, class ... Types> void g1(Types ..., T1);

void h(int x, float& y) {
  const int z = x;
  f(x, y, z);  // Types deduced as int, float, const int
  g(x, y, z);  // T1 deduced as int; Types deduced as float, int
  g1(x, y, z);  // error: Types is not deduced
  g1<int, int, int>(x, y, z);  // OK, no deduction occurs
}
```

—end example]

2 If P is not a reference type:

1. If A is an array type, the pointer type produced by the array-to-pointer standard conversion (7.3.3) is used in place of A for type deduction; otherwise,
2. If A is a function type, the pointer type produced by the function-to-pointer standard conversion (7.3.4) is used in place of A for type deduction; otherwise,
3. If A is a cv-qualified type, the top-level cv-qualifiers of A’s type are ignored for type deduction.

3 If P is a cv-qualified type, the top-level cv-qualifiers of P’s type are ignored for type deduction. If P is a reference type, the type referred to by P is used for type deduction.

[Example 3]:

```cpp
template<class T> int f(const T&);
int n1 = f(5);  // calls f<int>(const int&)
const int i = 0;
int n2 = f(i);  // calls f<int>(const int&)
template <class T> int g(volatile T&);
int n3 = g(i);  // calls g<x<volatile int>(const volatile int&)
```

—end example]

§ 13.10.3.2
A **forwarding reference** is an rvalue reference to a cv-unqualified template parameter that does not represent a template parameter of a class template (during class template argument deduction (12.2.2.9)). If P is a forwarding reference and the argument is an lvalue, the type “lvalue reference to A” is used in place of A for type deduction.

**Example 4:**

```cpp
template <class T> int f(T&& heisenreference);
template <class T> int g(const T&&);
int i;
int n1 = f(i); // calls f<int&>(int&)
int n2 = f(0); // calls f<int>(int&&)
int n3 = g(i); // error: would call g<int>(const int&&), which
                    // would bind an rvalue reference to an lvalue

template <class T> struct A {
    template <class U>
    A(T&&, U&&, int*); // #1: T&& is not a forwarding reference.
    A(T&&, int*);     // #2
};

template <class T> A(T&&, int*) -> A<T>; // #3: T&& is a forwarding reference.

int *ip;
A a{i, 0, ip};  // error: cannot deduce from #1
A a0{0, 0, ip}; // uses #1 to deduce A<int> and #1 to initialize
A a2{i, ip};   // uses #3 to deduce A<int&> and #2 to initialize

— end example 4
```

In general, the deduction process attempts to find template argument values that will make the deduced A identical to A (after the type A is transformed as described above). However, there are three cases that allow a difference:

1. **If the original P is a reference type, the deduced A (i.e., the type referred to by the reference) can be more cv-qualified than the transformed A.**

2. The transformed A can be another pointer or pointer-to-member type that can be converted to the deduced A via a function pointer conversion (7.3.14) and/or qualification conversion (7.3.6).

3. **If P is a class and P has the form simple-template-id, then the transformed A can be a derived class D of the deduced A.** Likewise, if P is a pointer to a class of the form simple-template-id, the transformed A can be a pointer to a derived class D pointed to by the deduced A. However, if there is a class C that is a (direct or indirect) base class of D and derived (directly or indirectly) from a class B and that would be a valid deduced A, the deduced A cannot be B or pointer to B, respectively.

**Example 5:**

```cpp
template <typename... T> struct X;
template <> struct X<> {};  
template <typename T, typename... Ts>
struct X<T, Ts...> : X<Ts...> {}; 
struct D : X<int> {}; 
struct E : X<X<int> > {}; 

template <typename... T>
int f(const X<T...>&); 
int x = f(D()); // calls f<int>, not f<> 
                    // B is X<X<int> >, C is X<int>
int z = f(E()); // calls f<int>, not f<> 

— end example 5
```

These alternatives are considered only if type deduction would otherwise fail. If they yield more than one possible deduced A, the type deduction fails.

**Note 1:** If a template-parameter is not used in any of the function parameters of a function template, or is used only in a non-deduced context, its corresponding template-argument cannot be deduced from a function call and the template-argument must be explicitly specified.  

— end note
When \( P \) is a function type, function pointer type, or pointer-to-member-function type:

- If the argument is an overload set containing one or more function templates, the parameter is treated as a non-deduced context.
- If the argument is an overload set (not containing function templates), trial argument deduction is attempted using each of the members of the set. If deduction succeeds for only one of the overload set members, that member is used as the argument value for the deduction. If deduction succeeds for more than one member of the overload set the parameter is treated as a non-deduced context.

**Example 6:**

```c
// Only one function of an overload set matches the call so the function parameter is a deduced context.
template <class T> int f(T (*)(T))(T);
int g(int);
int g(char);
int i = f(g); // calls f(int (*)(int))
```

**Example 7:**

```c
// Ambiguous deduction causes the second function parameter to be a non-deduced context.
template <class T> int f(T, T (*)(T))(T);
int g(int);
char g(char);
int i = f(1, g); // calls f(int, int (*)(int))
```

**Example 8:**

```c
// The overload set contains a template, causing the second function parameter to be a non-deduced context.
template <class T> int f(T, T (*)(T))(T);
char g(char);
template <class T> T g(T);
int i = f(1, g); // calls f(int, int (*)(int))
```

### 13.10.3.3 Deducing template arguments taking the address of a function template

Template arguments can be deduced from the type specified when taking the address of an overload set (12.3). If there is a target, the function template's function type and the target type are used as the types of \( P \) and \( A \), and the deduction is done as described in 13.10.3.6. Otherwise, deduction is performed with empty sets of types \( P \) and \( A \).

A placeholder type (9.2.9.7) in the return type of a function template is a non-deduced context. If template argument deduction succeeds for such a function, the return type is determined from instantiation of the function body.

### 13.10.3.4 Deducing conversion function template arguments

Template argument deduction is done by comparing the return type of the conversion function template (call it \( P \)) with the type specified by the conversion-type-id of the conversion-function-id being looked up (call it \( A \)) as described in 13.10.3.6. If the conversion-function-id is constructed during overload resolution (12.2.2), the rules in the remainder of this subclause apply.

If \( P \) is a reference type, the type referred to by \( P \) is used in place of \( P \) for type deduction and for any further references to or transformations of \( P \) in the remainder of this subclause.

If \( A \) is not a reference type:

- If \( P \) is an array type, the pointer type produced by the array-to-pointer standard conversion (7.3.3) is used in place of \( P \) for type deduction; otherwise,
- If \( P \) is a function type, the pointer type produced by the function-to-pointer standard conversion (7.3.4) is used in place of \( P \) for type deduction; otherwise,
- If \( P \) is a cv-qualified type, the top-level cv-qualifiers of \( P \)'s type are ignored for type deduction.

If \( A \) is a cv-qualified type, the top-level cv-qualifiers of \( A \)'s type are ignored for type deduction. If \( A \) is a reference type, the type referred to by \( A \) is used for type deduction.
In general, the deduction process attempts to find template argument values that will make the deduced \( A \) identical to \( \tilde{A} \). However, certain attributes of \( \tilde{A} \) may be ignored:

1. If the original \( A \) is a reference type, any cv-qualifiers of \( \tilde{A} \) (i.e., the type referred to by the reference).
2. If the original \( A \) is a function pointer or pointer-to-member-function type with a potentially-throwing exception specification (14.5), the exception specification.
3. Any cv-qualifiers in \( \tilde{A} \) that can be restored by a qualification conversion.

These attributes are ignored only if type deduction would otherwise fail. If ignoring them allows more than one possible deduced \( A \), the type deduction fails.

### 13.10.3.5 Deducing template arguments during partial ordering

Template argument deduction is done by comparing certain types associated with the two function templates being compared.

Two sets of types are used to determine the partial ordering. For each of the templates involved there is the original function type and the transformed function type.

**Note 1:** The creation of the transformed type is described in 13.7.7.3. — end note

The deduction process uses the transformed type as the argument template and the original type of the other template as the parameter template. This process is done twice for each type involved in the partial ordering comparison: once using the transformed template-1 as the argument template and template-2 as the parameter template and again using the transformed template-2 as the argument template and template-1 as the parameter template.

The types used to determine the ordering depend on the context in which the partial ordering is done:

1. In the context of a function call, the types used are those function parameter types for which the function call has arguments.\(^{122}\)
2. In the context of a call to a conversion function, the return types of the conversion function templates are used.
3. In other contexts (13.7.7.3) the function template’s function type is used.

Each type nominated above from the parameter template and the corresponding type from the argument template are used as the types of \( \tilde{P} \) and \( P \).

Before the partial ordering is done, certain transformations are performed on the types used for partial ordering:

1. If \( \tilde{P} \) is a reference type, \( \tilde{P} \) is replaced by the type referred to.
2. If \( A \) is a reference type, \( A \) is replaced by the type referred to.
3. If both \( \tilde{P} \) and \( A \) were reference types (before being replaced with the type referred to above), determine which of the two types (if any) is more cv-qualified than the other; otherwise the types are considered to be equally cv-qualified for partial ordering purposes. The result of this determination will be used below.
4. Remove any top-level cv-qualifiers:
   1. If \( \tilde{P} \) is a cv-qualified type, \( \tilde{P} \) is replaced by the cv-unqualified version of \( \tilde{P} \).
   2. If \( A \) is a cv-qualified type, \( A \) is replaced by the cv-unqualified version of \( A \).
5. Using the resulting types \( \tilde{P} \) and \( A \), the deduction is then done as described in 13.10.3.6. If \( \tilde{P} \) is a function parameter pack, the type \( A \) of each remaining parameter type of the argument template is compared with the type \( \tilde{P} \) of the declarator-id of the function parameter pack. Each comparison deduces template arguments for subsequent positions in the template parameter packs expanded by the function parameter pack. Similarly, if \( A \) was transformed from a function parameter pack, it is compared with each remaining parameter type of the parameter template. If deduction succeeds for a given type, the type from the argument template is considered to be at least as specialized as the type from the parameter template.

**Example 1:**

```cpp
template<class... Args> void f(Args... args); // #1
template<class T1, class... Args> void f(T1 a1, Args... args); // #2
template<class T1, class T2> void f(T1 a1, T2 a2); // #3
```

\(^{122}\) Default arguments are not considered to be arguments in this context; they only become arguments after a function has been selected.
Function template \( F \) is \textit{at least as specialized as} function template \( G \) if, for each pair of types used to determine the ordering, the type from \( F \) is at least as specialized as the type from \( G \). \( F \) is \textit{more specialized than} \( G \) if \( F \) is at least as specialized as \( G \) and \( G \) is not at least as specialized as \( F \).

If, after considering the above, function template \( F \) is at least as specialized as function template \( G \) and vice-versa, and if \( G \) has a trailing function parameter pack for which \( F \) does not have a corresponding parameter, and if \( F \) does not have a trailing function parameter pack, then \( F \) is more specialized than \( G \).

In most cases, deduction fails if not all template parameters have values, but for partial ordering purposes a template parameter may remain without a value provided it is not used in the types being used for partial ordering.

\[ \text{Example 2:} \]
```
#include <utility>

template <class T> T f(int);               // #1
template <class T, class U> T f(U);        // #2

void g() {
    f<int>(1);                           // calls #1
}
```

\[ \text{Example 3:} \]
```
#include <utility>

template<class ...> struct Tuple { };

// #1
template<class ... Types> void g(Tuple<Types ...>);

// #2
template<class T1, class ... Types> void g(Tuple<T1, Types ...>);

// #3
template<class T1, class ... Types> void g(Tuple<T1, Types& ...>);

// calls #1
g(Tuple<>());
// calls #2
g(Tuple<int, float>());
// calls #3
g(Tuple<int, float&>());
// calls #3
```

\[ \text{Example 3:} \]

```
#include <utility>

template<class ...> struct Tuple { };

template<class ... Types> void g(Tuple<Types ...>);

template<class T1, class ... Types> void g(Tuple<T1, Types ...>);

template<class T1, class ... Types> void g(Tuple<T1, Types& ...>);

g(Tuple<>()); // calls #1
g(Tuple<int, float>()); // calls #2
g(Tuple<int, float&>()); // calls #3
```

\[ \text{Example 3:} \]

```
#include <utility>

template<class ...> struct Tuple { };

template<class ... Types> void g(Tuple<Types ...>);

template<class T1, class ... Types> void g(Tuple<T1, Types ...>);

template<class T1, class ... Types> void g(Tuple<T1, Types& ...>);

g(Tuple<>()); // calls #1
g(Tuple<int, float>()); // calls #2
g(Tuple<int, float&>()); // calls #3
```

\[ \text{Example 3:} \]

---

\[ \text{13.10.3.6 Deducing template arguments from a type} \]

Template arguments can be deduced in several different contexts, but in each case a type that is specified in terms of template parameters (call it \( P \)) is compared with an actual type (call it \( A \)), and an attempt is made to find template argument values (a type for a type parameter, a value for a non-type parameter, or a template for a template parameter) that will make \( P \), after substitution of the deduced values (call it the deduced \( A \)), compatible with \( A \).

In some cases, the deduction is done using a single set of types \( P \) and \( A \), in other cases, there will be a set of corresponding types \( P \) and \( A \). Type deduction is done independently for each \( P/A \) pair, and the deduced template argument values are then combined. If type deduction cannot be done for any \( P/A \) pair, or if for any pair the deduction leads to more than one possible set of deduced values, or if different pairs yield different deduced values, or if any template argument remains neither deduced nor explicitly specified, template
argument deduction fails. The type of a type parameter is only deduced from an array bound if it is not otherwise deduced.

A given type \( P \) can be composed from a number of other types, templates, and non-type values:

1. A function type includes the types of each of the function parameters, the return type, and its exception specification.
2. A pointer-to-member type includes the type of the class object pointed to and the type of the member pointed to.
3. A type that is a specialization of a class template (e.g., \( \text{A<int>} \)) includes the types, templates, and non-type values referenced by the template argument list of the specialization.
4. An array type includes the array element type and the value of the array bound.

In most cases, the types, templates, and non-type values that are used to compose \( P \) participate in template argument deduction. That is, they may be used to determine the value of a template argument, and template argument deduction fails if the value so determined is not consistent with the values determined elsewhere.

In certain contexts, however, the value does not participate in type deduction, but instead uses the values of template arguments that were either deduced elsewhere or explicitly specified. If a template parameter is used only in non-deduced contexts and is not explicitly specified, template argument deduction fails.

[Note 1: Under 13.10.3.2, if \( P \) contains no template-parameters that appear in deduced contexts, no deduction is done, so \( P \) and \( \text{A} \) need not have the same form. — end note]

The non-deduced contexts are:

1. The nested-name-specifier of a type that was specified using a qualified-id.
2. A pack-index-specifier or a pack-index-expression.
3. The expression of a decltype-specifier.
4. A non-type template argument or an array bound in which a subexpression references a template parameter.
5. A template parameter used in the parameter type of a function parameter that has a default argument that is being used in the call for which argument deduction is being done.
6. A function parameter for which the associated argument is an overload set (12.3), and one or more of the following apply:
   - more than one function matches the function parameter type (resulting in an ambiguous deduction), or
   - no function matches the function parameter type, or
   - the overload set supplied as an argument contains one or more function templates.
7. A function parameter for which the associated argument is an initializer list (9.4.5) but the parameter does not have a type for which deduction from an initializer list is specified (13.10.3.2).

[Example 1:

\[
\begin{align*}
\text{template<class T> void g(T);} \\
g({1,2,3}); \quad // \text{error: no argument deduced for } T \\
\end{align*}
\]

— end example]

— Function parameter pack that does not occur at the end of the parameter-declaration-list.

When a type name is specified in a way that includes a non-deduced context, all of the types that comprise that type name are also non-deduced. However, a compound type can include both deduced and non-deduced types.

[Example 2: If a type is specified as \( \text{A<T>::B<T2>} \), both \( T \) and \( T2 \) are non-deduced. Likewise, if a type is specified as \( \text{A<T1>::X<T2>} \), \( I \), \( J \), and \( T \) are non-deduced. If a type is specified as \( \text{void f(typename A<T>::B, A<T>} \), the \( T \) in \( A<T>::B \) is non-deduced but the \( T \) in \( A<T> \) is deduced. — end example]

[Example 3: Here is an example in which different parameter/argument pairs produce inconsistent template argument deductions:

\[
\begin{align*}
\text{template<class T> void f(T x, T y) \{ /* ... */ \}} \\
\text{struct A \{ /* ... */ \};} \\
\text{struct B : A \{ /* ... */ \};} \\
\end{align*}
\]

§ 13.10.3.6 ©ISO/IEC 456
void g(A a, B b) {
    f(a,b); // error: T deduced as both A and B
    f(b,a); // error: T deduced as both A and B
    f(a,a); // OK, T is A
    f(b,b); // OK, T is B
}

Here is an example where two template arguments are deduced from a single function parameter/argument pair. This can lead to conflicts that cause type deduction to fail:

```c
template <class T, class U> void f(T (*)(T, U, U));
```

```c
int g1(int, float, float);
char g2(int, float, float);
int g3(int, char, float);
```

```c
void r() {
    f(g1); // OK, T is int and U is float
    f(g2); // error: T deduced as both char and int
    f(g3); // error: U deduced as both char and float
}
```

Here is an example where the exception specification of a function type is deduced:

```c
template<bool E> void f1(void (*)() noexcept(E));
```

```c
template<bool> struct A { }
```

```c
template<bool B> void f2(void (*)(A<B>) noexcept(B));
```

```c
void g1();
void g2() noexcept;
void g3(A<true>);
```

```c
void h() {
    f1(g1); // OK, E is false
    f1(g2); // OK, E is true
    f2(g3); // error: B deduced as both true and false
}
```

Here is an example where a qualification conversion applies between the argument type on the function call and the deduced template argument type:

```c
template<class T> void f(const T*) { }
```

```c
int* p;
void s() {
    f(p); // f(const int*)
}
```

Here is an example where the template argument is used to instantiate a derived class type of the corresponding function parameter type:

```c
template <class T> struct B { }
```

```c
template <class T> struct D : public B<T> { }
```

```c
struct D2 : public B<int> { }
```

```c
template <class T> void f(B<T>&) {}
```

```c
void t() {
    D<int> d;
    D2 d2;
    f(d); // calls f(B<int>&)
    f(d2); // calls f(B<int>&)
}
```

--- end example]
\[ T_{opt} [i_{opt}] \]
\[ T_{opt} (T_{opt}) \text{ noexcept}(i_{opt}) \]
\[ T_{opt} T_{opt} ::* \]
\[ T_{opt} <T> \]
\[ T_{opt} <i> \]
\[ T_{opt} <TT> \]
\[ T_{opt} <> \]

where

- \( T_{opt} \) represents a type or parameter-type-list that either satisfies these rules recursively, is a non-deduced context in \( P \) or \( A \), or is the same non-dependent type in \( P \) and \( A \),

- \( TT_{opt} \) represents either a class template or a template template parameter,

- \( i_{opt} \) represents an expression that either is an \( i \), is value-dependent in \( P \) or \( A \), or has the same constant value in \( P \) and \( A \),

- \( \text{noexcept}(i_{opt}) \) represents an exception specification (14.5) in which the (possibly-implicit, see 9.3.4.6) \text{noexcept}-specifier’s operand satisfies the rules for an \( i_{opt} \) above.

[Note 2: If a type matches such a form but contains no Ts, is, or TTs, deduction is not possible. —end note]

Similarly, \(<T>\) represents template argument lists where at least one argument contains a \( T \), \(<i>\) represents template argument lists where at least one argument contains an \( i \) and \(<>\) represents template argument lists where no argument contains a \( T \) or an \( i \).

If \( P \) has a form that contains \( <T> \) or \( <i> \), then each argument \( P_i \) of the respective template argument list of \( P \) is compared with the corresponding argument \( A_i \) of the corresponding template argument list of \( A \). If the template argument list of \( P \) contains a pack expansion that is not the last template argument, the entire template argument list is a non-deduced context. If \( P_i \) is a pack expansion, then the pattern of \( P_i \) is compared with each remaining argument in the template argument list of \( A \). Each comparison deduces template arguments for subsequent positions in the template parameter packs expanded by \( P_i \). During partial ordering (13.10.3.5), if \( A_i \) was originally a pack expansion:

- (9.1) if \( P \) does not contain a template argument corresponding to \( A_i \), then \( A_i \) is ignored;

- (9.2) otherwise, if \( P_i \) is not a pack expansion, template argument deduction fails.

[Example 4]:

\[
\begin{align*}
\text{template<class T1, class... Z> class S;} & \quad // \#1 \\
\text{template<class T1, class... Z> class S<T1, const Z&...> \{}; & \quad // \#2 \\
\text{template<class T1, class T2> class S<T1, const T2&> \{}; & \quad // \#3 \\
S<int, const int&> s; & \quad // \text{both \#2 and \#3 match; \#3 is more specialized} \\
\text{template<class T, class... U> struct A \{}; & \quad // \#1 \\
\text{template<class T1, class T2, class... U struct A<T1, T2*, U...> \{}; & \quad // \#2 \\
\text{template<class T1, class T2> struct A<T1, T2> \{}; & \quad // \#3 \\
\text{template struct A<int, int*>; \quad // selects \#2} \\
\end{align*}
\]

Similarly, if \( P \) has a form that contains \( (T) \), then each parameter type \( P_i \) of the respective parameter-type-list (9.3.4.6) of \( P \) is compared with the corresponding parameter type \( A_i \) of the corresponding parameter-type-list of \( A \). If \( P \) and \( A \) are function types that originated from deduction when taking the address of a function template (13.10.3.3) or when deducing template arguments from a function declaration (13.10.3.7) and \( P_i \) and \( A_i \) are parameters of the top-level parameter-type-list of \( P \) and \( A \), respectively, \( P_i \) is adjusted if it is a forwarding reference (13.10.3.2) and \( A_i \) is an lvalue reference, in which case the type of \( P_i \) is changed to be the template parameter type (i.e., \( T&& \) is changed to simply \( T \)).

[Note 3: As a result, when \( P_i \) is \( T&& \) and \( A_i \) is \( X& \), the adjusted \( P_i \) will be \( T \), causing \( T \) to be deduced as \( X& \). —end note]

[Example 5]:

\[
\begin{align*}
\text{template <class T> void f(T&&);} & \quad // \#1 \\
\text{template <> void f(int&) \{} & \quad // \#1 \\
\text{template <> void f(int&&) \{} & \quad // \#2 \\
\text{void g(int i) \{} & \quad \text{calls} f<int&>(int&), \text{i.e., \#1} \\
\text{f(i);} & \quad \\
\end{align*}
\]

§ 13.10.3.6 ©ISO/IEC 458
f(0);                  // calls f<int>(int&&), i.e., #2
} — end example]

If the parameter-declaration corresponding to \( P_i \) is a function parameter pack, then the type of its declarator-id is compared with each remaining parameter type in the parameter-type-list of \( A \). Each comparison deduces template arguments for subsequent positions in the template parameter packs expanded by the function parameter pack. During partial ordering (13.10.3.5), if \( A_i \) was originally a function parameter pack:

1. if \( P \) does not contain a function parameter type corresponding to \( A_i \) then \( A_i \) is ignored;
2. otherwise, if \( P_i \) is not a function parameter pack, template argument deduction fails.

[Example 6:]

\[
\begin{align*}
\text{template}<&\text{class } T, \text{class... } U> & \text{ void } f(T*, U...) & \{ \} & \text{// #1} \\
\text{template}<&\text{class } T> & \text{ void } f(T) & \{ \} & \text{// #2} \\
\text{template} & \text{ void } f(\text{int}*) & \{ \} & \text{// selects #1}
\end{align*}
\]

— end example

11 These forms can be used in the same way as \( T \) is for further composition of types.

[Example 7:]

\[
X<int> (*)(\text{char}[6])
\]
is of the form

\[
\text{template-name}<T> \ (\ast)(\text{type}[i])
\]
which is a variant of

\[
\text{type} \ (\ast)(T)
\]
where type is \( X<int> \) and \( T \) is \( \text{char}[6] \). — end example

12 Template arguments cannot be deduced from function arguments involving constructs other than the ones specified above.

13 When the value of the argument corresponding to a non-type template parameter \( P \) that is declared with a dependent type is deduced from an expression, the template parameters in the type of \( P \) are deduced from the type of the value.

[Example 8:]

\[
\begin{align*}
\text{template}<&\text{long } n> & \text{ struct } A \ & \{ \} \\
\text{template}<\text{typename } T> & \text{ struct } C; \\
\text{template}<\text{typename } T, \ T \ n> & \text{ struct } C<A<n>> & \{ \\
& \text{ using } Q = T; \\
& \}; \\
\text{using } R & = \text{long}; \\
\text{using } R & = C<A<2>>::Q; \ & \text{// OK; } T \text{ was deduced as long from the template argument value in the type } A<2>
\end{align*}
\]

— end example

14 The type of \( N \) in the type \( T[N] \) is \text{std::size\_t}.

[Example 9:]

\[
\begin{align*}
\text{template}<\text{typename } T> & \text{ struct } S; \\
\text{template}<\text{typename } T, \ T \ n> & \text{ struct } S<int[n]> & \{ \\
& \text{ using } Q = T; \\
& \}; \\
\text{using } V & = \text{decltype}(<\text{sizeof } 0)>; \\
\text{using } V & = S<int[42]>::Q; \ & \text{// OK; } T \text{ was deduced as } \text{std::size\_t} \text{ from the type int[42]}
\end{align*}
\]

— end example

15 The type of \( B \) in the noexcept-specifier noexcept \( (B) \) of a function type is \text{bool}.

[Example 10:]

\[
\begin{align*}
\text{template}<\text{bool}> & \text{ struct } A \ & \{ \}
\end{align*}
\]
template<auto> struct B;

// Example 11:

Example 11:

template<class T, T i> void f1(int (&a)[i]);
int v[10];
void g() {
    f(v);
    // OK, T is std::size_t
}

— end example]

Note 4: Except for reference and pointer types, a major array bound is not part of a function parameter type and cannot be deduced from an argument:

Note 5: If, in the declaration of a function template with a non-type template parameter, the non-type template parameter is used in a subexpression in the function parameter list, the expression is a non-deduced context as specified above.

Example 12:

Example 12:

Note 6: Template parameters do not participate in template argument deduction if they are used only in non-deduced contexts. For example,

— end note]

— end note]

— end note]
If \( P \) has a form that contains \(<i>\), and if the type of \( i \) differs from the type of the corresponding template parameter of the template named by the enclosing \texttt{simple-template-id}, deduction fails. If \( P \) has a form that contains \([i]\), and if the type of \( i \) is not an integral type, deduction fails.\textsuperscript{123} If \( P \) has a form that includes \texttt{noexcept(i)} and the type of \( i \) is not \texttt{bool}, deduction fails.

\textbf{Example 13:}

\begin{verbatim}
template<int i> class A { /* ... */ };  
template<short s> void f(A<s>);  
void k1() {  
  A<i> a;  
  f(a);  // error: deduction fails for conversion from int to short  
  f<i>(a);  // OK  
}

template<const short cs> class B { };  
template<short s> void g(B<s>);  
void k2() {  
  B<i> b;  
  g(b);  // OK, cv-qualifiers are ignored on template parameter types  
}
\end{verbatim}

—end example]

A \textit{template-argument} can be deduced from a function, pointer to function, or pointer-to-member-function type.

\textbf{Example 14:}

\begin{verbatim}
template<class T> void f(void(*)(T,int));  
template<class T> void foo(T,int);  
void g(int,int);  
void g(char,int);  
void h(int,int,int);  
int m() {  
  f(&g);  // error: ambiguous  
  f(&h);  // OK, void h(char,int) is a unique match  
  f(&foo);  // error: type deduction fails because foo is a template  
}
\end{verbatim}

—end example]

A \textit{template type-parameter} cannot be deduced from the type of a function default argument.

\textbf{Example 15:}

\begin{verbatim}
template <class T> void f(T = 5, T = 7);  
void g() {  
  f(1);  // OK, calls f<int>(1,7)  
  f();  // error: cannot deduce T  
  f<int>();  // OK, calls f<int>(5,7)  
}
\end{verbatim}

—end example]

The \textit{template-argument} corresponding to a template \textit{template-parameter} is deduced from the type of the \textit{template-argument} of a class template specialization used in the argument list of a function call.

\textbf{Example 16:}

\begin{verbatim}
template <template <class T> class X> struct A { };  
template <template <class T> class X> void f(X<T>) { }  
template<class T> struct B { };  
A<X<T>> ab;  
f(ab);  // calls f(A<X<T>>)  
\end{verbatim}

—end example]

\textsuperscript{123} Although the \textit{template-argument} corresponding to a \textit{template-parameter} of type \texttt{bool} can be deduced from an array bound, the resulting value will always be \texttt{true} because the array bound will be nonzero.
24 [Note 7: Template argument deduction involving parameter packs (13.7.4) can deduce zero or more arguments for each parameter pack. — end note]

[Example 17:

```cpp
template<class> struct X { };
template<class R, class ... ArgTypes> struct X<R(int, ArgTypes ...)> { };
template<class ... Types> struct Y { };
template<class T, class ... Types> struct Y<T, Types& ...> { };

template<class ... Types> int f(void (*)(Types ...));
void g(int, float);

X<int> x1; // uses primary template
X<int(int, float, double)> x2; // uses partial specialization; ArgTypes contains float, double
X<int(float, int)> x3; // uses primary template
Y<> y1; // uses primary template; Types is empty
Y<int&, float&, double&> y2; // uses partial specialization; T is int&, Types contains float, double
Y<int, float, double> y3; // uses primary template; Types contains int, float, double
int fv = f(g); // OK; Types contains int, float
```
— end example]

13.10.3.7 Deducing template arguments from a function declaration [temp.deduct.decl]

In a declaration whose declarator-id refers to a specialization of a function template, template argument deduction is performed to identify the specialization to which the declaration refers. Specifically, this is done for explicit instantiations (13.9.3), explicit specializations (13.9.4), and certain friend declarations (13.7.5). This is also done to determine whether a deallocation function template specialization matches a placement operator new (6.7.5.5.3, 7.6.2.8). In all these cases, P is the type of the function template being considered as a potential match and A is either the function type from the declaration or the type of the deallocation function that would match the placement operator new as described in 7.6.2.8. The deduction is done as described in 13.10.3.6.

If, for the set of function templates so considered, there is either no match or more than one match after partial ordering has been considered (13.7.7.3), deduction fails and, in the declaration cases, the program is ill-formed.

13.10.4 Overload resolution [temp.over]

When a call of a function or function template is written (explicitly, or implicitly using the operator notation), template argument deduction (13.10.3) and checking of any explicit template arguments (13.4) are performed for each function template to find the template argument values (if any) that can be used with that function template to instantiate a function template specialization that can be invoked with the call arguments or, for conversion function templates, that can convert to the required type. For each function template:

1. If the argument deduction and checking succeeds, the template-arguments (deduced and/or explicit) are used to synthesize the declaration of a single function template specialization which is added to the candidate functions set to be used in overload resolution.

2. If the argument deduction fails or the synthesized function template specialization would be ill-formed, no such function is added to the set of candidate functions for that template.

The complete set of candidate functions includes all the synthesized declarations and all of the non-template functions found by name lookup. The synthesized declarations are treated like any other functions in the remainder of overload resolution, except as explicitly noted in 12.2.4.

[Example 1:

```cpp
template<class T> T max(T a, T b) { return a>b?a:b; }
```]

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void f(int a, int b, char c, char d) {
    int m1 = max(a,b);    // max(int, int)
    char m2 = max(c,d);   // max(char, char)
    int m3 = max(a,c);    // error: cannot generate max(int, char)
}

Adding the non-template function
int max(int,int);

to the example above would resolve the third call, by providing a function that can be called for max(a,c) after using
the standard conversion of char to int for c. — end example] 3

[Example 2: Here is an example involving conversions on a function argument involved in template-argument deduction:

    template<class T> struct B { /* ... */ };  
    template<class T> struct D : public B<T> { /* ... */ };  
    template<class T> void f(B<T>&);

    void g(B<int>& bi, D<int>& di) {
     f(bi); // f(bi)
     f(di); // f((B<int>&)di)
    }

— end example]

[Example 3: Here is an example involving conversions on a function argument not involved in template-parameter deduction:

    template<class T> void f(T*,int);  // #1
    template<class T> void f(T,char);  // #2

    void h(int* pi, int i, char c) {
     f(pi,i);  // #1: f<int*>(pi,i)
     f(pi,c);  // #2: f<int*>(pi,c)
     f(i,c);   // #2: f<int>(i,c)
     f(i,i);   // #2: f<int>(i,char(i))
    }

— end example]

Only the signature of a function template specialization is needed to enter the specialization in a set of candidate functions. Therefore only the function template declaration is needed to resolve a call for which a template specialization is a candidate.

[Example 4:

    template<class T> void f(T);    // declaration

    void g() {
     f("Annemarie");  // calls f<const char*>
    }

The call to f is well-formed even if the template f is only declared and not defined at the point of the call. The program will be ill-formed unless a specialization for f<const char*> is explicitly instantiated in some translation unit (13.1). — end example]
14 Exception handling

14.1 Preamble

Exception handling provides a way of transferring control and information from a point in the execution of a thread to an exception handler associated with a point previously passed by the execution. A handler will be invoked only by throwing an exception in code executed in the handler’s try block or in functions called from the handler’s try block.

\[
\text{try-block:} \quad \text{try compound-statement handler-seq}
\]

\[
\text{function-try-block:} \quad \text{try ctor-initializer} \text{opt} \text{ compound-statement handler-seq}
\]

\[
\text{handler-seq:} \quad \text{handler handler-seq} \text{opt}
\]

\[
\text{handler:} \quad \text{catch ( exception-declaration ) compound-statement}
\]

\[
\text{exception-declaration:} \quad \text{attribute-specifier-seq} \text{opt} \text{ type-specifier-seq declarator}
\]

\[
\text{attribute-specifier-seq} \text{opt} \text{ type-specifier-seq abstract-declarator} \text{opt}
\]

The optional attribute-specifier-seq in an exception-declaration appertains to the parameter of the catch clause (14.4).

2 A try-block is a statement (8.1).

[Note 1: Within this Clause “try block” is taken to mean both try-block and function-try-block. — end note]

3 The compound-statement of a try block or of a handler is a control-flow-limited statement (8.2).

[Example 1:]

```c
void f() {
    goto l1;  // error
    goto l2;  // error
    try {
        goto l1;  // OK
        goto l2;  // error
    l1: ;
    } catch (…) {
    l2: ;
        goto l1;  // error
        goto l2;  // OK
    }
}
```

— end example]

A goto, break, return, or continue statement can be used to transfer control out of a try block or handler. When this happens, each variable declared in the try block will be destroyed in the context that directly contains its declaration.

[Example 2:]

```c
lab: try {
    T1 t1;
    try {
        T2 t2;
        if (condition)
            goto lab;
    } catch(…) { /* handler 2 */ }
} catch(…) { /* handler 1 */ }
```

§ 14.1
Here, executing `goto lab;` will destroy first `t2`, then `t1`, assuming the `condition` does not declare a variable. Any exception thrown while destroying `t2` will result in executing handler 2; any exception thrown while destroying `t1` will result in executing handler 1. —end example

4 A `function-try-block` associates a `handler-seq` with the `ctor-initializer`, if present, and the `compound-statement`. An exception thrown during the execution of the `compound-statement` or, for constructors and destructors, during the initialization or destruction, respectively, of the class’s subobjects, transfers control to a handler in a `function-try-block` in the same way as an exception thrown during the execution of a `try-block` transfers control to other handlers.

[Example 3:

```cpp
int f(int);
class C {
   int i;
   double d;
public:
   C(int, double);
};
C::C(int ii, double id)
   try : i(f(ii)), d(id) {
      // constructor statements
   } catch (...) {
      // handles exceptions thrown from the ctor-initializer and from the constructor statements
   }
—end example
```

In this Clause, “before” and “after” refer to the “sequenced before” relation (6.9.1).

14.2 Throwing an exception

1 Throwing an exception transfers control to a handler.

[Note 1: An exception can be thrown from one of the following contexts: `throw-expressions` (7.6.18), allocation functions (6.7.5.5.2), `dynamic_cast` (7.6.1.7), `typeid` (7.6.1.8), `new-expression`s (7.6.2.8), and standard library functions (16.3.2.4). —end note]

An object is passed and the type of that object determines which handlers can catch it.

[Example 1:

```cpp
throw "Help!";
```

can be caught by a handler of `const char*` type:

```cpp
try {
   // ...
} catch(const char* p) {
   // handle character string exceptions here
}
```

and

```cpp
class Overflow {
public:
   Overflow(char,double,double);
};
```

```cpp
void f(double x) {
   throw Overflow('+',x,3.45e107);
}
```

can be caught by a handler for exceptions of type `Overflow`:

```cpp
try {
   f(1.2);
} catch(Overflow& oo) {
   // handle exceptions of type Overflow here
}
—end example
```
When an exception is thrown, control is transferred to the nearest handler with a matching type (14.4); “nearest” means the handler for which the compound-statement or ctor-initializer following the try keyword was most recently entered by the thread of control and not yet exited.

Throwing an exception initializes an object with dynamic storage duration, called the exception object. If the type of the exception object would be an incomplete type (6.8.1), an abstract class type (11.7.4), or a pointer to an incomplete type other than cv void (6.8.4), the program is ill-formed.

The memory for the exception object is allocated in an unspecified way, except as noted in 6.7.5.5.2. If a handler exits by rethrowing, control is passed to another handler for the same exception object. The points of potential destruction for the exception object are:

(4.1) — when an active handler for the exception exits by any means other than rethrowing, immediately after the destruction of the object (if any) declared in the exception-declaration in the handler;

(4.2) — when an object of type std::exception_ptr (17.9.7) that refers to the exception object is destroyed, before the destructor of std::exception_ptr returns.

Among all points of potential destruction for the exception object, there is an unspecified last one where the exception object is destroyed. All other points happen before that last one (6.9.2.2).

[Note 2: No other thread synchronization is implied in exception handling. — end note]

The implementation may then deallocate the memory for the exception object; any such deallocation is done in an unspecified way.

[Note 3: A thrown exception does not propagate to other threads unless caught, stored, and rethrown using appropriate library functions; see 17.9.7 and 33.10. — end note]

Let T denote the type of the exception object. Copy-initialization of an object of type T from an lvalue of type const T in a context unrelated to T shall be well-formed. If T is a class type, the selected constructor is odr-used (6.3) and the destructor of T is potentially invoked (11.4.7).

An exception is considered caught when a handler for that exception becomes active (14.4).

[Note 4: An exception can have active handlers and still be considered uncaught if it is rethrown. — end note]

If the exception handling mechanism handling an uncaught exception (14.6.3) directly invokes a function that exits via an exception, the function std::terminate is invoked (14.6.2).

[Example 2:

```cpp
struct C {
    C() { }
    C(const C&) {
        if (std::uncaught_exceptions()) {
            throw 0;       // throw during copy to handler’s exception-declaration object (14.4)
        }
    }
};

int main() {
    try {
        throw C();       // calls std::terminate if construction of the handler’s
                         // exception-declaration object is not elided (11.9.6)
    } catch(C) { } // exception-declaration object is not elided (11.9.6)
} catch(C) { } // exception-declaration object is not elided (11.9.6)

    — end example]

[Note 5: If a destructor directly invoked by stack unwinding exits via an exception, std::terminate is invoked. — end note]

14.3  Constructors and destructors  [except.ctor]

As control passes from the point where an exception is thrown to a handler, objects are destroyed by a process, specified in this subclause, called stack unwinding.

Each object with automatic storage duration is destroyed if it has been constructed, but not yet destroyed, since the try block was entered. If an exception is thrown during the destruction of temporaries or local variables for a return statement (8.7.4), the destructor for the returned object (if any) is also invoked. The objects are destroyed in the reverse order of the completion of their construction.
Example 1:

```cpp
struct A { };

struct Y { ~Y() noexcept(false) { throw 0; } };

A f() {
    try {
        A a;
        Y y;
        A b;
        return {};// #1
    } catch (...) {
    // #2
    return {};
    }

    return {}; // #2
}

At #1, the returned object of type A is constructed. Then, the local variable b is destroyed (8.7). Next, the local variable y is destroyed, causing stack unwinding, resulting in the destruction of the returned object, followed by the destruction of the local variable a. Finally, the returned object is constructed again at #2. — end example]

3 If the initialization of an object other than by delegating constructor is terminated by an exception, the destructor is invoked for each of the object’s subobjects that were known to be initialized by the object’s initialization and whose initialization has completed (9.4).

[Note 1: If such an object has a reference member that extends the lifetime of a temporary object, this ends the lifetime of the reference member, so the lifetime of the temporary object is effectively not extended. — end note]

A subobject is known to be initialized if it is not an anonymous union member and its initialization is specified

1 (3.1) — in 11.9.3 for initialization by constructor,
2 (3.2) — in 11.4.5.3 for initialization by defaulted copy/move constructor,
3 (3.3) — in 11.9.4 for initialization by inherited constructor,
4 (3.4) — in 9.4.2 for aggregate initialization,
5 (3.5) — in 7.5.6.3 for the initialization of the closure object when evaluating a lambda-expression,
6 (3.6) — in 9.4.1 for default-initialization, value-initialization, or direct-initialization of an array.

[Note 2: This includes virtual base class subobjects if the initialization is for a complete object, and can include variant members that were nominated explicitly by a mem-initializer or designated-initializer-clause or that have a default member initializer. — end note]

If the destructor of an object is terminated by an exception, each destructor invocation that would be performed after executing the body of the destructor (11.4.7) and that has not yet begun execution is performed.

[Note 3: This includes virtual base class subobjects if the destructor was invoked for a complete object. — end note]

The subobjects are destroyed in the reverse order of the completion of their construction. Such destruction is sequenced before entering a handler of the function-try-block of the constructor or destructor, if any.

4 If the compound-statement of the function-body of a delegating constructor for an object exits via an exception, the object’s destructor is invoked. Such destruction is sequenced before entering a handler of the function-try-block of a delegating constructor for that object, if any.

5 [Note 4: If the object was allocated by a new-expression (7.6.2.8), the matching deallocation function (6.7.5.5.3), if any, is called to free the storage occupied by the object. — end note]

14.4 Handling an exception [except.handle]

1 The exception-declaration in a handler describes the type(s) of exceptions that can cause that handler to be entered. The exception-declaration shall not denote an incomplete type, an abstract class type, or an rvalue reference type. The exception-declaration shall not denote a pointer or reference to an incomplete type, other than “pointer to cv void”.

2 A handler of type “array of T” or function type T is adjusted to be of type “pointer to T”.

3 A handler is a match for an exception object of type E if
— The handler is of type \(cv\ T\) or \(cv\ T&\) and \(E\) and \(T\) are the same type (ignoring the top-level \(cv\)-qualifiers), or

— the handler is of type \(cv\ T\) or \(cv\ T&\) and \(T\) is an unambiguous public base class of \(E\), or

— the handler is of type \(cv\ T\) or \(const\ T&\) where \(T\) is a pointer or pointer-to-member type and \(E\) is a pointer or pointer-to-member type that can be converted to \(T\) by one or more of

— a standard pointer conversion (7.3.12) not involving conversions to pointers to private or protected or ambiguous classes

— a function pointer conversion (7.3.14)

— a qualification conversion (7.3.6), or

— the handler is of type \(cv\ T\) or \(const\ T&\) where \(T\) is a pointer or pointer-to-member type and \(E\) is \(std::nullptr_t\).

[Note 1: A throw-expression whose operand is an integer literal with value zero does not match a handler of pointer or pointer-to-member type. A handler of reference to array or function type is never a match for any exception object (7.6.18). — end note]

Example 1:

```c++
class Matherr { /* ... */ virtual void vf(); };  
class Overflow: public Matherr { /* ... */ };  
class Underflow: public Matherr { /* ... */ };  
class Zerodivide: public Matherr { /* ... */ };  

void f() {  
  try {  
    g(); 
    } catch (Overflow oo) {  
      // ...  
    } catch (Matherr mm) {  
      // ...  
    }  
}
```

Here, the Overflow handler will catch exceptions of type Overflow and the Matherr handler will catch exceptions of type Matherr and of all types publicly derived from Matherr including exceptions of type Underflow and Zerodivide. — end example]

The handlers for a try block are tried in order of appearance.

[Note 2: This makes it possible to write handlers that can never be executed, for example by placing a handler for a final derived class after a handler for a corresponding unambiguous public base class. — end note]

A ... in a handler’s exception-declaration functions similarly to ... in a function parameter declaration; it specifies a match for any exception. If present, a ... handler shall be the last handler for its try block.

If no match is found among the handlers for a try block, the search for a matching handler continues in a dynamically surrounding try block of the same thread.

A handler is considered active when initialization is complete for the parameter (if any) of the catch clause.

[Note 3: The stack will have been unwound at that point. — end note]

Also, an implicit handler is considered active when the function \(std::terminate\) is entered due to a throw. A handler is no longer considered active when the catch clause exits.

The exception with the most recently activated handler that is still active is called the currently handled exception.

If no matching handler is found, the function \(std::terminate\) is invoked; whether or not the stack is unwound before this invocation of \(std::terminate\) is implementation-defined (14.6.2).

Referring to any non-static member or base class of an object in the handler for a function-try-block of a constructor or destructor for that object results in undefined behavior.

Exceptions thrown in destructors of objects with static storage duration or in constructors of objects associated with non-block variables with static storage duration are not caught by a function-try-block on the main function (6.9.3.1). Exceptions thrown in destructors of objects with thread storage duration or in
constructors of objects associated with non-block variables with thread storage duration are not caught by a
function-try-block on the initial function of the thread.

12 If a return statement (8.7.4) appears in a handler of the function-try-block of a constructor, the program is
ill-formed.

13 The currently handled exception is rethrown if control reaches the end of a handler of the function-try-block
of a constructor or destructor. Otherwise, flowing off the end of the compound-statement of a handler of a
function-try-block is equivalent to flowing off the end of the compound-statement of that function (see 8.7.4).

14 The variable declared by the exception-declaration, of type cv T or cv T&, is initialized from the exception
object, of type E, as follows:

(14.1) — if T is a base class of E, the variable is copy-initialized (9.4) from an lvalue of type T designating the
corresponding base class subobject of the exception object;

(14.2) — otherwise, the variable is copy-initialized (9.4) from an lvalue of type E designating the exception object.

The lifetime of the variable ends when the handler exits, after the destruction of any objects with automatic
storage duration initialized within the handler.

15 When the handler declares an object, any changes to that object will not affect the exception object. When
the handler declares a reference to an object, any changes to the referenced object are changes to the exception
object and will have effect should that object be rethrown.

14.5 Exception specifications [except.spec]

1 The predicate indicating whether a function cannot exit via an exception is called the exception specification
of the function. If the predicate is false, the function has a potentially-throwing exception specification,
otherwise it has a non-throwing exception specification. The exception specification is either defined implicitly,
or defined explicitly by using a noexcept-specifier as a suffix of a function declarator (9.3.4.6).

    noexcept-specifier:
    noexcept ( constant-expression )
    noexcept

2 In a noexcept-specifier, the constant-expression, if supplied, shall be a contextually converted constant
expression of type bool (7.7); that constant expression is the exception specification of the function type
in which the noexcept-specifier appears. A ( token that follows noexcept is part of the noexcept-specifier
and does not commence an initializer (9.4). The noexcept-specifier noexcept without a constant-expression is
equivalent to the noexcept-specifier noexcept(true).

[Example 1:

    void f() noexcept(sizeof(char[2])); // error: narrowing conversion of value 2 to type bool
    void g() noexcept(sizeof(char));     // OK, conversion of value 1 to type bool is non-narrowing
    — end example]

3 If a declaration of a function does not have a noexcept-specifier, the declaration has a potentially throwing
exception specification unless it is a destructor or a deallocation function or is defaulted on its first declaration,
in which cases the exception specification is as specified below and no other declaration for that function
shall have a noexcept-specifier. In an explicit instantiation (13.9.3) a noexcept-specifier may be specified, but
is not required. If a noexcept-specifier is specified in an explicit instantiation, the exception specification shall
be the same as the exception specification of all other declarations of that function. A diagnostic is required
only if the exception specifications are not the same within a single translation unit.

4 If a virtual function has a non-throwing exception specification, all declarations, including the definition, of
any function that overrides that virtual function in any derived class shall have a non-throwing exception
specification, unless the overriding function is defined as deleted.

[Example 2:

    struct B {
        virtual void f() noexcept;
        virtual void g();
        virtual void h() noexcept = delete;
    };

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struct D: B {
    void f();           // error
    void g() noexcept;  // OK
    void h() = delete;  // OK
};

The declaration of D::f is ill-formed because it has a potentially-throwing exception specification, whereas B::f has a non-throwing exception specification. — end example

Whenever an exception is thrown and the search for a handler (14.4) encounters the outermost block of a function with a non-throwing exception specification, the function std::terminate is invoked (14.6.2).

[Note 1: An implementation is not permitted to reject an expression merely because, when executed, it throws or might throw an exception from a function with a non-throwing exception specification. — end note]

[Example 3:
	exttt{extern void f();} // potentially-throwing

void g() noexcept {
    f();                   // valid, even if \texttt{f} throws
    throw 42;             // valid, effectively a call to \texttt{std::terminate}
}

The call to \texttt{f} is well-formed despite the possibility for it to throw an exception. — end example]

An expression \( E \) is potentially-throwing if

1. \( E \) is a function call (7.6.1.3) whose postfix-expression has a function type, or a pointer-to-function type, with a potentially-throwing exception specification, or
2. \( E \) implicitly invokes a function (such as an overloaded operator, an allocation function in a new-expression, a constructor for a function argument, or a destructor if \( E \) is a full-expression (6.9.1)) that has a potentially-throwing exception specification, or
3. \( E \) is a throw-expression (7.6.18), or
4. \( E \) is a dynamic_cast expression that casts to a reference type and requires a runtime check (7.6.1.7), or
5. \( E \) is a typeid expression applied to a (possibly parenthesized) built-in unary \* operator applied to a pointer to a polymorphic class type (7.6.1.8), or
6. any of the immediate subexpressions (6.9.1) of \( E \) is potentially-throwing.

An implicitly-declared constructor for a class \( X \), or a constructor without a noexcept-specifier that is defaulted on its first declaration, has a potentially-throwing exception specification if and only if any of the following constructs is potentially-throwing:

1. the invocation of a constructor selected by overload resolution in the implicit definition of the constructor for class \( X \) to initialize a potentially constructed subobject, or
2. a subexpression of such an initialization, such as a default argument expression, or,
3. for a default constructor, a default member initializer.

[Note 2: Even though destructors for fully-constructed subobjects are invoked when an exception is thrown during the execution of a constructor (14.3), their exception specifications do not contribute to the exception specification of the constructor, because an exception thrown from such a destructor would call the function std::terminate rather than escape the constructor (14.2, 14.6.2). — end note]

The exception specification for an implicitly-declared destructor, or a destructor without a noexcept-specifier, is potentially-throwing if and only if any of the destructors for any of its potentially constructed subobjects has a potentially-throwing exception specification or the destructor is virtual and the destructor of any virtual base class has a potentially-throwing exception specification.

The exception specification for an implicitly-declared assignment operator, or an assignment-operator without a noexcept-specifier that is defaulted on its first declaration, is potentially-throwing if and only if the invocation of any assignment operator in the implicit definition is potentially-throwing.

A deallocation function (6.7.5.5.3) with no explicit noexcept-specifier has a non-throwing exception specification.
The exception specification for a comparison operator function (12.4.3) without a noexcept-specifier that is defaulted on its first declaration is potentially-throwing if and only if any expression in the implicit definition is potentially-throwing.

Example 4:

```cpp
struct A {
    A(int = (A(5), 0)) noexcept;
    A(const A&) noexcept;
    A(A&&) noexcept;
    ~A();
};

struct B {
    B() noexcept;
    B(const B&) = default; // implicit exception specification is noexcept(true)
    B(B&&, int = (throw 42, 0)) noexcept;
    ~B() noexcept(false);
};

int n = 7;
struct D : public A, public B {
    int * p = new int[n];
    // D::D() potentially-throwing, as the new operator may throw bad_alloc or bad_array_new_length
    // D::D(const D&) non-throwing
    // D::D(D&&) potentially-throwing, as the default argument for B's constructor may throw
    // D::~D() potentially-throwing
};
```

Furthermore, if A::~A() were virtual, the program would be ill-formed since a function that overrides a virtual function from a base class shall not have a potentially-throwing exception specification if the base class function has a non-throwing exception specification. — end example

An exception specification is considered to be needed when:

(11.1) — in an expression, the function is selected by overload resolution (12.2, 12.3);

(11.2) — the function is odr-used (6.3) or, if it appears in an unevaluated operand, would be odr-used if the expression were potentially-evaluated;

(11.3) — the exception specification is compared to that of another declaration (e.g., an explicit specialization or an overriding virtual function);

(11.4) — the function is defined; or

(11.5) — the exception specification is needed for a defaulted function that calls the function.

[Note 3: A defaulted declaration does not require the exception specification of a base member function to be evaluated until the implicit exception specification of the derived function is needed, but an explicit noexcept-specifier needs the implicit exception specification to compare against. — end note]

The exception specification of a defaulted function is evaluated as described above only when needed; similarly, the noexcept-specifier of a specialization of a function template or member function of a class template is instantiated only when needed.

14.6 Special functions [except.special]

14.6.1 General [except.special.general]

The function std::terminate (14.6.2) is used by the exception handling mechanism for coping with errors related to the exception handling mechanism itself. The function std::current_exception() (17.9.7) and the class std::nested_exception (17.9.8) can be used by a program to capture the currently handled exception.

14.6.2 The std::terminate function [except.terminate]

In some situations, exception handling is abandoned for less subtle error handling techniques.

[Note 1: These situations are:

(1.1) — when the exception handling mechanism, after completing the initialization of the exception object but before activation of a handler for the exception (14.2), calls a function that exits via an exception, or

(1.2) — when the exception handling mechanism cannot find a handler for a thrown exception (14.4), or

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471
— when the search for a handler (14.4) encounters the outermost block of a function with a non-throwing exception specification (14.5), or

— when the destruction of an object during stack unwinding (14.3) terminates by throwing an exception, or

— when initialization of a non-block variable with static or thread storage duration (6.9.3.3) exits via an exception, or

— when destruction of an object with static or thread storage duration exits via an exception (6.9.3.4), or

— when execution of a function registered with std::atexit or std::at_quick_exit exits via an exception (17.5), or

— when a throw-expression (7.6.18) with no operand attempts to rethrow an exception and no exception is being handled (14.2), or

— when the function std::nested_exception::rethrow_nested is called for an object that has captured no exception (17.9.8), or

— when execution of the initial function of a thread exits via an exception (33.4.3.3), or

— for a parallel algorithm whose ExecutionPolicy specifies such behavior (22.12.4, 22.12.5, 22.12.6), when execution of an element access function (27.3.1) of the parallel algorithm exits via an exception (27.3.4), or

— when the destructor or the move assignment operator is invoked on an object of type std::thread that refers to a joinable thread (33.4.3.4, 33.4.3.5), or

— when a call to a wait(), wait_until(), or wait_for() function on a condition variable (33.7.4, 33.7.5) fails to meet a postcondition.

In such cases, the function std::terminate is invoked (17.9.5). In the situation where no matching handler is found, it is implementation-defined whether or not the stack is unwound before std::terminate is invoked. In the situation where the search for a handler (14.4) encounters the outermost block of a function with a non-throwing exception specification (14.5), it is implementation-defined whether the stack is unwound, unwound partially, or not unwound at all before the function std::terminate is invoked. In all other situations, the stack shall not be unwound before the function std::terminate is invoked. An implementation is not permitted to finish stack unwinding prematurely based on a determination that the unwind process will eventually cause an invocation of the function std::terminate.

14.6.3 The std::uncaught_exceptions function

An exception is considered uncaught after completing the initialization of the exception object (14.2) until completing the activation of a handler for the exception (14.4).

[Note 1: As a consequence, an exception is considered uncaught during any stack unwinding resulting from it being thrown. — end note]

If an exception is rethrown (7.6.18, 17.9.7), it is considered uncaught from the point of rethrow until the rethrown exception is caught. The function std::uncaught_exceptions (17.9.6) returns the number of uncaught exceptions in the current thread.
15 Preprocessing directives

15.1 Preamble

 preprocess-file:
     group opt
     module-file

 module-file:
     pp-global-module-fragment opt pp-module group opt pp-private-module-fragment opt

 pp-global-module-fragment:
     module ; new-line group opt

 pp-private-module-fragment:
     module : private ; new-line group opt

 group:
     group-part
     group group-part

 group-part:
     control-line
     if-section
     text-line
     # conditionally-supported-directive

 control-line:
   # include pp-tokens new-line
   pp-import
   # define identifier replacement-list new-line
   # define identifier lparen identifier-list opt ) replacement-list new-line
   # define identifier lparen ... ) replacement-list new-line
   # define identifier lparen identifier-list , ... ) replacement-list new-line
   # undef identifier new-line
   # line pp-tokens new-line
   # error pp-tokens opt new-line
   # warning pp-tokens opt new-line
   # pragma pp-tokens opt new-line
   # new-line

 if-section:
   if-group elif-groups opt else-group opt endif-line

 if-group:
   # if constant-expression new-line group opt
   # ifdef identifier new-line group opt
   # ifndef identifier new-line group opt

 elif-groups:
   elif-group
   elif-groups elif-group

 elif-group:
   # elif constant-expression new-line group opt
   # elifdef identifier new-line group opt
   # elifndef identifier new-line group opt

 else-group:
   # else new-line group opt

 endif-line:
   # endif new-line

 text-line:
     pp-tokens opt new-line

 conditionally-supported-directive:
     pp-tokens new-line
A preprocessing directive consists of a sequence of preprocessing tokens that satisfies the following constraints:

At the start of translation phase 4, the first token in the sequence, referred to as a directive-introducing token, begins with the first character in the source file (optionally after whitespace containing no new-line characters) or follows whitespace containing at least one new-line character, and is

1. a `#` preprocessing token, or
2. an `import` preprocessing token immediately followed on the same logical line by a `header-name`, `<`, `identifier`, `string-literal`, or `:` preprocessing token, or
3. a `module` preprocessing token immediately followed on the same logical line by an `identifier`, `;`, or `;` preprocessing token, or
4. an `export` preprocessing token immediately followed on the same logical line by one of the two preceding forms.

The last token in the sequence is the first token within the sequence that is immediately followed by whitespace containing a new-line character.

[Note 1: A new-line character ends the preprocessing directive even if it occurs within what would otherwise be an invocation of a function-like macro. —end note]

[Example 1:

```plaintext
#include // preprocessing directive
module ; // preprocessing directive
export module leftrightpad; // preprocessing directive
import <string>; // preprocessing directive
export import "squee"; // preprocessing directive
import rightpad; // preprocessing directive
import :part; // preprocessing directive
module // not a preprocessing directive
; // not a preprocessing directive
export // not a preprocessing directive
import // not a preprocessing directive
foo; // not a preprocessing directive
export // not a preprocessing directive
import foo; // preprocessing directive (ill-formed at phase 7)
import :: // not a preprocessing directive
import -> // not a preprocessing directive
--- end example]

A sequence of preprocessing tokens is only a text-line if it does not begin with a directive-introducing token. A sequence of preprocessing tokens is only a conditionally-supported-directive if it does not begin with any of the directive names appearing after a `#` in the syntax. A conditionally-supported-directive is conditionally-supported with implementation-defined semantics.

125) Thus, preprocessing directives are commonly called “lines”. These “lines” have no other syntactic significance, as all whitespace is equivalent except in certain situations during preprocessing (see the `#` character string literal creation operator in 15.6.3, for example).
At the start of phase 4 of translation, the group of a pp-global-module-fragment shall contain neither a text-line nor a pp-import.

When in a group that is skipped (15.2), the directive syntax is relaxed to allow any sequence of preprocessing tokens to occur between the directive name and the following new-line character.

The only whitespace characters that shall appear between preprocessing tokens within a preprocessing directive (from just after the directive-introducing token through just before the terminating new-line character) are space and horizontal-tab (including spaces that have replaced comments or possibly other whitespace characters in translation phase 3).

The implementation can process and skip sections of source files conditionally, include other source files, import macros from header units, and replace macros. These capabilities are called preprocessing, because conceptually they occur before translation of the resulting translation unit.

The preprocessing tokens within a preprocessing directive are not subject to macro expansion unless otherwise stated.

[Example 2: In:
#define EMPTY
EMPTY # include <file.h>
the sequence of preprocessing tokens on the second line is not a preprocessing directive, because it does not begin with a # at the start of translation phase 4, even though it will do so after the macro EMPTY has been replaced. — end example]

15.2 Conditional inclusion [cpp.cond]

defined-macro-expression:
  defined identifier
  defined ( identifier )

h-preprocessing-token:
  any preprocessing-token other than >

h-pp-tokens:
  h-preprocessing-token
  h-pp-tokens h-preprocessing-token

header-name-tokens:
  string-literal
  < h-pp-tokens >

has-include-expression:
  __has_include ( header-name )
  __has_include ( header-name-tokens )

has-attribute-expression:
  __has_cpp_attribute ( pp-tokens )

1 The expression that controls conditional inclusion shall be an integral constant expression except that identifiers (including those lexically identical to keywords) are interpreted as described below and it may contain zero or more defined-macro-expressions and/or has-include-expressions and/or has-attribute-expressions as unary operator expressions.

2 A defined-macro-expression evaluates to 1 if the identifier is currently defined as a macro name (that is, if it is predefined or if it has one or more active macro definitions (15.5), for example because it has been the subject of a #define preprocessing directive without an intervening #undef directive with the same subject identifier), 0 if it is not.

3 The second form of has-include-expression is considered only if the first form does not match, in which case the preprocessing tokens are processed just as in normal text.

4 The header or source file identified by the parenthesized preprocessing token sequence in each contained has-include-expression is searched for as if that preprocessing token sequence were the pp-tokens in a #include directive, except that no further macro expansion is performed. If such a directive would not satisfy the syntactic requirements of a #include directive, the program is ill-formed. The has-include-expression evaluates to 1 if the search for the source file succeeds, and to 0 if the search fails.

126) Because the controlling constant expression is evaluated during translation phase 4, all identifiers either are or are not macro names — there simply are no keywords, enumeration constants, etc.
Each has-attribute-expression is replaced by a non-zero pp-number matching the form of an integer-literal if the implementation supports an attribute with the name specified by interpreting the pp-tokens, after macro expansion, as an attribute-token, and by 0 otherwise. The program is ill-formed if the pp-tokens do not match the form of an attribute-token.

For an attribute specified in this document, it is implementation-defined whether the value of the has-attribute-expression is 0 or is given by Table 21. For other attributes recognized by the implementation, the value is implementation-defined.

[Note 1: It is expected that the availability of an attribute can be detected by any non-zero result. — end note]

Table 21 — __has_cpp_attribute values

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>assume</td>
<td>202207L</td>
</tr>
<tr>
<td>carries_dependency</td>
<td>200809L</td>
</tr>
<tr>
<td>deprecated</td>
<td>201309L</td>
</tr>
<tr>
<td>fallthrough</td>
<td>201603L</td>
</tr>
<tr>
<td>likely</td>
<td>201803L</td>
</tr>
<tr>
<td>maybe_unused</td>
<td>201603L</td>
</tr>
<tr>
<td>no_unique_address</td>
<td>201803L</td>
</tr>
<tr>
<td>nodiscard</td>
<td>201907L</td>
</tr>
<tr>
<td>noreturn</td>
<td>200809L</td>
</tr>
<tr>
<td>unlikely</td>
<td>201803L</td>
</tr>
</tbody>
</table>

The #ifdef, #ifndef, #elifdef, and #elifndef directives, and the defined conditional inclusion operator, shall treat __has_include and __has_cpp_attribute as if they were the names of defined macros. The identifiers __has_include and __has_cpp_attribute shall not appear in any context not mentioned in this subclause.

Each preprocessing token that remains (in the list of preprocessing tokens that will become the controlling expression) after all macro replacements have occurred shall be in the lexical form of a token (5.6).

Preprocessing directives of the forms

```c
#if constant-expression new-line group
#else constant-expression new-line group
```

check whether the controlling constant expression evaluates to nonzero.

Prior to evaluation, macro invocations in the list of preprocessing tokens that will become the controlling constant expression are replaced (except for those macro names modified by the defined unary operator), just as in normal text. If the token defined is generated as a result of this replacement process or use of the defined unary operator does not match one of the two specified forms prior to macro replacement, the behavior is undefined.

After all replacements due to macro expansion and evaluations of defined-macro-expressions, has-include-expressions, and has-attribute-expressions have been performed, all remaining identifiers and keywords, except for true and false, are replaced with the pp-number 0, and then each preprocessing token is converted into a token.

[Note 2: An alternative token (5.5) is not an identifier, even when its spelling consists entirely of letters and underscores. Therefore it is not subject to this replacement. — end note]

The resulting tokens comprise the controlling constant expression which is evaluated according to the rules of 7.7 using arithmetic that has at least the ranges specified in 17.3. For the purposes of this token conversion and evaluation all signed and unsigned integer types act as if they have the same representation as, respectively, intmax_t or uintmax_t (17.4.1).

[Note 3: Thus on an implementation where std::numeric_limits<int>::max() is 0x7FFF and std::numeric_limits<unsigned int>::max() is 0xFFFF, the integer literal 0x8000 is signed and positive within a #if expression even though it is unsigned in translation phase 7 (5.2). — end note]

This includes interpreting character-literals according to the rules in 5.13.3.

[Note 4: The associated character encodings of literals are the same in #if and #elif directives and in any expression. — end note]
Each subexpression with type `bool` is subjected to integral promotion before processing continues.

13 Preprocessing directives of the forms

```
#define identifier new-line group
#define !identifier new-line group
#define !identifier new-line group
```

check whether the identifier is or is not currently defined as a macro name. Their conditions are equivalent to `#if defined identifier, #if !defined identifier, #elif defined identifier, and #elif !defined identifier`, respectively.

14 Each directive’s condition is checked in order. If it evaluates to false (zero), the group that it controls is skipped: directives are processed only through the name that determines the directive in order to keep track of the level of nested conditionals; the rest of the directives’ preprocessing tokens are ignored, as are the other preprocessing tokens in the group. Only the first group whose control condition evaluates to true (nonzero) is processed; any following groups are skipped and their controlling directives are processed as if they were in a group that is skipped. If none of the conditions evaluates to true, and there is a `#else` directive, the group controlled by the `#else` is processed; lacking a `#else` directive, all the groups until the `#endif` are skipped.\footnote{As indicated by the syntax, a preprocessing token cannot follow a `#else` or `#endif` directive before the terminating new-line character. However, comments can appear anywhere in a source file, including within a preprocessing directive.}

15 [Example 1]: This demonstrates a way to include a library `optional` facility only if it is available:

```
#include <optional>
#if __cpp_lib_optional >= 201603
#define have_optional 1
#else
#endif
#endif
 ifndef have_optional
#define have_optional 0
endif
```

—end example]  

16 [Example 2]: This demonstrates a way to use the attribute `[[acme::deprecated]]` only if it is available.

```
#if __has_cpp_attribute(acme::deprecated)
#define ATTR_DEPRECATED(msg) [[acme::deprecated(msg)]
#else
#define ATTR_DEPRECATED(msg) [[deprecated(msg)]
#endif
ATTR_DEPRECATED("This function is deprecated") void anvil();
```

—end example]

15.3 Source file inclusion

A `#include` directive shall identify a header or source file that can be processed by the implementation.

A preprocessing directive of the form

```
#include <h-char-sequence> new-line
```

searches a sequence of implementation-defined places for a header identified uniquely by the specified sequence between the `<` and `>` delimiters, and causes the replacement of that directive by the entire contents of the header. How the places are specified or the header identified is implementation-defined.

A preprocessing directive of the form

```
#include "q-char-sequence " new-line
```
causes the replacement of that directive by the entire contents of the source file identified by the specified sequence between the " delimiters. The named source file is searched for in an implementation-defined manner. If this search is not supported, or if the search fails, the directive is reprocessed as if it read

\[ \texttt{# include < h-char-sequence > new-line} \]

with the identical contained sequence (including > characters, if any) from the original directive.

4 A preprocessing directive of the form

\[ \texttt{# include pp-tokens new-line} \]

(that does not match one of the two previous forms) is permitted. The preprocessing tokens after include in the directive are processed just as in normal text (i.e., each identifier currently defined as a macro name is replaced by its replacement list of preprocessing tokens). If the directive resulting after all replacements does not match one of the two previous forms, the behavior is undefined. The method by which a sequence of preprocessing tokens between a < and a > preprocessing token pair or a pair of " characters is combined into a single header name preprocessing token is implementation-defined.

5 The implementation shall provide unique mappings for sequences consisting of one or more nondigits or digits (5.10) followed by a period (.) and a single nondigit. The first character shall not be a digit. The implementation may ignore distinctions of alphabetical case.

6 A #include preprocessing directive may appear in a source file that has been read because of a #include directive in another file, up to an implementation-defined nesting limit.

7 If the header identified by the header-name denotes an importable header (10.3), it is implementation-defined whether the #include preprocessing directive is instead replaced by an import directive (15.5) of the form

\[ \texttt{import header-name ; new-line} \]

8 [Note 1: An implementation can provide a mechanism for making arbitrary source files available to the < > search. However, using the < > form for headers provided with the implementation and the " " form for sources outside the control of the implementation achieves wider portability. For instance:

\begin{verbatim}
#include <stdio.h>
#include <unistd.h>
#include "usefullib.h"
#include "myprog.h"
\end{verbatim}
—end note]

9 [Example 1: This illustrates macro-replaced #include directives:

\begin{verbatim}
#if VERSION == 1
#define INCFILE "vers1.h"
#elif VERSION == 2
#define INCFILE "vers2.h"  // and so on
#else
#define INCFILE "versN.h"
#endif
#include INCFILE
\end{verbatim}
—end example]

15.4 Module directive [cpp.module]

\[ \texttt{pp-module: export_opt module pp-tokens_opt ; new-line} \]

1 A pp-module shall not appear in a context where module or (if it is the first token of the pp-module) export is an identifier defined as an object-like macro.

2 The pp-tokens, if any, of a pp-module shall be of the form:

\[ \texttt{pp-module-name pp-module-partition_opt pp-tokens_opt} \]

where the pp-tokens (if any) shall not begin with a ( preprocessing token and the grammar non-terminals are defined as:

---

128) Note that adjacent string-literals are not concatenated into a single string-literal (see the translation phases in 5.2); thus, an expansion that results in two string-literals is an invalid directive.
No identifier in the pp-module-name or pp-module-partition shall currently be defined as an object-like macro.

Any preprocessing tokens after the module preprocessing token in the module directive are processed just as in normal text.

[Note 1: Each identifier currently defined as a macro name is replaced by its replacement list of preprocessing tokens. — end note]

The module and export (if it exists) preprocessing tokens are replaced by the module-keyword and export-keyword preprocessing tokens respectively.

[Note 2: This makes the line no longer a directive so it is not removed at the end of phase 4. — end note]

15.5 Header unit importation [cpp.import]

A pp-import shall not appear in a context where import or (if it is the first token of the pp-import) export is an identifier defined as an object-like macro.

The preprocessing tokens after the import preprocessing token in the import control-line are processed just as in normal text (i.e., each identifier currently defined as a macro name is replaced by its replacement list of preprocessing tokens).

[Note 1: An import directive matching the first two forms of a pp-import instructs the preprocessor to import macros from the header unit (10.3) denoted by the header-name, as described below. — end note]

The point of macro import for the first two forms of pp-import is immediately after the new-line terminating the pp-import. The last form of pp-import is only considered if the first two forms did not match, and does not have a point of macro import.

If a pp-import is produced by source file inclusion (including by the rewrite produced when a #include directive names an importable header) while processing the group of a module-file, the program is ill-formed.

In all three forms of pp-import, the import and export (if it exists) preprocessing tokens are replaced by the import-keyword and export-keyword preprocessing tokens respectively.

[Note 2: This makes the line no longer a directive so it is not removed at the end of phase 4. — end note]

Additionally, in the second form of pp-import, a header-name token is formed as if the header-name-tokens were the pp-tokens of a #include directive. The header-name-tokens are replaced by the header-name token.

[Note 3: This ensures that imports are treated consistently by the preprocessor and later phases of translation. — end note]

Each #define directive encountered when preprocessing each translation unit in a program results in a distinct macro definition.

[Note 4: A predefined macro name (15.11) is not introduced by a #define directive. Implementations providing mechanisms to redefine additional macros are encouraged to not treat them as being introduced by a #define directive. — end note]

Each macro definition has at most one point of definition in each translation unit and at most one point of undefinition, as follows:

(5.1) — The point of definition of a macro definition within a translation unit T is

(5.1.1) — if the #define directive of the macro definition occurs within T, the point at which that directive occurs, or otherwise,
(5.1.2) — if the macro name is not lexically identical to a keyword (5.11) or to the identifiers module or import, the first point of macro import in T of a header unit containing a point of definition for the macro definition, if any.

In the latter case, the macro is said to be imported from the header unit.

(5.2) — The point of undefinition of a macro definition within a translation unit is the first point at which a #undef directive naming the macro occurs after its point of definition, or the first point of macro import of a header unit containing a point of undefinition for the macro definition, whichever (if any) occurs first.

6 A macro directive is active at a source location if it has a point of definition in that translation unit preceding the location, and does not have a point of undefinition in that translation unit preceding the location.

7 If a macro would be replaced or redefined, and multiple macro definitions are active for that macro name, the active macro definitions shall all be valid redefinitions of the same macro (15.6).

[Note 5: The relative order of pp-imports has no bearing on whether a particular macro definition is active. — end note]

8 [Example 1:

Importable header "a.h":

```c
#define X 123 // #1
#define Y 45  // #2
#define Z a   // #3
#undef X     // point of undefinition of #1 in "a.h"
```

Importable header "b.h":

```c
import "a.h";  // point of definition of #1, #2, and #3, point of undefinition of #1 in "b.h"
#define X 456    // OK, #1 is not active
#define Y 6       // error: #2 is active
```

Importable header "c.h":

```c
#define Y 45  // #4
#define Z c   // #5
```

Importable header "d.h":

```c
import "c.h";  // point of definition of #4 and #5 in "d.h"
```

Importable header "e.h":

```c
import "a.h";  // point of definition of #1, #2, and #3, point of undefinition of #1 in "e.h"
import "d.h";  // point of definition of #4 and #5 in "e.h"
int a = Y;     // OK, active macro definitions #2 and #4 are valid redefinitions
int c = Z;     // error: active macro definitions #3 and #5 are not valid redefinitions of Z
```

Module unit f:

```c
export module f;
export import "a.h";

int a = Y;  // OK
```

Translation unit #1:

```c
import f;
int x = Y;  // error: Y is neither a defined macro nor a declared name
```

— end example]

15.6 Macro replacement [cpp.replace]

15.6.1 General [cpp.replace.general]

1 Two replacement lists are identical if and only if the preprocessing tokens in both have the same number, ordering, spelling, and whitespace separation, where all whitespace separations are considered identical.

2 An identifier currently defined as an object-like macro (see below) may be redefined by another #define preprocessing directive provided that the second definition is an object-like macro definition and the two replacement lists are identical, otherwise the program is ill-formed. Likewise, an identifier currently defined as
a function-like macro (see below) may be redefined by another \#define preprocessing directive provided that
the second definition is a function-like macro definition that has the same number and spelling of parameters,
and the two replacement lists are identical, otherwise the program is ill-formed.

[Example 1: The following sequence is valid:

```c
#define OBJ_LIKE (1-1)
#define OBJ_LIKE /* whitespace */ (1-1) /* other */
#define FUNC_LIKE(a) ( a ) /* note the whitespace */
#define FUNC_LIKE( a ) /* other stuff on this line */
```

But the following redefinitions are invalid:

```c
#define OBJ_LIKE (0) // different token sequence
#define OBJ_LIKE (1 - 1) // different whitespace
#define FUNC_LIKE(b) ( a ) // different parameter usage
#define FUNC_LIKE(b) ( b ) // different parameter spelling
```

—end example]

4 There shall be whitespace between the identifier and the replacement list in the definition of an object-like
macro.

5 If the identifier-list in the macro definition does not end with an ellipsis, the number of arguments (including
those arguments consisting of no preprocessing tokens) in an invocation of a function-like macro shall equal
the number of parameters in the macro definition. Otherwise, there shall be at least as many arguments in
the invocation as there are parameters in the macro definition (excluding the . . .). There shall exist a ]
preprocessing token that terminates the invocation.

6 The identifiers __VA_ARGS__ and __VA_OPT__ shall occur only in the replacement-list of a function-like macro
that uses the ellipsis notation in the parameters.

7 A parameter identifier in a function-like macro shall be uniquely declared within its scope.

8 The identifier immediately following the define is called the macro name. There is one name space for
macro names. Any whitespace characters preceding or following the replacement list of preprocessing tokens
are not considered part of the replacement list for either form of macro.

9 If a # preprocessing token, followed by an identifier, occurs lexically at the point at which a preprocessing
directive can begin, the identifier is not subject to macro replacement.

10 A preprocessing directive of the form

```c
#define identifier replacement-list new-line
```

defines an object-like macro that causes each subsequent instance of the macro name to be replaced by the
replacement list of preprocessing tokens that constitute the remainder of the directive. The replacement
list is then rescanned for more macro names as specified below.

11 [Example 2: The simplest use of this facility is to define a “manifest constant”, as in

```c
#define TABSIZE (0) // different token sequence
#define OBJ_LIKE (1 - 1) // different whitespace
#define FUNC_LIKE(b) ( a ) // different parameter usage
#define FUNC_LIKE(b) ( b ) // different parameter spelling
```

—end example]

12 A preprocessing directive of the form

```c
#define identifier (paren identifier-list_opt ) replacement-list new-line
#define identifier (paren . . . ) replacement-list new-line
#define identifier (paren identifier-list , . . . ) replacement-list new-line
```

defines a function-like macro with parameters, whose use is similar syntactically to a function call. The
parameters are specified by the optional list of identifiers. Each subsequent instance of the function-like macro
name followed by a ( as the next preprocessing token introduces the sequence of preprocessing tokens
that is replaced by the replacement list in the definition (an invocation of the macro). The replaced sequence of
preprocessing tokens is terminated by the matching ) preprocessing token, skipping intervening matched

129) Since, by macro-replacement time, all character-literals and string-literals are preprocessing tokens, not sequences possibly
containing identifier-like subsequences (see 5.2, translation phases), they are never scanned for macro names or parameters.

130) An alternative token (5.5) is not an identifier, even when its spelling consists entirely of letters and underscores. Therefore
it is not possible to define a macro whose name is the same as that of an alternative token.
pairs of left and right parenthesis preprocessing tokens. Within the sequence of preprocessing tokens making up an invocation of a function-like macro, new-line is considered a normal whitespace character.

The sequence of preprocessing tokens bounded by the outside-most matching parentheses forms the list of arguments for the function-like macro. The individual arguments within the list are separated by comma preprocessing tokens, but comma preprocessing tokens between matching inner parentheses do not separate arguments. If there are sequences of preprocessing tokens within the list of arguments that would otherwise act as preprocessing directives, the behavior is undefined.

[Example 3: The following defines a function-like macro whose value is the maximum of its arguments. It has the disadvantages of evaluating one or the other of its arguments a second time (including side effects) and generating more code than a function if invoked several times. It also cannot have its address taken, as it has none.

```c
#define max(a, b) ((a) > (b) ? (a) : (b))
```
The parentheses ensure that the arguments and the resulting expression are bound properly. —end example]

If there is a ... immediately preceding the ) in the function-like macro definition, then the trailing arguments (if any), including any separating comma preprocessing tokens, are merged to form a single item: the variable arguments. The number of arguments so combined is such that, following merger, the number of arguments is either equal to or one more than the number of parameters in the macro definition (excluding the ...).

15.6.2 Argument substitution [cpp.subst]

va-opt-replacement:

```c
__VA_OPT__ ( pp-tokensopt )
```

After the arguments for the invocation of a function-like macro have been identified, argument substitution takes place. For each parameter in the replacement list that is neither preceded by a # or ## preprocessing token nor followed by a ## preprocessing token nor followed by a # preprocessing token, the preprocessing tokens naming the parameter are replaced by a token sequence determined as follows:

1. If the parameter is of the form va-opt-replacement, the replacement preprocessing tokens are the preprocessing token sequence for the corresponding argument, as specified below.
2. Otherwise, the replacement preprocessing tokens are the preprocessing tokens of corresponding argument after all macros contained therein have been expanded. The argument’s preprocessing tokens are completely macro replaced before being substituted as if they formed the rest of the preprocessing file with no other preprocessing tokens being available.

[Example 1:

```c
#define LPAREN() (
#define G(Q) 42
#define F(R, X, ...) __VA_OPT__(G R X)
int x = F(LPAREN(), 0, <:-);  // replaced by int x = 42;
```
—end example]

An identifier __VA_ARGS__ that occurs in the replacement list shall be treated as if it were a parameter, and the variable arguments shall form the preprocessing tokens used to replace it.

[Example 2:

```c
#define debug(...) fprintf(stderr, __VA_ARGS__)
#define showlist(...) puts(#__VA_ARGS__)
#define report(test, ...) ((test) ? puts(#test) : printf(__VA_ARGS__))
debug("Flag");
debug("X = %d\n", x);
showlist(The first, second, and third items.);
report(x>y, "x is %d but y is %d", x, y);
```
results in

```c
fprintf(stderr, "Flag");
fprintf(stderr, "X = %d\n", x);
puts("The first, second, and third items.");
((x>y) ? puts("x>y") : printf("x is %d but y is %d", x, y));
```
—end example]

131) A conditionally-supported-directive is a preprocessing directive regardless of whether the implementation supports it.
The identifier \_\_VA\_OPT\_\_ shall always occur as part of the preprocessing token sequence va-opt-replacement; its closing \)) is determined by skipping intervening pairs of matching left and right parentheses in its pp-tokens. The pp-tokens of a va-opt-replacement shall not contain \_\_VA\_OPT\_\_. If the pp-tokens would be ill-formed as the replacement list of the current function-like macro, the program is ill-formed. A va-opt-replacement is treated as if it were a parameter, and the preprocessing token sequence for the corresponding argument is defined as follows. If the substitution of \_\_VA_ARGS\_\_ as neither an operand of \# nor ## consists of no preprocessing tokens, the argument consists of a single placemarker preprocessing token (15.6.4, 15.6.5). Otherwise, the argument consists of the results of the expansion of the contained pp-tokens as the replacement list of the current function-like macro before removal of placemarker tokens, rescanning, and further replacement.

[Note 1: The placemarker tokens are removed before stringization (15.6.3), and can be removed by rescanning and further replacement (15.6.5). — end note]

Example 3:

#define F(...) f(0 \_\_VA\_OPT\_\_, , \_\_VA\_ARGS\_\_)  
#define G(X, ...) f(0, X \_\_VA\_OPT\_\_, , \_\_VA\_ARGS\_\_)  
#define SDEF(sname, ...) S sname \_\_VA\_OPT\_\_={ \_\_VA\_ARGS\_\_ })  
#define EMP

F(a, b, c) // replaced by f(0, a, b, c)  
F() // replaced by f(0)  
F(EMP) // replaced by f(0)

G(a, b, c) // replaced by f(0, a, b, c)  
G(a,) // replaced by f(0, a)  
G(a) // replaced by f(0, a)

SDEF(foos); // replaced by S foos;  
SDEF(bar, 1, 2); // replaced by S bar = { 1, 2 };

#define H1(X, ...) X \_\_VA\_OPT\_\_(*#)# \_\_VA\_ARGS\_\_ // error: ## may not appear at  
// the beginning of a replacement list (15.6.4)

#define H2(X, Y, ...) \_\_VA\_OPT\_\_(X # Y#,) \_\_VA\_ARGS\_\_  
H2(a, b, c, d) // replaced by ab, c, d

#define H3(X, ...) \#\_\_VA\_OPT\_\_(X##X X##X)  
H3(), 0) // replaced by ""

#define H4(X, ...) \_\_VA\_OPT\_\_(a X # X) # b  
H4(), 1) // replaced by a b

#define H5(A(...), \_\_VA\_OPT\_\_()/**/\_\_VA\_OPT\_\_()  
#define HSB(X) a # X # b  
#define HSC(X) HSB(X)  
HSC(H5A()); // replaced by ab

— end example]

15.6.3 The \# operator

Each \# preprocessing token in the replacement list for a function-like macro shall be followed by a parameter as the next preprocessing token in the replacement list.

A character string literal is a string-literal with no prefix. If, in the replacement list, a parameter is immediately preceded by a \# preprocessing token, both are replaced by a single character string literal preprocessing token that contains the spelling of the preprocessing token sequence for the corresponding argument (excluding placemarker tokens). Let the stringizing argument be the preprocessing token sequence for the corresponding argument with placemarker tokens removed. Each occurrence of whitespace between the stringizing argument’s preprocessing tokens becomes a single space character in the character string literal. Whitespace before the first preprocessing token and after the last preprocessing token comprising the stringizing argument is deleted. Otherwise, the original spelling of each preprocessing token in the stringizing argument is retained in the character string literal, except for special handling for producing the spelling of string-literals and character-literals: a \ character is inserted before each " and \ character of a character-literal or string-literal.
(including the delimiting " characters). If the replacement that results is not a valid character string literal, the behavior is undefined. The character string literal corresponding to an empty stringizing argument is "". The order of evaluation of # and ## operators is unspecified.

15.6.4 The ## operator

A ## preprocessing token shall not occur at the beginning or at the end of a replacement list for either form of macro definition.

1 If, in the replacement list of a function-like macro, a parameter is immediately preceded or followed by a ## preprocessing token, the parameter is replaced by the corresponding argument’s preprocessing token sequence; however, if an argument consists of no preprocessing tokens, the parameter is replaced by a placemarker preprocessing token instead.\(^{132}\)

2 For both object-like and function-like macro invocations, before the replacement list is reexamined for more macro names to replace, each instance of a ## preprocessing token in the replacement list (not from an argument) is deleted and the preceding preprocessing token is concatenated with the following preprocessing token. Placemarker preprocessing tokens are handled specially: concatenation of two placemarkers results in a single placemarker preprocessing token, and concatenation of a placemarker with a non-placemarker preprocessing token results in the non-placemarker preprocessing token.

[Note 1: Concatenation can form a universal-character-name (5.3). — end note]

If the result is not a valid preprocessing token, the behavior is undefined. The resulting token is available for further macro replacement. The order of evaluation of ## operators is unspecified.

3 [Example 1: The sequence]

```c
#define str(s) # s
#define xstr(s) str(s)
#define debug(s, t) printf("x" # s "= %d, x" # t "= %s", \
    x # s, x ## t)
#define INCFILE(n) vers ## n
#define glue(a, b) a ## b
#define xglue(a, b) glue(a, b)
#define HIGHLOW "hello"
#define LOW LOW ", world"

dump(1, 2);
puts(str(strncmp("abc\0d", "abc", '\\4')) // this goes away
    == 0) str(\n
    include xstr(INCFILE(2).h)
    glue(HIGH, LOW);
xglue(HIGH, LOW)
results in
printf("x" "1" "= \d, x" "2" "= \%s", x1, x2);
puts("strncmp("abc\0d", "abc", '\\4') == 0": \n    include "vers2.h" (after macro replacement, before file access)
    "hello";
    "hello" ", world"
or, after concatenation of the character string literals,
printf("x1= \d, x2= \%s", x1, x2);
puts("strncmp("abc\0d", "abc", '\\4') == 0": \n    include "vers2.h" (after macro replacement, before file access)
    "hello";
    "hello, world"
Space around the # and ## tokens in the macro definition is optional. — end example]
```

4 [Example 2: In the following fragment:

132) Placemarker preprocessing tokens do not appear in the syntax because they are temporary entities that exist only within translation phase 4.
#define hash_hash # ## #
#define mkstr(a) # a
#define in_between(a) mkstr(a)
#define join(c, d) in_between(c hash_hash d)
char p[] = join(x, y);
// equivalent to char p[] = "x ## y";

The expansion produces, at various stages:
join(x, y)
in_between(x hash_hash y)
in_between(x ## y)
mkstr(x ## y)
"x ## y"

In other words, expanding hash_hash produces a new token, consisting of two adjacent sharp signs, but this new
token is not the ## operator. — end example]

Example 3: To illustrate the rules for placemarker preprocessing tokens, the sequence

```c
#define t(x,y,z) x ## y ## z
int j[] = { t(1,2,3), t(,4,5), t(6,7), t(8,9),
t(10,), t(,11,), t(,,12), t(,,) };
```
results in
```c
int j[] = { 123, 45, 67, 89,
10, 11, 12, };
— end example]
```

15.6.5 Rescanning and further replacement [cpp.rescan]

After all parameters in the replacement list have been substituted and # and ## processing has taken place, all
placemarker preprocessing tokens are removed. Then the resulting preprocessing token sequence is rescanned,
along with all subsequent preprocessing tokens of the source file, for more macro names to replace.

Example 1: The sequence

```c
#define x 3
#define f(a) f(x * (a))
#undef x
#define x 2
#define g f
#define z z[0]
#define h g(~
#define m(a) a(w)
#define w 0,1
#define t(a) a
#define p() int
#define q(x) x
#define r(x,y) x ## y
#define str(x) # x
f(y+1) + f(f(x)) % t(t(g)(0) + t)(1);
g(x+(3,4)-w) | h 5) & m
(f)^m(m);
p() i[q()] = { q(1), r(2,3), r(4,), r(5), r(,) };
char c[2][6] = { str(hello), str() };
```
results in
```c
f(2 * (y+1)) + f(2 * (f(2 * (z[0]))) % f(2 * (0)) + t(1);
f(2 * (2+(3,4)-0,1)) | f(2 * (~ 5)) & f(2 * (0,1))^m(0,1);
int i[] = { 1, 23, 4, 5, };
char c[2][6] = { "hello", "" };
— end example]
```

3 If the name of the macro being replaced is found during this scan of the replacement list (not including the rest
of the source file’s preprocessing tokens), it is not replaced. Furthermore, if any nested replacements encounter
the name of the macro being replaced, it is not replaced. These nonreplaced macro name preprocessing
tokens are no longer available for further replacement even if they are later (re)examined in contexts in which that macro name preprocessing token would otherwise have been replaced.

4 The resulting completely macro-replaced preprocessing token sequence is not processed as a preprocessing directive even if it resembles one, but all pragma unary operator expressions within it are then processed as specified in 15.12 below.

15.6.6 Scope of macro definitions

A macro definition lasts (independent of block structure) until a corresponding \#undef directive is encountered or (if none is encountered) until the end of the translation unit. Macro definitions have no significance after translation phase 4.

2 A preprocessing directive of the form

\# undef identifier new-line

causes the specified identifier no longer to be defined as a macro name. It is ignored if the specified identifier is not currently defined as a macro name.

15.7 Line control

The string-literal of a \#line directive, if present, shall be a character string literal.

2 The line number of the current source line is one greater than the number of new-line characters read or introduced in translation phase 1 (5.2) while processing the source file to the current token.

3 A preprocessing directive of the form

\# line digit-sequence new-line

causes the implementation to behave as if the following sequence of source lines begins with a source line that has a line number as specified by the digit sequence (interpreted as a decimal integer). If the digit sequence specifies zero or a number greater than 2147483647, the behavior is undefined.

4 A preprocessing directive of the form

\# line digit-sequence " s-char-sequence_opt " new-line

sets the presumed line number similarly and changes the presumed name of the source file to be the contents of the character string literal.

5 A preprocessing directive of the form

\# line pp-tokens new-line

(that does not match one of the two previous forms) is permitted. The preprocessing tokens after line on the directive are processed just as in normal text (each identifier currently defined as a macro name is replaced by its replacement list of preprocessing tokens). If the directive resulting after all replacements does not match one of the two previous forms, the behavior is undefined; otherwise, the result is processed as appropriate.

15.8 Diagnostic directives

A preprocessing directive of the form

\# error pp-tokens_opt new-line

renders the program ill-formed. A preprocessing directive of the form

\# warning pp-tokens_opt new-line

requires the implementation to produce at least one diagnostic message for the preprocessing translation unit (4.1.1). Recommended practice: Any diagnostic message caused by either of these directives should include the specified sequence of preprocessing tokens.

15.9 Pragma directive

A preprocessing directive of the form

\# pragma pp-tokens_opt new-line

causes the implementation to behave in an implementation-defined manner. The behavior may cause translation to fail or cause the translator or the resulting program to behave in a non-conforming manner. Any pragma that is not recognized by the implementation is ignored.
15.10 **Null directive**  
A preprocessing directive of the form

```cpp
# new-line
```

has no effect.

15.11 **Predefined macro names**

The following macro names shall be defined by the implementation:

```cpp
c__cplusplus

The integer literal 202302L.

[Note 1: Future revisions of this document will replace the value of this macro with a greater value. — end note]
```

The names listed in Table 22.

The macros defined in Table 22 shall be defined to the corresponding integer literal.

[Note 2: Future revisions of this document might replace the values of these macros with greater values. — end note]

```cpp
c_DATE_

The date of translation of the source file: a character string literal of the form "Mmm dd yyyy", where the names of the months are the same as those generated by the `asctime` function, and the first character of `dd` is a space character if the value is less than 10. If the date of translation is not available, an implementation-defined valid date shall be supplied.
```

```cpp
c_FILE_

The presumed name of the current source file (a character string literal).
```

```cpp
c_LINE_

The presumed line number (within the current source file) of the current source line (an integer literal).
```

```cpp
c_STDCC_HOSTED_

The integer literal 1 if the implementation is a hosted implementation or the integer literal 0 if it is a freestanding implementation (4.1).
```

```cpp
c_STDCCPP_DEFAULT_NEW_ALIGNMENT_

An integer literal of type `std::size_t` whose value is the alignment guaranteed by a call to `operator new(std::size_t)` or `operator new[](std::size_t)`.  
[Note 3: Larger alignments will be passed to `operator new(std::size_t, std::align_val_t)` etc. (7.6.2.8). — end note]
```

```cpp
c_STDCCPP_FLOAT16_T_

Defined as the integer literal 1 if and only if the implementation supports the ISO/IEC 60559 floating-point interchange format binary16 as an extended floating-point type (6.8.3).
```

```cpp
c_STDCCPP_FLOAT32_T_

Defined as the integer literal 1 if and only if the implementation supports the ISO/IEC 60559 floating-point interchange format binary32 as an extended floating-point type.
```

```cpp
c_STDCCPP_FLOAT64_T_

Defined as the integer literal 1 if and only if the implementation supports the ISO/IEC 60559 floating-point interchange format binary64 as an extended floating-point type.
```

```cpp
c_STDCCPP_FLOAT128_T_

Defined as the integer literal 1 if and only if the implementation supports the ISO/IEC 60559 floating-point interchange format binary128 as an extended floating-point type.
```

133) The presumed source file name can be changed by the `#line` directive.

134) The presumed line number can be changed by the `#line` directive.
--STDCPP_BFLOAT16_T--
Defined as the integer literal 1 if and only if the implementation supports an extended floating-point
type with the properties of the typedef-name std::bfloat16_t as described in 6.8.3.

--TIME--
The time of translation of the source file: a character string literal of the form "hh:mm:ss" as in the time
generated by the asctime function. If the time of translation is not available, an implementation-defined
valid time shall be supplied.

Table 22 — Feature-test macros

<table>
<thead>
<tr>
<th>Macro name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>__cpp_aggregate_bases</td>
<td>201603L</td>
</tr>
<tr>
<td>__cpp_aggregate_nsdmi</td>
<td>201304L</td>
</tr>
<tr>
<td>__cpp_aggregate_paren_init</td>
<td>201902L</td>
</tr>
<tr>
<td>__cpp_alias_templates</td>
<td>200704L</td>
</tr>
<tr>
<td>__cpp_aligned_new</td>
<td>201606L</td>
</tr>
<tr>
<td>__cpp_attributes</td>
<td>200809L</td>
</tr>
<tr>
<td>__cpp_auto_cast</td>
<td>202110L</td>
</tr>
<tr>
<td>__cpp_binary_literals</td>
<td>201304L</td>
</tr>
<tr>
<td>__cpp_capture_star_this</td>
<td>201603L</td>
</tr>
<tr>
<td>__cpp_char8_t</td>
<td>202207L</td>
</tr>
<tr>
<td>__cpp_concepts</td>
<td>202002L</td>
</tr>
<tr>
<td>__cpp_conditional_explicit</td>
<td>201806L</td>
</tr>
<tr>
<td>__cpp_constexpr</td>
<td>202406L</td>
</tr>
<tr>
<td>__cpp_constexpr_dynamic_alloc</td>
<td>201907L</td>
</tr>
<tr>
<td>__cpp_constexpr_in_dectype</td>
<td>201711L</td>
</tr>
<tr>
<td>__cpp_consteval</td>
<td>202211L</td>
</tr>
<tr>
<td>__cpp_constinit</td>
<td>201907L</td>
</tr>
<tr>
<td>__cpp_decltype</td>
<td>200707L</td>
</tr>
<tr>
<td>__cpp_decltype_auto</td>
<td>201304L</td>
</tr>
<tr>
<td>__cpp_deduction_guides</td>
<td>201907L</td>
</tr>
<tr>
<td>__cpp_delegating_constructors</td>
<td>200604L</td>
</tr>
<tr>
<td>__cpp_deleted_function</td>
<td>202403L</td>
</tr>
<tr>
<td>__cpp_designated_initializers</td>
<td>201707L</td>
</tr>
<tr>
<td>__cpp_enumerator_attributes</td>
<td>201411L</td>
</tr>
<tr>
<td>__cpp_explicit_this_parameter</td>
<td>202110L</td>
</tr>
<tr>
<td>__cpp_fold_expressions</td>
<td>201603L</td>
</tr>
<tr>
<td>__cpp_generic_lambdas</td>
<td>201707L</td>
</tr>
<tr>
<td>__cpp_guaranteed_copy_elision</td>
<td>201606L</td>
</tr>
<tr>
<td>__cpp_hex_float</td>
<td>201603L</td>
</tr>
<tr>
<td>__cpp_if_consteval</td>
<td>202106L</td>
</tr>
<tr>
<td>__cpp_if_constexpr</td>
<td>201606L</td>
</tr>
<tr>
<td>__cpp_impl_coroutine</td>
<td>201902L</td>
</tr>
<tr>
<td>__cpp_impl_destroying_delete</td>
<td>201806L</td>
</tr>
<tr>
<td>__cpp_impl_three_way_comparison</td>
<td>201907L</td>
</tr>
<tr>
<td>__cppImplicit_move</td>
<td>202207L</td>
</tr>
<tr>
<td>__cpp_inheriting_constructors</td>
<td>201511L</td>
</tr>
<tr>
<td>__cpp_init_captures</td>
<td>201803L</td>
</tr>
<tr>
<td>__cpp_initializer_lists</td>
<td>200806L</td>
</tr>
<tr>
<td>__cpp_inline_variables</td>
<td>201606L</td>
</tr>
<tr>
<td>__cpp_lambdas</td>
<td>200907L</td>
</tr>
<tr>
<td>__cpp_modules</td>
<td>201907L</td>
</tr>
<tr>
<td>__cpp_multidimensional_subscript</td>
<td>202211L</td>
</tr>
<tr>
<td>__cpp_named_character_escapes</td>
<td>202207L</td>
</tr>
<tr>
<td>__cpp_namespace_attributes</td>
<td>201411L</td>
</tr>
<tr>
<td>__cpp_noexcept_function_type</td>
<td>201510L</td>
</tr>
</tbody>
</table>
Table 22 — Feature-test macros (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>__cpp_nontype_template_args</td>
<td>201911L</td>
</tr>
<tr>
<td>__cpp_nontype_template_parameter_auto</td>
<td>201606L</td>
</tr>
<tr>
<td>__cpp_nsdmi</td>
<td>200809L</td>
</tr>
<tr>
<td>__cpp_pack_indexing</td>
<td>202311L</td>
</tr>
<tr>
<td>__cpp_placeholder_variables</td>
<td>202306L</td>
</tr>
<tr>
<td>__cpp_range_based_for</td>
<td>202211L</td>
</tr>
<tr>
<td>__cpp_raw_strings</td>
<td>200710L</td>
</tr>
<tr>
<td>__cpp_ref_qualifiers</td>
<td>200710L</td>
</tr>
<tr>
<td>__cpp_return_type_deduction</td>
<td>201304L</td>
</tr>
<tr>
<td>__cpp_rvalue_references</td>
<td>200610L</td>
</tr>
<tr>
<td>__cpp_size_t_suffix</td>
<td>202011L</td>
</tr>
<tr>
<td>__cpp_sized_deallocation</td>
<td>201309L</td>
</tr>
<tr>
<td>__cpp_static_assert</td>
<td>202306L</td>
</tr>
<tr>
<td>__cpp_static_call_operator</td>
<td>202207L</td>
</tr>
<tr>
<td>__cpp_structured_bindings</td>
<td>202403L</td>
</tr>
<tr>
<td>__cpp_template_template_args</td>
<td>201611L</td>
</tr>
<tr>
<td>__cpp_threadsafe_static_init</td>
<td>200806L</td>
</tr>
<tr>
<td>__cpp_unicode_characters</td>
<td>200704L</td>
</tr>
<tr>
<td>__cpp_unicode_literals</td>
<td>200710L</td>
</tr>
<tr>
<td>__cpp_user_defined_literals</td>
<td>200809L</td>
</tr>
<tr>
<td>__cpp_using_enum</td>
<td>201907L</td>
</tr>
<tr>
<td>__cpp_variable_templates</td>
<td>201304L</td>
</tr>
<tr>
<td>__cpp_variadic_friend</td>
<td>202403L</td>
</tr>
<tr>
<td>__cpp_variadic_templates</td>
<td>200704L</td>
</tr>
<tr>
<td>__cpp_variadic_using</td>
<td>201611L</td>
</tr>
</tbody>
</table>

2 The following macro names are conditionally defined by the implementation:

```c
__STDC__
```

Whether __STDC__ is predefined and if so, what its value is, are implementation-defined.

```c
__STDC_MB_MIGHT_NEQ_WC__
```

The integer literal 1, intended to indicate that, in the encoding for wchar_t, a member of the basic character set need not have a code value equal to its value when used as the lone character in an ordinary character literal.

```c
__STDC_VERSION__
```

Whether __STDC_VERSION__ is predefined and if so, what its value is, are implementation-defined.

```c
__STDC_ISO_10646__
```

An integer literal of the form yyyyymmL (for example, 199712L). Whether __STDC_ISO_10646__ is predefined and if so, what its value is, are implementation-defined.

```c
__STDCPP_THREADS__
```

Defined, and has the value integer literal 1, if and only if a program can have more than one thread of execution (6.9.2).

3 The values of the predefined macros (except for __FILE__ and __LINE__) remain constant throughout the translation unit.

4 If any of the pre-defined macro names in this subclause, or the identifier defined, is the subject of a #define or a #undef preprocessing directive, the behavior is undefined. Any other predefined macro names shall begin with a leading underscore followed by an uppercase letter or a second underscore.

§ 15.11
15.12 Pragma operator

A unary operator expression of the form:

```
Pragma ( string-literal )
```

is processed as follows: The string-literal is destringized by deleting the L prefix, if present, deleting the leading and trailing double-quotes, replacing each escape sequence \" by a double-quote, and replacing each escape sequence \ by a single backslash. The resulting sequence of characters is processed through translation phase 3 to produce preprocessing tokens that are executed as if they were the pp-tokens in a pragma directive. The original four preprocessing tokens in the unary operator expression are removed.

Example 1:

```
#pragma listing on "..\listing.dir"
```

can also be expressed as:

```
Pragma ( "listing on \"..\\listing.dir\\""
```

The latter form is processed in the same way whether it appears literally as shown, or results from macro replacement, as in:

```
#define LISTING(x) PRAGMA(listing on #x)
#define PRAGMA(x) _Pragma(#x)

LISTING( ..\listing.dir )
```

— end example]
16 Library introduction

16.1 General

1 This Clause describes the contents of the \textit{C++ standard library}, how a well-formed C++ program makes use of the library, and how a conforming implementation may provide the entities in the library.

2 The following subclauses describe the method of description (16.3) and organization (16.4.2) of the library. 16.4, Clause 17 through Clause 33, and Annex D specify the contents of the library, as well as library requirements and constraints on both well-formed C++ programs and conforming implementations.

3 Detailed specifications for each of the components in the library are in Clause 17–Clause 33, as shown in Table 23.

<table>
<thead>
<tr>
<th>Clause</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clause 17</td>
<td>Language support library</td>
</tr>
<tr>
<td>Clause 18</td>
<td>Concepts library</td>
</tr>
<tr>
<td>Clause 19</td>
<td>Diagnostics library</td>
</tr>
<tr>
<td>Clause 20</td>
<td>Memory management library</td>
</tr>
<tr>
<td>Clause 21</td>
<td>Metaprogramming library</td>
</tr>
<tr>
<td>Clause 22</td>
<td>General utilities library</td>
</tr>
<tr>
<td>Clause 23</td>
<td>Strings library</td>
</tr>
<tr>
<td>Clause 24</td>
<td>Containers library</td>
</tr>
<tr>
<td>Clause 25</td>
<td>Iterators library</td>
</tr>
<tr>
<td>Clause 26</td>
<td>Ranges library</td>
</tr>
<tr>
<td>Clause 27</td>
<td>Algorithms library</td>
</tr>
<tr>
<td>Clause 28</td>
<td>Numerics library</td>
</tr>
<tr>
<td>Clause 29</td>
<td>Time library</td>
</tr>
<tr>
<td>Clause 30</td>
<td>Localization library</td>
</tr>
<tr>
<td>Clause 31</td>
<td>Input/output library</td>
</tr>
<tr>
<td>Clause 32</td>
<td>Regular expressions library</td>
</tr>
<tr>
<td>Clause 33</td>
<td>Concurrency support library</td>
</tr>
</tbody>
</table>

§ 16.1

4 The operating system interface described in ISO/IEC/IEEE 9945:2009 is hereinafter called \textit{POSIX}.

5 The language support library (Clause 17) provides components that are required by certain parts of the C++ language, such as memory allocation (7.6.2.8, 7.6.2.9) and exception processing (Clause 14).

6 The concepts library (Clause 18) describes library components that C++ programs may use to perform compile-time validation of template arguments and perform function dispatch based on properties of types.

7 The diagnostics library (Clause 19) provides a consistent framework for reporting errors in a C++ program, including predefined exception classes.

8 The memory management library (Clause 20) provides components for memory management, including smart pointers and scoped allocators.

9 The metaprogramming library (Clause 21) describes facilities for use in templates and during constant evaluation, including type traits, integer sequences, and rational arithmetic.

10 The general utilities library (Clause 22) includes components used by other library elements, such as a predefined storage allocator for dynamic storage management (6.7.5.5), and components used as infrastructure in C++ programs, such as tuples and function wrappers.

11 The strings library (Clause 23) provides support for manipulating text represented as sequences of type \textit{char}, sequences of type \textit{char8_t}, sequences of type \textit{char16_t}, sequences of type \textit{char32_t}, sequences of type \textit{wchar_t}, and sequences of any other character-like type.
The containers (Clause 24), iterators (Clause 25), ranges (Clause 26), and algorithms (Clause 27) libraries provide a C++ program with access to a subset of the most widely used algorithms and data structures.

The numerics library (Clause 28) provides numeric algorithms and complex number components that extend support for numeric processing. The valarray component provides support for \( n \)-at-a-time processing, potentially implemented as parallel operations on platforms that support such processing. The random number component provides facilities for generating pseudo-random numbers.

The time library (Clause 29) provides generally useful time utilities.

The localization library (Clause 30) provides extended internationalization support for text processing.

The input/output library (Clause 31) provides the iostream components that are the primary mechanism for C++ program input and output. They can be used with other elements of the library, particularly strings, locales, and iterators.

The regular expressions library (Clause 32) provides regular expression matching and searching.

The concurrency support library (Clause 33) provides components to create and manage threads, including atomic operations, mutual exclusion, and interthread communication.

16.2 The C standard library

The C++ standard library also makes available the facilities of the C standard library, suitably adjusted to ensure static type safety.

The descriptions of many library functions rely on the C standard library for the semantics of those functions. In some cases, the signatures specified in this document may be different from the signatures in the C standard library, and additional overloads may be declared in this document, but the behavior and the preconditions (including any preconditions implied by the use of a C restrict qualifier) are the same unless otherwise stated.

A call to a C standard library function is a non-constant library call (3.34) if it raises a floating-point exception other than FE_INEXACT. The semantics of a call to a C standard library function evaluated as a core constant expression are those specified in ISO/IEC 9899:2018, Annex F\[135\] to the extent applicable to the floating-point types (6.8.2) that are parameter types of the called function.

[Note 1: Annex F specifies the conditions under which floating-point exceptions are raised and the behavior when NaNs and/or infinities are passed as arguments. — end note]

[Note 2: Equivalently, a call to a C standard library function is a non-constant library call if errno is set when math_errhandling & MATH_ERRNO is true. — end note]

16.3 Method of description

16.3.1 General

Subclause 16.3 describes the conventions used to specify the C++ standard library. 16.3.2 describes the structure of Clause 17 through Clause 33 and Annex D. 16.3.3 describes other editorial conventions.

16.3.2 Structure of each clause

16.3.2.1 Elements

Each library clause contains the following elements, as applicable:\[136\]

(1.1) — Summary
(1.2) — Requirements
(1.3) — Detailed specifications
(1.4) — References to the C standard library

16.3.2.2 Summary

The Summary provides a synopsis of the category, and introduces the first-level subclauses. Each subclause also provides a summary, listing the headers specified in the subclause and the library entities provided in each header.

\[135\) See also ISO/IEC 9899:2018, 7.6.

\[136\) To save space, items that do not apply to a Clause are omitted. For example, if a Clause does not specify any requirements, there will be no “Requirements” subclause.
The contents of the summary and the detailed specifications include:

- macros
- values
- types and alias templates
- classes and class templates
- functions and function templates
- objects and variable templates
- concepts

### 16.3.2.3 Requirements

Requirements describe constraints that shall be met by a C++ program that extends the standard library. Such extensions are generally one of the following:

- Template arguments
- Derived classes
- Containers, iterators, and algorithms that meet an interface convention or model a concept

The string and iostream components use an explicit representation of operations required of template arguments. They use a class template `char_traits` to define these constraints.

Interface convention requirements are stated as generally as possible. Instead of stating “class X has to define a member function `operator++()`”, the interface requires “for any object x of class X, ++x is defined”. That is, whether the operator is a member is unspecified.

Requirements are stated in terms of well-defined expressions that define valid terms of the types that meet the requirements. For every set of well-defined expression requirements there is either a named concept or a table that specifies an initial set of the valid expressions and their semantics. Any generic algorithm (Clause 27) that uses the well-defined expression requirements is described in terms of the valid expressions for its template type parameters.

The library specification uses a typographical convention for naming requirements. Names in *italic* type that begin with the prefix `Cpp17` refer to sets of well-defined expression requirements typically presented in tabular form, possibly with additional prose semantic requirements. For example, `Cpp17Destructible` (Table 35) is such a named requirement. Names in *constant width* type refer to library concepts which are presented as a concept definition (Clause 13), possibly with additional prose semantic requirements. For example, `destructible` (18.4.10) is such a named requirement.

Template argument requirements are sometimes referenced by name. See 16.3.3.3.

In some cases the semantic requirements are presented as C++ code. Such code is intended as a specification of equivalence of a construct to another construct, not necessarily as the way the construct must be implemented.

Required operations of any concept defined in this document need not be total functions; that is, some arguments to a required operation may result in the required semantics failing to be met.

*Example 1*: The required < operator of the `totally_ordered` concept (18.5.5) does not meet the semantic requirements of that concept when operating on NaNs. — *end example*

This does not affect whether a type models the concept.

A declaration may explicitly impose requirements through its associated constraints (13.5.3). When the associated constraints refer to a concept (13.7.9), the semantic constraints specified for that concept are additionally imposed on the use of the declaration.

### 16.3.2.4 Detailed specifications

The detailed specifications each contain the following elements:

- name and brief description
- synopsis (class definition or function declaration, as appropriate)
- restrictions on template arguments, if any

[16.3.2.4] ISO/IEC 493
Descriptions of class member functions follow the order (as appropriate):\(^{1,38}\)

- (2.1) constructor(s) and destructor
- (2.2) copying, moving & assignment functions
- (2.3) comparison operator functions
- (2.4) modifier functions
- (2.5) observer functions
- (2.6) operators and other non-member functions

Descriptions of function semantics contain the following elements (as appropriate):\(^{1,39}\)

- (3.1) **Constraints**: the conditions for the function’s participation in overload resolution (12.2).
  
  [Note 1: Failure to meet such a condition results in the function’s silent non-viability. — end note]
  
  [Example 1: An implementation can express such a condition via a constraint-expression (13.5.3). — end example]

- (3.2) **Mandates**: the conditions that, if not met, render the program ill-formed.
  
  [Example 2: An implementation can express such a condition via the constant-expression in a static_assert-declaration (9.1). If the diagnostic is to be emitted only after the function has been selected by overload resolution, an implementation can express such a condition via a constraint-expression (13.5.3) and also define the function as deleted. — end example]

- (3.3) **Preconditions**: the conditions that the function assumes to hold whenever it is called; violation of any preconditions results in undefined behavior.

- (3.4) **Effects**: the actions performed by the function.

- (3.5) **Synchronization**: the synchronization operations (6.9.2) applicable to the function.

- (3.6) **Postconditions**: the conditions (sometimes termed observable results) established by the function.

- (3.7) **Result**: for a typename-specifier, a description of the named type; for an expression, a description of the type of the expression; the expression is an lvalue if the type is an lvalue reference type, an xvalue if the type is an rvalue reference type, and a prvalue otherwise.

- (3.8) **Returns**: a description of the value(s) returned by the function.

- (3.9) **Throws**: any exceptions thrown by the function, and the conditions that would cause the exception.

- (3.10) **Complexity**: the time and/or space complexity of the function.

- (3.11) **Remarks**: additional semantic constraints on the function.

- (3.12) **Error conditions**: the error conditions for error codes reported by the function.

Whenever the **Effects** element specifies that the semantics of some function F are Equivalent to some code sequence, then the various elements are interpreted as follows. If F’s semantics specifies any **Constraints** or **Mandates** elements, then those requirements are logically imposed prior to the equivalent-to semantics. Next, the semantics of the code sequence are determined by the **Constraints**, **Mandates**, **Preconditions**, **Effects**, **Synchronization**, **Postconditions**, **Returns**, **Throws**, **Complexity**, **Remarks**, and **Error conditions** specified for the function invocations contained in the code sequence. The value returned from F is specified by F’s **Returns** element, or if F has no **Returns** element, a non-void return from F is specified by the **return** statements (8.7.4) in the code sequence. If F’s semantics contains a **Throws**, **Postconditions**, or **Complexity** element, then that supersedes any occurrences of that element in the code sequence.

For non-reserved replacement and handler functions, Clause 17 specifies two behaviors for the functions in question: their required and default behavior. The default behavior describes a function definition provided by the implementation. The required behavior describes the semantics of a function definition provided by either the implementation or a C++ program. Where no distinction is explicitly made in the description, the behavior described is the required behavior.

---

\(^{1,38}\) To save space, items that do not apply to a class are omitted. For example, if a class does not specify any comparison operator functions, there will be no “Comparison operator functions” subclause.

\(^{1,39}\) To save space, elements that do not apply to a function are omitted. For example, if a function specifies no preconditions, there will be no Preconditions: element.
If the formulation of a complexity requirement calls for a negative number of operations, the actual requirement is zero operations.\textsuperscript{140}

Complexity requirements specified in the library clauses are upper bounds, and implementations that provide better complexity guarantees meet the requirements.

Error conditions specify conditions where a function may fail. The conditions are listed, together with a suitable explanation, as the \texttt{enum class errc} constants (19.5).

16.3.2.5 C library

Paragraphs labeled “SEE ALSO” contain cross-references to the relevant portions of other standards (Clause 2).

16.3.3 Other conventions

16.3.3.1 General

Subclause 16.3.3 describes several editorial conventions used to describe the contents of the C++ standard library. These conventions are for describing implementation-defined types (16.3.3.3), and member functions (16.3.3.4).

16.3.3.2 Exposition-only entities, etc.

Several entities and \texttt{typedef-names} defined in Clause 17 through Clause 33 and Annex D are only defined for the purpose of exposition. The declaration of such an entity or \texttt{typedef-name} is followed by a comment ending in \textit{exposition only}.

The following are defined for exposition only to aid in the specification of the library:

\begin{verbatim}
namespace std {
    template<class T>
    requires convertible_to<T, decay_t<T>>
    constexpr decay_t<T>
    decay-copy(T&& v) noexcept(is_nothrow_convertible_v<T, decay_t<T>>)
    { return std::forward<T>(v); }

    constexpr auto synth-three-way = []<class T, class U>(const T& t, const U& u)
    requires requires {
        { t < u } -> boolean-testable;
        { u < t } -> boolean-testable;
    }
    { if constexpr (three_wayComparableWith<T, U>) {
        return t <=> u;
    } else {
        if (t < u) return weak_ordering::less;
        if (u < t) return weak_ordering::greater;
        return weak_ordering::equivalent;
    }
};

template<class T, class U=T>
using synth-three-way-result = decltype(synth-three-way(declval<T&>(), declval<U&>()));
\end{verbatim}

16.3.3.3 Type descriptions

16.3.3.3.1 General

The Requirements subclauses may describe names that are used to specify constraints on template arguments.\textsuperscript{141} These names are used in library Clauses to describe the types that may be supplied as arguments by a C++ program when instantiating template components from the library.

\textsuperscript{140} This simplifies the presentation of complexity requirements in some cases.

\textsuperscript{141} Examples from 16.4.4 include: \texttt{Cpp17EqualityComparable}, \texttt{Cpp17LessThanComparable}, \texttt{Cpp17CopyConstructible}. Examples from 25.3 include: \texttt{Cpp17InputIterator}, \texttt{Cpp17ForwardIterator}.
Certain types defined in Clause 31 are used to describe implementation-defined types. They are based on other types, but with added constraints.

### 16.3.3.3.2 Enumerated types

Several types defined in Clause 31 are enumerated types. Each enumerated type may be implemented as an enumeration or as a synonym for an enumeration.\textsuperscript{142}

The enumerated type \texttt{enumerated} can be written:

```c
enum enumerated { V_0, V_1, V_2, V_3, ... ;
inline const enumerated C_0(V_0);
inline const enumerated C_1(V_1);
inline const enumerated C_2(V_2);
inline const enumerated C_3(V_3);
...
```

Here, the names \texttt{C_0}, \texttt{C_1}, etc. represent enumerated elements for this particular enumerated type. All such elements have distinct values.

### 16.3.3.3 Bitmask types

Several types defined in Clause 17 through Clause 33 and Annex D are bitmask types. Each bitmask type can be implemented as an enumerated type that overloads certain operators, as an integer type, or as a bitset (22.9.2).

The bitmask type \texttt{bitmask} can be written:

```c
// For exposition only.
// \texttt{int\_type} is an integral type capable of representing all values of the bitmask type.
enum bitmask : int\_type {
  V_0 = 1 << 0, V_1 = 1 << 1, V_2 = 1 << 2, V_3 = 1 << 3, ... ;
};
inline constexpr bitmask C_0(V_0);
inline constexpr bitmask C_1(V_1);
inline constexpr bitmask C_2(V_2);
inline constexpr bitmask C_3(V_3);
...
```

constexpr bitmask operator\&(bitmask X, bitmask Y) {
  return static\_cast<bitmask>(static\_cast<int\_type>(X) & static\_cast<int\_type>(Y));
}
constexpr bitmask operator|(bitmask X, bitmask Y) {
  return static\_cast<bitmask>(static\_cast<int\_type>(X) | static\_cast<int\_type>(Y));
}
constexpr bitmask operator^ (bitmask X, bitmask Y) {
  return static\_cast<bitmask>(static\_cast<int\_type>(X) ^ static\_cast<int\_type>(Y));
}
constexpr bitmask operator~(bitmask X) {
  return static\_cast<bitmask>(~static\_cast<int\_type>(X));
}
```

\textsuperscript{142} Such as an integer type, with constant integer values (6.8.2).
Here, the names $C_0$, $C_1$, etc. represent bitmask elements for this particular bitmask type. All such elements have distinct, nonzero values such that, for any pair $C_i$ and $C_j$ where $i \neq j$, $C_i \& C_j$ is nonzero and $C_i \& C_j$ is zero. Additionally, the value 0 is used to represent an empty bitmask, in which no bitmask elements are set.

The following terms apply to objects and values of bitmask types:

(4.1) To set a value $Y$ in an object $X$ is to evaluate the expression $X |= Y$.

(4.2) To clear a value $Y$ in an object $X$ is to evaluate the expression $X &= Y$.

(4.3) The value $Y$ is set in the object $X$ if the expression $X \& Y$ is nonzero.

16.3.3.4 Character sequences

16.3.3.4.1 General

The C standard library makes widespread use of characters and character sequences that follow a few uniform conventions:

(1.1) Properties specified as locale-specific may change during program execution by a call to `setlocale(int, const char*)` (30.5.1), or by a change to a locale object, as described in 30.3 and Clause 31.

(1.2) The execution character set and the execution wide-character set are supersets of the basic literal character set (5.3). The encodings of the execution character sets and the sets of additional elements (if any) are locale-specific. Each element of the execution wide-character set is encoded as a single code unit representable by a value of type `wchar_t`.

[Note 1: The encodings of the execution character sets can be unrelated to any literal encoding. — end note]

(1.3) A letter is any of the 26 lowercase or 26 uppercase letters in the basic character set.

(1.4) The decimal-point character is the locale-specific (single-byte) character used by functions that convert between a (single-byte) character sequence and a value of one of the floating-point types. It is used in the character sequence to denote the beginning of a fractional part. It is represented in Clause 17 through Clause 33 and Annex D by a period, ‘.’, which is also its value in the "C" locale.

(1.5) A character sequence is an array object (9.3.4.5) $A$ that can be declared as `T A[N]`, where $T$ is any of the types `char`, `unsigned char`, or `signed char` (6.8.2), optionally qualified by any combination of `const` or `volatile`. The initial elements of the array have defined contents up to and including an element determined by some predicate. A character sequence can be designated by a pointer value $S$ that points to its first element.

16.3.3.4.2 Byte strings

A null-terminated byte string, or `ntbs`, is a character sequence whose highest-addressed element with defined content has the value zero (the terminating null character); no other element in the sequence has the value zero. 143

The length of an `ntbs` is the number of elements that precede the terminating null character. An empty `ntbs` has a length of zero.

The value of an `ntbs` is the sequence of values of the elements up to and including the terminating null character.

A static `ntbs` is an `ntbs` with static storage duration. 144

16.3.3.4.3 Multibyte strings

A multibyte character is a sequence of one or more bytes representing the code unit sequence for an encoded character of the execution character set.

A null-terminated multibyte string, or `ntmbss`, is an `ntbs` that constitutes a sequence of valid multibyte characters, beginning and ending in the initial shift state. 145

A static `ntmbss` is an `ntmbss` with static storage duration.

---

143 Many of the objects manipulated by function signatures declared in `<cstring>` (23.5.3) are character sequences or `ntbs`. The size of some of these character sequences is limited by a length value, maintained separately from the character sequence.

144 A string-literal, such as "abc", is a static `ntbs`.

145 An `ntbs` that contains characters only from the basic literal character set is also an `ntmbss`. Each multibyte character then consists of a single byte.
16.3.3.3.5 Customization Point Object types

A customization point object is a function object (22.10) with a literal class type that interacts with program-defined types while enforcing semantic requirements on that interaction.

1. The type of a customization point object, ignoring cv-qualifiers, shall model semiregular (18.6).

2. All instances of a specific customization point object type shall be equal (18.2). The effects of invoking different instances of a specific customization point object type on the same arguments are equivalent.

3. The type \( T \) of a customization point object, ignoring cv-qualifiers, shall model \( \text{invocable}<T&, \text{Args}...>, \text{invocable}<\text{const } T&, \text{Args}...>, \text{invocable}<T, \text{Args}...>, \text{invocable}<\text{const } T, \text{Args}...> \) (18.7.2) when the types in \( \text{Args}... \) meet the requirements specified in that customization point object’s definition. When the types of \( \text{Args}... \) do not meet the customization point object’s requirements, \( T \) shall not have a function call operator that participates in overload resolution.

4. For a given customization point object \( o \), let \( p \) be a variable initialized as if by \texttt{auto p = o;} . Then for any sequence of arguments \( \text{args}... \), the following expressions have effects equivalent to \( o(\text{args}...) \):

\[
\begin{align*}
(1.1) & \quad p(\text{args}...) \\
(1.2) & \quad \text{as}\_\text{const}(p)(\text{args}...) \\
(1.3) & \quad \text{std}::\text{move}(p)(\text{args}...) \\
(1.4) & \quad \text{std}::\text{move}(\text{as}\_\text{const}(p))(\text{args}...) \\
\end{align*}
\]

5. Each customization point object type constrains its return type to model a particular concept.

16.3.3.4 Functions within classes

For the sake of exposition, Clause 17 through Clause 33 and Annex D do not describe copy/move constructors, assignment operators, or (non-virtual) destructors with the same apparent semantics as those that can be generated by default (11.4.5.3, 11.4.6, 11.4.7). It is unspecified whether the implementation provides explicit definitions for such member function signatures, or for virtual destructors that can be generated by default.

16.3.3.5 Private members

Clause 17 through Clause 33 and Annex D do not specify the representation of classes, and intentionally omit specification of class members (11.4). An implementation may define static or non-static class members, or both, as needed to implement the semantics of the member functions specified in Clause 17 through Clause 33 and Annex D.

2. For the sake of exposition, some subclauses provide representative declarations, and semantic requirements, for private members of classes that meet the external specifications of the classes. The declarations for such members are followed by a comment that ends with exposition only, as in:

\[
\text{streambuf}\* \text{sb;} \quad // \text{exposition only}
\]

3. An implementation may use any technique that provides equivalent observable behavior.

16.3.3.6 Freestanding items

A freestanding item is a declaration, entity, typedef-name, or macro that is required to be present in a freestanding implementation and a hosted implementation.

2. Unless otherwise specified, the requirements on freestanding items for a freestanding implementation are the same as the corresponding requirements for a hosted implementation, except that not all of the members of those items are required to be present.

3. Function declarations and function template declarations followed by a comment that include freestanding-deleted are freestanding deleted functions. On freestanding implementations, it is implementation-defined whether each entity introduced by a freestanding deleted function is a deleted function (9.5.3) or whether the requirements are the same as the corresponding requirements for a hosted implementation.

[Note 1: Deleted definitions reduce the chance of overload resolution silently changing when migrating from a freestanding implementation to a hosted implementation. — end note]

[Example 1:

\[
\text{double abs(double j);} \quad // \text{freestanding-deleted}
\]

— end example]
A declaration in a synopsis is a freestanding item if

1. it is followed by a comment that includes `freestanding`,
2. it is followed by a comment that includes `freestanding-deleted`, or
3. the header synopsis begins with a comment that includes `freestanding` and the declaration is not followed by a comment that includes `hosted`.

[Note 2: Declarations followed by `hosted` in freestanding headers are not freestanding items. As a result, looking up the name of such functions can vary between hosted and freestanding implementations. —end note]

[Example 2:]

```c
// all freestanding
namespace std {
  // end example
```

An entity, deduction guide, or `typedef-name` is a freestanding item if it is:

1. introduced by a declaration that is a freestanding item,
2. a member of a freestanding item other than a namespace,
3. an enumerator of a freestanding item,
4. a deduction guide of a freestanding item,
5. an enclosing namespace of a freestanding item,
6. a friend of a freestanding item,
7. denoted by a `typedef-name` that is a freestanding item, or
8. denoted by an alias template that is a freestanding item.

A macro is a freestanding item if it is defined in a header synopsis and

1. the definition is followed by a comment that includes `freestanding`, or
2. the header synopsis begins with a comment that includes `freestanding` and the definition is not followed by a comment that includes `hosted`.

[Example 3:]

```
#define NULL see below // freestanding
  // end example
```

[Note 3: Freestanding annotations follow some additional exposition conventions that do not impose any additional normative requirements. Header synopses that begin with a comment containing "all freestanding" contain no hosted items and no freestanding deleted functions. Header synopses that begin with a comment containing "mostly freestanding" contain at least one hosted item or freestanding deleted function. Classes and class templates followed by a comment containing "partially freestanding" contain at least one hosted item or freestanding deleted function. —end note]

[Example 4:]

```c
template<typename T, size_t N> struct array; // partially freestanding
template<typename T, size_t N>
struct array {
  constexpr reference operator[](size_type n);
  constexpr const_reference operator[](size_type n) const;
  constexpr reference at(size_type n); // freestanding-deleted
  constexpr const_reference at(size_type n) const; // freestanding-deleted
};
  // end example
```

## 16.4 Library-wide requirements

### 16.4.1 General

Subclause 16.4 specifies requirements that apply to the entire C++ standard library. Clause 17 through Clause 33 and Annex D specify the requirements of individual entities within the library.

Requirements specified in terms of interactions between threads do not apply to programs having only a single thread of execution.
16.4.2 describes the library’s contents and organization, 16.4.3 describes how well-formed C++ programs gain access to library entities, 16.4.4 describes constraints on types and functions used with the C++ standard library, 16.4.5 describes constraints on well-formed C++ programs, and 16.4.6 describes constraints on conforming implementations.

16.4.2 Library contents and organization

16.4.2.1 General

16.4.2 describes the entities and macros defined in the C++ standard library. 16.4.2.3 lists the standard library headers and some constraints on those headers. 16.4.2.5 lists requirements for a freestanding implementation of the C++ standard library.

16.4.2.2 Library contents

The C++ standard library provides definitions for the entities and macros described in the synopses of the C++ standard library headers (16.4.2.3), unless otherwise specified.

All library entities except operator new and operator delete are defined within the namespace std or namespaces nested within namespace std. It is unspecified whether names declared in a specific namespace are declared directly in that namespace or in an inline namespace inside that namespace.

Whenever an unqualified name other than swap, make_error_code, make_error_condition, or submdspan_mapping is used in the specification of a declaration D in Clause 17 through Clause 33 or Annex D, its meaning is established as-if by performing unqualified name lookup (6.5.3) in the context of D.

[Note 1: Argument-dependent lookup is not performed. —end note]

Similarly, the meaning of a qualified-id is established as-if by performing qualified name lookup (6.5.5) in the context of D.

[Example 1: The reference to is_array_v in the specification of std::to_array (24.3.8.6) refers to ::std::is_array_v. —end example]

[Note 2: Operators in expressions (12.2.2.3) are not so constrained; see 16.4.6.4. —end note]

The meaning of the unqualified name swap is established in an overload resolution context for swappable values (16.4.4.3). The meanings of the unqualified names make_error_code, make_error_condition, and submdspan_mapping are established as-if by performing argument-dependent lookup (6.5.4).

16.4.2.3 Headers

Each element of the C++ standard library is declared or defined (as appropriate) in a header.

The C++ standard library provides the C++ library headers, shown in Table 24.

The facilities of the C standard library are provided in the additional headers shown in Table 25.

The headers listed in Table 24, or, for a freestanding implementation, the subset of such headers that are provided by the implementation, are collectively known as the importable C++ library headers.

[Note 1: Importable C++ library headers can be imported (10.3). —end note]

[Example 1:
import <vector>;
std::vector<int> vi;  // OK
—end example]

Except as noted in Clause 16 through Clause 33 and Annex D, the contents of each header cname is the same as that of the corresponding header name.h as specified in the C standard library (Clause 2). In the C++ standard library, however, the declarations (except for names which are defined as macros in C) are within namespace scope (6.4.6) of the namespace std. It is unspecified whether these names (including any overloads added in Clause 17 through Clause 33 and Annex D) are first declared within the global namespace scope and are then injected into namespace std by explicit using-declarations (9.9).

146) The C standard library headers (17.14) also define names within the global namespace, while the C++ headers for C library facilities (16.4.2.3) can also define names within the global namespace.

147) This gives implementers freedom to use inline namespaces to support multiple configurations of the library.

148) A header is not necessarily a source file, nor are the sequences delimited by < and > in header names necessarily valid source file names (15.3).

149) It is intentional that there is no C++ header for any of these C headers: <stdnoreturn.h>, <threads.h>.
Table 24 — C++ library headers  
[tab:headers.cpp]

| <algorithm> | <forward_list> | <mutex> | <stacktrace> |
| <any>       | <fstream>    | <new>   | <stlexception> |
| <array>     | <functional> | <numbers> | <stdfloat> |
| <atomic>    | <future>    | <numeric> | <stop_token> |
| <barrier>   | <generator> | <optional> | <streambuf> |
| <bit>       | <hazard_pointer> | <ostream> | <string> |
| <bitset>    | <initializer_list> | <print> | <string_view> |
| <charconv>  | <inplace_vector> | <queue> | <sstream> |
| <chrono>    | <romanip>   | <random> | <system_error> |
| <compare>   | <ios>       | <ranges> | <text_encoding> |
| <complex>   | <iosfwd>    | <ratio> | <thread> |
| <concepts>  | <iostream>  | <rcu>   | <tuple> |
| <condition_variable> | <iostream> | <regex> | <type_traits> |
| <coroutine> | <iterator>  | <scoped_allocator> | <typeindex> |
| <debugging> | <latch>     | <semaphore> | <typeinfo> |
| <dequeue>   | <limits>    | <set>   | <unordered_map> |
| <exception> | <linalg>    | <shared_mutex> | <unordered_set> |
| <execution> | <list>      | <source_location> | <utility> |
| <expected>  | <locale>    | <span>  | <valarray> |
| <filesystem> | <map>      | <spanstream> | <variant> |
| <flat_map>  | <mdspan>    | <sstream> | <vector> |
| <flat_set>  | <memory>    | <stack> | <version> |
| <format>    | <memory_resource> |

Table 25 — C++ headers for C library facilities  
[tab:headers.cpp.c]

| <cassert>   | <cfenv>     | <climits> | <csetjmp> | <cstddef> | <cuchar> |
| <ctype>     | <cfloat>    | <locale>  | <csignal> | <cstdlib> | <cwchar> |
| <cerrno>    | <cinttypes> | <cmath>   | <cstdarg> | <cstring> | <cwctype> |

6 Names which are defined as macros in C shall be defined as macros in the C++ standard library, even if C grants license for implementation as functions.

[Note 2: The names defined as macros in C include the following: assert, offsetof, setjmp, va_arg, va_end, and va_start. — end note]

7 Names that are defined as functions in C shall be defined as functions in the C++ standard library.

8 Identifiers that are keywords or operators in C++ shall not be defined as macros in C++ standard library headers.

9 Subclause 17.14 describes the effects of using the name.h (C header) form in a C++ program.

10 ISO/IEC 9899:2018, Annex K describes a large number of functions, with associated types and macros, which "promote safer, more secure programming" than many of the traditional C library functions. The names of the functions have a suffix of _s; most of them provide the same service as the C library function with the unsuffixed name, but generally take an additional argument whose value is the size of the result array. If any C++ header is included, it is implementation-defined whether any of these names is declared in the global namespace. (None of them is declared in namespace std.) The .h headers dump all their names into the global namespace, whereas the newer forms keep their names in namespace std. Therefore, the newer forms are the preferred forms for all uses except for C++ programs which are intended to be strictly compatible with C.

11 Table 26 lists the Annex K names that may be declared in some header. These names are also subject to the restrictions of 16.4.5.3.3.

150) This disallows the practice, allowed in C, of providing a masking macro in addition to the function prototype. The only way to achieve equivalent inline behavior in C++ is to provide a definition as an extern inline function.

151) In particular, including the standard header <iso646.h> has no effect.

152) The *.h* headers dump all their names into the global namespace, whereas the newer forms keep their names in namespace std. Therefore, the newer forms are the preferred forms for all uses except for C++ programs which are intended to be strictly compatible with C.
Table 26 — Names from ISO/IEC 9899:2018, Annex K  [tab:c.annex.k.names]

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Function Name</th>
<th>Function Name</th>
<th>Function Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>abort_handler_s</td>
<td>mbstowcs_s</td>
<td>strncat_s</td>
<td>vswscanf_s</td>
</tr>
<tr>
<td>asctime_s</td>
<td>memcpy_s</td>
<td>strncpy_s</td>
<td>vwprintf_s</td>
</tr>
<tr>
<td>bsearch_s</td>
<td>memmove_s</td>
<td>strtok_s</td>
<td>wvscanf_s</td>
</tr>
<tr>
<td>constraint_handler_t</td>
<td>memset_s</td>
<td>swprintf_s</td>
<td>wcrtomb_s</td>
</tr>
<tr>
<td>ctime_s</td>
<td>printf_s</td>
<td>swscanf_s</td>
<td>wccat_s</td>
</tr>
<tr>
<td>errno_t</td>
<td>qsort_s</td>
<td>tmpfile_s</td>
<td>wcscpy_s</td>
</tr>
<tr>
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<td>RSIZE_MAX</td>
<td>tmpnam_s</td>
<td>wcscat_s</td>
</tr>
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<td>rszize_t</td>
<td>vfprintf_s</td>
<td>wcsnyp_s</td>
</tr>
<tr>
<td>freopen_s</td>
<td>scanf_s</td>
<td>vfwprintf_s</td>
<td>wcsnlen_s</td>
</tr>
<tr>
<td>fscanf_s</td>
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<td>vfwscanf_s</td>
<td>wcstrombs_s</td>
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<td>snprintf_s</td>
<td>vfprintf_s</td>
<td>wctomb_s</td>
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<td>sprintf_s</td>
<td>vfwscanf_s</td>
<td>wctombs_s</td>
</tr>
<tr>
<td>getenv_s</td>
<td>svprintf_s</td>
<td>vprintf_s</td>
<td>wmemcpy_s</td>
</tr>
<tr>
<td>gets_s</td>
<td>svscanf_s</td>
<td>vsprintf_s</td>
<td>wmemmove_s</td>
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<td>vscanf_s</td>
<td>wmemmove_s</td>
</tr>
<tr>
<td>ignore_handler_s</td>
<td>strncpy_s</td>
<td>vsnprintf_s</td>
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<td>localtime_s</td>
<td>strftime_s</td>
<td>vsprintf_s</td>
<td>wscanf_s</td>
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<tr>
<td>L_tmpnam_s</td>
<td>strerrorlen_s</td>
<td>vsprintf_s</td>
<td>wscanf_s</td>
</tr>
<tr>
<td>mbstowcs_s</td>
<td>strlen_s</td>
<td>vsprintf_s</td>
<td>wscanf_s</td>
</tr>
</tbody>
</table>

16.4.2.4 Modules

1 The C++ standard library provides the following C++ library modules.

2 The named module std exports declarations in namespace std that are provided by the importable C++ library headers (Table 24 or the subset provided by a freestanding implementation) and the C++ headers for C library facilities (Table 25). It additionally exports declarations in the global namespace for the storage allocation and deallocation functions that are provided by <new> (17.6.2).

3 The named module std.compat exports the same declarations as the named module std, and additionally exports declarations in the global namespace corresponding to the declarations in namespace std that are provided by the C++ headers for C library facilities (Table 25), except the explicitly excluded declarations described in 17.14.7.

4 It is unspecified to which module a declaration in the standard library is attached.

[Note 1: Conforming implementations ensure that mixing #include and import does not result in conflicting attachments (6.6). — end note]

Recommended practice: Implementations should ensure such attachments do not preclude further evolution or decomposition of the standard library modules.

5 A declaration in the standard library denotes the same entity regardless of whether it was made reachable through including a header, importing a header unit, or importing a C++ library module.

6 Recommended practice: Implementations should avoid exporting any other declarations from the C++ library modules.

[Note 2: Like all named modules, the C++ library modules do not make macros visible (10.3), such as assert (19.3.2), errno (19.4.2), offsetof (17.2.1), and va_arg (17.13.2). — end note]

16.4.2.5 Freestanding implementations

1 Two kinds of implementations are defined: hosted and freestanding (4.1); the kind of the implementation is implementation-defined. For a hosted implementation, this document describes the set of available headers.

2 A freestanding implementation has an implementation-defined set of headers. This set shall include at least the headers shown in Table 27.

3 For each of the headers listed in Table 27, a freestanding implementation provides at least the freestanding items (16.3.3.6) declared in the header.

4 The hosted library facilities are the set of facilities described in this document that are required for hosted implementations, but not required for freestanding implementations. A freestanding implementation provides
Table 27 — C++ headers for freestanding implementations [tab:headers.cpp.fs]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2 Common definitions</td>
<td><code>&lt;cstdlib&gt;</code></td>
</tr>
<tr>
<td>17.2.2 C standard library</td>
<td><code>&lt;cstddef&gt;</code></td>
</tr>
<tr>
<td>17.3 Implementation properties</td>
<td><code>&lt;cfloat&gt;, &lt;climits&gt;, &lt;limits&gt;, &lt;version&gt;</code></td>
</tr>
<tr>
<td>17.4.1 Integer types</td>
<td><code>&lt;cstdint&gt;</code></td>
</tr>
<tr>
<td>17.6 Dynamic memory management</td>
<td><code>&lt;new&gt;</code></td>
</tr>
<tr>
<td>17.7 Type identification</td>
<td><code>&lt;typeinfo&gt;</code></td>
</tr>
<tr>
<td>17.8 Source location</td>
<td><code>&lt;source_location&gt;</code></td>
</tr>
<tr>
<td>17.9 Exception handling</td>
<td><code>&lt;exception&gt;</code></td>
</tr>
<tr>
<td>17.10 Initializer lists</td>
<td><code>&lt;initializer_list&gt;</code></td>
</tr>
<tr>
<td>17.11 Comparisons</td>
<td><code>&lt;compare&gt;</code></td>
</tr>
<tr>
<td>17.12 Coroutines support</td>
<td><code>&lt;coroutine&gt;</code></td>
</tr>
<tr>
<td>17.13 Other runtime support</td>
<td><code>&lt;cstdlib&gt;</code></td>
</tr>
<tr>
<td>Clause 18 Concepts library</td>
<td><code>&lt;concepts&gt;</code></td>
</tr>
<tr>
<td>19.4 Error numbers</td>
<td><code>&lt;cerrno&gt;</code></td>
</tr>
<tr>
<td>19.5 System error support</td>
<td><code>&lt;system_error&gt;</code></td>
</tr>
<tr>
<td>20.2 Memory</td>
<td><code>&lt;memory&gt;</code></td>
</tr>
<tr>
<td>21.3 Type traits</td>
<td><code>&lt;type_traits&gt;</code></td>
</tr>
<tr>
<td>21.4 Compile-time rational arithmetic</td>
<td><code>&lt;ratio&gt;</code></td>
</tr>
<tr>
<td>22.2 Utility components</td>
<td><code>&lt;utility&gt;</code></td>
</tr>
<tr>
<td>22.4 Tuples</td>
<td><code>&lt;tuple&gt;</code></td>
</tr>
<tr>
<td>22.5 Optional objects</td>
<td><code>&lt;optional&gt;</code></td>
</tr>
<tr>
<td>22.6 Variants</td>
<td><code>&lt;variant&gt;</code></td>
</tr>
<tr>
<td>22.8 Expected objects</td>
<td><code>&lt;expected&gt;</code></td>
</tr>
<tr>
<td>22.10 Function objects</td>
<td><code>&lt;functional&gt;</code></td>
</tr>
<tr>
<td>22.13 Primitive numeric conversions</td>
<td><code>&lt;charconv&gt;</code></td>
</tr>
<tr>
<td>22.15 Bit manipulation</td>
<td><code>&lt;bit&gt;</code></td>
</tr>
<tr>
<td>22.16 Debugging</td>
<td><code>&lt;debugging&gt;</code></td>
</tr>
<tr>
<td>23.3 String view classes</td>
<td><code>&lt;string_view&gt;</code></td>
</tr>
<tr>
<td>23.4 String classes</td>
<td><code>&lt;string&gt;</code></td>
</tr>
<tr>
<td>23.5 Null-terminated sequence utilities</td>
<td><code>&lt;cstring&gt;, &lt;cwchar&gt;</code></td>
</tr>
<tr>
<td>Clause 24 Containers library</td>
<td><code>&lt;inplace_vector&gt;</code></td>
</tr>
<tr>
<td>24.3.8 Class template array</td>
<td><code>&lt;array&gt;</code></td>
</tr>
<tr>
<td>24.7.2 Contiguous access</td>
<td><code>&lt;span&gt;</code></td>
</tr>
<tr>
<td>24.7.3 Multidimensional access</td>
<td><code>&lt;mdspan&gt;</code></td>
</tr>
<tr>
<td>Clause 25 Iterators library</td>
<td><code>&lt;iterator&gt;</code></td>
</tr>
<tr>
<td>Clause 26 Ranges library</td>
<td><code>&lt;ranges&gt;</code></td>
</tr>
<tr>
<td>Clause 27 Algorithms library</td>
<td><code>&lt;algorithm&gt;, &lt;numeric&gt;</code></td>
</tr>
<tr>
<td>28.7 Mathematical functions for floating-point types</td>
<td><code>&lt;cmath&gt;</code></td>
</tr>
<tr>
<td>33.5 Atomics</td>
<td><code>&lt;atomic&gt;</code></td>
</tr>
</tbody>
</table>
a (possibly empty) implementation-defined subset of the hosted library facilities. Unless otherwise specified, the requirements on each declaration, entity, typedef-name, and macro provided in this way are the same as the corresponding requirements for a hosted implementation, except that not all of the members of the namespaces are required to be present.

A freestanding implementation provides deleted definitions (9.5.3) for a (possibly empty) implementation-defined subset of the namespace-scope functions and function templates from the hosted library facilities. [Note 1: An implementation can provide a deleted definition so that the result of overload resolution does not silently change when migrating a program from a freestanding implementation to a hosted implementation. — end note]

16.4.3 Using the library

16.4.3.1 Overview

Subclause 16.4.3 describes how a C++ program gains access to the facilities of the C++ standard library. 16.4.3.2 describes effects during translation phase 4, while 16.4.3.3 describes effects during phase 8 (5.2).

16.4.3.2 Headers

The entities in the C++ standard library are defined in headers, whose contents are made available to a translation unit when it contains the appropriate #include preprocessing directive (15.3) or the appropriate import declaration (10.3).

A translation unit may include library headers in any order (5.1). Each may be included more than once, with no effect different from being included exactly once, except that the effect of including either <cassert> (19.3.2) or <assert.h> (17.14) depends each time on the lexically current definition of NDEBUG.153 A translation unit shall include a header only outside of any declaration or definition and, in the case of a module unit, only in its global-module-fragment, and shall include the header or import the corresponding header unit lexically before the first reference in that translation unit to any of the entities declared in that header. No diagnostic is required.

16.4.3.3 Linkage

Entities in the C++ standard library have external linkage (6.6). Unless otherwise specified, objects and functions have the default extern "C++" linkage (9.11).

Whether a name from the C standard library declared with external linkage has extern "C" or extern "C++" linkage is implementation-defined. It is recommended that an implementation use extern "C++" linkage for this purpose.154 Objects and functions defined in the library and required by a C++ program are included in the program prior to program startup.

See also replacement functions (16.4.5.6), runtime changes (16.4.5.7).

16.4.4 Requirements on types and expressions

16.4.4.1 General

16.4.4.2 describes requirements on types and expressions used to instantiate templates defined in the C++ standard library. 16.4.4.3 describes the requirements on swappable types and swappable expressions. 16.4.4.4 describes the requirements on pointer-like types that support null values. 16.4.4.5 describes the requirements on hash function objects. 16.4.4.6 describes the requirements on storage allocators.

16.4.4.2 Template argument requirements

The template definitions in the C++ standard library refer to various named requirements whose details are set out in Tables 28–35. In these tables,

(1.1) — T denotes an object or reference type to be supplied by a C++ program instantiating a template,

(1.2) — a, b, and c denote values of type (possibly const) T,

(1.3) — s and t denote modifiable lvalues of type T,

(1.4) — u denotes an identifier,

153) This is the same as the C standard library.

154) The only reliable way to declare an object or function signature from the C standard library is by including the header that declares it, notwithstanding the latitude granted in ISO/IEC 9899:2018, 7.1.4.
— rv denotes an rvalue of type T, and
— v denotes an lvalue of type (possibly const) T or an rvalue of type const T.

2 In general, a default constructor is not required. Certain container class member function signatures specify
T() as a default argument. T() shall be a well-defined expression (9.4) if one of those signatures is called
using the default argument (9.3.4.7).

Table 28 — Cpp17EqualityComparable requirements [tab:cpp17.equalitycomparable]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
</table>
| a == b     | decltype(a == b) | == is an equivalence relation, that is, it has the following properties:
  
  — For all a, a == a.
  
  — If a == b, then b == a.
  
  — If a == b and b == c, then a == c. |

Table 29 — Cpp17LessThanComparable requirements [tab:cpp17.lessthancomparable]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>a &lt; b</td>
<td>decltype(a &lt; b)</td>
<td>&lt; is a strict weak ordering relation (27.8)</td>
</tr>
</tbody>
</table>

Table 30 — Cpp17DefaultConstructible requirements [tab:cpp17.defaultconstructible]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>T t;</td>
<td>object t is default-initialized</td>
</tr>
<tr>
<td>T u{};</td>
<td>object u is value-initialized or aggregate-initialized</td>
</tr>
<tr>
<td>T()</td>
<td>an object of type T is value-initialized or aggregate-initialized</td>
</tr>
<tr>
<td>T{}</td>
<td></td>
</tr>
</tbody>
</table>

Table 31 — Cpp17MoveConstructible requirements [tab:cpp17.moveconstructible]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>T u = rv;</td>
<td>u is equivalent to the value of rv before the construction</td>
</tr>
<tr>
<td>T(rv)</td>
<td>T(rv) is equivalent to the value of rv before the construction</td>
</tr>
<tr>
<td>rv's state is unspecified</td>
<td></td>
</tr>
</tbody>
</table>

[Note 1: rv must still meet the requirements of the library component that is using it. The operations listed in these requirements must work as specified whether rv has been moved from or not. — end note]  

16.4.4.3 Swappable requirements [swappable.requirements]

This subclause provides definitions for swappable types and expressions. In these definitions, let t denote an expression of type T, and let u denote an expression of type U.

2 An object t is swappable with an object u if and only if

— the expressions swap(t, u) and swap(u, t) are valid when evaluated in the context described below, and
Table 32 — Cpp17CopyConstructible requirements (in addition to Cpp17MoveConstructible) [tab:cpp17.copyconstructible]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>T u = v;</td>
<td>the value of v is unchanged and is equivalent to u</td>
</tr>
<tr>
<td>T(v)</td>
<td>the value of v is unchanged and is equivalent to T(v)</td>
</tr>
</tbody>
</table>

Table 33 — Cpp17MoveAssignable requirements [tab:cpp17.moveassignable]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Return value</th>
<th>Post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = rv</td>
<td>T&amp; t</td>
<td>t</td>
<td>If t and rv do not refer to the same object, t is equivalent to the value of rv before the assignment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>rv’s state is unspecified.</td>
</tr>
</tbody>
</table>

[Note 2: rv must still meet the requirements of the library component that is using it, whether or not t and rv refer to the same object. The operations listed in those requirements must work as specified whether rv has been moved from or not. — end note]

Table 34 — Cpp17CopyAssignable requirements (in addition to Cpp17MoveAssignble) [tab:cpp17.copyassignable]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Return value</th>
<th>Post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = v</td>
<td>T&amp; t</td>
<td>t</td>
<td>t is equivalent to v, the value of v is unchanged</td>
</tr>
</tbody>
</table>

Table 35 — Cpp17Destructible requirements [tab:cpp17.destructible]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>u. ~T()</td>
<td>All resources owned by u are reclaimed, no exception is propagated.</td>
</tr>
</tbody>
</table>

[Note 3: Array types and non-object types are not Cpp17Destructible. — end note]

(2.2) — these expressions have the following effects:

(2.2.1) — the object referred to by t has the value originally held by u and

(2.2.2) — the object referred to by u has the value originally held by t.

3 The context in which swap(t, u) and swap(u, t) are evaluated shall ensure that a binary non-member function named “swap” is selected via overload resolution (12.2) on a candidate set that includes:

(3.1) — the two swap function templates defined in <utility> (22.2.1) and

(3.2) — the lookup set produced by argument-dependent lookup (6.5.4).

[Note 1: If T and U are both fundamental types or arrays of fundamental types and the declarations from the header <utility> are in scope, the overall lookup set described above is equivalent to that of the qualified name lookup applied to the expression std::swap(t, u) or std::swap(u, t) as appropriate. — end note]

[Note 2: It is unspecified whether a library component that has a swappable requirement includes the header <utility> to ensure an appropriate evaluation context. — end note]

4 An rvalue or lvalue t is swappable if and only if t is swappable with any rvalue or lvalue, respectively, of type T.

5 A type X meets the Cpp17Swappable requirements if lvalues of type X are swappable.

6 A type X meeting any of the iterator requirements (25.3) meets the Cpp17ValueSwappable requirements if, for any dereferenceable object x of type X, *x is swappable.
Example 1: User code can ensure that the evaluation of swap calls is performed in an appropriate context under the various conditions as follows:

```cpp
#include <cassert>
#include <utility>

// Preconditions: std::forward<T>(t) is swappable with std::forward<U>(u).
template<class T, class U>
void value_swap(T&& t, U&& u) {
    using std::swap;
    swap(std::forward<T>(t), std::forward<U>(u)); // OK, uses "swappable with" conditions
    // for rvalues and lvalues
}

// Preconditions: T meets the Cpp17Swappable requirements.
template<class T>
void lv_swap(T& t1, T& t2) {
    using std::swap;
    swap(t1, t2); // OK, uses swappable conditions for lvalues of type T
}

namespace N {
    struct A { int m; }
    struct Proxy { A* a; }
    Proxy proxy(A& a) { return Proxy{ &a }; }

    void swap(A& x, Proxy p) {
        std::swap(x.m, p.a->m); // OK, uses context equivalent to swappable
        // conditions for fundamental types
    }
    void swap(Proxy p, A& x) { swap(x, p); } // satisfy symmetry constraint
}

int main() {
    int i = 1, j = 2;
    lv_swap(i, j);
    assert(i == 2 && j == 1);
    N::A a1 = { 5 }, a2 = { -5 };
    value_swap(a1, proxy(a2));
    assert(a1.m == -5 && a2.m == 5);
}

—end example—

16.4.4.4 Cpp17NullablePointer requirements

A Cpp17NullablePointer type is a pointer-like type that supports null values. A type P meets the Cpp17NullablePointer requirements if

1.1 — P meets the Cpp17EqualityComparable, Cpp17DefaultConstructible, Cpp17CopyConstructible, Cpp17CopyAssignable, Cpp17Swappable, and Cpp17Destructible requirements,

1.2 — the expressions shown in Table 36 are valid and have the indicated semantics, and

1.3 — P meets all the other requirements of this subclause.

2 A value-initialized object of type P produces the null value of the type. The null value shall be equivalent only to itself. A default-initialized object of type P may have an indeterminate or erroneous value.

[Note 1: Operations involving indeterminate values can cause undefined behavior, and operations involving erroneous values can cause erroneous behavior (6.7.4). — end note]

3 An object p of type P can be contextually converted to bool (7.3). The effect shall be as if p != nullptr had been evaluated in place of p.

4 No operation which is part of the Cpp17NullablePointer requirements shall exit via an exception.

5 In Table 36, u denotes an identifier, t denotes a non-const lvalue of type P, a and b denote values of type (possibly const) P, and np denotes a value of type (possibly const) std::nullptr_t.
Table 36 — Cpp17NullablePointer requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
</tr>
</thead>
<tbody>
<tr>
<td>P u(np);</td>
<td></td>
<td>Postconditions: u == nullptr</td>
</tr>
<tr>
<td>P u = np;</td>
<td></td>
<td>Postconditions: P(np) == nullptr</td>
</tr>
<tr>
<td>t = np</td>
<td>P&amp;</td>
<td>Postconditions: t == nullptr</td>
</tr>
<tr>
<td>a != b</td>
<td>decltype(a != b) models</td>
<td>!(a == b)</td>
</tr>
<tr>
<td>a == np</td>
<td>decltype(a == np) and a == P()</td>
<td></td>
</tr>
<tr>
<td>np == a</td>
<td>decltype(np == a) each model</td>
<td></td>
</tr>
<tr>
<td>!a == np</td>
<td>decltype(a != np) and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>!(!a == np)</td>
<td></td>
</tr>
</tbody>
</table>

16.4.4.5 Cpp17Hash requirements

1 A type `H` meets the Cpp17Hash requirements if
   (1.1) — it is a function object type (22.10),
   (1.2) — it meets the Cpp17CopyConstructible (Table 32) and Cpp17Destructible (Table 35) requirements, and
   (1.3) — the expressions shown in Table 37 are valid and have the indicated semantics.
2 Given `Key` is an argument type for function objects of type `H`, in Table 37 `h` is a value of type (possibly const) `H`, `u` is an lvalue of type `Key`, and `k` is a value of a type convertible to (possibly const) `Key`.

Table 37 — Cpp17Hash requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
</table>
| h(k)       | size_t      | The value returned shall depend only on the argument `k` for the duration of the program. [Note 1: Thus all evaluations of the expression `h(k)` with the same value for `k` yield the same result for a given execution of the program. — end note] For two different values `t1` and `t2`, the probability that `h(t1)` and `h(t2)` compare equal should be very small, approaching `1.0 / numeric_limits<size_t>::max()`.
| h(u)       | size_t      | Shall not modify `u`.                           |

16.4.4.6 Cpp17Allocator requirements

16.4.4.6.1 General

1 The library describes a standard set of requirements for allocators, which are class-type objects that encapsulate the information about an allocation model. This information includes the knowledge of pointer types, the type of their difference, the type of the size of objects in this allocation model, as well as the memory allocation and deallocation primitives for it. All of the string types (Clause 23), containers (Clause 24) (except array and inplace_vector), string buffers and string streams (Clause 31), and match_results (Clause 32) are parameterized in terms of allocators.
2 In 16.4.4.6,
   (2.1) — `T`, `U`, `C` denote any cv-unqualified object type (6.8.1),
   (2.2) — `X` denotes an allocator class for type `T`,
   (2.3) — `Y` denotes the corresponding allocator class for type `U`,

§ 16.4.4.6.1 ©ISO/IEC 508
XX denotes the type `allocator_traits<X>`,
YY denotes the type `allocator_traits<Y>`,
a, a1, a2 denote lvalues of type X,
u denotes the name of a variable being declared,
b denotes a value of type Y,
c denotes a pointer of type C* through which indirection is valid,
p denotes a value of type XX::pointer obtained by calling a1.allocate, where a1 == a,
q denotes a value of type XX::const_pointer obtained by conversion from a value p,
r denotes a value of type T& obtained by the expression *p,
v denotes a value of type XX::void_pointer obtained by conversion from a value p,
x denotes a value of type XX::const_void_pointer obtained by conversion from a value q or a value w,
y denotes a value of type XX::const_void_pointer obtained by conversion from a result value of YY::allocate, or else a value of type (possibly const) std::nullptr_t,
n denotes a value of type XX::size_type,
Args denotes a template parameter pack, and
args denotes a function parameter pack with the pattern Args&&.

The class template `allocator_traits` (20.2.9) supplies a uniform interface to all allocator types. This subclause describes the requirements on allocator types and thus on types used to instantiate `allocator_traits`. A requirement is optional if a default for a given type or expression is specified. Within the standard library `allocator_traits` template, an optional requirement that is not supplied by an allocator is replaced by the specified default type or expression.

[Note 1: There are no program-defined specializations of `allocator_traits`. — end note]

typename X::pointer
Remarks: Default: T*

typename X::const_pointer
Mandates: XX::pointer is convertible to XX::const_pointer.
Remarks: Default: `pointer_traits<XX::pointer>::rebind<const T>`

.typename X::void_pointer
typename Y::void_pointer
Mandates: XX::pointer is convertible to XX::void_pointer. XX::void_pointer and YY::void_pointer are the same type.
Remarks: Default: `pointer_traits<XX::pointer>::rebind<void>`

.typename X::const_void_pointer
typename Y::const_void_pointer
Mandates: XX::pointer, XX::const_pointer, and XX::void_pointer are convertible to XX::const_void_pointer. XX::const_void_pointer and YY::const_void_pointer are the same type.
Remarks: Default: `pointer_traits<XX::pointer>::rebind<const void>`

.typename X::value_type
Result: Identical to T.

.typename X::size_type
Result: An unsigned integer type that can represent the size of the largest object in the allocation model.
Remarks: Default: `make_unsigned_t<XX::difference_type>`
typedef X::difference_type

Result: A signed integer type that can represent the difference between any two pointers in the allocation model.

Remarks: Default: pointer_traits<XX::pointer>::difference_type

typename X::template rebind<U>::other

Result: Y

Postconditions: For all U (including T), YY::rebind_alloc<T> is X.

Remarks: If Allocator is a class template instantiation of the form SomeAllocator<T, Args>, where Args is zero or more type arguments, and Allocator does not supply a rebind member template, the standard allocator_traits template uses SomeAllocator<U, Args> in place of Allocator::rebind<U>::other by default. For allocator types that are not template instantiations of the above form, no default is provided.

[Note 2: The member class template rebind of X is effectively a typedef template. In general, if the name Allocator is bound to SomeAllocator<T>, then Allocator::rebind<U>::other is the same type as SomeAllocator<U>, where SomeAllocator<T>::value_type is T and SomeAllocator<U>::value_type is U. — end note]

*p

Result: T&

*q

Result: const T&

Postconditions: *q refers to the same object as *p.

p->m

Result: Type of T::m.

Preconditions: (*p).m is well-defined.

Effects: Equivalent to (*p).m.

q->m

Result: Type of T::m.

Preconditions: (*q).m is well-defined.

Effects: Equivalent to (*q).m.

static_cast<XX::pointer>(w)

Result: XX::pointer

Postconditions: static_cast<XX::pointer>(w) == p.

static_cast<XX::const_pointer>(x)

Result: XX::const_pointer

Postconditions: static_cast<XX::const_pointer>(x) == q.

pointer_traits<XX::pointer>::pointer_to(r)

Result: XX::pointer

Postconditions: Same as p.
Throws: `allocate` may throw an appropriate exception.

[Note 3: It is intended that `a.allocate` be an efficient means of allocating a single object of type T, even when `sizeof(T)` is small. That is, there is no need for a container to maintain its own free list. — end note]

Remarks: If `n == 0`, the return value is unspecified.

`a.allocate(n, y)`

Result: `XX::pointer`

Effects: Same as `a.allocate(n)`. The use of `y` is unspecified, but it is intended as an aid to locality.

Remarks: Default: `a.allocate(n)`

`a.allocate_at_least(n)`

Result: `allocation_result<XX::pointer, XX::size_type>`

Returns: `allocation_result<XX::pointer, XX::size_type>{ptr, count}` where `ptr` is memory allocated for an array of `count T` and such an object is created but array elements are not constructed, such that `count ≥ n`. If `n == 0`, the return value is unspecified.

Throws: `allocate_at_least` may throw an appropriate exception.

Remarks: Default: `{a.allocate(n), n}`.

`a.deallocate(p, n)`

Result: (not used)

Preconditions:

(48.1) If `p` is memory that was obtained by a call to `a.allocate_at_least`, let `ret` be the value returned and `req` be the value passed as the first argument of that call. `p` is equal to `ret.ptr` and `n` is a value such that `req ≤ n ≤ ret.count`.

(48.2) Otherwise, `p` is a pointer value obtained from `allocate`. `n` equals the value passed as the first argument to the invocation of `allocate` which returned `p`. `p` has not been invalidated by an intervening call to `deallocate`.

Throws: Nothing.

`a.max_size()`

Result: `XX::size_type`

Returns: The largest value `n` that can meaningfully be passed to `a.allocate(n)`.

Remarks: Default: `numeric_limits<size_type>::max() / sizeof(value_type)`

`a1 == a2`

Result: `bool`

Returns: `true` only if storage allocated from each can be deallocated via the other.

Throws: Nothing.

Remarks: `operator==` shall be reflexive, symmetric, and transitive.

`a1 != a2`

Result: `bool`

Returns: `!(a1 == a2)`.

`a == b`

Result: `bool`

Returns: `a == YY::rebind_alloc<T>(b)`.

`a != b`

Result: `bool`

Returns: `!(a == b)`.
X u(a);
X u = a;

Postconditions: u == a

Throws: Nothing.

X u(b);

Postconditions: Y(u) == b and u == X(b).

Throws: Nothing.

X u(std::move(a));
X u = std::move(a);

Postconditions: The value of a is unchanged and is equal to u.

Throws: Nothing.

X u(std::move(b));

Postconditions: u is equal to the prior value of X(b).

Throws: Nothing.

a.construct(c, args...)

Result: (not used)

Effects: Constructs an object of type C at c.

Remarks: Default: construct_at(c, std::forward<Args>(args)...)

a.destroy(c)

Result: (not used)

Effects: Destroys the object at c.

Remarks: Default: destroy_at(c)

a.select_on_container_copy_construction()

Result: X

Returns: Typically returns either a or X().

Remarks: Default: return a;

typename X::propagate_on_container_copy_assignment

Result: Identical to or derived from true_type or false_type.

Returns: true_type only if an allocator of type X should be copied when the client container is
copy-assigned; if so, X shall meet the Cpp17CopyAssignable requirements (Table 34) and the copy
operation shall not throw exceptions.

Remarks: Default: false_type

typename X::propagate_on_container_move_assignment

Result: Identical to or derived from true_type or false_type.

Returns: true_type only if an allocator of type X should be moved when the client container is
move-assigned; if so, X shall meet the Cpp17MoveAssignable requirements (Table 33) and the move
operation shall not throw exceptions.

Remarks: Default: false_type

typename X::propagate_on_container_swap

Result: Identical to or derived from true_type or false_type.

Returns: true_type only if an allocator of type X should be swapped when the client container is
swapped; if so, X shall meet the Cpp17Swappable requirements (16.4.4.3) and the swap operation shall
not throw exceptions.

Remarks: Default: false_type

§ 16.4.4.6.1
typename X::is_always_equal

**Result:** Identical to or derived from `true_type` or `false_type`.

**Returns:** `true_type` only if the expression `a1 == a2` is guaranteed to be `true` for any two (possibly const) values `a1, a2` of type `X`.

**Remarks:** Default: `is_empty<X>::type`

An allocator type `X` shall meet the `Cpp17CopyConstructible` requirements (Table 32). The `X::pointer, X::const_pointer, X::void_pointer, and X::const_void_pointer` types shall meet the `Cpp17NullablePointer` requirements (Table 36). No constructor, comparison operator function, copy operation, move operation, or swap operation on these pointer types shall exit via an exception. `X::pointer` and `X::const_pointer` shall also meet the requirements for a `Cpp17RandomAccessIterator` (25.3.5.7) and the additional requirement that, when `p` and `(p + n)` are dereferenceable pointer values for some integral value `n`,

```c++
    addressof(*p) == n
```

is true.

Let `x1` and `x2` denote objects of (possibly different) types `X::void_pointer, X::const_void_pointer, X::pointer, or X::const_pointer`. Then, `x1` and `x2` are equivalently-valued pointer values, if and only if both `x1` and `x2` can be explicitly converted to the two corresponding objects `px1` and `px2` of type `X::const_pointer`, using a sequence of `static_cast`s using only these four types, and the expression `px1 == px2` evaluates to `true`.

Let `w1` and `w2` denote objects of type `X::void_pointer`. Then for the expressions

```c++
    w1 == w2
    w1 != w2
```

either or both objects may be replaced by an equivalently-valued object of type `X::const_void_pointer` with no change in semantics.

Let `p1` and `p2` denote objects of type `X::pointer`. Then for the expressions

```c++
    p1 == p2
    p1 != p2
    p1 < p2
    p1 <= p2
    p1 > p2
    p1 >= p2
    p1 - p2
```

either or both objects may be replaced by an equivalently-valued object of type `X::const_pointer` with no change in semantics.

An allocator may constrain the types on which it can be instantiated and the arguments for which its `construct` or `destroy` members may be called. If a type cannot be used with a particular allocator, the allocator class or the call to `construct` or `destroy` may fail to instantiate.

If the alignment associated with a specific over-aligned type is not supported by an allocator, instantiation of the allocator for that type may fail. The allocator also may silently ignore the requested alignment.

[Note 4: Additionally, the member function `allocate` for that type can fail by throwing an object of type `std::bad_alloc`. —end note]

**Example 2:** The following is an allocator class template supporting the minimal interface that meets the requirements of 16.4.4.6.1:

```c++
template<class T>
struct SimpleAllocator {
    using value_type = T;
    SimpleAllocator(ctor args);

    template<class U> SimpleAllocator(const SimpleAllocator<U>& other);

    T* allocate(std::size_t n);
    void deallocate(T* p, std::size_t n);

    template<class U> bool operator==(const SimpleAllocator<U>& rhs) const;
};
```

§ 16.4.4.6.1 ©ISO/IEC
16.4.4.6.2 Allocator completeness requirements

If \( X \) is an allocator class for type \( T \), \( X \) additionally meets the allocator completeness requirements if, whether or not \( T \) is a complete type:

1. \( X \) is a complete type, and
2. all the member types of \( \text{allocator_traits}<X> \) (20.2.9) other than \( \text{value_type} \) are complete types.

16.4.5 Constraints on programs

16.4.5.1 Overview

Subclause 16.4.5 describes restrictions on C++ programs that use the facilities of the C++ standard library. The following subclauses specify constraints on the program’s use of namespaces (16.4.5.2.1), its use of various reserved names (16.4.5.3), its use of standard library classes as base classes (16.4.5.5), its definitions of replacement functions (16.4.5.6), and its installation of handler functions during execution (16.4.5.7).

16.4.5.2 Namespace use

16.4.5.2.1 Namespace \( \text{std} \)

Unless otherwise specified, the behavior of a C++ program is undefined if it adds declarations or definitions to namespace \( \text{std} \) or to a namespace within namespace \( \text{std} \).

Unless explicitly prohibited, a program may add a template specialization for any standard library class template to namespace \( \text{std} \) provided that:

1. the added declaration depends on at least one program-defined type, and
2. the specialization meets the standard library requirements for the original template.\(^{155}\)

The behavior of a C++ program is undefined if it declares an explicit or partial specialization of any standard library variable template, except where explicitly permitted by the specification of that variable template.\(^{155}\)

A program may explicitly instantiate a class template defined in the standard library only if the declaration depends on the name of at least one program-defined type, and

Let \( F \) denote a standard library function (16.4.6.4), a standard library static member function, or an instantiation of a standard library function template. Unless \( F \) is designated an \( \text{addressable function} \), the behavior of a C++ program is unspecified (possibly ill-formed) if it explicitly or implicitly attempts to form a pointer to \( F \).

Moreover, the behavior of a C++ program is unspecified (possibly ill-formed) if it attempts to form a reference to \( F \) or if it attempts to form a pointer-to-member designating either a standard library non-static member function (16.4.6.5) or an instantiation of a standard library member function template.

A translation unit shall not declare namespace \( \text{std} \) to be an inline namespace (9.8.2).

\(^{155}\) Any library code that instantiates other library templates must be prepared to work adequately with any user-supplied specialization that meets the minimum requirements of this document.
16.4.5.2.2 Namespace posix

The behavior of a C++ program is undefined if it adds declarations or definitions to namespace posix or to a namespace within namespace posix unless otherwise specified. The namespace posix is reserved for use by ISO/IEC/IEEE 9945 and other POSIX standards.

16.4.5.2.3 Namespaces for future standardization

Top-level namespaces whose namespace-name consists of std followed by one or more digits (5.10) are reserved for future standardization. The behavior of a C++ program is undefined if it adds declarations or definitions to such a namespace.

[Example 1: The top-level namespace std2 is reserved for use by future revisions of this International Standard. —end example]

16.4.5.3 Reserved names

16.4.5.3.1 General

The C++ standard library reserves the following kinds of names:

(1.1) — macros
(1.2) — global names
(1.3) — names with external linkage

If a program declares or defines a name in a context where it is reserved, other than as explicitly allowed by Clause 16, its behavior is undefined.

16.4.5.3.2 Zombie names

In namespace std, the names shown in Table 38 are reserved for previous standardization:

Table 38 — Zombie names in namespace std

<table>
<thead>
<tr>
<th>auto_ptr</th>
<th>generate_header</th>
<th>pointer_to_binary_function</th>
</tr>
</thead>
<tbody>
<tr>
<td>auto_ptr_ref</td>
<td>get_pointer_safety</td>
<td>pointer_to Unary_function</td>
</tr>
<tr>
<td>binary_function</td>
<td>get_temporary_buffer</td>
<td>ptr_fun</td>
</tr>
<tr>
<td>binary_negate</td>
<td>get_unexpected</td>
<td>random_shuffle</td>
</tr>
<tr>
<td>bind1st</td>
<td>gets</td>
<td>raw_storage_iterator</td>
</tr>
<tr>
<td>bind2nd</td>
<td>is_literal_type</td>
<td>result_of</td>
</tr>
<tr>
<td>binder1st</td>
<td>is_literal_type_v</td>
<td>result_of_t</td>
</tr>
<tr>
<td>binder2nd</td>
<td>istringstream</td>
<td>return_temporary_buffer</td>
</tr>
<tr>
<td>codecvt_mode</td>
<td>little_endian</td>
<td>set_unexpected</td>
</tr>
<tr>
<td>codecvt_utf16</td>
<td>mem_funi_ref_t</td>
<td>strstream</td>
</tr>
<tr>
<td>codecvt_utf8</td>
<td>mem_funi_t</td>
<td>streambuf</td>
</tr>
<tr>
<td>codecvt_utf8_utf16</td>
<td>mem_fun_ref_t</td>
<td>unary_function</td>
</tr>
<tr>
<td>const_mem_fun1_ref_t</td>
<td>mem_fun</td>
<td>unary_negate</td>
</tr>
<tr>
<td>const_mem_fun1_t</td>
<td>mem_fun_t</td>
<td>uncauht_exception</td>
</tr>
<tr>
<td>const_mem_fun_ref_t</td>
<td>mem_fun</td>
<td>undeclare_no_pointers</td>
</tr>
<tr>
<td>const_mem_fun_t</td>
<td>not1</td>
<td>undeclare_reachable</td>
</tr>
<tr>
<td>consume_header</td>
<td>not2</td>
<td>unexpected_handler</td>
</tr>
<tr>
<td>declare_no_pointers</td>
<td>ostrstream</td>
<td>wbuffer_convert</td>
</tr>
<tr>
<td>declare_reachable</td>
<td>pointer_safety</td>
<td>wstring_convert</td>
</tr>
</tbody>
</table>

The names shown in Table 39 are reserved as members for previous standardization, and may not be used as a name for object-like macros in portable code:

Table 39 — Zombie object-like macros

<table>
<thead>
<tr>
<th>argument_type</th>
<th>op</th>
<th>second_argument_type</th>
</tr>
</thead>
<tbody>
<tr>
<td>first_argument_type</td>
<td>open_mode</td>
<td>seek_dir</td>
</tr>
<tr>
<td>io_state</td>
<td>preferred</td>
<td>strict</td>
</tr>
</tbody>
</table>
The names shown in Table 40 are reserved as member functions for previous standardization, and may not be used as a name for function-like macros in portable code:

Table 40 — Zombie function-like macros

| converted | freeze | from_bytes | pcount | stoss | to_bytes |

The header names shown in Table 41 are reserved for previous standardization:

Table 41 — Zombie headers

| <ccomplex> | <codecvt> | <cstdbool> | <ctgmath> | <sstream> |
| <ciso646> | <cstdalign> |

16.4.5.3.3 Macro names

A translation unit that includes a standard library header shall not `#define` or `#undef` names declared in any standard library header.

A translation unit shall not `#define` or `#undef` names lexically identical to keywords, to the identifiers listed in Table 4, or to the attribute-tokens described in 9.12, except that the names likely and unlikely may be defined as function-like macros (15.6).

16.4.5.3.4 External linkage

Each name declared as an object with external linkage in a header is reserved to the implementation to designate that library object with external linkage, both in namespace `std` and in the global namespace.

Each global function signature declared with external linkage in a header is reserved to the implementation to designate that function signature with external linkage.

Each name from the C standard library declared with external linkage is reserved to the implementation for use as a name with `extern "C"` linkage, both in namespace `std` and in the global namespace.

Each function signature from the C standard library declared with external linkage is reserved to the implementation for use as a function signature with both `extern "C"` and `extern "C++"` linkage, or as a name of namespace scope in the global namespace.

16.4.5.3.5 Types

For each type `T` from the C standard library, the types `::T` and `std::T` are reserved to the implementation and, when defined, `::T` shall be identical to `std::T`.

16.4.5.3.6 User-defined literal suffixes

Literal suffix identifiers (12.6) that do not start with an underscore are reserved for future standardization. Literal suffix identifiers that contain a double underscore `__` are reserved for use by C++ implementations.

16.4.5.4 Headers

If a file with a name equivalent to the derived file name for one of the C++ standard library headers is not provided as part of the implementation, and a file with that name is placed in any of the standard places for a source file to be included, the behavior is undefined.

16.4.5.5 Derived classes

Virtual member function signatures defined for a base class in the C++ standard library may be overridden in a derived class defined in the program (11.7.3).

156) The list of such reserved names includes `errno`, declared or defined in `<cerrno>` (19.4.2).

157) The list of such reserved function signatures with external linkage includes `setjmp(jmp_buf)`, declared or defined in `<csetjmp>` (17.13.3), and `va_end(va_list)`, declared or defined in `<cstdarg>` (17.13.2).

158) The function signatures declared in `<cuchar>` (23.5.5), `<cwchar>` (23.5.4), and `<cwctype>` (23.5.2) are always reserved, notwithstanding the restrictions imposed in subclause 4.5.1 of Amendment 1 to the C Standard for these headers.
16.4.5.6 Replacement functions

Clause 17 through Clause 33 and Annex D describe the behavior of numerous functions defined by the C++ standard library. Under some circumstances, however, certain of these function descriptions also apply to replacement functions defined in the program.

A C++ program may provide the definition for any of the following dynamic memory allocation function signatures declared in header `<new>` (6.7.5.5, 17.6.2):

- `operator new(std::size_t)`
- `operator new(std::size_t, std::align_val_t)`
- `operator new(std::size_t, const std::nothrow_t&)`  
- `operator new(std::size_t, std::align_val_t, const std::nothrow_t&)`  
- `operator delete(void*)`  
- `operator delete(void*, std::size_t)`  
- `operator delete(void*, std::align_val_t)`  
- `operator delete(void*, std::size_t, std::align_val_t)`  
- `operator delete(void*, const std::nothrow_t&)`  
- `operator delete(void*, std::align_val_t, const std::nothrow_t&)`  
- `operator new[](std::size_t)`  
- `operator new[](std::size_t, std::align_val_t)`  
- `operator new[](std::size_t, const std::nothrow_t&)`  
- `operator new[](std::size_t, std::align_val_t, const std::nothrow_t&)`  
- `operator delete[](void*)`  
- `operator delete[](void*, std::size_t)`  
- `operator delete[](void*, std::align_val_t)`  
- `operator delete[](void*, std::size_t, std::align_val_t)`  
- `operator delete[](void*, const std::nothrow_t&)`  
- `operator delete[](void*, std::align_val_t, const std::nothrow_t&)`

A C++ program may provide the definition of the following function signature declared in header `<debugging>` (22.16.2):

```
bool std::is_debugger_present() noexcept
```

The program’s definitions are used instead of the default versions supplied by the implementation (17.6.3). Such replacement occurs prior to program startup (6.3, 6.9.3). The program’s declarations shall not be specified as `inline`. No diagnostic is required.

16.4.5.7 Handler functions

The C++ standard library provides a default version of the following handler function (Clause 17):

- `terminate_handler`

A C++ program may install different handler functions during execution, by supplying a pointer to a function defined in the program or the library as an argument to (respectively):

- `set_new_handler`
- `set_terminate`

See also subclauses 17.6.4, Storage allocation errors, and 17.9, Exception handling.

A C++ program can get a pointer to the current handler function by calling the following functions:

- `get_new_handler`
- `get_terminate`

Calling the `set_*` and `get_*` functions shall not incur a data race (6.9.2.2). A call to any of the `set_*` functions shall synchronize with subsequent calls to the same `set_*` function and to the corresponding `get_*` function.

16.4.5.8 Other functions

In certain cases (replacement functions, handler functions, operations on types used to instantiate standard library template components), the C++ standard library depends on components supplied by a C++ program. If these components do not meet their requirements, this document places no requirements on the implementation.

In particular, the behavior is undefined in the following cases:
For replacement functions (17.6.3), if the installed replacement function does not implement the semantics of the applicable Required behavior: paragraph.

For handler functions (17.6.4.3, 17.9.5.1), if the installed handler function does not implement the semantics of the applicable Required behavior: paragraph.

For types used as template arguments when instantiating a template component, if the operations on the type do not implement the semantics of the applicable Requirements subclause (16.4.4.6, 24.2, 25.3, 27.2, 28.2). Operations on such types can report a failure by throwing an exception unless otherwise specified.

If any replacement function or handler function or destructor operation exits via an exception, unless specifically allowed in the applicable Required behavior: paragraph.

If an incomplete type (6.8.1) is used as a template argument when instantiating a template component or evaluating a concept, unless specifically allowed for that component.

16.4.5.9 Function arguments

Each of the following applies to all arguments to functions defined in the C++ standard library, unless explicitly stated otherwise.

(1.1) If an argument to a function has an invalid value (such as a value outside the domain of the function or a pointer invalid for its intended use), the behavior is undefined.

(1.2) If a function argument is described as being an array, the pointer actually passed to the function shall have a value such that all address computations and accesses to objects (that would be valid if the pointer did point to the first element of such an array) are in fact valid.

(1.3) If a function argument is bound to an rvalue reference parameter, the implementation may assume that this parameter is a unique reference to this argument, except that the argument passed to a move assignment operator may be a reference to *this (16.4.6.15).

[Note 1: If the type of a parameter is a forwarding reference (13.10.3.2) that is deduced to an lvalue reference type, then the argument is not bound to an rvalue reference. — end note]

[Note 2: If a program casts an lvalue to an xvalue while passing that lvalue to a library function (e.g., by calling the function with the argument std::move(x)), the program is effectively asking that function to treat that lvalue as a temporary object. The implementation is free to optimize away aliasing checks which would possibly be needed if the argument was an lvalue. — end note]

16.4.5.10 Library object access

The behavior of a program is undefined if calls to standard library functions from different threads may introduce a data race. The conditions under which this may occur are specified in 16.4.6.10.

[Note 1: Modifying an object of a standard library type that is shared between threads risks undefined behavior unless objects of that type are explicitly specified as being shareable without data races or the user supplies a locking mechanism. — end note]

If an object of a standard library type is accessed, and the beginning of the object’s lifetime (6.7.3) does not happen before the access, or the access does not happen before the end of the object’s lifetime, the behavior is undefined unless otherwise specified.

[Note 2: This applies even to objects such as mutexes intended for thread synchronization. — end note]

16.4.5.11 Semantic requirements

A sequence Args of template arguments is said to model a concept C if Args satisfies C (13.5.3) and meets all semantic requirements (if any) given in the specification of C.

If the validity or meaning of a program depends on whether a sequence of template arguments models a concept, and the concept is satisfied but not modeled, the program is ill-formed, no diagnostic required.

If the semantic requirements of a declaration’s constraints (16.3.2.3) are not modeled at the point of use, the program is ill-formed, no diagnostic required.

16.4.6 Conforming implementations

16.4.6.1 Overview

Subclause 16.4.6 describes the constraints upon, and latitude of, implementations of the C++ standard library.
An implementation’s use of headers is discussed in 16.4.6.2, its use of macros in 16.4.6.3, non-member functions in 16.4.6.4, member functions in 16.4.6.5, data race avoidance in 16.4.6.10, access specifiers in 16.4.6.11, class derivation in 16.4.6.12, and exceptions in 16.4.6.13.

16.4.6.2 Headers

A C++ header may include other C++ headers. A C++ header shall provide the declarations and definitions that appear in its synopsis. A C++ header shown in its synopsis as including other C++ headers shall provide the declarations and definitions that appear in the synopses of those other headers.

Certain types and macros are defined in more than one header. Every such entity shall be defined such that any header that defines it may be included after any other header that also defines it (6.3).

The C standard library headers (17.14) shall include only their corresponding C++ standard library header, as described in 16.4.2.3.

16.4.6.3 Restrictions on macro definitions

The names and global function signatures described in 16.4.2.2 are reserved to the implementation.

All object-like macros defined by the C standard library and described in this Clause as expanding to integral constant expressions are also suitable for use in #if preprocessing directives, unless explicitly stated otherwise.

16.4.6.4 Non-member functions

It is unspecified whether any non-member functions in the C++ standard library are defined as inline (9.2.8).

A call to a non-member function signature described in Clause 17 through Clause 33 and Annex D shall behave as if the implementation declared no additional non-member function signatures.

An implementation shall not declare a non-member function signature with additional default arguments.

Unless otherwise specified, calls made by functions in the standard library to non-operator, non-member functions do not use functions from another namespace which are found through argument-dependent name lookup (6.5.4).

[Note 1: The phrase “unless otherwise specified” applies to cases such as the swappable with requirements (16.4.4.3). The exception for overloaded operators allows argument-dependent lookup in cases like that of ostream_iterator::operator= (25.6.3.3):

Effects:

*out_stream << value;
if (delim != 0)
  *out_stream << delim;
return *this;
—end note]

16.4.6.5 Member functions

It is unspecified whether any member functions in the C++ standard library are defined as inline (9.2.8).

For a non-virtual member function described in the C++ standard library, an implementation may declare a different set of member function signatures, provided that any call to the member function that would select an overload from the set of declarations described in this document behaves as if that overload were selected.

[Note 1: For instance, an implementation can add parameters with default values, or replace a member function with default arguments with two or more member functions with equivalent behavior, or add additional signatures for a member function name. —end note]

16.4.6.6 Friend functions

Whenever this document specifies a friend declaration of a function or function template within a class or class template definition, that declaration shall be the only declaration of that function or function template provided by an implementation.

[Note 1: In particular, a conforming implementation does not provide any additional declarations of that function or function template at namespace scope. —end note]

[Note 2: Such a friend function or function template declaration is known as a hidden friend, as it is visible neither to ordinary unqualified lookup (6.5.3) nor to qualified lookup (6.5.5). —end note]

159) A valid C++ program always calls the expected library non-member function. An implementation can also define additional non-member functions that would otherwise not be called by a valid C++ program.
16.4.6.7 Constexpr functions and constructors

This document explicitly requires that certain standard library functions are constexpr (9.2.6). An implementation shall not declare any standard library function signature as constexpr except for those where it is explicitly required. Within any header that provides any non-defining declarations of constexpr functions or constructors an implementation shall provide corresponding definitions.

16.4.6.8 Requirements for stable algorithms

When the requirements for an algorithm state that it is “stable” without further elaboration, it means:

1. For the sort algorithms the relative order of equivalent elements is preserved.
2. For the remove and copy algorithms the relative order of the elements that are not removed is preserved.
3. For the merge algorithms, for equivalent elements in the original two ranges, the elements from the first range (preserving their original order) precede the elements from the second range (preserving their original order).

16.4.6.9 Reentrancy

Except where explicitly specified in this document, it is implementation-defined which functions in the C++ standard library may be recursively reentered.

16.4.6.10 Data race avoidance

This subclause specifies requirements that implementations shall meet to prevent data races (6.9.2). Every standard library function shall meet each requirement unless otherwise specified. Implementations may prevent data races in cases other than those specified below.

A C++ standard library function shall not directly or indirectly access objects (6.9.2) accessible by threads other than the current thread unless the objects are accessed directly or indirectly via the function’s arguments, including this.

A C++ standard library function shall not directly or indirectly modify objects (6.9.2) accessible by threads other than the current thread unless the objects are accessed directly or indirectly via the function’s non-const arguments, including this.

[Note 1: This means, for example, that implementations can’t use an object with static storage duration for internal purposes without synchronization because doing so can cause a data race even in programs that do not explicitly share objects between threads. — end note]

A C++ standard library function shall not access objects indirectly accessible via its arguments or via elements of its container arguments except by invoking functions required by its specification on those container elements.

Operations on iterators obtained by calling a standard library container or string member function may access the underlying container, but shall not modify it.

[Note 2: In particular, container operations that invalidate iterators conflict with operations on iterators associated with that container. — end note]

Implementations may share their own internal objects between threads if the objects are not visible to users and are protected against data races.

Unless otherwise specified, C++ standard library functions shall perform all operations solely within the current thread if those operations have effects that are visible (6.9.2) to users.

[Note 3: This allows implementations to parallelize operations if there are no visible side effects. — end note]

16.4.6.11 Protection within classes

It is unspecified whether any function signature or class described in Clause 17 through Clause 33 and Annex D is a friend of another class in the C++ standard library.

16.4.6.12 Derived classes

An implementation may derive any class in the C++ standard library from a class with a name reserved to the implementation.

Certain classes defined in the C++ standard library are required to be derived from other classes in the C++ standard library. An implementation may derive such a class directly from the required base or indirectly through a hierarchy of base classes with names reserved to the implementation.
In any case:

— Every base class described as virtual shall be virtual;

— Every base class not specified as virtual shall not be virtual;

— Unless explicitly stated otherwise, types with distinct names shall be distinct types.

[Note 1: There is an implicit exception to this rule for types that are described as synonyms (9.2.4, 9.9), such as size_t (17.2) and streamoff (31.2.2). — end note]

All types specified in the C++ standard library shall be non-final types unless otherwise specified.

16.4.6.13 Restrictions on exception handling

Any of the functions defined in the C++ standard library can report a failure by throwing an exception of a type described in its Throws: paragraph, or of a type derived from a type named in the Throws: paragraph that would be caught by a handler (14.4) for the base type.

Functions from the C standard library shall not throw exceptions except when such a function calls a program-supplied function that throws an exception.

Destructor operations defined in the C++ standard library shall not throw exceptions. Every destructor in the C++ standard library shall behave as if it had a non-throwing exception specification (14.5).

Functions defined in the C++ standard library that do not have a Throws: paragraph but do have a potentially-throwing exception specification may throw implementation-defined exceptions. Implementations should report errors by throwing exceptions of or derived from the standard exception classes (17.6.4.1, 17.9, 19.2).

An implementation may strengthen the exception specification for a non-virtual function by adding a non-throwing exception specification.

16.4.6.14 Value of error codes

Certain functions in the C++ standard library report errors via a std::error_code (19.5.4.1) object. That object’s category() member shall return std::system_category() for errors originating from the operating system, or a reference to an implementation-defined error_category object for errors originating elsewhere. The implementation shall define the possible values of value() for each of these error categories.

[Example 1: For operating systems that are based on POSIX, implementations should define the std::system_category() values as identical to the POSIX errno values, with additional values as defined by the operating system’s documentation. Implementations for operating systems that are not based on POSIX should define values identical to the operating system’s values. For errors that do not originate from the operating system, the implementation may provide enums for the associated values. — end example]

16.4.6.15 Moved-from state of library types

Objects of types defined in the C++ standard library may be moved from (11.4.5.3). Move operations may be explicitly specified or implicitly generated. Unless otherwise specified, such moved-from objects shall be placed in a valid but unspecified state.

An object of a type defined in the C++ standard library may be move-assigned (11.4.6) to itself. Unless otherwise specified, such an assignment places the object in a valid but unspecified state.

160) That is, the C standard library functions can all be treated as if they are marked noexcept. This allows implementations to make performance optimizations based on the absence of exceptions at runtime.

161) The functions qsort() and bsearch() (27.13) meet this condition.

162) In particular, they can report a failure to allocate storage by throwing an exception of type bad_alloc, or a class derived from bad_alloc (17.6.4.1).
17 Language support library [support]

17.1 General [support.general]
1 This Clause describes the function signatures that are called implicitly, and the types of objects generated implicitly, during the execution of some C++ programs. It also describes the headers that declare these function signatures and define any related types.
2 The following subclauses describe common type definitions used throughout the library, characteristics of the predefined types, functions supporting start and termination of a C++ program, support for dynamic memory management, support for dynamic type identification, support for exception processing, support for initializer lists, and other runtime support, as summarized in Table 42.

Table 42 — Language support library summary [tab:support.summary]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2 Common definitions</td>
<td><code>&lt;cstdint</code>, <code>&lt;stdfloat&gt;</code></td>
</tr>
<tr>
<td>17.3 Implementation properties</td>
<td><code>&lt;cfloat</code>, <code>&lt;climits</code>, <code>&lt;limits</code>, <code>&lt;version&gt;</code></td>
</tr>
<tr>
<td>17.4 Arithmetic types</td>
<td><code>&lt;cstdint</code>, <code>&lt;stdfloat&gt;</code></td>
</tr>
<tr>
<td>17.5 Start and termination</td>
<td><code>&lt;cstdlib&gt;</code></td>
</tr>
<tr>
<td>17.6 Dynamic memory management</td>
<td><code>&lt;new&gt;</code></td>
</tr>
<tr>
<td>17.7 Type identification</td>
<td><code>&lt;typeinfo&gt;</code></td>
</tr>
<tr>
<td>17.8 Source location</td>
<td><code>&lt;source_location&gt;</code></td>
</tr>
<tr>
<td>17.9 Exception handling</td>
<td><code>&lt;exception&gt;</code></td>
</tr>
<tr>
<td>17.10 Initializer lists</td>
<td><code>&lt;initializer_list&gt;</code></td>
</tr>
<tr>
<td>17.11 Comparisons</td>
<td><code>&lt;compare&gt;</code></td>
</tr>
<tr>
<td>17.12 Coroutines</td>
<td><code>&lt;coroutine&gt;</code></td>
</tr>
<tr>
<td>17.13 Other runtime support</td>
<td><code>&lt;csetjmp</code>, <code>&lt;csignal</code>, <code>&lt;cstdlib</code>, <code>&lt;cstdlib&gt;</code></td>
</tr>
</tbody>
</table>

17.2 Common definitions [support.types]
17.2.1 Header `<cstdlib>` synopsis [cstdlib.syn]

```c
// all freestanding
namespace std {
    using ptrdiff_t = see below;
    using size_t = see below;
    using max_align_t = see below;
    using nullptr_t = decltype(nullptr);

    enum class byte : unsigned char {};

    // 17.2.5, byte type operations
    template<class IntType>
        constexpr byte& operator<<=(byte& b, IntType shift) noexcept;
    template<class IntType>
        constexpr byte operator<<(byte b, IntType shift) noexcept;
    template<class IntType>
        constexpr byte& operator>>=(byte& b, IntType shift) noexcept;
    template<class IntType>
        constexpr byte operator>>(byte b, IntType shift) noexcept;
    constexpr byte& operator|=(byte& l, byte r) noexcept;
    constexpr byte operator|(byte l, byte r) noexcept;
    constexpr byte& operator&=(byte& l, byte r) noexcept;
    constexpr byte operator&(byte l, byte r) noexcept;
    constexpr byte& operator^=(byte& l, byte r) noexcept;
    constexpr byte operator^(byte l, byte r) noexcept;
    constexpr byte operator~(byte b) noexcept;
```
template<class IntType>
  constexpr IntType to_integer(byte b) noexcept;
}

#define NULL see below
#define offsetof(P, D) see below

The contents and meaning of the header `<cstdlib>` are the same as the C standard library header `<stdlib.h>`, except that it does not declare the type `wchar_t`, that it also declares the type `byte` and its associated operations (17.2.5), and as noted in 17.2.3 and 17.2.4.

See also: ISO/IEC 9899:2018, 7.19

§ 17.2.2 Header `<cstdlib>` synopsis

_namespace std {
  using size_t = see below;  // freestanding
  using div_t = see below;    // freestanding
  using ldiv_t = see below;   // freestanding
  using lldiv_t = see below;  // freestanding
}

#define NULL see below
#define EXIT_FAILURE see below
#define EXIT_SUCCESS see below
#define RAND_MAX see below
#define MB_CUR_MAX see below

_namespace std {
  // Exposition-only function type aliases
  extern "C" using c_atexit_handler = void(); // exposition only
  extern "C++" using atexit_handler = void();  // exposition only
  extern "C" using c_compare_pred = int(const void*, const void*); // exposition only
  extern "C++" using compare_pred = int(const void*, const void*); // exposition only

  // 17.5, start and termination
  [[noreturn]] void abort() noexcept;          // freestanding
  int atexit(c_atexit_handler* func) noexcept; // freestanding
  int atexit(atexit_handler* func) noexcept;   // freestanding
  int at_quick_exit(c_atexit_handler* func) noexcept; // freestanding
  int at_quick_exit(atexit_handler* func) noexcept; // freestanding
  [[noreturn]] void exit(int status);          // freestanding
  [[noreturn]] void _Exit(int status) noexcept; // freestanding
  [[noreturn]] void quick_exit(int status) noexcept; // freestanding

  char* getenv(const char* name);
  int system(const char* string);

  // 20.2.12, C library memory allocation
  void* aligned_alloc(size_t alignment, size_t size);
  void* calloc(size_t nmemb, size_t size);
  void free(void* ptr);
  void* malloc(size_t size);
  void* realloc(void* ptr, size_t size);

  double atof(const char* nptr);
  int atoi(const char* nptr);
  long int atol(const char* nptr);
  long long int atoll(const char* nptr);
  double strtof(const char* nptr, char** endptr);
  float strtof(const char* nptr, char** endptr);
  long double strtold(const char* nptr, char** endptr);
  long int strtol(const char* nptr, char** endptr, int base);
  long long intstrtoll(const char* nptr, char** endptr, int base);
  unsigned long int strtoul(const char* nptr, char** endptr, int base);
unsigned long long int strtoull(const char* nptr, char** endptr, int base);

// 23.5.6, multibyte / wide string and character conversion functions
int mbtowc(wchar_t* pw, const char* s, size_t n);
int wcstombs(char* s, const wchar_t* pwcs, size_t n);
size_t wcstowcs(wchar_t* pwcs, const char* s, size_t n);

// 27.13, C standard library algorithms
void* bsearch(const void* key, const void* base, size_t nmemb, size_t size,
               compare-pred* compar);
void* bsearch(const void* key, const void* base, size_t nmemb, size_t size,
               compare-pred* compar);
void qsort(void* base, size_t nmemb, size_t size,
          compare-pred* compar);

// 28.5.10, low-quality random number generation
int rand();
void srand(unsigned int seed);

// 28.7.2, absolute values
constexpr int abs(int j);
constexpr long int abs(long int j);
constexpr long long int abs(long long int j);
constexpr floating-point-type abs(floating-point-type j);
constexpr long int labs(long int j);
constexpr long long int llabs(long long int j);
constexpr div_t div(int numer, int denom);
constexpr ldiv_t div(long int numer, long int denom);
constexpr lldiv_t div(long long int numer, long long int denom);
constexpr ldiv_t ldiv(long int numer, long int denom);
constexpr lldiv_t lldiv(long long int numer, long long int denom);

1 The contents and meaning of the header `<cstdlib>` are the same as the C standard library header `<stdlib.h>`, except that it does not declare the type `wchar_t`, and except as noted in 17.2.3, 17.2.4, 17.5, 20.2.12, 23.5.6, 27.13, 28.5.10, and 28.7.2.

[Note 1: Several functions have additional overloads in this document, but they have the same behavior as in the C standard library (16.2). — end note]

See also: ISO/IEC 9899:2018, 7.22

17.2.3 Null pointers [support.types.nullptr]

1 The type `nullptr_t` is a synonym for the type of a `nullptr` expression, and it has the characteristics described in 6.8.2 and 7.3.12.

[Note 1: Although `nullptr`'s address cannot be taken, the address of another `nullptr_t` object that is an lvalue can be taken. — end note]

2 The macro `NULL` is an implementation-defined null pointer constant.

See also: ISO/IEC 9899:2018, 7.19

17.2.4 Sizes, alignments, and offsets [support.types.layout]

1 The macro `offsetof(type, member-designator)` has the same semantics as the corresponding macro in the C standard library header `<stddef.h>`, but accepts a restricted set of `type` arguments in this document. Use of the `offsetof` macro with a `type` other than a standard-layout class (11.2) is conditionally-supported.

The expression `offsetof(type, member-designator)` is never type-dependent (13.8.3.3) and it is value-dependent (13.8.3.4) if and only if `type` is dependent. The result of applying the `offsetof` macro to a static

163) Possible definitions include 0 and 0L, but not `(void*)0`.
164) Note that `offsetof` is required to work as specified even if unary `offsetof` is overloaded for any of the types involved.
data member or a function member is undefined. No operation invoked by the `offsetof` macro shall throw an exception and `noexcept(offsetof(type, member-designator))` shall be `true`.

2 The type `ptrdiff_t` is an implementation-defined signed integer type that can hold the difference of two subscripts in an array object, as described in 7.6.6.

3 The type `size_t` is an implementation-defined unsigned integer type that is large enough to contain the size in bytes of any object (7.6.2.5).

4 Recommended practice: An implementation should choose types for `ptrdiff_t` and `size_t` whose integer conversion ranks (6.8.6) are no greater than that of `signed long int` unless a larger size is necessary to contain all the possible values.

5 The type `max_align_t` is a trivial standard-layout type whose alignment requirement is at least as great as that of every scalar type, and whose alignment requirement is supported in every context (6.7.6).

See also: ISO/IEC 9899:2018, 7.19

17.2.5  byte type operations  [support.types.byteops]

```cpp
template<class IntType>
constexpr byte& operator<<=(byte& b, IntType shift) noexcept;
```

1

Constraints: `is_integral_v<IntType>` is true.

2

Effects: Equivalent to: `return b = b << shift;`

```cpp
template<class IntType>
constexpr byte operator<<(byte b, IntType shift) noexcept;
```

3

Constraints: `is_integral_v<IntType>` is true.

4

Effects: Equivalent to:
```
return static_cast<byte>(static_cast<unsigned int>(b) << shift);
```

```cpp
template<class IntType>
constexpr byte& operator>>(byte& b, IntType shift) noexcept;
```

5

Constraints: `is_integral_v<IntType>` is true.

6

Effects: Equivalent to:
```
return b = b >> shift;
```

```cpp
template<class IntType>
constexpr byte operator>>(byte b, IntType shift) noexcept;
```

7

Constraints: `is_integral_v<IntType>` is true.

8

Effects: Equivalent to:
```
return static_cast<byte>(static_cast<unsigned int>(b) >> shift);
```

```cpp
constexpr byte& operator|=(byte& l, byte r) noexcept;
```

9

Effects: Equivalent to:
```
return l = l | r;
```

```cpp
constexpr byte operator|(byte l, byte r) noexcept;
```

10

Effects: Equivalent to:
```
return static_cast<byte>(static_cast<unsigned int>(l) | static_cast<unsigned int>(r));
```

```cpp
constexpr byte& operator&=(byte& l, byte r) noexcept;
```

11

Effects: Equivalent to:
```
return l = l & r;
```

```cpp
constexpr byte operator&(byte l, byte r) noexcept;
```

12

Effects: Equivalent to:
```
return static_cast<byte>(static_cast<unsigned int>(l) & static_cast<unsigned int>(r));
```

```cpp
constexpr byte& operator^=(byte& l, byte r) noexcept;
```

13

Effects: Equivalent to:
```
return l = l ^ r;
```

§ 17.2.5  ©ISO/IEC 525
constexpr byte operator^(byte l, byte r) noexcept;
Effects: Equivalent to:
  return static_cast<byte>(static_cast<unsigned int>(l) ^ static_cast<unsigned int>(r));

constexpr byte operator~(byte b) noexcept;
Effects: Equivalent to:
  return static_cast<byte>(~static_cast<unsigned int>(b));

template<class IntType>
constexpr IntType to_integer(byte b) noexcept;
Effects: Equivalent to:
  return static_cast<IntType>(b);

17.3 Implementation properties
17.3.1 General

The headers <limits> (17.3.3), <climits> (17.3.6), and <cfloat> (17.3.7) supply characteristics of implementation-dependent arithmetic types (6.8.2).

17.3.2 Header <version> synopsis

The header <version> supplies implementation-dependent information about the C++ standard library (e.g., version number and release date).

[Note 1: Future revisions of this document might replace the values of these macros with greater values. — end note]

#define __cpp_lib_adaptor_iterator_pair_constructor 202106L // also in <stack>, <queue>
define __cpp_lib_addressof_constrExpr 201603L // freestanding, also in <memory>
define __cpp_lib_algorithm_default_value_type 202405L // also in <algorithm>, <ranges>, <string>, <deque>, <list>, <forward_list>, <vector>
define __cpp_lib_algorithm_iterator_requirements 202207L // also in <algorithm>, <numeric>, <memory>
define __cpp_lib_allocate_at_least 202302L // also in <memory>
define __cpp_lib_allocator_traits_is_always_equal 201411L // freestanding, also in <memory>, <scoped_allocator>, <string>, <deque>, <forward_list>, <list>, <vector>, <map>, <set>, <unordered_map>, <unordered_set>
define __cpp_lib_any 201606L // also in <any>
define __cpp_lib_apply 201603L // freestanding, also in <tuple>
define __cpp_lib_array_constexpr 201811L // also in <iterator>, <array>
define __cpp_lib_as_const 201510L // freestanding, also in <utility>
define __cpp_lib_associative_heterogeneous_erasu 202110L // also in <map>, <set>, <unordered_map>, <unordered_set>
define __cpp_lib_associative_heterogeneous_insertion 202306L // also in <map>, <set>, <unordered_map>, <unordered_set>
define __cpp_lib_assume_aligned 201811L // freestanding, also in <memory>
define __cpp_lib_atomic_flag_test 201907L // freestanding, also in <atomic>
define __cpp_lib_atomic_float 201711L // freestanding, also in <atomic>
define __cpp_lib_atomic_is_always_lock_free 201603L // freestanding, also in <atomic>
define __cpp_lib_atomic_lock_free_type_aliases 201907L // also in <atomic>
define __cpp_lib_atomic_min_max 202403L // freestanding, also in <atomic>
define __cpp_lib_atomic_shared_ptr 201711L // freestanding, also in <atomic>
define __cpp_lib_atomic_value_initialization 201911L // freestanding, also in <atomic>, <memory>
define __cpp_lib_atomic_wait 201907L // freestanding, also in <atomic>
define __cpp_lib_barricade 202302L // also in <barrier>
define __cpp_lib_bind_back 202306L // freestanding, also in <functional>
define __cpp_lib_bind_front 202306L // freestanding, also in <functional>
define __cpp_lib_bit_cast 201806L // freestanding, also in <atomic>
define __cpp_lib_bitops 201907L // freestanding, also in <bit>
define __cpp_lib_bitset 202306L // also in <bitset>
define __cpp_lib_bool_constant 201505L // freestanding, also in <type_traits>

§ 17.3.2 © ISO/IEC 526
#define __cpp_lib_bounded_array_traits 201902L // freestanding, also in <type_traits>
#define __cpp_lib_boyer_moore_searcher 201603L // also in <functional>
#define __cpp_lib_byte 201603L // freestanding, also in <cstdlib>
#define __cpp_lib_byteswap 202110L // freestanding, also in <bit>
#define __cpp_lib_char8_t 201907L
// freestanding, also in <atomic>, <filesystem>, <iostream>, <limits>, <locale>, <ostream>, <string>,
// <string_view>
#define __cpp_lib_chrono 202306L // also in <chrono>
#define __cpp_lib_chrono_udls 201304L // also in <chrono>
#define __cpp_lib_clamp 201603L // also in <algorithm>
#define __cpp_lib_common_reference 202302L // also in <type_traits>
#define __cpp_lib_common_reference_traits 202302L // also in <functional>
#define __cpp_lib_complex_udls 201309L // also in <complex>
#define __cpp_lib_concepts 202207L
// freestanding, also in <algorithm>, <utility>
#define __cpp_lib_constrained_equality 202406L // freestanding, also in <new>
#define __cpp_lib_constrained_typeinfo 202106L // freestanding, also in <typeinfo>
#define __cpp_lib_constexpr_algorithms 202306L // also in <numeric>
#define __cpp_lib_constexpr_array_traits 201907L // also in <string>
#define __cpp_lib_constexpr_bitset 201907L // also in <string_view>
#define __cpp_lib_constexpr_cmath 202306L // also in <cmath>
#define __cpp_lib_constexpr_complex 202306L // also in <complex>
#define __cpp_lib_constexpr_dynamic_alloc 201907L // also in <memory>
#define __cpp_lib_constexpr_functional 201907L // freestanding, also in <functional>
#define __cpp_lib_constexpr_iterable 201811L // freestanding, also in <iterator>
#define __cpp_lib_constexpr_map_traits 202202L // freestanding, also in <memory>
#define __cpp_lib_constexpr_new 202406L // freestanding, also in <new>
#define __cpp_lib_constexpr_numeric 201911L // also in <numeric>
#define __cpp_lib_constexpr_string 201907L // also in <string>
#define __cpp_lib_constexpr_string_view 201811L // also in <string_view>
#define __cpp_lib_constexpr_string_view_typeid 201811L // freestanding, also in <typeid>
#define __cpp_lib_constexpr_typeinfo 202106L // freestanding, also in <typeinfo>
#define __cpp_lib_constexpr_vector 201907L // also in <vector>
#define __cpp_lib_constexpr_traits 202403L // freestanding, also in <utility>, <tuple>, <optional>, <variant>
#define __cpp_lib_containers_ranges 202202L
// also in <vector>, <list>, <forward_list>, <map>, <set>, <unordered_map>, <unordered_set>,
// <deque>, <queue>, <stack>, <string>
#define __cpp_lib_copyable_function 202306L // also in <functional>
#define __cpp_libCoroutine 201902L // also in <coroutine>
#define __cpp_libDebugging 202403L // freestanding, also in <debugging>
#define __cpp_libDestroyingDelete 201806L // freestanding, also in <new>
#define __cpp_libEnableSharedFromThis 201603L // also in <memory>
#define __cpp_libEndian 201907L // freestanding, also in <bit>
#define __cpp_libEraseIf 202002L // also in <string>, <deque>, <forward_list>, <list>, <vector>, <map>, <set>, <unordered_map>,
// <unordered_set>
#define __cpp_libExchangeFunction 201304L // freestanding, also in <utility>
#define __cpp_libExecution 201902L // also in <execution>
#define __cpp_libExpected 202211L // also in <expected>
#define __cpp_libFilesystem 201703L // also in <filesystem>
#define __cpp_libFlatMap 202207L // also in <flat_map>
#define __cpp_libFlatSet 202207L // also in <flat_set>
#define __cpp_libFormatRanges 201811L // also in <format>
#define __cpp_libFormatPath 202002L // also in <filesystem>
#define __cpp_libFormatUchar 202311L // also in <format>
#define __cpp_libFormats 202302L // also in <stacktrace>, <thread>
#define __cpp_libForwardLike 202207L // freestanding, also in <utility>
#define __cpp_libFreestandingAlgorithm 202311L // freestanding, also in <algorithm>
#define __cpp_libFreestandingArray 202311L // freestanding, also in <array>
#define __cpp_libFreestandingCharTraits 202306L // freestanding, also in <string>
#define __cpp_libFreestandingCharConv 202306L // freestanding, also in <charconv>
#define __cpp_libFreestandingCstdlib 202306L // freestanding, also in <cstdlib>, <cmath>
#define __cpp_libFreestandingCstring 202311L // freestanding, also in <cstring>
N4986

#define __cpp_lib_freestanding_cwchar
#define __cpp_lib_freestanding_errc
// freestanding, also in <cerrno>, <system_error>
#define __cpp_lib_freestanding_expected
#define __cpp_lib_freestanding_feature_test_macros
#define __cpp_lib_freestanding_functional
#define __cpp_lib_freestanding_iterator
#define __cpp_lib_freestanding_mdspan
#define __cpp_lib_freestanding_memory
#define __cpp_lib_freestanding_numeric
#define __cpp_lib_freestanding_operator_new
#define __cpp_lib_freestanding_optional
#define __cpp_lib_freestanding_ranges
#define __cpp_lib_freestanding_ratio
#define __cpp_lib_freestanding_string_view
#define __cpp_lib_freestanding_tuple
#define __cpp_lib_freestanding_utility
#define __cpp_lib_freestanding_variant
#define __cpp_lib_fstream_native_handle
#define __cpp_lib_function_ref
#define __cpp_lib_gcd_lcm
#define __cpp_lib_generator
#define __cpp_lib_generic_associative_lookup
#define __cpp_lib_generic_unordered_lookup
// also in <unordered_map>, <unordered_set>
#define __cpp_lib_hardware_interference_size
#define __cpp_lib_has_unique_object_representations
#define __cpp_lib_hazard_pointer
#define __cpp_lib_hypot
#define __cpp_lib_incomplete_container_elements
// also in <forward_list>, <list>, <vector>
#define __cpp_lib_inplace_vector
#define __cpp_lib_int_pow2
#define __cpp_lib_integer_comparison_functions
#define __cpp_lib_integer_sequence
#define __cpp_lib_integral_constant_callable
#define __cpp_lib_interpolate
#define __cpp_lib_invoke
#define __cpp_lib_invoke_r
#define __cpp_lib_ios_noreplace
#define __cpp_lib_is_aggregate
#define __cpp_lib_is_constant_evaluated
#define __cpp_lib_is_final
#define __cpp_lib_is_implicit_lifetime
#define __cpp_lib_is_invocable
#define __cpp_lib_is_layout_compatible
#define __cpp_lib_is_nothrow_convertible
#define __cpp_lib_is_null_pointer
#define __cpp_lib_is_pointer_interconvertible
#define __cpp_lib_is_scoped_enum
#define __cpp_lib_is_swappable
#define __cpp_lib_is_virtual_base_of
#define __cpp_lib_is_within_lifetime
#define __cpp_lib_jthread
#define __cpp_lib_latch
#define __cpp_lib_launder
#define __cpp_lib_linalg
#define __cpp_lib_list_remove_return_type
#define __cpp_lib_logical_traits
#define __cpp_lib_make_from_tuple
#define __cpp_lib_make_reverse_iterator
#define __cpp_lib_make_unique
#define __cpp_lib_map_try_emplace
#define __cpp_lib_math_constants

§ 17.3.2

202306L // freestanding, also in <cwchar>
202306L
202311L // freestanding, also in <expected>
202306L // freestanding
202306L // freestanding, also in <functional>
202306L // freestanding, also in <iterator>
202311L // freestanding, also in <mdspan>
202306L // freestanding, also in <memory>
202311L // freestanding, also in <numeric>
see below // freestanding, also in <new>
202311L // freestanding, also in <optional>
202306L // freestanding, also in <ranges>
202306L // freestanding, also in <ratio>
202311L // freestanding, also in <string_view>
202306L // freestanding, also in <tuple>
202306L // freestanding, also in <utility>
202311L // freestanding, also in <variant>
202306L // also in <fstream>
202306L // also in <functional>
201606L // also in <numeric>
202207L // also in <generator>
201304L // also in <map>, <set>
201811L
201703L
201606L
202306L
201603L
201505L

//
//
//
//

freestanding, also in <new>
freestanding, also in <type_traits>
also in <hazard_pointer>
also in <cmath>

202406L
202002L
202002L
201304L
201304L
201902L
201411L
202106L
202207L
201703L
201811L
201402L
202302L
201703L
201907L
201806L
201309L
201907L
202011L
201603L
202406L
202306L
201911L
201907L
201606L
202311L
201806L
201510L
201606L
201402L
201304L
201411L
201907L

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also in <inplace_vector>
freestanding, also in <bit>
also in <utility>
freestanding, also in <utility>
freestanding, also in <type_traits>
also in <cmath>, <numeric>
freestanding, also in <functional>
freestanding, also in <functional>
also in <ios>
freestanding, also in <type_traits>
freestanding, also in <type_traits>
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freestanding, also in <type_traits>
freestanding, also in <type_traits>
also in <type_traits>
also in <type_traits>
also in <stop_token>, <thread>
also in <latch>
freestanding, also in <new>
also in <linalg>
also in <forward_list>, <list>
freestanding, also in <type_traits>
freestanding, also in <tuple>
freestanding, also in <iterator>
also in <memory>
also in <map>
also in <numbers>

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528


The macro `__cpp_lib_freestanding_operator_new` is defined to the integer literal `202306L` if all the default versions of the replaceable global allocation functions meet the requirements of a hosted implementation, and to the integer literal `0` otherwise (17.6.3).

**Recommended practice:** Freestanding implementations should only define a macro from `<version>` if the implementation provides the corresponding facility in its entirety.

### 17.3.3 Header `<limits>` synopsis

**[limits.syn]**  
// all freestanding
namespace std {
  // 17.3.4, enumeration float_round_style
  enum float_round_style;

  // 17.3.5, class template numeric_limits
  template<class T> class numeric_limits;
  template<class T> class numeric_limits<const T>;
  template<class T> class numeric_limits<volatile T>;
  template<class T> class numeric_limits<const volatile T>;
  template<> class numeric_limits<bool>;
  template<> class numeric_limits<char>;
  template<> class numeric_limits<signed char>;
  template<> class numeric_limits<unsigned char>;
  template<> class numeric_limits<char8_t>;
  template<> class numeric_limits<char16_t>;

  // 17.3.3 © ISO/IEC 530
template<> class numeric_limits<char32_t>;

namespace std {
enum float_round_style {
  round_indeterminate = -1,
  round_toward_zero = 0,
  round_to_nearest = 1,
  round_toward_infinity = 2,
  round_toward_neg_infinity = 3
};
}

17.3.4 Enum float_round_style

17.3.5 Class template numeric_limits

17.3.5.1 General

1 The rounding mode for floating-point arithmetic is characterized by the values:

(1.1) — round_indeterminate if the rounding style is indeterminable
(1.2) — round_toward_zero if the rounding style is toward zero
(1.3) — round_to_nearest if the rounding style is to the nearest representable value
(1.4) — round_toward_infinity if the rounding style is toward infinity
(1.5) — round_toward_neg_infinity if the rounding style is toward negative infinity

1 The numeric_limits class template provides a C++ program with information about various properties of the implementation’s representation of the arithmetic types.
static constexpr int max_exponent10 = 0;
static constexpr bool has_infinity = false;
static constexpr bool has_quiet_NaN = false;
static constexpr bool has_signaling_NaN = false;
static constexpr T infinity() noexcept { return T(); }
static constexpr T quiet_NaN() noexcept { return T(); }
static constexpr T signaling_NaN() noexcept { return T(); }
static constexpr T denorm_min() noexcept { return T(); }
static constexpr bool is_iec559 = false;
static constexpr bool is_bounded = false;
static constexpr bool is_modulo = false;
static constexpr bool traps = false;
static constexpr bool tinyness_before = false;
static constexpr float_round_style round_style = round_toward_zero;

For all members declared static constexpr in the numeric_limits template, specializations shall define these values in such a way that they are usable as constant expressions.

For the numeric_limits primary template, all data members are value-initialized and all member functions return a value-initialized object.

[Note 1: This means all members have zero or false values unless numeric_limits is specialized for a type. — end note]

Specializations shall be provided for each arithmetic type, both floating-point and integer, including bool. The member is_specialized shall be true for all such specializations of numeric_limits.

The value of each member of a specialization of numeric_limits on a cv-qualified type cv T shall be equal to the value of the corresponding member of the specialization on the unqualified type T.

Non-arithmetic standard types, such as complex<T> (28.4.3), shall not have specializations.

17.3.5.2 numeric_limits members

Each member function defined in this subclause is signal-safe (17.13.5).

[Note 1: The arithmetic specification described in ISO/IEC 10967-1:2012 is commonly termed LIA-1. — end note]

static constexpr T min() noexcept;
Minimum finite value.

For floating-point types with subnormal numbers, returns the minimum positive normalized value.
Meaningful for all specializations in which is_bounded != false, or is_bounded == false && is_signed == false.

static constexpr T max() noexcept;
Maximum finite value.

Meaningful for all specializations in which is_bounded != false.

static constexpr T lowest() noexcept;
A finite value x such that there is no other finite value y where y < x.
Meaningful for all specializations in which is_bounded != false.

static constexpr int digits;
Number of radix digits that can be represented without change.

For integer types, the number of non-sign bits in the representation.

---

165) Equivalent to CHAR_MIN, SHRT_MIN, FLT_MIN, DBL_MIN, etc.

166) Equivalent to CHAR_MAX, SHRT_MAX, FLT_MAX, DBL_MAX, etc.

167) lowest() is necessary because not all floating-point representations have a smallest (most negative) value that is the negative of the largest (most positive) finite value.
For floating-point types, the number of radix digits in the significand.\textsuperscript{168}

```cpp
static constexpr int digits10;
```

Number of base 10 digits that can be represented without change.\textsuperscript{169}
Meaningful for all specializations in which is_bounded != false.

```cpp
static constexpr int max_digits10;
```

Number of base 10 digits required to ensure that values which differ are always differentiated.
Meaningful for all floating-point types.

```cpp
static constexpr bool is_signed;
```

true if the type is signed.
Meaningful for all specializations.

```cpp
static constexpr bool is_integer;
```

true if the type is integer.
Meaningful for all specializations.

```cpp
static constexpr bool is_exact;
```

true if the type uses an exact representation. All integer types are exact, but not all exact types are integer. For example, rational and fixed-exponent representations are exact but not integer.
Meaningful for all specializations.

```cpp
static constexpr int radix;
```

For floating-point types, specifies the base or radix of the exponent representation (often 2).\textsuperscript{170}
For integer types, specifies the base of the representation.\textsuperscript{171}
Meaningful for all specializations.

```cpp
static constexpr T epsilon() noexcept;
```

Machine epsilon: the difference between 1 and the least value greater than 1 that is representable.\textsuperscript{172}
Meaningful for all floating-point types.

```cpp
static constexpr T round_error() noexcept;
```

Measure of the maximum rounding error.\textsuperscript{173}

```cpp
static constexpr int min_exponent;
```

Minimum negative integer such that radix raised to the power of one less than that integer is a normalized floating-point number.\textsuperscript{174}
Meaningful for all floating-point types.

```cpp
static constexpr int min_exponent10;
```

Minimum negative integer such that 10 raised to that power is in the range of normalized floating-point numbers.\textsuperscript{175}
Meaningful for all floating-point types.

\textsuperscript{168} Equivalent to FLT_MANT_DIG, DBL_MANT_DIG, LDBL_MANT_DIG.
\textsuperscript{169} Equivalent to FLT_DIG, DBL_DIG, LDBL_DIG.
\textsuperscript{170} Equivalent to FLT_RADIX.
\textsuperscript{171} Distinguishes types with bases other than 2 (e.g., BCD).
\textsuperscript{172} Equivalent to FLT_EPSILON, DBL_EPSILON, LDBL_EPSILON.
\textsuperscript{173} Rounding error is described in ISO/IEC 10967-1:2012 Section 5.2.4 and Annex C Rationale Section C.5.2.4 — Rounding and rounding constants.
\textsuperscript{174} Equivalent to FLT_MIN_EXP, DBL_MIN_EXP, LDBL_MIN_EXP.
\textsuperscript{175} Equivalent to FLT_MIN_10_EXP, DBL_MIN_10_EXP, LDBL_MIN_10_EXP.
static constexpr int max_exponent;
   Maximum positive integer such that radix raised to the power one less than that integer is a representable finite floating-point number.\(^\text{176}\)
   Meaningful for all floating-point types.

static constexpr int max_exponent10;
   Maximum positive integer such that 10 raised to that power is in the range of representable finite floating-point numbers.\(^\text{177}\)
   Meaningful for all floating-point types.

static constexpr bool has_infinity;
   true if the type has a representation for positive infinity.
   Meaningful for all floating-point types.
   Shall be true for all specializations in which is_iec559 != false.

static constexpr bool has_quiet_NaN;
   true if the type has a representation for a quiet (non-signaling) “Not a Number”.\(^\text{178}\)
   Meaningful for all floating-point types.
   Shall be true for all specializations in which is_iec559 != false.

static constexpr bool has_signaling_NaN;
   true if the type has a representation for a signaling “Not a Number”.\(^\text{179}\)
   Meaningful for all floating-point types.
   Shall be true for all specializations in which is_iec559 != false.

static constexpr T infinity() noexcept;
   Representation of positive infinity, if available.\(^\text{180}\)
   Meaningful for all specializations for which has_infinity != false. Required in specializations for which is_iec559 != false.

static constexpr T quiet_NaN() noexcept;
   Representation of a quiet “Not a Number”, if available.\(^\text{181}\)
   Meaningful for all specializations for which has_quiet_NaN != false. Required in specializations for which is_iec559 != false.

static constexpr T signaling_NaN() noexcept;
   Representation of a signaling “Not a Number”, if available.\(^\text{182}\)
   Meaningful for all specializations for which has_signaling_NaN != false. Required in specializations for which is_iec559 != false.

static constexpr T denorm_min() noexcept;
   Minimum positive subnormal value, if available.\(^\text{183}\) Otherwise, minimum positive normalized value.
   Meaningful for all floating-point types.

static constexpr bool is_iec559;
   true if and only if the type adheres to ISO/IEC 60559.\(^\text{184}\)

\(^{176}\) Equivalent to FLT_MAX_EXP, DBL_MAX_EXP, LDBL_MAX_EXP.
\(^{177}\) Equivalent to FLT_MAX_10_EXP, DBL_MAX_10_EXP, LDBL_MAX_10_EXP.
\(^{178}\) Required by ISO/IEC 10967-1:2012.
\(^{179}\) Required by ISO/IEC 10967-1:2012.
\(^{180}\) Required by ISO/IEC 10967-1:2012.
\(^{181}\) Required by ISO/IEC 10967-1:2012.
\(^{182}\) Required by ISO/IEC 10967-1:2012.
\(^{183}\) Required by ISO/IEC 10967-1:2012.
\(^{184}\) ISO/IEC 60559:2020 is the same as IEEE 754-2019.
Meaningful for all floating-point types.

### static constexpr bool is_bounded;

`true` if the set of values representable by the type is finite.\(^{185}\)

### static constexpr bool is_modulo;

`true` if the type is modulo.\(^{186}\) A type is modulo if, for any operation involving `+`, `-`, or `*` on values of that type whose result would fall outside the range `[min(), max()]`, the value returned differs from the true value by an integer multiple of `max() - min() + 1`.

### Example 1: is_modulo is `false` for signed integer types (6.8.2) unless an implementation, as an extension to this document, defines signed integer overflow to wrap. — end example

### static constexpr bool traps;

`true` if, at the start of the program, there exists a value of the type that would cause an arithmetic operation using that value to trap.\(^{187}\)

### static constexpr bool tinyness_before;

`true` if tinyness is detected before rounding.\(^{188}\)

Meaningful for all floating-point types.

### static constexpr float_round_style round_style;

The rounding style for the type.\(^{189}\)

Meaningful for all floating-point types. Specializations for integer types shall return `round_toward_-zero`.

### 17.3.5.3 numeric_limits specializations

All members shall be provided for all specializations. However, many values are only required to be meaningful under certain conditions (for example, `epsilon()` is only meaningful if `is_integer` is `false`). Any value that is not “meaningful” shall be set to 0 or `false`.

### Example 1:

```cpp
namespace std {
    template<> class numeric_limits<float> {
        public:
            static constexpr bool is_specialized = true;

            static constexpr float min() noexcept { return 1.17549435E-38F; }
            static constexpr float max() noexcept { return 3.40282347E+38F; }
            static constexpr float lowest() noexcept { return -3.40282347E+38F; }
            static constexpr int digits = 24;
            static constexpr int digits10 = 6;
            static constexpr int max_digits10 = 9;
}
```

\(^{185}\) Required by ISO/IEC 10967-1:2012.

\(^{186}\) Required by ISO/IEC 10967-1:2012.


\(^{189}\) Equivalent to `FLT_ROUNDS`. Required by ISO/IEC 10967-1:2012.
static constexpr bool is_signed = true;
static constexpr bool is_integer = false;
static constexpr bool is_exact = false;
static constexpr int radix = 2;
static constexpr float epsilon() noexcept { return 1.19209290E-07F; }
static constexpr float round_error() noexcept { return 0.5F; }
static constexpr int min_exponent = -125;
static constexpr int min_exponent10 = -37;
static constexpr int max_exponent = +128;
static constexpr int max_exponent10 = +38;
static constexpr bool has_infinity = true;
static constexpr bool has_quiet_NaN = true;
static constexpr bool has_signaling_NaN = true;
static constexpr float infinity() noexcept { return 0; }
static constexpr float quiet_NaN() noexcept { return 0; }
static constexpr float signaling_NaN() noexcept { return 0; }
static constexpr float denorm_min() noexcept { return 0; }
static constexpr bool is_iec559 = true;
static constexpr bool is_bounded = true;
static constexpr bool is_modulo = false;
static constexpr bool traps = true;
static constexpr bool tinyness_before = true;
static constexpr float_round_style round_style = round_to_nearest;

namespace std {

template<> class numeric_limits<bool> {
public:
static constexpr bool is_specialized = true;
static constexpr bool min() noexcept { return false; }
static constexpr bool max() noexcept { return true; }
static constexpr bool lowest() noexcept { return false; }
static constexpr int digits = 1;
static constexpr int digits10 = 0;
static constexpr int max_digits10 = 0;
static constexpr bool is_signed = false;
static constexpr bool is_integer = true;
static constexpr bool is_exact = true;
static constexpr int radix = 2;
static constexpr float epsilon() noexcept { return 0; }
static constexpr float round_error() noexcept { return 0; }
static constexpr int min_exponent = 0;
static constexpr int min_exponent10 = 0;
static constexpr int max_exponent = 0;
static constexpr int max_exponent10 = 0;
static constexpr bool has_infinity = false;
static constexpr bool has_quiet_NaN = false;
static constexpr bool has_signaling_NaN = false;
static constexpr bool infinity() noexcept { return 0; }
static constexpr bool quiet_NaN() noexcept { return 0; }
static constexpr bool signaling_NaN() noexcept { return 0; }
};

— end example —

3 The specialization for bool shall be provided as follows:

namespace std {

template<> class numeric_limits<bool> {
public:
static constexpr bool is_specialized = true;
static constexpr bool min() noexcept { return false; }
static constexpr bool max() noexcept { return true; }
static constexpr bool lowest() noexcept { return false; }
static constexpr int digits = 1;
static constexpr int digits10 = 0;
static constexpr int max_digits10 = 0;
static constexpr bool is_signed = false;
static constexpr bool is_integer = true;
static constexpr bool is_exact = true;
static constexpr int radix = 2;
static constexpr float epsilon() noexcept { return 0; }
static constexpr float round_error() noexcept { return 0; }
static constexpr int min_exponent = 0;
static constexpr int min_exponent10 = 0;
static constexpr int max_exponent = 0;
static constexpr int max_exponent10 = 0;
static constexpr bool has_infinity = false;
static constexpr bool has_quiet_NaN = false;
static constexpr bool has_signaling_NaN = false;
static constexpr bool infinity() noexcept { return 0; }
static constexpr bool quiet_NaN() noexcept { return 0; }
static constexpr bool signaling_NaN() noexcept { return 0; }
};

§ 17.3.5.3

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536
static constexpr bool denorm_min() noexcept { return 0; }
static constexpr bool is_iec559 = false;
static constexpr bool is_bounded = true;
static constexpr bool is_modulo = false;
static constexpr bool traps = false;
static constexpr bool tinyness_before = false;
static constexpr float_round_style round_style = round_toward_zero;
};

17.3.6 Header <climits> synopsis
[climits.syn]

// all freestanding
#define CHAR_BIT see below
#define SCHAR_MIN see below
#define SCHAR_MAX see below
#define UCHAR_MAX see below
#define CHAR_MIN see below
#define CHAR_MAX see below
#define MB_LEN_MAX see below
#define SHRT_MIN see below
#define SHRT_MAX see below
#define USHRT_MAX see below
#define INT_MIN see below
#define INT_MAX see below
#define UINT_MAX see below
#define LONG_MIN see below
#define LONG_MAX see below
#define ULONG_MAX see below
#define LLONG_MIN see below
#define LLONG_MAX see below
#define ULLONG_MAX see below

The header <climits> defines all macros the same as the C standard library header <limits.h>.
[Note 1: Except for CHAR_BIT and MB_LEN_MAX, a macro referring to an integer type T defines a constant whose type is the promoted type of T (7.3.7). — end note]

See also: ISO/IEC 9899:2018, 5.2.4.2.1

17.3.7 Header <cfloat> synopsis
[cfloat.syn]

// all freestanding
#define FLT_ROUNDS see below
#define FLT_EVAL_METHOD see below
#define FLT_HAS_SUBNORM see below
#define DBL_HAS_SUBNORM see below
#define LDBL_HAS_SUBNORM see below
#define FLT_RADIX see below
#define FLT_MANT_DIG see below
#define DBL_MANT_DIG see below
#define LDBL_MANT_DIG see below
#define FLT_DECIMAL_DIG see below
#define DBL_DECIMAL_DIG see below
#define LDBL_DECIMAL_DIG see below
#define DECIMAL_DIG see below
#define FLT_DIG see below
#define DBL_DIG see below
#define LDBL_DIG see below
#define FLT_MIN_EXP see below
#define DBL_MIN_EXP see below
#define LDBL_MIN_EXP see below
#define FLT_MIN_10_EXP see below
#define DBL_MIN_10_EXP see below
#define LDBL_MIN_10_EXP see below

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The header `<cfloat>` defines all macros the same as the C standard library header `<float.h>`. See also: ISO/IEC 9899:2018, 5.2.4.2.2

17.4 Arithmetic types

17.4.1 Header `<cstdint>` synopsis

The header `<cstdint>` supplies integer types having specified widths, and macros that specify limits of integer types.

// all freestanding
namespace std {
    using int8_t = signed integer type; // optional
    using int16_t = signed integer type; // optional
    using int32_t = signed integer type; // optional
    using int64_t = signed integer type; // optional
    using int_fast8_t = signed integer type;
    using int_fast16_t = signed integer type;
    using int_fast32_t = signed integer type;
    using int_fast64_t = signed integer type;
    using int_fastN_t = see below; // optional
    using int_least8_t = signed integer type;
    using int_least16_t = signed integer type;
    using int_least32_t = signed integer type;
    using int_least64_t = signed integer type;
    using int_leastN_t = see below; // optional
    using intmax_t = signed integer type;
    using intptr_t = signed integer type; // optional
    using uint8_t = unsigned integer type; // optional
    using uint16_t = unsigned integer type; // optional
    using uint32_t = unsigned integer type; // optional
    using uint64_t = unsigned integer type; // optional
    using uint_N_t = see below; // optional
    using uint_fast8_t = unsigned integer type;
    using uint_fast16_t = unsigned integer type;
    using uint_fast32_t = unsigned integer type;
    using uint_fast64_t = unsigned integer type;
    using uint_fastN_t = see below; // optional
}
using uint_least8_t = unsigned integer type;
using uint_least16_t = unsigned integer type;
using uint_least32_t = unsigned integer type;
using uint_least64_t = see below; // optional
using uintmax_t = unsigned integer type;
using uintptr_t = unsigned integer type; // optional
}
#define INTN_MIN see below
#define INTN_MAX see below
#define UINTN_MAX see below
#define INT_FASTN_MIN see below
#define INT_FASTN_MAX see below
#define UINT_FASTN_MAX see below
#define INT_LEASTN_MIN see below
#define INT_LEASTN_MAX see below
#define UINT_LEASTN_MAX see below
#define INTMAX_MIN see below
#define INTMAX_MAX see below
#define UINTMAX_MAX see below
#define INTPTR_MIN see below // optional
#define INTPTR_MAX see below // optional
#define UINTPTR_MAX see below // optional
#define PTRDIFF_MIN see below
#define PTRDIFF_MAX see below
#define SIZE_MAX see below
#define SIG_ATOMIC_MIN see below
#define SIG_ATOMIC_MAX see below
#define WCHAR_MIN see below
#define WCHAR_MAX see below
#define WINT_MIN see below
#define WINT_MAX see below
#define INTN_C(value) see below
#define UINTN_C(value) see below
#define INTMAX_C(value) see below
#define UINTMAX_C(value) see below

The header defines all types and macros the same as the C standard library header <stdint.h>.

See also: ISO/IEC 9899:2018, 7.20

All types that use the placeholder \( N \) are optional when \( N \) is not 8, 16, 32, or 64. The exact-width types \( \text{int}_N \_t \) and \( \text{uint}_N \_t \) for \( N = 8, 16, 32, \) and 64 are also optional; however, if an implementation defines integer types with the corresponding width and no padding bits, it defines the corresponding typedef-names. Each of the macros listed in this subclause is defined if and only if the implementation defines the corresponding typedef-name.

[Note 1: The macros \( \text{INT}_N \_C \) and \( \text{UINT}_N \_C \) correspond to the typedef-names \( \text{int}_\text{least}_N \_t \) and \( \text{uint}_\text{least}_N \_t \), respectively. — end note]
namespace std {
    #if defined(__STDCPP_FLOAT16_T__)  
        using float16_t = implementation-defined;  // see 6.8.3  
    #endif
    #if defined(__STDCPP_FLOAT32_T__)  
        using float32_t = implementation-defined;  // see 6.8.3  
    #endif
    #if defined(__STDCPP_FLOAT64_T__)  
        using float64_t = implementation-defined;  // see 6.8.3  
    #endif
    #if defined(__STDCPP_FLOAT128_T__)  
        using float128_t = implementation-defined;  // see 6.8.3  
    #endif
    #if defined(__STDCPP_BFLOAT16_T__)  
        using bfloat16_t = implementation-defined;  // see 6.8.3  
    #endif
}

17.5 Startup and termination

[Note 1: The header `<cstdlib>` (17.2.2) declares the functions described in this subclause. — end note]

[[noreturn]] void _Exit(int status) noexcept;

Effects: This function has the semantics specified in the C standard library.

Remarks: The program is terminated without executing destructors for objects of automatic, thread, or static storage duration and without calling functions passed to `atexit()` (6.9.3.4). The function `_Exit` is signal-safe (17.13.5).

[[noreturn]] void abort() noexcept;

Effects: This function has the semantics specified in the C standard library.

Remarks: The program is terminated without executing destructors for objects of automatic, thread, or static storage duration and without calling functions passed to `atexit()` (6.9.3.4). The function `abort` is signal-safe (17.13.5).

int atexit(c-atexit-handler* f) noexcept;
int atexit(atexit-handler* f) noexcept;

Effects: The `atexit()` functions register the function pointed to by `f` to be called without arguments at normal program termination. It is unspecified whether a call to `atexit()` that does not happen before (6.9.2) a call to `exit()` will succeed.

[Note 2: The `atexit()` functions do not introduce a data race (16.4.6.10). — end note]

Implementation limits: The implementation shall support the registration of at least 32 functions.

Returns: The `atexit()` function returns zero if the registration succeeds, nonzero if it fails.

[[noreturn]] void exit(int status);

Effects:

(9.1) First, objects with thread storage duration and associated with the current thread are destroyed. Next, objects with static storage duration are destroyed and functions registered by calling `atexit` are called. See 6.9.3.4 for the order of destructions and calls. (Objects with automatic storage duration are not destroyed as a result of calling `exit()`.)

If a registered function invoked by `exit` exits via an exception, the function `std::terminate` is invoked (14.6.2).

(9.2) Next, all open C streams (as mediated by the function signatures declared in `<cstdio>` (31.13.1)) with unwritten buffered data are flushed, all open C streams are closed, and all files created by calling `tmpfile()` are removed.

190) A function is called for every time it is registered.
191) Objects with automatic storage duration are all destroyed in a program whose `main` function (6.9.3.1) contains no objects with automatic storage duration and executes the call to `exit()`. Control can be transferred directly to such a `main` function by throwing an exception that is caught in `main`. 

§ 17.5 ©ISO/IEC 540
Finally, control is returned to the host environment. If `status` is zero or `EXIT_SUCCESS`, an implementation-defined form of the status `successful termination` is returned. If `status` is `EXIT_FAILURE`, an implementation-defined form of the status `unsuccessful termination` is returned. Otherwise the status returned is implementation-defined.\(^{192}\)

\[
\text{int at_quick_exit(c-atesit-handler* f) noexcept; \int at_quick_exit(atexit-handler* f) noexcept;}
\]

**Effects:** The `at_quick_exit()` functions register the function pointed to by `f` to be called without arguments when `quick_exit` is called. It is unspecified whether a call to `at_quick_exit()` that does not happen before (6.9.2) all calls to `quick_exit` will succeed.

\[\text{[Note 3: The at_quick_exit() functions do not introduce a data race (16.4.6.10). — end note]}\]

\[\text{[Note 4: The order of registration could be indeterminate if at_quick_exit was called from more than one thread. — end note]}\]

\[\text{[Note 5: The at_quick_exit registrations are distinct from the atexit registrations, and applications might need to call both registration functions with the same argument. — end note]}\]

**Implementation limits:** The implementation shall support the registration of at least 32 functions.

**Returns:** Zero if the registration succeeds, nonzero if it fails.

\[
\text{[noreturn] void quick_exit(int status) noexcept;}
\]

**Effects:** Functions registered by calls to `at_quick_exit` are called in the reverse order of their registration, except that a function shall be called after any previously registered functions that had already been called at the time it was registered. Objects shall not be destroyed as a result of calling `quick_exit`. If a registered function invoked by `quick_exit` exits via an exception, the function `std::terminate` is invoked (14.6.2).

\[\text{[Note 6: A function registered via at_quick_exit is invoked by the thread that calls quick_exit, which can be a different thread than the one that registered it, so registered functions cannot rely on the identity of objects with thread storage duration. — end note]}\]

After calling registered functions, `quick_exit` shall call `_Exit(status)`.

**Remarks:** The function `quick_exit` is signal-safe (17.13.5) when the functions registered with `at_­quick_exit` are.

**See also:** ISO/IEC 9899:2018, 7.22.4

---

1 The header `<new>` defines several functions that manage the allocation of dynamic storage in a program. It also defines components for reporting storage management errors.

### 17.6 Dynamic memory management

#### 17.6.1 General

The header `<new>` defines several functions that manage the allocation of dynamic storage in a program. It also defines components for reporting storage management errors.

### 17.6.2 Header `<new>` synopsis

```cpp
namespace std {
  // 17.6.4, storage allocation errors
  class bad_alloc;
  class bad_array_new_length;

  struct destroying_delete_t {
    explicit destroying_delete_t() = default;
  };
  inline constexpr destroying_delete_t destroying_delete{};

  // global operator new control
  enum class align_val_t : size_t {};

  struct nothrow_t {
    explicit nothrow_t() = default;
  };// extern const nothrow_t nothrow;
```

\(^{192}\) The macros `EXIT_FAILURE` and `EXIT_SUCCESS` are defined in `<cstdlib>` (17.2.2).
using new_handler = void (*)();
new_handler get_new_handler() noexcept;
new_handler set_new_handler(new_handler new_p) noexcept;

// 17.6.5, pointer optimization barrier
template<class T> [[nodiscard]] constexpr T* launder(T* p) noexcept;

// 17.6.6, hardware interference size
inline constexpr size_t hardware_destructive_interference_size = implementation-defined;
inline constexpr size_t hardware_constructive_interference_size = implementation-defined;

// 17.6.3, storage allocation and deallocation
[[nodiscard]] void* operator new(std::size_t size);
[[nodiscard]] void* operator new(std::size_t size, std::align_val_t alignment);
[[nodiscard]] void* operator new(std::size_t size, const std::nothrow_t&) noexcept;
[[nodiscard]] void* operator new(std::size_t size, std::align_val_t alignment,
const std::nothrow_t&) noexcept;
void operator delete(void* ptr) noexcept;
void operator delete(void* ptr, std::size_t size) noexcept;
void operator delete(void* ptr, std::align_val_t alignment) noexcept;
void operator delete(void* ptr, std::size_t size, std::align_val_t alignment) noexcept;
void operator delete(void* ptr, const std::nothrow_t&) noexcept;
void operator delete(void* ptr, std::align_val_t alignment, const std::nothrow_t&) noexcept;

17.6.3 Storage allocation and deallocation

17.6.3.1 General

1 Except where otherwise specified, the provisions of 6.7.5.5 apply to the library versions of operator new and operator delete. If the value of an alignment argument passed to any of these functions is not a valid alignment value, the behavior is undefined.

2 On freestanding implementations, it is implementation-defined whether the default versions of the replaceable global allocation functions satisfy the required behaviors described in 17.6.3.2 and 17.6.3.3.

[Note 1: A freestanding implementation’s default versions of the replaceable global allocation functions can cause undefined behavior when invoked. During constant evaluation, the behaviors of those default versions are irrelevant, as those calls are omitted (7.6.2.8). — end note]

Recommended practice: If any of the default versions of the replaceable global allocation functions meet the requirements of a hosted implementation, they all should.

17.6.3.2 Single-object forms

[[nodiscard]] void* operator new(std::size_t size);

§ 17.6.3.2 ©ISO/IEC
[[nodiscard]] void* operator new(std::size_t size, std::align_val_t alignment);

**Effects:** The allocation functions (6.7.5.5.2) called by a *new-expression* (7.6.2.8) to allocate *size* bytes of storage. The second form is called for a type with new-extended alignment, and the first form is called otherwise.

**Replaceable:** A C++ program may define functions with either of these function signatures, and thereby displace the default versions defined by the C++ standard library.

**Required behavior:** Return a non-null pointer to suitably aligned storage (6.7.5.5), or else throw a bad_alloc exception. This requirement is binding on any replacement versions of these functions.

**Default behavior:**

(4.1) — Executes a loop: Within the loop, the function first attempts to allocate the requested storage. Whether the attempt involves a call to the C standard library functions malloc or aligned_alloc is unspecified.

(4.2) — Returns a pointer to the allocated storage if the attempt is successful. Otherwise, if the current new_handler (17.6.4.5) is a null pointer value, throws bad_alloc.

(4.3) — Otherwise, the function calls the current new_handler function (17.6.4.3). If the called function returns, the loop repeats.

(4.4) — The loop terminates when an attempt to allocate the requested storage is successful or when a called new_handler function does not return.

[[nodiscard]] void* operator new(std::size_t size, const std::nothrow_t&) noexcept;
[[nodiscard]] void* operator new(std::size_t size, std::align_val_t alignment, const std::nothrow_t&) noexcept;

**Effects:** Same as above, except that these are called by a placement version of a *new-expression* when a C++ program prefers a null pointer result as an error indication, instead of a bad_alloc exception.

**Replaceable:** A C++ program may define functions with any of these function signatures, and thereby displace the default versions defined by the C++ standard library.

**Required behavior:** Return a non-null pointer to suitably aligned storage (6.7.5.5), or else return a null pointer. Each of these nothrow versions of operator new returns a pointer obtained as if acquired from the (possibly replaced) corresponding non-placement function. This requirement is binding on any replacement versions of these functions.

**Default behavior:** Calls operator new(size), or operator new(size, alignment), respectively. If the call returns normally, returns the result of that call. Otherwise, returns a null pointer.

[Example 1:]

```c++
T* p1 = new T; // throws bad_alloc if it fails
T* p2 = new(nothrow) T; // returns nullptr if it fails
```

— end example]

void operator delete(void* ptr) noexcept;
void operator delete(void* ptr, std::size_t size) noexcept;
void operator delete(void* ptr, std::align_val_t alignment) noexcept;
void operator delete(void* ptr, std::size_t size, std::align_val_t alignment) noexcept;

**Preconditions:** *ptr* is a null pointer or its value represents the address of a block of memory allocated by an earlier call to a (possibly replaced) operator new(std::size_t) or operator new(std::size_t, std::align_val_t) which has not been invalidated by an intervening call to operator delete.

If the alignment parameter is not present, *ptr* was returned by an allocation function without an alignment parameter. If present, the alignment argument is equal to the alignment argument passed to the allocation function that returned *ptr*. If present, the size argument is equal to the size argument passed to the allocation function that returned *ptr*.

**Effects:** The deallocation functions (6.7.5.5.3) called by a delete-expression (7.6.2.9) to render the value of *ptr* invalid.

**Replaceable:** A C++ program may define functions with any of these function signatures, and thereby displace the default versions defined by the C++ standard library. If a function without a size parameter is defined, the program should also define the corresponding function with a size parameter. If a
function with a size parameter is defined, the program shall also define the corresponding version without the size parameter.

[Note 1: The default behavior below might change in the future, which will require replacing both deallocation functions when replacing the allocation function. —end note]

**Required behavior**: A call to an operator delete with a size parameter may be changed to a call to the corresponding operator delete without a size parameter, without affecting memory allocation. [Note 2: A conforming implementation is for operator delete(void* ptr, std::size_t size) to simply call operator delete(ptr). —end note]

**Default behavior**: The functions that have a size parameter forward their other parameters to the corresponding function without a size parameter. [Note 3: See the note in the above Replaceable: paragraph. —end note]

**Remarks**: It is unspecified under what conditions part or all of such reclaimed storage will be allocated by subsequent calls to operator new or any of aligned_alloc, malloc, malloc, or realloc, declared in <cstdlib> (17.2.2).

```
void operator delete(void* ptr, const std::nothrow_t&) noexcept;
void operator delete(void* ptr, std::align_val_t alignment, const std::nothrow_t&) noexcept;
```

**Preconditions**: ptr is a null pointer or its value represents the address of a block of memory allocated by an earlier call to a (possibly replaced) operator new(std::size_t) or operator new(std::size_t, std::align_val_t) which has not been invalidated by an intervening call to operator delete.

If the alignment parameter is not present, ptr was returned by an allocation function without an alignment parameter. If present, the alignment argument is equal to the alignment argument passed to the allocation function that returned ptr.

**Effects**: The deallocation functions (6.7.5.5.3) called by the implementation to render the value of ptr invalid when the constructor invoked from a nothrow placement version of the new-expression throws an exception.

**Replaceable**: A C++ program may define functions with either of these function signatures, and thereby displace the default versions defined by the C++ standard library.

**Default behavior**: Calls operator delete(ptr), or operator delete(ptr, alignment), respectively.

### 17.6.3.3 Array forms

[[nodiscard]] void* operator new[](std::size_t size);
[[nodiscard]] void* operator new[](std::size_t size, std::align_val_t alignment);

**Effects**: The allocation functions (6.7.5.5.2) called by the array form of a new-expression (7.6.2.8) to allocate size bytes of storage. The second form is called for a type with new-extended alignment, and the first form is called otherwise.193

**Replaceable**: A C++ program may define functions with either of these function signatures, and thereby displace the default versions defined by the C++ standard library.

**Required behavior**: Same as for the corresponding single-object forms. This requirement is binding on any replacement versions of these functions.

**Default behavior**: Returns operator new(size), or operator new(size, alignment), respectively.

```
[[nodiscard]] void* operator new[](std::size_t size, const std::nothrow_t&) noexcept;
[[nodiscard]] void* operator new[](std::size_t size, std::align_val_t alignment, const std::nothrow_t&) noexcept;
```

**Effects**: Same as above, except that these are called by a placement version of a new-expression when a C++ program prefers a null pointer result as an error indication, instead of a bad_alloc exception.

193) It is not the direct responsibility of operator new[] or operator delete[] to note the repetition count or element size of the array. Those operations are performed elsewhere in the array new and delete expressions. The array new expression, can, however, increase the size argument to operator new[] to obtain space to store supplemental information.
Replaceable: A C++ program may define functions with either of these function signatures, and thereby displace the default versions defined by the C++ standard library.

Required behavior: Return a non-null pointer to suitably aligned storage (6.7.5.5), or else return a null pointer. Each of these nothrow versions of `operator new[]` returns a pointer obtained as if acquired from the (possibly replaced) corresponding non-placement function. This requirement is binding on any replacement versions of these functions.

Default behavior: Calls `operator new[](size)`, or `operator new[](size, alignment)`, respectively. If the call returns normally, returns the result of that call. Otherwise, returns a null pointer.

```cpp
void operator delete[](void* ptr) noexcept;
void operator delete[](void* ptr, std::size_t size) noexcept;
void operator delete[](void* ptr, std::align_val_t alignment) noexcept;
void operator delete[](void* ptr, std::size_t size, std::align_val_t alignment) noexcept;
```

Preconditions: `ptr` is a null pointer or its value represents the address of a block of memory allocated by an earlier call to a (possibly replaced) `operator new[]`(std::size_t) or `operator new[]`(std::size_t, std::align_val_t) which has not been invalidated by an intervening call to `operator delete[]`.

If the `alignment` parameter is not present, `ptr` was returned by an allocation function without an `alignment` parameter. If present, the `alignment` argument is equal to the `alignment` argument passed to the allocation function that returned `ptr`. If present, the `size` argument is equal to the `size` argument passed to the allocation function that returned `ptr`.

Effects: The deallocation functions (6.7.5.5.3) called by the array form of a `delete-expression` to render the value of `ptr` invalid.

Replaceable: A C++ program may define functions with any of these function signatures, and thereby displace the default versions defined by the C++ standard library. If a function without a `size` parameter is defined, the program should also define the corresponding function with a `size` parameter. If a function with a `size` parameter is defined, the program shall also define the corresponding version without the `size` parameter.

[Note 1: The default behavior below might change in the future, which will require replacing both deallocation functions when replacing the allocation function. —end note]

Required behavior: A call to an `operator delete[]` with a `size` parameter may be changed to a call to the corresponding `operator delete[]` without a `size` parameter, without affecting memory allocation.

[Note 2: A conforming implementation is for `operator delete[](void* ptr, std::size_t size)` to simply call `operator delete[](ptr)`. —end note]

Default behavior: The functions that have a `size` parameter forward their other parameters to the corresponding function without a `size` parameter. The functions that do not have a `size` parameter forward their parameters to the corresponding `operator delete` (single-object) function.

```cpp
void operator delete[](void* ptr, const std::nothrow_t&) noexcept;
void operator delete[](void* ptr, std::align_val_t alignment, const std::nothrow_t&) noexcept;
```

Preconditions: `ptr` is a null pointer or its value represents the address of a block of memory allocated by an earlier call to a (possibly replaced) `operator new[]`(std::size_t) or `operator new[]`(std::size_t, std::align_val_t) which has not been invalidated by an intervening call to `operator delete[]`.

If the `alignment` parameter is not present, `ptr` was returned by an allocation function without an `alignment` parameter. If present, the `alignment` argument is equal to the `alignment` argument passed to the allocation function that returned `ptr`.

Effects: The deallocation functions (6.7.5.5.3) called by the implementation to render the value of `ptr` invalid when the constructor invoked from a nothrow placement version of the array `new-expression` throws an exception.

Replaceable: A C++ program may define functions with either of these function signatures, and thereby displace the default versions defined by the C++ standard library.

Default behavior: Calls `operator delete[](ptr)`, or `operator delete[](ptr, alignment)`, respectively.
17.6.3.4 Non-allocating forms

These functions are reserved; a C++ program may not define functions that displace the versions in the C++ standard library (16.4.5). The provisions of 6.7.5.5 do not apply to these reserved placement forms of operator new and operator delete.

[[nodiscard]] constexpr void* operator new(std::size_t size, void* ptr) noexcept;

Returns: ptr.

Remarks: Intentionally performs no other action.

[Example 1: This can be useful for constructing an object at a known address:

void* place = operator new(sizeof(Something));
Something* p = new (place) Something();
—end example]

[[nodiscard]] constexpr void* operator new[](std::size_t size, void* ptr) noexcept;

Returns: ptr.

Remarks: Intentionally performs no other action.

void operator delete(void* ptr, void*) noexcept;

Effects: Intentionally performs no action.

Remarks: Default function called when any part of the initialization in a placement new-expression that invokes the library’s non-array placement operator new terminates by throwing an exception (7.6.2.8).

void operator delete[](void* ptr, void*) noexcept;

Effects: Intentionally performs no action.

Remarks: Default function called when any part of the initialization in a placement new-expression that invokes the library’s array placement operator new terminates by throwing an exception (7.6.2.8).

17.6.3.5 Data races

For purposes of determining the existence of data races, the library versions of operator new, user replacement versions of global operator new, the C standard library functions aligned_alloc, calloc, and malloc, the library versions of operator delete, user replacement versions of operator delete, the C standard library function free, and the C standard library function realloc shall not introduce a data race (16.4.6.10). Calls to these functions that allocate or deallocate a particular unit of storage shall occur in a single total order, and each such deallocation call shall happen before (6.9.2) the next allocation (if any) in this order.

17.6.4 Storage allocation errors

17.6.4.1 Class bad_alloc

namespace std {

    class bad_alloc : public exception {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    };
}

The class bad_alloc defines the type of objects thrown as exceptions by the implementation to report a failure to allocate storage.

const char* what() const noexcept override;

Returns: An implementation-defined NTBS.

17.6.4.2 Class bad_array_new_length

namespace std {

    class bad_array_new_length : public bad_alloc {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    };
}
The class `bad_array_new_length` defines the type of objects thrown as exceptions by the implementation to report an attempt to allocate an array of size less than zero or greater than an implementation-defined limit (7.6.2.8).

```cpp
const char* what() const noexcept override;
```

Returns: An implementation-defined NTBS.

### 17.6.4.3 Type `new_handler` [new.handler]

```cpp
using new_handler = void (*)();
```

The type of a `handler function` to be called by `operator new()` or `operator new[]()` (17.6.3) when they cannot satisfy a request for additional storage.

**Required behavior:** A `new_handler` shall perform one of the following:

1. **(2.1)** make more storage available for allocation and then return;
2. **(2.2)** throw an exception of type `bad_alloc` or a class derived from `bad_alloc`;
3. **(2.3)** terminate execution of the program without returning to the caller.

### 17.6.4.4 `set_new_handler` [set.new.handler]

```cpp
new_handler set_new_handler(new_handler new_p) noexcept;
```

**Effects:** Establishes the function designated by `new_p` as the current `new_handler`.

**Returns:** The previous `new_handler`.

**Remarks:** The initial `new_handler` is a null pointer.

### 17.6.4.5 `get_new_handler` [get.new.handler]

```cpp
new_handler get_new_handler() noexcept;
```

**Returns:** The current `new_handler`.

[Note 1: This can be a null pointer value. — end note]

### 17.6.5 Pointer optimization barrier [ptr.launder]

```cpp
template<class T> [[nodiscard]] constexpr T* launder(T* p) noexcept;
```

**Mandates:** `!is_function_v<T> && !is_void_v<T>` is true.

**Preconditions:** `p` represents the address \( A \) of a byte in memory. An object \( X \) that is within its lifetime (6.7.3) and whose type is similar (7.3.6) to \( T \) is located at the address \( A \). All bytes of storage that would be reachable through (6.8.4) the result are reachable through \( p \).

**Returns:** A value of type \( T* \) that points to \( X \).

**Remarks:** An invocation of this function may be used in a core constant expression if and only if the (converted) value of its argument may be used in place of the function invocation.

[Note 1: If a new object is created in storage occupied by an existing object of the same type, a pointer to the original object can be used to refer to the new object unless its complete object is a const object or it is a base class subobject; in the latter cases, this function can be used to obtain a usable pointer to the new object. See 6.7.3. — end note]

**Example 1:**

```cpp
struct X { int n; };
const X *p = new const X{3};
const int a = p->n;
new (const_cast<X*>(p)) const X{5}; // p does not point to new object (6.7.3) because its type is const
const int b = p->n; // undefined behavior
const int c = std::launder(p)->n; // OK
— end example
```
17.6.6 Hardware interference size

inline constexpr size_t hardware_destructive_interference_size = implementation-defined;

This number is the minimum recommended offset between two concurrently-accessed objects to avoid additional performance degradation due to contention introduced by the implementation. It shall be at least alignof(max_align_t).

[Example 1:
struct keep_apart {
    alignas(hardware_destructive_interference_size) atomic<int> cat;
    alignas(hardware_destructive_interference_size) atomic<int> dog;
};
— end example]

inline constexpr size_t hardware_constructive_interference_size = implementation-defined;

This number is the maximum recommended size of contiguous memory occupied by two objects accessed with temporal locality by concurrent threads. It shall be at least alignof(max_align_t).

[Example 2:
struct together {
    atomic<int> dog;
    int puppy;
};
struct kennel {
    // Other data members...
    alignas(sizeof(together)) together pack;
    // Other data members...
};
static_assert(sizeof(together) <= hardware_constructive_interference_size);
— end example]

17.7 Type identification

17.7.1 General

The header <typeinfo> defines a type associated with type information generated by the implementation. It also defines two types for reporting dynamic type identification errors.

17.7.2 Header <typeinfo> synopsis

// all freestanding
namespace std {
    class type_info;
    class bad_cast;
    class bad_typeid;
}

17.7.3 Class type_info

namespace std {
    class type_info {
    public:
    virtual ~type_info();
    constexpr bool operator==(const type_info& rhs) const noexcept;
    bool before(const type_info& rhs) const noexcept;
    size_t hash_code() const noexcept;
    const char* name() const noexcept;
    type_info(const type_info&) = delete; // cannot be copied
    type_info& operator=(const type_info&) = delete; // cannot be copied
    
    
    
};
}

The class type_info describes type information generated by the implementation (7.6.1.8). Objects of this class effectively store a pointer to a name for the type, and an encoded value suitable for comparing two types
for equality or collating order. The names, encoding rule, and collating sequence for types are all unspecified and may differ between programs.

```cpp
constexpr bool operator==(const type_info& rhs) const noexcept;
```

*Effects:* Compares the current object with `rhs`.

*Returns:* `true` if the two values describe the same type.

```cpp
bool before(const type_info& rhs) const noexcept;
```

*Effects:* Compares the current object with `rhs`.

*Returns:* `true` if `*this` precedes `rhs` in the implementation’s collation order.

```cpp
size_t hash_code() const noexcept;
```

*Returns:* An unspecified value, except that within a single execution of the program, it shall return the same value for any two `type_info` objects which compare equal.

*Remarks:* An implementation should return different values for two `type_info` objects which do not compare equal.

```cpp
const char* name() const noexcept;
```

*Returns:* An implementation-defined `ntbs`.

*Remarks:* The message may be a null-terminated multibyte string (16.3.3.4.3), suitable for conversion and display as a `wstring` (23.4, 30.4.2.5).

17.7.4 Class `bad_cast`  

```cpp
namespace std {
    class bad_cast : public exception {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    };
}
```

The class `bad_cast` defines the type of objects thrown as exceptions by the implementation to report the execution of an invalid `dynamic_cast` expression (7.6.1.7).

```cpp
const char* what() const noexcept override;
```

*Returns:* An implementation-defined `ntbs`.

17.7.5 Class `bad_typeid`  

```cpp
namespace std {
    class bad_typeid : public exception {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    };
}
```

The class `bad_typeid` defines the type of objects thrown as exceptions by the implementation to report a null pointer in a `typeid` expression (7.6.1.8).

```cpp
const char* what() const noexcept override;
```

*Returns:* An implementation-defined `ntbs`.

17.8 Source location  

17.8.1 Header `<source_location>` synopsis  

The header `<source_location>` defines the class `source_location` that provides a means to obtain source location information.
// all freestanding
namespace std {
    struct source_location;
}

17.8.2 Class source_location

17.8.2.1 General

namespace std {
    struct source_location {
        // source location construction
        static consteval source_location current() noexcept;
        constexpr source_location() noexcept;

        // source location field access
        constexpr uint_least32_t line() const noexcept;
        constexpr uint_least32_t column() const noexcept;
        constexpr const char* file_name() const noexcept;
        constexpr const char* function_name() const noexcept;

        private:
            uint_least32_t line_;    // exposition only
            uint_least32_t column_;  // exposition only
            const char* file_name_;  // exposition only
            const char* function_name_;  // exposition only
    };
}

1 The type source_location meets the Cpp17DefaultConstructible, Cpp17CopyConstructible, Cpp17CopyAssignable, Cpp17Swappable, and Cpp17Destructible requirements (16.4.4.2, 16.4.4.3). All of the following conditions are true:

(1.1) is_nothrow_move_constructible_v<source_location>
(1.2) is_nothrow_move_assignable_v<source_location>
(1.3) is_nothrow_swappable_v<source_location>

[Note 1: The intent of source_location is to have a small size and efficient copying. It is unspecified whether the copy/move constructors and the copy/move assignment operators are trivial and/or constexpr. — end note]

2 The data members file_name_ and function_name_ always each refer to an NTBS.

3 The copy/move constructors and the copy/move assignment operators of source_location meet the following postconditions: Given two objects lhs and rhs of type source_location, where lhs is a copy/move result of rhs, and where rhs_p is a value denoting the state of rhs before the corresponding copy/move operation, then each of the following conditions is true:

(3.1) strcmp(lhs.file_name(), rhs_p.file_name()) == 0
(3.2) strcmp(lhs.function_name(), rhs_p.function_name()) == 0
(3.3) lhs.line() == rhs_p.line()
(3.4) lhs.column() == rhs_p.column()

17.8.2.2 Creation

static consteval source_location current() noexcept;

Returns:

(1.1) When invoked by a function call whose postfix-expression is a (possibly parenthesized) id-expression naming current, returns a source_location with an implementation-defined value. The value should be affected by #line (15.7) in the same manner as for __LINE__ and __FILE__. The values of the exposition-only data members of the returned source_location object are indicated in Table 43.

(1.2) Otherwise, when invoked in some other way, returns a source_location whose data members are initialized with valid but unspecified values.
Table 43 — Value of object returned by \texttt{current}  

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{line_}</td>
<td>A presumed line number (15.11). Line numbers are presumed to be 1-indexed; however, an implementation is encouraged to use 0 when the line number is unknown.</td>
</tr>
<tr>
<td>\texttt{column_}</td>
<td>An implementation-defined value denoting some offset from the start of the line denoted by \texttt{line_}. Column numbers are presumed to be 1-indexed; however, an implementation is encouraged to use 0 when the column number is unknown.</td>
</tr>
<tr>
<td>\texttt{file_name_}</td>
<td>A presumed name of the current source file (15.11) as an NTBS.</td>
</tr>
<tr>
<td>\texttt{function_name_}</td>
<td>A name of the current function such as in \texttt{<strong>func</strong>} (9.5.1) if any, an empty string otherwise.</td>
</tr>
</tbody>
</table>

Remarks: Any call to \texttt{current} that appears as a default member initializer (11.4), or as a subexpression thereof, should correspond to the location of the constructor definition or aggregate initialization that uses the default member initializer. Any call to \texttt{current} that appears as a default argument (9.3.4.7), or as a subexpression thereof, should correspond to the location of the invocation of the function that uses the default argument (7.6.1.3).

Example 1:

```c
struct s {
    source_location member = source_location::current();
    int other_member;
    s(source_location loc = source_location::current()) :
        member(loc) // values of \texttt{member} refer to the location of the calling function (9.3.4.7)
    {}
    s(int blather) :
        other_member(blather) // values of \texttt{member} refer to this location
    {}
    s(double) // values of \texttt{member} refer to this location
    {}
};
void f(source_location a = source_location::current()) {
    source_location b = source_location::current(); // values in \texttt{b} refer to this line
}
void g() {
    f(); // \texttt{f}'s first argument corresponds to this line of code
    source_location c = source_location::current();
    f(c); // \texttt{f}'s first argument gets the same values as \texttt{c}, above
}
@end example
```

Effects: The data members are initialized with valid but unspecified values.

17.8.2.3 Observers

```c
constexpr source_location() noexcept;
```

Returns: \texttt{line_}.

```c
constexpr uint_least32_t line() const noexcept;
```

Returns: \texttt{column_}.

§ 17.8.2.3
constexpr const char* file_name() const noexcept;

>Returns: file_name_.

constexpr const char* function_name() const noexcept;

>Returns: function_name_.

17.9 Exception handling

17.9.1 General

The header <exception> defines several types and functions related to the handling of exceptions in a C++ program.

17.9.2 Header <exception> synopsis

namespace std {
  class exception;
  class bad_exception;
  class nested_exception;

  using terminate_handler = void (*)();
  terminate_handler get_terminate() noexcept;
  terminate_handler set_terminate(terminate_handler f) noexcept;
  [[noreturn]] void terminate() noexcept;
  int uncaught_exceptions() noexcept;
  using exception_ptr = unspecified;
  exception_ptr current_exception() noexcept;
  [[noreturn]] void rethrow_exception(exception_ptr p);
  template<class E> exception_ptr make_exception_ptr(E e) noexcept;
  template<class T> [[noreturn]] void throw_with_nested(T&& t);
  template<class E> void rethrow_if_nested(const E& e);
}

17.9.3 Class exception

namespace std {
  class exception {
    public:
      exception() noexcept;
      exception(const exception&) noexcept;
      exception& operator=(const exception&) noexcept;
      virtual ~exception();
      virtual const char* what() const noexcept;
  };
}

1 The class exception defines the base class for the types of objects thrown as exceptions by C++ standard library components, and certain expressions, to report errors detected during program execution.

2 Except where explicitly specified otherwise, each standard library class T that derives from class exception has the following publicly accessible member functions, each of them having a non-throwing exception specification (14.5): (2.1) — default constructor (unless the class synopsis shows other constructors) (2.2) — copy constructor (2.3) — copy assignment operator

The copy constructor and the copy assignment operator meet the following postcondition: If two objects lhs and rhs both have dynamic type T and lhs is a copy of rhs, then strcmp(lhs.what(), rhs.what()) is equal to 0. The what() member function of each such T satisfies the constraints specified for exception::what() (see below).
exception(const exception& rhs) noexcept;
exception& operator=(const exception& rhs) noexcept;

Postconditions: If *this and rhs both have dynamic type exception then the value of the expression strcmp(what(), rhs.what()) shall equal 0.

virtual ~exception();

Effects: Destroys an object of class exception.

virtual const char* what() const noexcept;

Returns: An implementation-defined NTBS.

Remarks: The message may be a null-terminated multibyte string (16.3.3.4.3), suitable for conversion and display as a wstring (23.4, 30.4.2.5). The return value remains valid until the exception object from which it is obtained is destroyed or a non-const member function of the exception object is called.

17.9.4 Class bad_exception

namespace std {
    class bad_exception : public exception {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    };
}

The class bad_exception defines the type of the object referenced by the exception_ptr returned from a call to current_exception (17.9.7) when the currently active exception object fails to copy.

const char* what() const noexcept override;

Returns: An implementation-defined NTBS.

17.9.5 Abnormal termination

17.9.5.1 Type terminate_handler

using terminate_handler = void (*)();

The type of a handler function to be invoked by terminate when terminating exception processing.

Required behavior: A terminate_handler shall terminate execution of the program without returning to the caller.

Default behavior: The implementation’s default terminate_handler calls abort().

17.9.5.2 set_terminate

terminate_handler set_terminate(terminate_handler f) noexcept;

Effects: Establishes the function designated by f as the current handler function for terminating exception processing.

Returns: The previous terminate_handler.

Remarks: It is unspecified whether a null pointer value designates the default terminate_handler.

17.9.5.3 get_terminate

terminate_handler get_terminate() noexcept;

Returns: The current terminate_handler.

[Note 1: This can be a null pointer value. — end note]

17.9.5.4 terminate

[[noreturn]] void terminate() noexcept;

Effects: Calls a terminate_handler function. It is unspecified which terminate_handler function will be called if an exception is active during a call to set_terminate. Otherwise calls the current terminate_handler function.
Remark: Called by the implementation when exception handling must be abandoned for any of several reasons (14.6.2). May also be called directly by the program.

17.9.6 uncaught_exceptions

```cpp
int uncaught_exceptions() noexcept;
```

Remarks: The number of uncaught exceptions (14.6.3).

17.9.7 Exception propagation

```cpp
using exception_ptr = unspecified;
```

The type `exception_ptr` can be used to refer to an exception object.

`exception_ptr` meets the requirements of `Cpp17NullablePointer` (Table 36).

Two non-null values of type `exception_ptr` are equivalent and compare equal if and only if they refer to the same exception.

The default constructor of `exception_ptr` produces the null value of the type.

`exception_ptr` shall not be implicitly convertible to any arithmetic, enumeration, or pointer type.

[Note 1: An implementation can use a reference-counted smart pointer as `exception_ptr`. — end note]

For purposes of determining the presence of a data race, operations on `exception_ptr` objects shall access and modify only the `exception_ptr` objects themselves and not the exceptions they refer to.

Use of `rethrow_exception` on `exception_ptr` objects that refer to the same exception object shall not introduce a data race.

[Note 2: If `rethrow_exception` rethrows the same exception object (rather than a copy), concurrent access to that rethrown exception object can introduce a data race. Changes in the number of `exception_ptr` objects that refer to a particular exception do not introduce a data race. — end note]

```cpp
exception_ptr current_exception() noexcept;
```

Returns: An `exception_ptr` object that refers to the currently handled exception (14.4) or a copy of the currently handled exception, or a null `exception_ptr` object if no exception is being handled. The referenced object shall remain valid at least as long as there is an `exception_ptr` object that refers to it. If the function needs to allocate memory and the attempt fails, it returns an `exception_ptr` object that refers to an instance of `bad_alloc`. It is unspecified whether the return values of two successive calls to `current_exception` refer to the same exception object.

[Note 3: That is, it is unspecified whether `current_exception` creates a new copy each time it is called. — end note]

If the attempt to copy the current exception object throws an exception, the function returns an `exception_ptr` object that refers to the thrown exception or, if this is not possible, to an instance of `bad_exception`. If allocating memory to form `u` fails, throws an instance of `bad_alloc`;

[Note 4: The copy constructor of the thrown exception can also fail, so the implementation can substitute a `bad_exception` object to avoid infinite recursion. — end note]

```cpp
[noreturn] void rethrow_exception(exception_ptr p);
```

Preconditions: `p` is not a null pointer.

Effects: Let `u` be the exception object to which `p` refers, or a copy of that exception object. It is unspecified whether a copy is made, and memory for the copy is allocated in an unspecified way.

- If allocating memory to form `u` fails, throws an instance of `bad_alloc`;
- otherwise, if copying the exception to which `p` refers to form `u` throws an exception, throws that exception;
- otherwise, throws `u`.  

§ 17.9.7 ©ISO/IEC 554
template<class E> exception_ptr make_exception_ptr(E e) noexcept;

Effects: Creates an exception_ptr object that refers to a copy of e, as if:

```cpp
try {
    throw e;
} catch(...) {
    return current_exception();
}
```

[Note 5: This function is provided for convenience and efficiency reasons. — end note]

### 17.9.8 nested_exception

```cpp
namespace std {
    class nested_exception {
        public:
            nested_exception() noexcept;
            nested_exception(const nested_exception&) noexcept = default;
            nested_exception& operator=(const nested_exception&) noexcept = default;
            virtual ~nested_exception() = default;

            // access functions
            [[noreturn]] void rethrow_nested() const;
            exception_ptr nested_ptr() const noexcept;
    }

    template<class T> [[noreturn]] void throw_with_nested(T&& t);
    template<class E> void rethrow_if_nested(const E& e);
}
```

The class `nested_exception` is designed for use as a mixin through multiple inheritance. It captures the currently handled exception and stores it for later use.

[Note 1: `nested_exception` has a virtual destructor to make it a polymorphic class. Its presence can be tested for with `dynamic_cast`. — end note]

`nested_exception()` noexcept;

Effects: The constructor calls `current_exception()` and stores the returned value.

```cpp
[[noreturn]] void rethrow_nested() const;
```

Effects: If `nested_ptr()` returns a null pointer, the function calls the function `std::terminate`. Otherwise, it throws the stored exception captured by `*this`.

```cpp
exception_ptr nested_ptr() const noexcept;
```

Returns: The stored exception captured by this `nested_exception` object.

```cpp
template<class T> [[noreturn]] void throw_with_nested(T&& t);
```

Let U be `decay_t<T>`.

Preconditions: U meets the `Cpp17CopyConstructible` requirements.

Throws: If `is_class_v<U> && !is_final_v<U> && !is_base_of_v<nested_exception, U>` is true, an exception of unspecified type that is publicly derived from both U and `nested_exception` and constructed from `std::forward<T>(t)`, otherwise `std::forward<T>(t)`.

```cpp
template<class E> void rethrow_if_nested(const E& e);
```

Effects: If E is not a polymorphic class type, or if `nested_exception` is an inaccessible or ambiguous base class of E, there is no effect. Otherwise, performs:

```cpp
if (auto p = dynamic_cast<const nested_exception*>(addressof(e)))
    p->rethrow_nested();
```
17.10 Initializer lists

17.10.1 General

The header `<initializer_list>` defines a class template and several support functions related to list-initialization (see 9.4.5). All functions specified in 17.10 are signal-safe (17.13.5).

17.10.2 Header `<initializer_list>` synopsis

```cpp
namespace std {
  template<class E> class initializer_list {
    public:
      using value_type = E;
      using reference = const E&;
      using const_reference = const E&;
      using size_type = size_t;
      using iterator = const E*;
      using const_iterator = const E*;

      constexpr initializer_list() noexcept;
      constexpr size_t size() const noexcept; // number of elements
      constexpr const E* begin() const noexcept; // first element
      constexpr const E* end() const noexcept; // one past the last element
  };
}
```

An object of type `initializer_list<E>` provides access to an array of objects of type `const E`.

[Note 1: A pair of pointers or a pointer plus a length would be obvious representations for `initializer_list`. `initializer_list` is used to implement initializer lists as specified in 9.4.5. Copying an `initializer_list` does not copy the underlying elements. — end note]

If an explicit specialization or partial specialization of `initializer_list` is declared, the program is ill-formed.

17.10.3 Initializer list constructors

```cpp
constexpr initializer_list() noexcept;
```

Postconditions: `size() == 0`.

17.10.4 Initializer list access

```cpp
constexpr const E* begin() const noexcept;
```

Returns: A pointer to the beginning of the array. If `size() == 0` the values of `begin()` and `end()` are unspecified but they shall be identical.

```cpp
constexpr const E* end() const noexcept;
```

Returns: `begin() + size()`.

```cpp
constexpr size_t size() const noexcept;
```

Returns: The number of elements in the array.

Complexity: Constant time.

17.10.5 Initializer list range access

```cpp
template<class E> constexpr const E* begin(initializer_list<E> il) noexcept;
```

Returns: `il.begin()`. 

§ 17.10.5 © ISO/IEC 556
template<class E> constexpr const E* end(initializer_list<E> il) noexcept;

Returns: il.end().

17.11 Comparisons

17.11.1 Header <compare> synopsis

The header <compare> specifies types, objects, and functions for use primarily in connection with the three-way comparison operator (7.6.8).

```cpp
// all freestanding
namespace std {
    // 17.11.2, comparison category types
    class partial_ordering;
    class weak_ordering;
    class strong_ordering;

    // named comparison functions
    constexpr bool is_eq (partial_ordering cmp) noexcept { return cmp == 0; }
    constexpr bool is_neq (partial_ordering cmp) noexcept { return cmp != 0; }
    constexpr bool is_lt (partial_ordering cmp) noexcept { return cmp < 0; }
    constexpr bool is_lteq(partial_ordering cmp) noexcept { return cmp <= 0; }
    constexpr bool is_gt (partial_ordering cmp) noexcept { return cmp > 0; }
    constexpr bool is_gteq(partial_ordering cmp) noexcept { return cmp >= 0; }

    // 17.11.3, common comparison category type
    template<class... Ts>
    struct common_comparison_category {
        using type = see below;
    };
    template<class... Ts>
    using common_comparison_category_t = typename common_comparison_category<Ts...>::type;

    // 17.11.4, concept three_way_comparable
    template<class T, class Cat = partial_ordering>
    concept three_way_comparable = see below;
    template<class T, class U, class Cat = partial_ordering>
    concept three_way_comparable_with = see below;

    // 17.11.5, result of three-way comparison
    template<class T, class U = T> struct compare_three_way_result;
    template<class T, class U = T>
    using compare_three_way_result_t = typename compare_three_way_result<T, U>::type;

    // 22.10.8.8, class compare_three_way
    struct compare_three_way;
}
```

17.11.2 Comparison category types

17.11.2.1 Preamble

The types `partial_ordering`, `weak_ordering`, and `strong_ordering` are collectively termed the comparison category types. Each is specified in terms of an exposition-only data member named `value` whose value typically corresponds to that of an enumerator from one of the following exposition-only enumerations:
enum class ord { equal = 0, equivalent = equal, less = -1, greater = 1 }; // exposition only
enum class ncmp { unordered = -127 }; // exposition only

[Note 1: The type strong_ordering corresponds to the term total ordering in mathematics. — end note]

The relational and equality operators for the comparison category types are specified with an anonymous parameter of unspecified type. This type shall be selected by the implementation such that these parameters can accept literal 0 as a corresponding argument.

[Example 1: nullptr_t meets this requirement. — end example]

In this context, the behavior of a program that supplies an argument other than a literal 0 is undefined.

For the purposes of 17.11.2, substitutability is the property that \( f(a) == f(b) \) is true whenever \( a == b \) is true, where \( f \) denotes a function that reads only comparison-salient state that is accessible via the argument’s public const members.

### 17.11.2.2 Class partial_ordering

The `partial_ordering` type is typically used as the result type of a three-way comparison operator (7.6.8) for a type that admits all of the six two-way comparison operators (7.6.9, 7.6.10), for which equality need not imply substitutability, and that permits two values to be incomparable.\(^\text{194}\)

```cpp
namespace std {
    class partial_ordering {
    private:
        int value;
        bool is_ordered;

    public:
        // valid values
        static const partial_ordering less;
        static const partial_ordering equivalent;
        static const partial_ordering greater;
        static const partial_ordering unordered;

        // comparisons
        friend constexpr bool operator==(partial_ordering v, unspecified) noexcept;
        friend constexpr bool operator<=(partial_ordering v, unspecified) noexcept;
    };
}
```

\(\text{194}\) That is, \(a < b\), \(a == b\), and \(a > b\) might all be false.
constexpr bool operator<=(partial_ordering v, unspecified) noexcept;
constexpr bool operator>=(partial_ordering v, unspecified) noexcept;

Returns: For operator@, v.is_ordered && v.value @ 0.

constexpr bool operator< (unspecified, partial_ordering v) noexcept;
constexpr bool operator> (unspecified, partial_ordering v) noexcept;
constexpr bool operator<=(unspecified, partial_ordering v) noexcept;
constexpr bool operator>=(unspecified, partial_ordering v) noexcept;

Returns: For operator@, v.is_ordered && 0 @ v.value.

constexpr partial_ordering operator<=>(partial_ordering v, unspecified) noexcept;

Returns: v.

constexpr partial_ordering operator<=>(unspecified, partial_ordering v) noexcept;

Returns: v < 0 ? partial_ordering::greater : v > 0 ? partial_ordering::less : v.

17.11.2.3 Class weak_ordering

The weak_ordering type is typically used as the result type of a three-way comparison operator (7.6.8) for a
type that admits all of the six two-way comparison operators (7.6.9, 7.6.10) and for which equality need not
imply substitutability.

namespace std {
    class weak_ordering {
        int value; // exposition only

        // exposition-only constructors
        constexpr explicit weak_ordering(ord v) noexcept : value(int(v)) {} // exposition only

    public:
        // valid values
        static const weak_ordering less;
        static const weak_ordering equivalent;
        static const weak_ordering greater;

        // conversions
        constexpr operator partial_ordering() const noexcept;

        // comparisons
        friend constexpr bool operator==(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator==(weak_ordering v, weak_ordering w) noexcept = default;
        friend constexpr bool operator<(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator<(weak_ordering v, weak_ordering w) noexcept;
        friend constexpr bool operator>(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator>(weak_ordering v, weak_ordering w) noexcept;
        friend constexpr bool operator<=(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator<=(weak_ordering v, weak_ordering w) noexcept;
        friend constexpr bool operator>=(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator>=(weak_ordering v, weak_ordering w) noexcept;

        friend constexpr weak_ordering operator<=>(weak_ordering v, unspecified) noexcept;
        friend constexpr weak_ordering operator<=>(weak_ordering v, weak_ordering w) noexcept;
    }

    // valid values' definitions
    inline constexpr weak_ordering weak_ordering::less(ord::less);
    inline constexpr weak_ordering weak_ordering::equivalent(ord::equivalent);
    inline constexpr weak_ordering weak_ordering::greater(ord::greater);
}

constexpr operator partial_ordering() const noexcept;

2

Returns:
value == 0 ? partial_ordering::equivalent : 
value < 0 ? partial_ordering::less : 
partial_ordering::greater

constexpr bool operator==(weak_ordering v, unspecified) noexcept;
constexpr bool operator< (weak_ordering v, unspecified) noexcept;
constexpr bool operator> (weak_ordering v, unspecified) noexcept;
constexpr bool operator<=(weak_ordering v, unspecified) noexcept;
constexpr bool operator>=(weak_ordering v, unspecified) noexcept;

Returns: v.value == 0 for operator@.

constexpr weak_ordering operator<=>(weak_ordering v, unspecified) noexcept;

Returns: 0 == v.value for operator@.

constexpr weak_ordering operator<=>(unspecified, weak_ordering v) noexcept;

Returns: v < 0 ? weak_ordering::greater : v > 0 ? weak_ordering::less : v.

17.11.2.4 Class strong_ordering [cmp.strongord]
The strong_ordering type is typically used as the result type of a three-way comparison operator (7.6.8) for a type that admits all of the six two-way comparison operators (7.6.9, 7.6.10) and for which equality does imply substitutability.

namespace std {
    class strong_ordering {
        int value; // exposition only
        // exposition-only constructors
        constexpr explicit strong_ordering(ord v) noexcept : value(int(v)) {} // exposition only
    public:
        // valid values
        static const strong_ordering less;
        static const strong_ordering equal;
        static const strong_ordering equivalent;
        static const strong_ordering greater;
        // conversions
        constexpr operator partial_ordering() const noexcept;
        constexpr operator weak_ordering() const noexcept;
        // comparisons
        friend constexpr bool operator==(strong_ordering v, unspecified) noexcept;
        friend constexpr bool operator==(strong_ordering v, strong_ordering w) noexcept = default;
        friend constexpr bool operator< (strong_ordering v, unspecified) noexcept;
        friend constexpr bool operator< (strong_ordering v, strong_ordering w) noexcept;
        friend constexpr bool operator> (strong_ordering v, unspecified) noexcept;
        friend constexpr bool operator> (strong_ordering v, strong_ordering w) noexcept;
        friend constexpr bool operator<= (strong_ordering v, unspecified) noexcept;
        friend constexpr bool operator<= (strong_ordering v, strong_ordering w) noexcept;
        friend constexpr bool operator>= (strong_ordering v, unspecified) noexcept;
        friend constexpr bool operator>= (strong_ordering v, strong_ordering w) noexcept;
        friend constexpr strong_ordering operator<=>(strong_ordering v, unspecified) noexcept;
        friend constexpr strong_ordering operator<=>(unspecified, strong_ordering v) noexcept;
    };
    // valid values' definitions
    inline constexpr strong_ordering strong_ordering::less(ord::less);
inline constexpr strong_ordering strong_ordering::equal(ord::equal);
inline constexpr strong_ordering strong_ordering::equivalent(ord::equivalent);
inline constexpr strong_ordering strong_ordering::greater(ord::greater);

constexpr operator partial_ordering() const noexcept;
Returns:
value == 0 ? partial_ordering::equivalent :
value < 0 ? partial_ordering::less :
partial_ordering::greater

constexpr operator weak_ordering() const noexcept;
Returns:
value == 0 ? weak_ordering::equivalent :
value < 0 ? weak_ordering::less :
weak_ordering::greater

constexpr operator==(strong_ordering v, unspecified) noexcept;
constexpr operator< (strong_ordering v, unspecified) noexcept;
constexpr operator> (strong_ordering v, unspecified) noexcept;
constexpr operator<=(strong_ordering v, unspecified) noexcept;
constexpr operator>=(strong_ordering v, unspecified) noexcept;

Returns: v.value @ 0 for operator@.

constexpr bool operator< (unspecified, strong_ordering v) noexcept;
constexpr bool operator> (unspecified, strong_ordering v) noexcept;
constexpr bool operator<= (unspecified, strong_ordering v) noexcept;
constexpr bool operator=>(unspecified, strong_ordering v) noexcept;

Returns: 0 @ v.value for operator@.

constexpr strong_ordering operator<=>(strong_ordering v, unspecified) noexcept;
constexpr strong_ordering operator<=>(unspecified, strong_ordering v) noexcept;

Returns: v < 0 ? strong_ordering::greater : v > 0 ? strong_ordering::less : v.

17.11.3 Class template common_comparison_category
The type common_comparison_category provides an alias for the strongest comparison category to which all of the template arguments can be converted.

[Note 1: A comparison category type is stronger than another if they are distinct types and an instance of the former can be converted to an instance of the latter. — end note]

template<class... Ts>
struct common_comparison_category {
    using type = see below;
};

Remarks: The member typedef-name type denotes the common comparison type (11.10.3) of Ts..., the expanded parameter pack, or void if any element of Ts is not a comparison category type.

[Note 2: This is std::strong_ordering if the expansion is empty. — end note]
\begin{verbatim} 
{ t > u } -> boolean-testable;
{ t <= u } -> boolean-testable;
{ t >= u } -> boolean-testable;
{ u < t } -> boolean-testable;
{ u > t } -> boolean-testable;
{ u <= t } -> boolean-testable;
{ u >= t } -> boolean-testable;
\end{verbatim}

1 Let \( t \) and \( u \) be lvalues of types \texttt{const remove\_reference\_t<T>} and \texttt{const remove\_reference\_t<U>}, respectively. \( T \) and \( U \) model partially-ordered-with \( \langle T, U \rangle \) only if

\begin{enumerate}
\item \( t < u, t <= u, t > u, t >= u, u < t, u <= t, u > t, \) and \( u >= t \) have the same domain,
\item \( \text{bool}(t < u) = \text{bool}(u > t) \) is true,
\item \( \text{bool}(u < t) = \text{bool}(t > u) \) is true,
\item \( \text{bool}(t <= u) = \text{bool}(u >= t) \) is true, and
\item \( \text{bool}(u <= t) = \text{bool}(t >= u) \) is true.
\end{enumerate}

\begin{verbatim} 
template<class T, class Cat = partial_ordering>
concept three_way_comparable =
  weakly-equality-comparable-with\langle T, T\rangle &&
  partially-ordered-with\langle T, T\rangle &&
  requires(const remove_reference_t<T>& a, const remove_reference_t<T>& b) {
    { a <=> b } -> compares-as\langle Cat\rangle;
  }
\end{verbatim}

2 Let \( a \) and \( b \) be lvalues of type \texttt{const remove\_reference\_t<T>}. \( T \) and \( Cat \) model three_way_comparable\langle T, Cat \rangle only if

\begin{enumerate}
\item \( (a <=> b == 0) == \text{bool}(a == b) \) is true,
\item \( (a <=> b != 0) == \text{bool}(a != b) \) is true,
\item \( ((a <=> b) <=> 0) \) and \( (0 <=> (b <=> a)) \) are equal,
\item \( (a <=> b < 0) == \text{bool}(a < b) \) is true,
\item \( (a <=> b > 0) == \text{bool}(a > b) \) is true,
\item \( (a <=> b <= 0) == \text{bool}(a <= b) \) is true,
\item \( (a <=> b >= 0) == \text{bool}(a >= b) \) is true, and
\item if \( Cat \) is convertible to strong\_ordering, \( T \) models totally\_ordered (18.5.5).
\end{enumerate}

\begin{verbatim} 
template<class T, class U, class Cat = partial_ordering>
concept three_way_comparable_with =
  three_way_comparable\langle T, Cat \rangle &&
  three_way_comparable\langle U, Cat \rangle &&
  comparison\_common\_type\_with\langle T, U \rangle &&
  three_way_comparable<
    common_reference_t<const remove_reference_t<T>&, const remove_reference_t<U>&>, Cat> &&
  weakly-equality\_comparable\_with\langle T, U \rangle &&
  partially\_ordered\_with\langle T, U \rangle &&
  requires(const remove_reference_t<T>& t, const remove_reference_t<U>& u) {
    { t <=> u } -> compares-as\langle Cat\rangle;
    { u <=> t } -> compares-as\langle Cat\rangle;
  }
\end{verbatim}

3 Let \( t \) and \( t2 \) be lvalues denoting distinct equal objects of types \texttt{const remove\_reference\_t<T>} and \texttt{remove\_cvref\_t<T>}, respectively, and let \( u \) and \( u2 \) be lvalues denoting distinct equal objects of types \texttt{const remove\_reference\_t<U>} and \texttt{remove\_cvref\_t<U>}, respectively. Let \( C \) be \texttt{common\_reference\_t<const remove\_reference\_t<T>&, const remove\_reference\_t<U>&, Cat>} and \texttt{convert\_to\_lvalue\langle C\rangle(E)} be defined as in 18.5.1. \( T, U, \) and \( Cat \) model \texttt{three\_way\_comp}arable\_with\langle T, U, Cat \rangle only if

\begin{enumerate}
\item \( t => u \) and \( u => t \) have the same domain,
\item \( (t <= u) <=> 0 \) and \( (0 <= (u <=> t)) \) are equal,
\item \( (t <= u == 0) == \text{bool}(t == u) \) is true,
\end{enumerate}
\begin{align*}
(3.4) & \quad (t \leftrightarrow u \neq 0) == \text{bool}(t \neq u) \text{ is true}, \\
(3.5) & \quad \text{Cat}(t \leftrightarrow u) == \text{Cat}(\text{CONVERT TO LVALUE}<\text{C}>(t2) \leftrightarrow \text{CONVERT TO LVALUE}<\text{C}>(u2)) \text{ is true}, \\
(3.6) & \quad (t \leftrightarrow u < 0) == \text{bool}(t < u) \text{ is true}, \\
(3.7) & \quad (t \leftrightarrow u > 0) == \text{bool}(t > u) \text{ is true}, \\
(3.8) & \quad (t \leftrightarrow u \leq 0) == \text{bool}(t \leq u) \text{ is true}, \\
(3.9) & \quad (t \leftrightarrow u \geq 0) == \text{bool}(t \geq u) \text{ is true}, \\
(3.10) & \quad \text{if Cat is convertible to strong_ordering, T and U model totally_ordered_with<T, U> (18.5.5).}
\end{align*}

17.11.5 Result of three-way comparison \[\text{cmp.result}\]

1 The behavior of a program that adds specializations for the \texttt{compare_three_way_result} template defined in this subclause is undefined.

2 For the \texttt{compare_three_way_result} type trait applied to the types T and U, let t and u denote lvalues of types \texttt{const remove_reference_t<T>} and \texttt{const remove_reference_t<U>}, respectively. If the expression \(t \leftrightarrow u\) is well-formed when treated as an unevaluated operand (7.2.3), the member \texttt{typedef-name type} denotes the type \texttt{decltype(t \leftrightarrow u)}. Otherwise, there is no member \texttt{type}.

17.11.6 Comparison algorithms \[\text{cmp.alg}\]

1 The name \texttt{strong_order} denotes a customization point object (16.3.3.3.5). Given subexpressions E and F, the expression \texttt{strong_order(E, F)} is expression-equivalent (3.21) to the following:

\begin{align*}
(1.1) & \quad \text{If the decayed types of E and F differ, strong_order(E, F) is ill-formed.} \\
(1.2) & \quad \text{Otherwise, strong_ordering(strong_order(E, F)) if it is a well-formed expression where the meaning of strong_order is established as-if by performing argument-dependent lookup only (6.5.4).} \\
(1.3) & \quad \text{Otherwise, if the decayed type T of E is a floating-point type, yields a value of type strong_ordering that is consistent with the ordering observed by T’s comparison operators, and if \texttt{numeric_limits<T>::is_iec559} is true, is additionally consistent with the \texttt{totalOrder} operation as specified in ISO/IEC 60559.} \\
(1.4) & \quad \text{Otherwise, strong_ordering(compare_three_way()(E, F)) if it is a well-formed expression.} \\
(1.5) & \quad \text{Otherwise, strong_order(E, F) is ill-formed.} \\
\end{align*}

\textit{[Note 1: Ill-formed cases above result in substitution failure when strong_order(E, F) appears in the immediate context of a template instantiation. — end note]}

2 The name \texttt{weak_order} denotes a customization point object (16.3.3.3.5). Given subexpressions E and F, the expression \texttt{weak_order(E, F)} is expression-equivalent (3.21) to the following:

\begin{align*}
(2.1) & \quad \text{If the decayed types of E and F differ, weak_order(E, F) is ill-formed.} \\
(2.2) & \quad \text{Otherwise, weak_ordering(weak_order(E, F)) if it is a well-formed expression where the meaning of weak_order is established as-if by performing argument-dependent lookup only (6.5.4).} \\
(2.3) & \quad \text{Otherwise, if the decayed type T of E is a floating-point type, yields a value of type weak_ordering that is consistent with the ordering observed by T’s comparison operators and strong_order, and if \texttt{numeric_limits<T>::is_iec559} is true, is additionally consistent with the following equivalence classes, ordered from lesser to greater:} \\
(2.3.1) & \quad \text{together, all negative NaN values;} \\
(2.3.2) & \quad \text{negative infinity;} \\
(2.3.3) & \quad \text{each normal negative value;} \\
(2.3.4) & \quad \text{each subnormal negative value;} \\
(2.3.5) & \quad \text{together, both zero values;} \\
(2.3.6) & \quad \text{each subnormal positive value;} \\
(2.3.7) & \quad \text{each normal positive value;} \\
(2.3.8) & \quad \text{positive infinity;} \\
(2.3.9) & \quad \text{together, all positive NaN values.} \\
(2.4) & \quad \text{Otherwise, weak_ordering(compare_three_way()(E, F)) if it is a well-formed expression.}
\end{align*}
— Otherwise, \texttt{weak\_ordering(strong\_order(E, F))} if it is a well-formed expression.

— Otherwise, \texttt{weak\_order(E, F)} is ill-formed.

\textbf{Note 2}: Ill-formed cases above result in substitution failure when \texttt{weak\_order(E, F)} appears in the immediate context of a template instantiation. \textit{— end note}\n
The name \texttt{partial\_order} denotes a customization point object (16.3.3.3.5). Given subexpressions \texttt{E} and \texttt{F}, the expression \texttt{partial\_order(E, F)} is expression-equivalent (3.21) to the following:

— If the decayed types of \texttt{E} and \texttt{F} differ, \texttt{partial\_order(E, F)} is ill-formed.

— Otherwise, \texttt{partial\_ordering(partial\_order(E, F))} if it is a well-formed expression where the meaning of \texttt{partial\_order} is established as-if by performing argument-dependent lookup only (6.5.4).

— Otherwise, \texttt{partial\_ordering(compare\_three\_way()(E, F))} if it is a well-formed expression.

— Otherwise, \texttt{partial\_ordering(weak\_order(E, F))} if it is a well-formed expression.

— Otherwise, \texttt{partial\_order(E, F)} is ill-formed.

\textbf{Note 3}: Ill-formed cases above result in substitution failure when \texttt{partial\_order(E, F)} appears in the immediate context of a template instantiation. \textit{— end note}\n
The name \texttt{compare\_strong\_order\_fallback} denotes a customization point object (16.3.3.3.5). Given subexpressions \texttt{E} and \texttt{F}, the expression \texttt{compare\_strong\_order\_fallback(E, F)} is expression-equivalent (3.21) to:

— If the decayed types of \texttt{E} and \texttt{F} differ, \texttt{compare\_strong\_order\_fallback(E, F)} is ill-formed.

— Otherwise, \texttt{strong\_order(E, F)} if it is a well-formed expression.

— Otherwise, if the expressions \texttt{E == F} and \texttt{E < F} are both well-formed and each of \texttt{decltype(E == F)} and \texttt{decltype(E < F)} models \texttt{boolean-testable},
  \begin{verbatim}
  E == F ? strong\_ordering::equal :
  E < F ? strong\_ordering::less :
  strong\_ordering::greater
  \end{verbatim}
  except that \texttt{E} and \texttt{F} are evaluated only once.

— Otherwise, \texttt{compare\_strong\_order\_fallback(E, F)} is ill-formed.

\textbf{Note 4}: Ill-formed cases above result in substitution failure when \texttt{compare\_strong\_order\_fallback(E, F)} appears in the immediate context of a template instantiation. \textit{— end note}\n
The name \texttt{compare\_weak\_order\_fallback} denotes a customization point object (16.3.3.3.5). Given subexpressions \texttt{E} and \texttt{F}, the expression \texttt{compare\_weak\_order\_fallback(E, F)} is expression-equivalent (3.21) to:

— If the decayed types of \texttt{E} and \texttt{F} differ, \texttt{compare\_weak\_order\_fallback(E, F)} is ill-formed.

— Otherwise, \texttt{weak\_order(E, F)} if it is a well-formed expression.

— Otherwise, if the expressions \texttt{E == F}, \texttt{E < F}, and \texttt{F < E} are all well-formed and each of \texttt{decltype(E == F)} and \texttt{decltype(E < F)} models \texttt{boolean-testable},
  \begin{verbatim}
  E == F ? weak\_ordering::equivalent :
  E < F ? weak\_ordering::less :
  weak\_ordering::greater
  \end{verbatim}
  except that \texttt{E} and \texttt{F} are evaluated only once.

— Otherwise, \texttt{compare\_weak\_order\_fallback(E, F)} is ill-formed.

\textbf{Note 5}: Ill-formed cases above result in substitution failure when \texttt{compare\_weak\_order\_fallback(E, F)} appears in the immediate context of a template instantiation. \textit{— end note}\n
The name \texttt{compare\_partial\_order\_fallback} denotes a customization point object (16.3.3.3.5). Given subexpressions \texttt{E} and \texttt{F}, the expression \texttt{compare\_partial\_order\_fallback(E, F)} is expression-equivalent (3.21) to:

— If the decayed types of \texttt{E} and \texttt{F} differ, \texttt{compare\_partial\_order\_fallback(E, F)} is ill-formed.

— Otherwise, \texttt{partial\_order(E, F)} if it is a well-formed expression.

— Otherwise, if the expressions \texttt{E == F}, \texttt{E < F}, and \texttt{F < E} are all well-formed and each of \texttt{decltype(E == F)} and \texttt{decltype(E < F)} models \texttt{boolean-testable}.

§ 17.11.6 ©ISO/IEC 564
E == F ? partial_ordering::equivalent :
E < F ? partial_ordering::less :
F < E ? partial_ordering::greater :
partial_ordering::unordered

except that E and F are evaluated only once.

— Otherwise, compare_partial_order_fallback(E, F) is ill-formed.

[Note 6: Ill-formed cases above result in substitution failure when compare_partial_order_fallback(E, F) appears in the immediate context of a template instantiation. — end note]

17.12 Coroutines

17.12.1 General

The header <coroutine> defines several types providing compile and run-time support for coroutines in a C++ program.

17.12.2 Header <coroutine> synopsis

```
// all freestanding
#include <compare>       // see 17.11.1

namespace std {
    // 17.12.3, coroutine traits
    template<class R, class... ArgTypes>
    struct coroutine_traits;

    // 17.12.4, coroutine handle
    template<class Promise = void>
    struct coroutine_handle;

    // 17.12.4.8, comparison operators
    constexpr bool operator==(coroutine_handle<> x, coroutine_handle<> y) noexcept;
    constexpr strong_ordering operator<=>(coroutine_handle<> x, coroutine_handle<> y) noexcept;

    // 17.12.4.9, hash support
    template<class T> struct hash;
    template<class P> struct hash<coroutine_handle<P>>;

    // 17.12.5, no-op coroutines
    struct noop_coroutine_promise;
    template<> struct coroutine_handle<noop_coroutine_promise>;
    using noop_coroutine_handle = coroutine_handle<noop_coroutine_promise>;

    // 17.12.6, trivial awaitables
    struct suspend_never;
    struct suspend_always;
}
```

17.12.3 Coroutine traits

17.12.3.1 General

Subclause 17.12.3 defines requirements on classes representing coroutine traits, and defines the class template coroutine_traits that meets those requirements.

17.12.3.2 Class template coroutine_traits

The header <coroutine> defines the primary template coroutine_traits such that if ArgTypes is a parameter pack of types and if the qualified-id R::promise_type is valid and denotes a type (13.10.3), then coroutine_traits<R, ArgTypes...> has the following publicly accessible member:

```c++
    using promise_type = typename R::promise_type;
```
Otherwise, `coroutine_traits<R, ArgTypes...>` has no members.

Program-defined specializations of this template shall define a publicly accessible nested type named `promise_type`.

### 17.12.4 Class template coroutine_handle

#### 17.12.4.1 General

```cpp
namespace std {
    template<class R, class ArgTypes...> struct coroutine_traits {
        // has no members.
    };

    template<class R, class ArgTypes...> struct coroutine_traits<
        R, ArgTypes...> {
        // has no members.
    };

    template<> struct coroutine_traits<void> {
        // 17.12.4.2, construct/reset
        constexpr coroutine_handle() noexcept;
        constexpr coroutine_handle(nullptr_t) noexcept;
        coroutine_handle& operator=(nullptr_t) noexcept;

        // 17.12.4.4, export/import
        constexpr void* address() const noexcept;
        static constexpr coroutine_handle from_address(void* addr);

        // 17.12.4.5, observers
        constexpr explicit operator bool() const noexcept;
        bool done() const;

        // 17.12.4.6, resumption
        void operator()() const;
        void resume() const;
        void destroy() const;

        private:
            void* ptr; // exposition only
    };

    template<class Promise> struct coroutine_handle {
        // 17.12.4.2, construct/reset
        constexpr coroutine_handle() noexcept;
        constexpr coroutine_handle(nullptr_t) noexcept;
        static coroutine_handle from_promise(Promise&);
        coroutine_handle& operator=(nullptr_t) noexcept;

        // 17.12.4.4, export/import
        constexpr void* address() const noexcept;
        static constexpr coroutine_handle from_address(void* addr);

        // 17.12.4.3, conversion
        constexpr operator coroutine_handle<>() const noexcept;

        // 17.12.4.5, observers
        constexpr explicit operator bool() const noexcept;
        bool done() const;

        // 17.12.4.6, resumption
        void operator()() const;
        void resume() const;
        void destroy() const;

        // 17.12.4.7, promise access
        Promise& promise() const;

        private:
            void* ptr; // exposition only
    };
}
```

---

§ 17.12.4.1
An object of type `coroutine_handle<T>` is called a coroutine handle and can be used to refer to a suspended or executing coroutine. A coroutine handle object whose member `address()` returns a null pointer value does not refer to any coroutine. Two coroutine handle objects refer to the same coroutine if and only if their member `address()` returns the same non-null value.

If a program declares an explicit or partial specialization of `coroutine_handle`, the behavior is undefined.

### 17.12.4.2 Construct/reset

```cpp
constexpr coroutine_handle() noexcept;
constexpr coroutine_handle(nullptr_t) noexcept;
```

**Postconditions:** `address() == nullptr`.

```cpp
static coroutine_handle from_promise(Promise& p);
```

**Preconditions:** `p` is a reference to a promise object of a coroutine.

**Postconditions:** `addressof(h.promise()) == addressof(p)`.

**Returns:** A coroutine handle `h` referring to the coroutine.

```cpp
coroutine_handle& operator=(nullptr_t) noexcept;
```

**Postconditions:** `address() == nullptr`.

**Returns:** `*this`.

### 17.12.4.3 Conversion

```cpp
constexpr operator coroutine_handle<>() const noexcept;
```

**Effects:** Equivalent to: `return coroutine_handle<>::from_address(address());`

### 17.12.4.4 Export/import

```cpp
constexpr void* address() const noexcept;
```

**Returns:** `ptr`.

```cpp
static constexpr coroutine_handle<> coroutine_handle<>::from_address(void* addr);
```

**Preconditions:** `addr` was obtained via a prior call to `address` on an object whose type is a specialization of `coroutine_handle`.

**Postconditions:** `from_address(address()) == *this`.

```cpp
static constexpr coroutine_handle<Promise> coroutine_handle<Promise>::from_address(void* addr);
```

**Preconditions:** `addr` was obtained via a prior call to `address` on an object of type `cv coroutine_-
handle<Promise>`.

**Postconditions:** `from_address(address()) == *this`.

### 17.12.4.5 Observers

```cpp
constexpr explicit operator bool() const noexcept;
```

**Returns:** `address() != nullptr`.

```cpp
bool done() const;
```

**Preconditions:** `*this` refers to a suspended coroutine.

**Returns:** `true` if the coroutine is suspended at its final suspend point, otherwise `false`.

### 17.12.4.6 Resumption

Resuming a coroutine via `resume, operator()`, or `destroy` on an execution agent other than the one on which it was suspended has implementation-defined behavior unless each execution agent either is an instance of `std::thread` or `std::jthread`, or is the thread that executes `main`. 

§ 17.12.4.6 ©ISO/IEC 567
void operator()() const;
void resume() const;

Preconditions: *this refers to a suspended coroutine. The coroutine is not suspended at its final suspend point.
Effects: Resumes the execution of the coroutine.

void destroy() const;
Preconditions: *this refers to a suspended coroutine.
Effects: Destroys the coroutine (9.5.4).

17.12.4.7 Promise access

Promise& promise() const;

Preconditions: *this refers to a coroutine.
Returns: A reference to the promise of the coroutine.

17.12.4.8 Comparison operators

constexpr bool operator==(coroutine_handle<> x, coroutine_handle<> y) noexcept;
Returns: x.address() == y.address().

constexpr strong_ordering operator<=>(coroutine_handle<> x, coroutine_handle<> y) noexcept;
Returns: compare_three_way()(x.address(), y.address()).

17.12.4.9 Hash support

template<class P> struct hash<coroutine_handle<P>>;
The specialization is enabled (22.10.19).

17.12.5 No-op coroutines

17.12.5.1 Class noop_coroutine_promise

struct noop_coroutine_promise {};
The class noop_coroutine_promise defines the promise type for the coroutine referred to by
noop_coroutine_handle (17.12.2).

17.12.5.2 Class coroutine_handle<noop_coroutine_promise>

namespace std {
    template<>
    struct coroutine_handle<noop_coroutine_promise>
    {
        // 17.12.5.2.2, conversion
        constexpr operator coroutine_handle<>() const noexcept;

        // 17.12.5.2.3, observers
        constexpr explicit operator bool() const noexcept;
        constexpr bool done() const noexcept;

        // 17.12.5.2.4, resumption
        constexpr void operator()() const noexcept;
        constexpr void resume() const noexcept;
        constexpr void destroy() const noexcept;

        // 17.12.5.2.5, promise access
        noop_coroutine_promise& promise() const noexcept;
    }
}

§ 17.12.5.2.1 © ISO/IEC 568
// 17.12.5.2.6, address
constexpr void* address() const noexcept;
private:
    coroutine_handle(unspecified);
    void* ptr; // exposition only
};

17.12.5.2.2 Conversion {coroutine.handle.noop.conv]
constexpr operator coroutine_handle<>() const noexcept;
1
    Effects: Equivalent to: return coroutine_handle<>::~from_address(address());

17.12.5.2.3 Observers {coroutine.handle.noop.observers]
constexpr explicit operator bool() const noexcept;
1
    Returns: true.

constexpr bool done() const noexcept;
2
    Returns: false.

17.12.5.2.4 Resumption {coroutine.handle.noop.resumption]
constexpr void operator()() const noexcept;
constexpr void resume() const noexcept;
constexpr void destroy() const noexcept;
1
    Effects: None.
2
    Remarks: If noop_coroutine_handle is converted to coroutine_handle<>, calls to operator(),
    resume and destroy on that handle will also have no observable effects.

17.12.5.2.5 Promise access {coroutine.handle.noop.promise]
nop_coroutine_promise& promise() const noexcept;
1
    Returns: A reference to the promise object associated with this coroutine handle.

17.12.5.2.6 Address {coroutine.handle.noop.address]
constexpr void* address() const noexcept;
1
    Returns: ptr.
2
    Remarks: A noop_coroutine_handle’s ptr is always a non-null pointer value.

17.12.5.3 Function noop_coroutine {coroutine.noop.coroutine]
nop_coroutine_handle noop_coroutine() noexcept;
1
    Returns: A handle to a coroutine that has no observable effects when resumed or destroyed.
2
    Remarks: A handle returned from noop_coroutine may or may not compare equal to a handle returned
    from another invocation of noop_coroutine.

17.12.6 Trivial awaitables {coroutine.trivial.awaitables]
namespace std {
    struct suspend_never {
        constexpr bool await_ready() const noexcept { return true; }
        constexpr void await_suspend(coroutine_handle<>) const noexcept {}
        constexpr void await_resume() const noexcept {}
    };
    struct suspend_always {
        constexpr bool await_ready() const noexcept { return false; }
        constexpr void await_suspend(coroutine_handle<>) const noexcept {}
        constexpr void await_resume() const noexcept {}
    };
}
17.13 Other runtime support

17.13.1 General

Note 1: The types suspend_never and suspend_always can be used to indicate that an await-expression either never suspends or always suspends, and in either case does not produce a value. — end note

17.13.2 Header <cstdlib> synopsis

// all freestanding
namespace std {
    using va_list = see below;
}

#define va_arg(V, P) see below
#define va_copy(VDST, VSRC) see below
#define va_end(V) see below
#define va_start(V, P) see below

1 The contents of the header <cstdlib> are the same as the C standard library header <stdarg.h>, with the following changes:

(1.1) — In lieu of the default argument promotions specified in ISO/IEC 9899:2018 6.5.2.2, the definition in 7.6.1.3 applies.

(1.2) — The restrictions that C places on the second parameter to the va_start macro in header <stdarg.h> are different in this document. The parameter parmN is the rightmost parameter in the variable parameter list of the function definition (the one just before the ...). If the parameter parmN is a pack expansion (13.7.4) or an entity resulting from a lambda capture (7.5.6), the program is ill-formed, no diagnostic required. If the parameter parmN is of a reference type, or of a type that is not compatible with the type that results when passing an argument for which there is no parameter, the behavior is undefined.

See also: ISO/IEC 9899:2018, 7.16.1.1

17.13.3 Header <csetjmp> synopsis

namespace std {
    using jmp_buf = see below;
    [[noreturn]] void longjmp(jmp_buf env, int val);
}

#define setjmp(env) see below

1 The contents of the header <csetjmp> are the same as the C standard library header <setjmp.h>.

2 The function signature longjmp(jmp_buf jbuf, int val) has more restricted behavior in this document. A setjmp/longjmp call pair has undefined behavior if replacing the setjmp and longjmp by catch and throw would invoke any non-trivial destructors for any objects with automatic storage duration. A call to setjmp or longjmp has undefined behavior if invoked in a suspension context of a coroutine (7.6.2.4).

See also: ISO/IEC 9899:2018, 7.13

17.13.4 Header <csignal> synopsis

namespace std {
    using sig_atomic_t = see below;

195) Note that va_start is required to work as specified even if unary operator& is overloaded for the type of parmN.
17.13.5 Signal handlers

A call to the function `signal` synchronizes with any resulting invocation of the signal handler so installed. A plain lock-free atomic operation is an invocation of a function `f` from 33.5, such that:

1. `f` is the function `atomic_is_lock_free()`, or
2. `f` is the member function `is_lock_free()`, or
3. `f` is a non-static member function of class `atomic_flag`, or
4. `f` is a non-member function, and the first parameter of `f` has type `cv atomic_flag*`, or
5. `f` is a non-static member function invoked on an object `A`, such that `A.is_lock_free()` yields `true`, or
6. `f` is a non-member function, and for every pointer-to-atomic argument `A` passed to `f`, `atomic_is_lock_free(A)` yields `true`.

An evaluation is signal-safe unless it includes one of the following:

1. A call to any standard library function, except for plain lock-free atomic operations and functions explicitly identified as signal-safe;
   
   [Note 1: This implicitly excludes the use of `new` and `delete` expressions that rely on a library-provided memory allocator. — end note]

2. An access to an object with thread storage duration;
3. A `dynamic_cast` expression;
4. Throwing of an exception;
5. Control entering a `try-block` or `function-try-block`;
6. Initialization of a variable with static storage duration requiring dynamic initialization (6.9.3.3, 8.8)\(^{196}\); or
7. Waiting for the completion of the initialization of a variable with static storage duration (8.8).

A signal handler invocation has undefined behavior if it includes an evaluation that is not signal-safe.

The function `signal` is signal-safe if it is invoked with the first argument equal to the signal number corresponding to the signal that caused the invocation of the handler.

See also: ISO/IEC 9899:2018, 7.14

17.14 C headers

17.14.1 General

For compatibility with the C standard library, the C++ standard library provides the C headers shown in Table 44. The intended use of these headers is for interoperability only. It is possible that C++ source files need to include one of these headers in order to be valid C. Source files that are not intended to also be valid C should not use any of the C headers.

\(^{196}\) Such initialization can occur because it is the first odr-use (6.3) of that variable.
Note 1: The C headers either have no effect, such as `<stdbool.h>` (17.14.5) and `<stdalign.h>` (17.14.4), or otherwise the corresponding header of the form `<cname>` provides the same facilities and assuredly defines them in namespace `std`. — end note

Example 1: The following source file is both valid C++ and valid C. Viewed as C++, it declares a function with C language linkage; viewed as C it simply declares a function (and provides a prototype).

```c
#include <stdbool.h>  // for `bool` in C, no effect in C++
#include <stddef.h>   // for `size_t`

#ifdef __cplusplus
  extern "C"
  // see 9.11
#endif

void f(bool b[], size_t n);
— end example
```

Table 44 — C headers [tab:c.headers]

| `<assert.h>` | `<inttypes.h>` | `<signal.h>` | `<stdarg.h>` | `<uchar.h>` |
| `<complex.h>` | `<iso646.h>` | `<stdalign.h>` | `<stdio.h>` | `<wchar.h>` |
| `<ctype.h>` | `<limits.h>` | `<stdarg.h>` | `<stdlib.h>` | `<wctype.h>` |
| `<errno.h>` | `<locale.h>` | `<stdatomic.h>` | `<string.h>` | |
| `<fenv.h>` | `<math.h>` | `<stdbool.h>` | `<tgmath.h>` | |
| `<float.h>` | `<setjmp.h>` | `<stdbool.h>` | `<time.h>` | |

17.14.2 Header `<complex.h>` synopsis [complex.h.syn]

```c
#include <complex>
```

1 The header `<complex.h>` behaves as if it simply includes the header `<complex>` (28.4.2).

2 [Note 1: Names introduced by `<complex>` in namespace `std` are not placed into the global namespace scope by `<complex.h>`. — end note]

17.14.3 Header `<iso646.h>` synopsis [iso646.h.syn]

```c
The C++ header `<iso646.h>` is empty.
```

[Note 1: `and, and_eq, bitand, bitor, compl, not, not_eq, or, or_eq, xor, and xor_eq` are keywords in C++ (5.11). — end note]

17.14.4 Header `<stdalign.h>` synopsis [stdalign.h.syn]

```c
The contents of the C++ header `<stdalign.h>` are the same as the C standard library header `<stdalign.h>`, with the following changes: The header `<stdalign.h>` does not define a macro named `alignas`.
```

See also: ISO/IEC 9899:2018, 7.15

17.14.5 Header `<stdbool.h>` synopsis [stdbool.h.syn]

```c
The contents of the C++ header `<stdbool.h>` are the same as the C standard library header `<stdbool.h>`, with the following changes: The header `<stdbool.h>` does not define macros named `bool`, `true`, or `false`.
```

See also: ISO/IEC 9899:2018, 7.18

17.14.6 Header `<tgmath.h>` synopsis [tgmath.h.syn]

```c
#include `<cmath`
#include `<complex`
```

1 The header `<tgmath.h>` behaves as if it simply includes the headers `<cmath>` (28.7.1) and `<complex>` (28.4.2).

2 [Note 1: The overloads provided in C by type-generic macros are already provided in `<complex>` and `<cmath>` by "sufficient" additional overloads. — end note]

3 [Note 2: Names introduced by `<cmath>` or `<complex>` in namespace `std` are not placed into the global namespace scope by `<tgmath.h>`. — end note]
17.14.7 Other C headers

Every C header other than `<complex.h>` (17.14.2), `<iso646.h>` (17.14.3), `<stdlib.h>` (17.14.4), `<stdatomic.h>` (33.5.12), `<stdbool.h>` (17.14.5), and `<tgmath.h>` (17.14.6), each of which has a name of the form `<name.h>`, behaves as if each name placed in the standard library namespace by the corresponding `<cname>` header is placed within the global namespace scope, except for the functions described in 28.7.6, the `std::lerp` function overloads (28.7.4), the declaration of `std::byte` (17.2.1), and the functions and function templates described in 17.2.5. It is unspecified whether these names are first declared or defined within namespace scope (6.4.6) of the namespace `std` and are then injected into the global namespace scope by explicit `using-declarations` (9.9).

[Example 1: The header `<cstdlib>` assuredly provides its declarations and definitions within the namespace `std`. It may also provide these names within the global namespace. The header `<stdlib.h>` assuredly provides the same declarations and definitions within the global namespace, much as in ISO/IEC 9899. It may also provide these names within the namespace `std`. — end example]
18 Concepts library

18.1 General

This Clause describes library components that C++ programs may use to perform compile-time validation of template arguments and perform function dispatch based on properties of types. The purpose of these concepts is to establish a foundation for equational reasoning in programs.

The following subclauses describe language-related concepts, comparison concepts, object concepts, and callable concepts as summarized in Table 45.

Table 45 — Fundamental concepts library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.2</td>
<td>Equality preservation</td>
</tr>
<tr>
<td>18.4</td>
<td>Language-related concepts</td>
</tr>
<tr>
<td>18.5</td>
<td>Comparison concepts</td>
</tr>
<tr>
<td>18.6</td>
<td>Object concepts</td>
</tr>
<tr>
<td>18.7</td>
<td>Callable concepts</td>
</tr>
</tbody>
</table>

18.2 Equality preservation

An expression is equality-preserving if, given equal inputs, the expression results in equal outputs. The inputs to an expression are the set of the expression’s operands. The output of an expression is the expression’s result and all operands modified by the expression. For the purposes of this subclause, the operands of an expression are the largest subexpressions that include only:

1. An id-expression (7.5.5), and
2. invocations of the library function templates std::move, std::forward, and std::declval (22.2.4, 22.2.6).

[Example 1: The operands of the expression a = std::move(b) are a and std::move(b). — end example]

Not all input values need be valid for a given expression.

[Example 2: For integers a and b, the expression a / b is not well-defined when b is 0. This does not preclude the expression a / b being equality-preserving. — end example]

The domain of an expression is the set of input values for which the expression is required to be well-defined.

Expressions required to be equality-preserving are further required to be stable: two evaluations of such an expression with the same input objects are required to have equal outputs absent any explicit intervening modification of those input objects.

[Note 1: This requirement allows generic code to reason about the current values of objects based on knowledge of the prior values as observed via equality-preserving expressions. It effectively forbids spontaneous changes to an object, changes to an object from another thread of execution, changes to an object as side effects of non-modifying expressions, and changes to an object as side effects of modifying a distinct object if those changes could be observable to a library function via an equality-preserving expression that is required to be valid for that object. — end note]

Expressions declared in a requires-expression in the library clauses are required to be equality-preserving, except for those annotated with the comment “not required to be equality-preserving.” An expression so annotated may be equality-preserving, but is not required to be so.

An expression that may alter the value of one or more of its inputs in a manner observable to equality-preserving expressions is said to modify those inputs. The library clauses use a notational convention to specify which expressions declared in a requires-expression modify which inputs: except where otherwise specified, an expression operand that is a non-constant lvalue or rvalue may be modified. Operands that are constant lvalues or rvalues are required to not be modified. For the purposes of this subclause, the cv-qualification and value category of each operand are determined by assuming that each template type parameter denotes a cv-unqualified complete non-array object type.
Where a requires-expression declares an expression that is non-modifying for some constant lvalue operand, additional variations of that expression that accept a non-constant lvalue or (possibly constant) rvalue for the given operand are also required except where such an expression variation is explicitly required with differing semantics. These implicit expression variations are required to meet the semantic requirements of the declared expression. The extent to which an implementation validates the syntax of the variations is unspecified.

[Example 3:]

```cpp
template<class T> concept C = requires(T a, T b, const T c, const T d) {
  c == d;  // #1
  a = std::move(b);  // #2
  a = c;  // #3
};
```

For the above example:

(7.1) Expression #1 does not modify either of its operands, #2 modifies both of its operands, and #3 modifies only its first operand a.

(7.2) Expression #1 implicitly requires additional expression variations that meet the requirements for c == d (including non-modification), as if the expressions

```
c == b;
c == std::move(b);
std::move(c) == d; std::move(c) == b;
std::move(c) == std::move(d); std::move(c) == std::move(b);
```

had been declared as well.

(7.3) Expression #3 implicitly requires additional expression variations that meet the requirements for a == c (including non-modification of the second operand), as if the expressions a == b and a == std::move(c) had been declared. Expression #3 does not implicitly require an expression variation with a non-constant rvalue second operand, since expression #2 already specifies exactly such an expression explicitly.

— end example

[Example 4:]
The following type T meets the explicitly stated syntactic requirements of concept C above but does not meet the additional implicit requirements:

```cpp
struct T {
  bool operator==(const T&) const { return true; }
  bool operator==(T&) = delete;
};
```

T fails to meet the implicit requirements of C, so T satisfies but does not model C. Since implementations are not required to validate the syntax of implicit requirements, it is unspecified whether an implementation diagnoses as ill-formed a program that requires C<T>. — end example

18.3 Header <concepts> synopsis

```cpp
§ 18.3 © ISO/IEC

// all freestanding
namespace std {
  // 18.4, language-related concepts
  // 18.4.2, concept same_as
  template<class T, class U>
  concept same_as = see below;

  // 18.4.3, concept derived_from
  template<class Derived, class Base>
  concept derived_from = see below;

  // 18.4.4, concept convertible_to
  template<class From, class To>
  concept convertible_to = see below;
```
18.4.5, concept common_reference_with
  template<class T, class U>
  concept common_reference_with = see below;

18.4.6, concept common_with
  template<class T, class U>
  concept common_with = see below;

18.4.7, arithmetic concepts
  template<class T>
  concept integral = see below;
  template<class T>
  concept signed_integral = see below;
  template<class T>
  concept unsigned_integral = see below;
  template<class T>
  concept floating_point = see below;

18.4.8, concept assignable_from
  template<class LHS, class RHS>
  concept assignable_from = see below;

18.4.9, concept swappable
  namespace ranges {
    inline namespace unspecified {
      inline constexpr unspecified swap = unspecified;
    }
  }
  template<class T>
  concept swappable = see below;
  template<class T, class U>
  concept swappable_with = see below;

18.4.10, concept destructible
  template<class T>
  concept destructible = see below;

18.4.11, concept constructible_from
  template<class T, class... Args>
  concept constructible_from = see below;

18.4.12, concept default_initializable
  template<class T>
  concept default_initializable = see below;

18.4.13, concept move_constructible
  template<class T>
  concept move_constructible = see below;

18.4.14, concept copy_constructible
  template<class T>
  concept copy_constructible = see below;

18.5, comparison concepts
18.5.4, concept equality_comparable
  template<class T>
  concept equality_comparable = see below;
  template<class T, class U>
  concept equality_comparable_with = see below;

18.5.5, concept totally_ordered
  template<class T>
  concept totally_ordered = see below;
template<class T, class U>
    concept totally_ordered_with = see below;

    // 18.6. object concepts
    template<class T>
        concept movable = see below;
    template<class T>
        concept copyable = see below;
    template<class T>
        concept semiregular = see below;
    template<class T>
        concept regular = see below;

    // 18.7. callable concepts
    // 18.7.2, concept invocable
    template<class F, class... Args>
        concept invocable = see below;

    // 18.7.3, concept regular_invocable
    template<class F, class... Args>
        concept regular_invocable = see below;

    // 18.7.4, concept predicate
    template<class F, class... Args>
        concept predicate = see below;

    // 18.7.5, concept relation
    template<class R, class T, class U>
        concept relation = see below;

    // 18.7.6, concept equivalence_relation
    template<class R, class T, class U>
        concept equivalence_relation = see below;

    // 18.7.7, concept strict_weak_order
    template<class R, class T, class U>
        concept strict_weak_order = see below;

} 18.4 Language-related concepts [concepts.lang]
18.4.1 General [concepts.lang.general]

Subclause 18.4 contains the definition of concepts corresponding to language features. These concepts express
relationships between types, type classifications, and fundamental type properties.

18.4.2 Concept same_as [concept.same]

    template<class T, class U>
        concept same_as_impl = is_same_v<T, U>;  // exposition only

    template<class T, class U>
        concept same_as = same_as_impl<T, U> && same_as_impl<U, T>;

        [Note 1: same_as<T, U> subsumes same_as<U, T> and vice versa. — end note]

18.4.3 Concept derived_from [concept.derived]

    template<class Derived, class Base>
        concept derived_from =
            is_base_of_v<Derived, Base> &&
            is_convertible_v<Derived*, const volatile Base*>
            [Note 1: derived_from<Derived, Base> is satisfied if and only if Derived is publicly and unambiguously
derived from Base, or Derived and Base are the same class type ignoring cv-qualifiers. — end note]
18.4.4 Concept convertible_to

Given types From and To and an expression E whose type and value category are the same as those of declval<From>(), convertible_to<From, To> requires E to be both implicitly and explicitly convertible to type To. The implicit and explicit conversions are required to produce equal results.

```
template<class From, class To>
concept convertible_to =
    is_convertible_v<From, To> &&
    requires {
        static_cast<To>(declval<From>(());
    };
```

Let FromR be add_rvalue_reference_t<From> and test be the invented function:

```
To test(FromR (&f)()) {
    return f();
}
```

and let f be a function with no arguments and return type FromR such that f() is equality-preserving. Types From and To model convertible_to<From, To> only if:

1. To is not an object or reference-to-object type, or static_cast<To>(f()) is equal to test(f).
2. FromR is not a reference-to-object type, or
   1. If FromR is an rvalue reference to a non const-qualified type, the resulting state of the object referenced by f() after either above expression is valid but unspecified (16.4.6.15).
   2. Otherwise, the object referred to by f() is not modified by either above expression.

18.4.5 Concept common_reference_with

For two types T and U, if common_reference_t<T, U> is well-formed and denotes a type C such that both convertible_to<T, C> and convertible_to<U, C> are modeled, then T and U share a common reference type, C.

```
template<class T, class U>
concept common_reference_with =
    same_as<common_reference_t<T, U>, common_reference_t<U, T>> &&
    convertible_to<T, common_reference_t<T, U>>,
    convertible_to<U, common_reference_t<T, U>>;
```

Let C be common_reference_t<T, U>. Let t1 and t2 be equality-preserving expressions (18.2) such that decltype((t1)) and decltype((t2)) are each T, and let u1 and u2 be equality-preserving expressions such that decltype((u1)) and decltype((u2)) are each U. T and U model common_reference_with<T, U> only if:

1. C(t1) equals C(t2) if and only if t1 equals t2, and
2. C(u1) equals C(u2) if and only if u1 equals u2.

[Note 2: Users can customize the behavior of common_reference_with by specializing the basic_common_reference class template (21.3.8.7). — end note]

18.4.6 Concept common_with

If T and U can both be explicitly converted to some third type, C, then T and U share a common type, C.

```
template<class T, class U>
concept common_with =
    same_as<common_type_t<T, U>, common_type_t<U, T>> &&
    requires {
        static_cast<common_type_t<T, U>>(declval<T>(());
        static_cast<common_type_t<T, U>>(declval<U>(());
    } &&
```

[Note 1: C can be the same as T or U, or can be a different type. C can be a reference type. — end note]
common_reference_with<
    add_lvalue_reference_t<const T>,
    add_lvalue_reference_t<const U> &&
common_reference_with<
    add_lvalue_reference_t<common_type_t<T, U>>,
    common_reference_t<
        add_lvalue_reference_t<const T>,
        add_lvalue_reference_t<const U>>;

Let C be common_type_t<T, U>. Let t1 and t2 be equality-preserving expressions (18.2) such that decltype((t1)) and decltype((t2)) are each T, and let u1 and u2 be equality-preserving expressions such that decltype((u1)) and decltype((u2)) are each U. T and U model common_with<T, U> only if

(2.1) C(t1) equals C(t2) if and only if t1 equals t2, and
(2.2) C(u1) equals C(u2) if and only if u1 equals u2.

[Note 2: Users can customize the behavior of common_with by specializing the common_type class template (21.3.8.7). —end note]

18.4.7 Arithmetic concepts
[concepts.arithmetic]

template<class T>
concept integral = is_integral_v<T>;
template<class T>
concept signed_integral = integral<T> && is_signed_v<T>;
template<class T>
concept unsigned_integral = integral<T> && !signed_integral<T>;
template<class T>
concept floating_point = is_floating_point_v<T>;

[Note 1: signed_integral can be modeled even by types that are not signed integer types (6.8.2); for example, char. —end note]

[Note 2: unsigned_integral can be modeled even by types that are not unsigned integer types (6.8.2); for example, bool. —end note]

18.4.8 Concept assignable_from
[concept.assignable]

template<class LHS, class RHS>
concept assignable_from =
    is_lvalue_reference_v<LHS> &&
common_reference_with<
    const remove_reference_t<LHS>&, 
    const remove_reference_t<RHS>&> &&
requires(LHS lhs, RHS&& rhs) {
    ( lhs = std::forward<RHS>(rhs) ) -> same_as<LHS>;
};

Let:
(1.1) lhs be an lvalue that refers to an object lcopy such that decltype((lhs)) is LHS,
(1.2) rhs be an expression such that decltype((rhs)) is RHS, and
(1.3) rcopy be a distinct object that is equal to rhs.

LHS and RHS model assignable_from<LHS, RHS> only if
(1.4) addressof(lhs = rhs) == addressof(lcopy).
(1.5) After evaluating lhs = rhs:
(1.5.1) lhs is equal to rcopy, unless rhs is a non-const xvalue that refers to lcopy.
(1.5.2) If rhs is a non-const xvalue, the resulting state of the object to which it refers is valid but unspecified (16.4.6.15).
(1.5.3) Otherwise, if rhs is a glvalue, the object to which it refers is not modified.

[Note 1: Assignment need not be a total function (16.3.2.3); in particular, if assignment to an object x can result in a modification of some other object y, then x = y is likely not in the domain of =. —end note]
18.4.9 Concept swappable

Let \( t_1 \) and \( t_2 \) be equality-preserving expressions that denote distinct equal objects of type \( T \), and let \( u_1 \) and \( u_2 \) similarly denote distinct equal objects of type \( U \).

[Note 1: \( t_1 \) and \( u_1 \) can denote distinct objects, or the same object. — end note]

An operation exchanges the values denoted by \( t_1 \) and \( u_1 \) if and only if the operation modifies neither \( t_2 \) nor \( u_2 \) and:

1. If \( T \) and \( U \) are the same type, the result of the operation is that \( t_1 \) equals \( u_2 \) and \( u_1 \) equals \( t_2 \).
2. If \( T \) and \( U \) are different types and \( \text{common_reference_with}<\text{decltype((t1))}, \text{decltype((u1))}> \) is modeled, the result of the operation is that \( C(t_1) \) equals \( C(u_2) \) and \( C(u_1) \) equals \( C(t_2) \) where \( C \) is \( \text{common_reference_t}<\text{decltype((t1))}, \text{decltype((u1))}> \).

The name \( \text{ranges}::\text{swap} \) denotes a customization point object (16.3.3.3.5). The expression \( \text{ranges}::\text{swap}(E1, E2) \) for subexpressions \( E1 \) and \( E2 \) is expression-equivalent to an expression \( S \) determined as follows:

1. \( S \) is \( (\text{void})\text{swap}(E1, E2) \) if \( E1 \) or \( E2 \) has class or enumeration type (6.8.4) and that expression is valid, with overload resolution performed in a context that includes the declaration

   ```cpp
   template<class T>
   void swap(T&, T&) = delete;
   ```

   and does not include a declaration of \( \text{ranges}::\text{swap} \). If the function selected by overload resolution does not exchange the values denoted by \( E1 \) and \( E2 \), the program is ill-formed, no diagnostic required.

   [Note 2: This precludes calling unconstrained program-defined overloads of \( \text{swap} \). When the deleted overload is viable, program-defined overloads need to be more specialized (13.7.7.3) to be selected. — end note]

2. Otherwise, if \( E1 \) and \( E2 \) are lvalues of array types (6.8.4) with equal extent and \( \text{ranges}::\text{swap}(*E1, *E2) \) is a valid expression, \( S \) is \( (\text{void})\text{ranges}::\text{swap_ranges}(E1, E2) \), except that \( \text{noexcept}(S) \) is equal to \( \text{noexcept}(\text{ranges}::\text{swap}(*E1, *E2)) \).

3. Otherwise, if \( E1 \) and \( E2 \) are lvalues of the same type \( T \) that models \( \text{move_constructible}<T> \) and \( \text{assignable_from}<T&, T> \), \( S \) is an expression that exchanges the denoted values. \( S \) is a constant expression if:
   1. \( T \) is a literal type (6.8.1),
   2. both \( E1 = \text{std}::\text{move}(E2) \) and \( E2 = \text{std}::\text{move}(E1) \) are constant subexpressions (3.14), and
   3. the full-expressions of the initializers in the declarations

      ```cpp
      T t1(std::move(E1));
      T t2(std::move(E2));
      ```

   are constant subexpressions.

   \( \text{noexcept}(S) \) is equal to \( \text{is_nothrow_move_constructible_v}<T> \) \&\& \( \text{is_nothrow_move_assignable_v}<T> \).

   [Note 3: This case can result in substitution failure when \( \text{ranges}::\text{swap}(E1, E2) \) appears in the immediate context of a template instantiation. — end note]

4. Otherwise, \( \text{ranges}::\text{swap}(E1, E2) \) is ill-formed.

   [Note 4: Whenever \( \text{ranges}::\text{swap}(E1, E2) \) is a valid expression, it exchanges the values denoted by \( E1 \) and \( E2 \) and has type \( \text{void} \). — end note]

```cpp
template<class T>
concept swappable = requires(T& a, T& b) { ranges::swap(a, b); };

template<class T, class U>
concept swappable_with =
    common_reference_with<T, U> && requires(T&& t, U&& u) {
        ranges::swap(std::forward<T>(t), std::forward<T>(t));
        ranges::swap(std::forward<U>(u), std::forward<U>(u));
        ranges::swap(std::forward<T>(t), std::forward<U>(u));
        ranges::swap(std::forward<U>(u), std::forward<T>(t));
    };
```

197) The name \( \text{swap} \) is used here unqualified.
The semantics of the `swappable` and `swappable_with` concepts are fully defined by the `ranges::swap` customization point object. — end note

Example 1: User code can ensure that the evaluation of `swap` calls is performed in an appropriate context under the various conditions as follows:

```cpp
#include <cassert>
#include <concepts>
#include <utility>
namespace ranges = std::ranges;

template<class T, std::swappable_with<T> U>
void value_swap(T&& t, U&& u) {
  ranges::swap(std::forward<T>(t), std::forward<U>(u));
}

template<std::swappable T>
void lv_swap(T& t1, T& t2) {
  ranges::swap(t1, t2);
}

namespace N {
  struct A { int m; };
  struct Proxy {
    A* a;
    Proxy(A& a) : a{&a} {}  
    friend void swap(Proxy x, Proxy y) {
      ranges::swap(*x.a, *y.a);
    }
  }
  Proxy proxy(A& a) { return Proxy{ a }; }
}

int main() {
  int i = 1, j = 2;
  lv_swap(i, j);
  assert(i == 2 && j == 1);
  N::A a1 = { 5 }, a2 = { -5 };
  value_swap(a1, proxy(a2));
  assert(a1.m == -5 && a2.m == 5);
}
— end example]
template<class T>
constexpr bool is-default-initializable = see below; // exposition only

template<class T>
concept default_initializable = constructible_from<T> &&
requires { T(); } &&
is-default-initializable<T>;

1 For a type T, is-default-initializable<T> is true if and only if the variable definition
T t;
is well-formed for some invented variable t; otherwise it is false. Access checking is performed as if in
a context unrelated to T. Only the validity of the immediate context of the variable initialization is
considered.

18.4.13 Concept move_constructible [concept.moveconstructible]

template<class T>
concept move_constructible = constructible_from<T, T> &&
convertible_to<T, T>;

1 If T is an object type, then let rv be an rvalue of type T and u2 a distinct object of type T equal to rv.
T models move_constructible only if
(1.1) — After the definition T u = rv;, u is equal to u2.
(1.2) — T(rv) is equal to u2.
(1.3) — If T is not const, rv’s resulting state is valid but unspecified (16.4.6.15); otherwise, it is unchanged.

18.4.14 Concept copy_constructible [concept.copyconstructible]

template<class T>
concept copy_constructible = move_constructible<T> &&
constructible_from<T, const T&> && convertible_to<const T&, T> &&
constructible_from<T, const T> && convertible_to<const T, T>;

1 If T is an object type, then let v be an lvalue of type T or const T or an rvalue of type const T. T
models copy_constructible only if
(1.1) — After the definition T u = v;, u is equal to v (18.2) and v is not modified.
(1.2) — T(v) is equal to v and does not modify v.

18.5 Comparison concepts [concepts.compare]

18.5.1 General [concepts.compare.general]

1 Subclause 18.5 describes concepts that establish relationships and orderings on values of possibly differing
object types.

2 Given an expression E and a type C, let CONVERT_TO_LVALUE<C>(E) be:
(2.1) — static_cast<const C&>(as_const(E)) if that is a valid expression, and
(2.2) — static_cast<const C&>(std::move(E)) otherwise.

18.5.2 Boolean testability [concept.booltestable]

1 The exposition-only boolean-testable concept specifies the requirements on expressions that are convertible
to bool and for which the logical operators (7.6.14, 7.6.15, 7.6.2.2) have the conventional semantics.

template<class T>
concept boolean-testable-impl = convertible_to<T, bool>; // exposition only

2 Let e be an expression such that decltype((e)) is T. T models boolean-testable-impl only if
(2.1) — either remove_cvref_t<T> is not a class type, or a search for the names operator&& and operator||
in the scope of remove_cvref_t<T> finds nothing; and
(2.2) — argument-dependent lookup (6.5.4) for the names operator&& and operator|| with T as the only
argument type finds no disqualifying declaration (defined below).
A disqualifying parameter is a function parameter whose declared type \( P \) is not dependent on a template parameter, and there exists an implicit conversion sequence (12.2.4.2) from \( e \) to \( P \); or

is dependent on one or more template parameters, and either

\( P \) contains no template parameter that participates in template argument deduction (13.10.3.6), or

template argument deduction using the rules for deducing template arguments in a function call (13.10.3.2) and \( e \) as the argument succeeds.

A key parameter of a function template \( D \) is a function parameter of type \( \texttt{cv} \ X \) or reference thereto, where \( X \) names a specialization of a class template that has the same innermost enclosing non-inline namespace as \( D \), and \( X \) contains at least one template parameter that participates in template argument deduction.

Example 1: In

```cpp
namespace Z {
    template<class> struct C {};  // exposition only
    template<class T>
    void operator&&(C<T> x, T y);
    template<class T>
    void operator||(C<type_identity_t<T>> x, T y);
}
```

the declaration of \( Z::\text{operator&&} \) contains one key parameter, \( \texttt{C<T>} \ x \), and the declaration of \( Z::\text{operator||} \) contains no key parameters. —end example]

A disqualifying declaration is

\( (5.1) \)

a (non-template) function declaration that contains at least one disqualifying parameter; or

\( (5.2) \)

a function template declaration that contains at least one disqualifying parameter, where

\( (5.2.1) \)

at least one disqualifying parameter is a key parameter; or

\( (5.2.2) \)

the declaration contains no key parameters; or

\( (5.2.3) \)

the declaration declares a function template to which no name is bound (9.3.4).

Note 1: The intention is to ensure that given two types \( T_1 \) and \( T_2 \) that each model boolean-testable-impl, the \&\& and || operators within the expressions declval\( \langle T_1\rangle() \) \&\& declval\( \langle T_2\rangle() \) and declval\( \langle T_1\rangle() || \) declval\( \langle T_2\rangle() \) resolve to the corresponding built-in operators. —end note]

```cpp
template<class T>
concept boolean-testable = // exposition only
    boolean-testable-impl<T> && requires(T&& t) {
        { !std::forward<T>(t) } -> boolean-testable-impl;
    };
```

Let \( e \) be an expression such that \( \text{decltype}((e)) \) is \( T \). \( T \) models \( \text{boolean-testable} \) only if \( \text{bool}(e) == \text{!bool}(\text{!e}) \).

Example 2: The types \( \text{bool}, \text{true_type} \) (21.3.3), \( \text{int*} \), and \( \text{bitset<N>::reference} \) (22.9.2) model boolean-testable. —end example]

18.5.3 Comparison common types

```cpp
template<class T, class U, class C = common_reference_t<const T&, const U&>>
concept comparison-common-type-with-impl = // exposition only
    same_as<common_reference_t<const T&, const U&>,
             common_reference_t<const U&, const T&>> &&
    requires {
        requires convertible_to<const T, const C&> || convertible_to<T, const C&>;
        requires convertible_to<const U, const C&> || convertible_to<U, const C&>;
    };
```

```cpp
template<class T, class U>
concept comparison-common-type-with = // exposition only
    comparison-common-type-with-impl<remove_cvref_t<T>, remove_cvref_t<U>>;
```
Let $C$ be `common_reference_t<const T&, const U&>`. Let $t_1$ and $t_2$ be equality-preserving expressions that are lvalues of type `remove_cvref_t<T>` and let $u_1$ and $u_2$ be equality-preserving expressions that are lvalues of type `remove_cvref_t<U>`. $T$ and $U$ model `comparison-common-type-with<T, U>` only if

1. $CONVERT_TO_LVALUE<C>(t1)$ equals $CONVERT_TO_LVALUE<C>(t2)$ if and only if $t1$ equals $t2$, and
2. $CONVERT_TO_LVALUE<C>(u1)$ equals $CONVERT_TO_LVALUE<C>(u2)$ if and only if $u1$ equals $u2$.

### 18.5.4 Concept `equality_comparable`

```cpp
template<class T, class U>
concept weakly-equality-comparable-with = // exposition only
    requires(const remove_reference_t<T>& t, const remove_reference_t<U>& u) {
        { t == u } -> boolean-testable;
        { t != u } -> boolean-testable;
        { u == t } -> boolean-testable;
        { u != t } -> boolean-testable;
    };
```

Given types $T$ and $U$, let $t$ and $u$ be lvalues of types `const remove_reference_t<T>` and `const remove_reference_t<U>` respectively. $T$ and $U$ model `weakly-equality-comparable-with<T, U>` only if

1. $t == u$, $u == t$, $t != u$, and $u != t$ have the same domain.
2. $bool(u == t) == bool(t == u)$.
3. $bool(t != u) == !bool(t == u)$.
4. $bool(u != t) == bool(t != u)$.

```cpp
template<class T, class U>
concept equality_comparable_with =
    equality_comparable<T> && equality_comparable<U> &&
    comparison-common-type-with<T, U> &&
    equality_comparable<
        common_reference_t<
            const remove_reference_t<T>&, const remove_reference_t<U>&>,
        weakly-equality-comparable-with<T, U>;
```

Given types $T$ and $U$, let $t$ and $t_2$ be lvalues denoting distinct equal objects of types `const remove_cvref_t<T>` and `remove_cvref_t<T>`, respectively, let $u$ and $u_2$ be lvalues denoting distinct equal objects of types `const remove_reference_t<U>` and `remove_cvref_t<U>`, respectively, and let $C$ be:

- `common_reference_t<const remove_reference_t<T>&, const remove_reference_t<U>&>`
- `weakly-equality-comparable-with<T, U>`

$T$ and $U$ model `equality_comparable_with<T, U>` only if

- $bool(t == u) == bool(CONVERT_TO_LVALUE<C>(t2) == CONVERT_TO_LVALUE<C>(u2))$.

### 18.5.5 Concept `totally_ordered`

```cpp
template<class T>
concept totally_ordered =
    equality_comparable<T> && partially-ordered-with<T, T>;
```

Given a type $T$, let $a$, $b$, and $c$ be lvalues of type `const remove_reference_t<T>`. $T$ models `totally_ordered` only if

1. Exactly one of $bool(a < b)$, $bool(a > b)$, or $bool(a == b)$ is true.
2. If $bool(a < b)$ and $bool(b < c)$, then $bool(a < c)$. 

§ 18.5.5 ©ISO/IEC
(1.3) \[ \text{bool}(a \leq b) == !\text{bool}(b < a). \]

(1.4) \[ \text{bool}(a \geq b) == !\text{bool}(a < b). \]

```cpp
template<class T, class U>
concept totally_ordered_with =
totally_ordered<T> && totally_ordered<U> &&
equality_comparable_with<T, U> &&
totally_ordered_<
    common_reference_t<
        const remove_reference_t<T>&, 
        const remove_reference_t<U>&>, 
    partially_ordered_with<T, U>;
```

2 Given types T and U, let t and t2 be lvalues denoting distinct equal objects of types `const remove_reference_t<T>` and `remove_cvref_t<T>`, respectively, let u and u2 be lvalues denoting distinct equal objects of types `const remove_reference_t<U>` and `remove_cvref_t<U>`, respectively, and let C be:

```cpp
common_reference_t<const remove_reference_t<T>&, const remove_reference_t<U>&>
```

T and U model `totally_ordered_with<T, U>` only if

- (2.1) \[ \text{bool}(t < u) == \text{bool}(\text{CONVERT_TO_LVALUE}(t2) < \text{CONVERT_TO_LVALUE}(u2)). \]
- (2.2) \[ \text{bool}(t > u) == \text{bool}(\text{CONVERT_TO_LVALUE}(t2) > \text{CONVERT_TO_LVALUE}(u2)). \]
- (2.3) \[ \text{bool}(t \leq u) == \text{bool}(\text{CONVERT_TO_LVALUE}(t2) \leq \text{CONVERT_TO_LVALUE}(u2)). \]
- (2.4) \[ \text{bool}(t \geq u) == \text{bool}(\text{CONVERT_TO_LVALUE}(t2) \geq \text{CONVERT_TO_LVALUE}(u2)). \]
- (2.5) \[ \text{bool}(u < t) == \text{bool}(\text{CONVERT_TO_LVALUE}(u2) < \text{CONVERT_TO_LVALUE}(t2)). \]
- (2.6) \[ \text{bool}(u > t) == \text{bool}(\text{CONVERT_TO_LVALUE}(u2) > \text{CONVERT_TO_LVALUE}(t2)). \]
- (2.7) \[ \text{bool}(u \leq t) == \text{bool}(\text{CONVERT_TO_LVALUE}(u2) \leq \text{CONVERT_TO_LVALUE}(t2)). \]
- (2.8) \[ \text{bool}(u \geq t) == \text{bool}(\text{CONVERT_TO_LVALUE}(u2) \geq \text{CONVERT_TO_LVALUE}(t2)). \]

18.6 Object concepts

[concepts.object]

1 This subclause describes concepts that specify the basis of the value-oriented programming style on which the library is based.

```cpp
template<class T>
concept movable = is_object_v<T> && move_constructible<T> &&
    assignable_from<T&, T> && swappable<T>;
```

```cpp
template<class T>
concept copyable = copy_constructible<T> && movable<T> &&
    assignable_from<T&, T> &&
    assignable_from<T&, const T&> && assignable_from<T&, const T>;
```

```cpp
template<class T>
concept semiregular = copyable<T> &&
    default_initializable<T>;
```

```cpp
template<class T>
concept regular = semiregular<T> &&
    equality_comparable<T>;
```

2 [Note 1: The `semiregular` concept is modeled by types that behave similarly to fundamental types like `int`, except that they need not be comparable with `==`. — end note]

3 [Note 2: The `regular` concept is modeled by types that behave similarly to fundamental types like `int` and that are comparable with `==`. — end note]

18.7 Callable concepts

[concepts.callable]

18.7.1 General

[concepts.callable.general]

1 The concepts in 18.7 describe the requirements on function objects (22.10) and their arguments.

18.7.2 Concept invocable

[concept.invocable]

1 The `invocable` concept specifies a relationship between a callable type (22.10.3) F and a set of argument types Args... which can be evaluated by the library function `invoke` (22.10.5).

```cpp
template<class F, class... Args>
concept invocable = requires(F&& f, Args&&... args) {
    invoke(std::forward<F>(f), std::forward<Args>(args)...); // not required to be equality-preserving
};
```
2

Example 1: A function that generates random numbers can model invocable, since the invoke function call expression is not required to be equality-preserving (18.2). —end example

18.7.3 Concept regular_invocable

template<class F, class... Args>
concept regular_invocable = invocable<F, Args...>;

1

The invoke function call expression shall be equality-preserving (18.2) and shall not modify the function object or the arguments.

[Note 1: This requirement supersedes the annotation in the definition of invocable. — end note]

2

Example 1: A random number generator does not model regular_invocable. —end example

3

[Note 2: The distinction between invocable and regular_invocable is purely semantic. —end note]

18.7.4 Concept predicate

template<class F, class... Args>
concept predicate =
 regular_invocable<F, Args...> && boolean-testable<invoke_result_t<F, Args...>>;

18.7.5 Concept relation

template<class R, class T, class U>
concept relation =
 predicate<R, T, T> && predicate<R, U, U> &&
 predicate<R, T, U> && predicate<R, U, T>;

18.7.6 Concept equivalence_relation

template<class R, class T, class U>
concept equivalence_relation = relation<R, T, U>;

A relation models equivalence_relation only if it imposes an equivalence relation on its arguments.

18.7.7 Concept strict_weak_order

template<class R, class T, class U>
concept strict_weak_order = relation<R, T, U>;

A relation models strict_weak_order only if it imposes a strict weak ordering on its arguments.

The term strict refers to the requirement of an irreflexive relation (!comp(x, x) for all x), and the term weak to requirements that are not as strong as those for a total ordering, but stronger than those for a partial ordering. If we define equiv(a, b) as !comp(a, b) && !comp(b, a), then the requirements are that comp and equiv both be transitive relations:

(2.1) comp(a, b) && comp(b, c) implies comp(a, c)
(2.2) equiv(a, b) && equiv(b, c) implies equiv(a, c)

[Note 1: Under these conditions, it can be shown that

(3.1) equiv is an equivalence relation,
(3.2) comp induces a well-defined relation on the equivalence classes determined by equiv, and
(3.3) the induced relation is a strict total ordering.

—end note]
19 Diagnostics library

19.1 General

This Clause describes components that C++ programs may use to detect and report error conditions.

The following subclauses describe components for reporting several kinds of exceptional conditions, documenting program assertions, obtaining stacktraces, and a global variable for error number codes, as summarized in Table 46.

Table 46 — Diagnostics library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.2 Exception classes</td>
<td>&lt;stdexcept&gt;</td>
</tr>
<tr>
<td>19.3 Assertions</td>
<td>&lt;cassert&gt;</td>
</tr>
<tr>
<td>19.4 Error numbers</td>
<td>&lt;cerrno&gt;</td>
</tr>
<tr>
<td>19.5 System error support</td>
<td>&lt;system_error&gt;</td>
</tr>
<tr>
<td>19.6 Stacktrace</td>
<td>&lt;stacktrace&gt;</td>
</tr>
</tbody>
</table>

19.2 Exception classes

19.2.1 General

The C++ standard library provides classes to be used to report certain errors (16.4.6.13) in C++ programs. In the error model reflected in these classes, errors are divided into two broad categories: logic errors and runtime errors.

1 By contrast, runtime errors are due to events beyond the scope of the program. They cannot be easily predicted in advance. The header `<stdexcept>` defines several types of predefined exceptions for reporting errors in a C++ program. These exceptions are related by inheritance.

19.2.2 Header `<stdexcept>` synopsis

```cpp
namespace std {
    class logic_error;    
    class domain_error;   
    class invalid_argument;  
    class length_error;      
    class out_of_range;    
    class runtime_error;   
    class range_error;    
    class overflow_error; 
    class underflow_error; 
}
```

19.2.3 Class `logic_error`

```cpp
namespace std {
    class logic_error : public exception {
        public:
            explicit logic_error(const string& what_arg);
            explicit logic_error(const char* what_arg);
    };
}
```

The class `logic_error` defines the type of objects thrown as exceptions to report errors presumably detectable before the program executes, such as violations of logical preconditions or class invariants.
logic_error(const string& what_arg);

Postconditions: strcmp(what(), what_arg.c_str()) == 0.

logic_error(const char* what_arg);

Postconditions: strcmp(what(), what_arg) == 0.

19.2.4 Class domain_error

namespace std {
    class domain_error : public logic_error {
    public:
        explicit domain_error(const string& what_arg);
        explicit domain_error(const char* what_arg);
    }
}

The class `domain_error` defines the type of objects thrown as exceptions by the implementation to report domain errors.

domain_error(const string& what_arg);

Postconditions: strcmp(what(), what_arg.c_str()) == 0.

domain_error(const char* what_arg);

Postconditions: strcmp(what(), what_arg) == 0.

19.2.5 Class invalid_argument

namespace std {
    class invalid_argument : public logic_error {
    public:
        explicit invalid_argument(const string& what_arg);
        explicit invalid_argument(const char* what_arg);
    }
}

The class `invalid_argument` defines the type of objects thrown as exceptions to report an invalid argument.

invalid_argument(const string& what_arg);

Postconditions: strcmp(what(), what_arg.c_str()) == 0.

invalid_argument(const char* what_arg);

Postconditions: strcmp(what(), what_arg) == 0.

19.2.6 Class length_error

namespace std {
    class length_error : public logic_error {
    public:
        explicit length_error(const string& what_arg);
        explicit length_error(const char* what_arg);
    }
}

The class `length_error` defines the type of objects thrown as exceptions to report an attempt to produce an object whose length exceeds its maximum allowable size.

length_error(const string& what_arg);

Postconditions: strcmp(what(), what_arg.c_str()) == 0.

length_error(const char* what_arg);

Postconditions: strcmp(what(), what_arg) == 0.
19.2.7 Class out_of_range

namespace std {
    class out_of_range : public logic_error {
    public:
        explicit out_of_range(const string& what_arg);
        explicit out_of_range(const char* what_arg);
    };
}

1 The class out_of_range defines the type of objects thrown as exceptions to report an argument value not in its expected range.

eout_of_range(const string& what_arg);

2 Postconditions: strcmp(what(), what_arg.c_str()) == 0.

eout_of_range(const char* what_arg);

3 Postconditions: strcmp(what(), what_arg) == 0.

19.2.8 Class runtime_error

namespace std {
    class runtime_error : public exception {
    public:
        explicit runtime_error(const string& what_arg);
        explicit runtime_error(const char* what_arg);
    };
}

1 The class runtime_error defines the type of objects thrown as exceptions to report errors presumably detectable only when the program executes.

eruntime_error(const string& what_arg);

2 Postconditions: strcmp(what(), what_arg.c_str()) == 0.

eruntime_error(const char* what_arg);

3 Postconditions: strcmp(what(), what_arg) == 0.

19.2.9 Class range_error

namespace std {
    class range_error : public runtime_error {
    public:
        explicit range_error(const string& what_arg);
        explicit range_error(const char* what_arg);
    };
}

1 The class range_error defines the type of objects thrown as exceptions to report range errors in internal computations.

erange_error(const string& what_arg);

2 Postconditions: strcmp(what(), what_arg.c_str()) == 0.

erange_error(const char* what_arg);

3 Postconditions: strcmp(what(), what_arg) == 0.

19.2.10 Class overflow_error

namespace std {
    class overflow_error : public runtime_error {
    public:
        explicit overflow_error(const string& what_arg);
        explicit overflow_error(const char* what_arg);
    };
}

§ 19.2.10 © ISO/IEC 589
1 The class `overflow_error` defines the type of objects thrown as exceptions to report an arithmetic overflow error.

```cpp
overflow_error(const string& what_arg);
```

**Postconditions:** `strcmp(what(), what_arg.c_str()) == 0`.

```cpp
overflow_error(const char* what_arg);
```

**Postconditions:** `strcmp(what(), what_arg) == 0`.

19.2.11 Class underflow_error

```cpp
namespace std {
  class underflow_error : public runtime_error {
    public:
      explicit underflow_error(const string& what_arg);
      explicit underflow_error(const char* what_arg);
  };
}
```

1 The class `underflow_error` defines the type of objects thrown as exceptions to report an arithmetic underflow error.

```cpp
underflow_error(const string& what_arg);
```

**Postconditions:** `strcmp(what(), what_arg.c_str()) == 0`.

```cpp
underflow_error(const char* what_arg);
```

**Postconditions:** `strcmp(what(), what_arg) == 0`.

19.3 Assertions

19.3.1 General

The header `<cassert>` provides a macro for documenting C++ program assertions and a mechanism for disabling the assertion checks through defining the macro `NDEBUG`.

19.3.2 Header `<cassert>` synopsis

```cpp
#define assert(...) see below
```

19.3.3 The assert macro

If `NDEBUG` is defined as a macro name at the point in the source file where `<cassert>` is included, the `assert` macro is defined as

```cpp
#define assert(...) ((void)0)
```

Otherwise, the `assert` macro puts a diagnostic test into programs; it expands to an expression of type `void` which has the following effects:

1. `__VA_ARGS__` is evaluated and contextually converted to `bool`.
2. If the evaluation yields `true` there are no further effects.
3. Otherwise, the `assert` macro's expression creates a diagnostic on the standard error stream in an implementation-defined format and calls `abort()`. The diagnostic contains `__VA_ARGS__` and information on the name of the source file, the source line number, and the name of the enclosing function (such as provided by `source_location::current()`).

If `__VA_ARGS__` does not expand to an `assignment-expression`, the program is ill-formed.

The macro `assert` is redefined according to the current state of `NDEBUG` each time that `<cassert>` is included.

An expression `assert(E)` is a constant subexpression (3.14), if

1. `NDEBUG` is defined at the point where `assert` is last defined or redefined, or

2. `E` contextually converted to `bool` (7.3) is a constant subexpression that evaluates to the value `true`. 

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19.4 Error numbers

19.4.1 General

The contents of the header `<cerrno>` are the same as the POSIX header `<errno.h>`, except that `errno` shall be defined as a macro.

[Note 1: The intent is to remain in close alignment with the POSIX standard. — end note]

A separate `errno` value is provided for each thread.

19.4.2 Header `<cerrno>` synopsis

```c
#define errno see below
#define E2BIG see below // freestanding
#define EACCES see below // freestanding
#define EADDRINUSE see below // freestanding
#define EADDRNOTAVAIL see below // freestanding
#define EAFNOSUPPORT see below // freestanding
#define EAGAIN see below // freestanding
#define EALREADY see below // freestanding
#define EBADF see below // freestanding
#define EBADMSG see below // freestanding
#define EBUSY see below // freestanding
#define ECANCELED see below // freestanding
#define ECHILD see below // freestanding
#define ECONNABORTED see below // freestanding
#define ECONNREFUSED see below // freestanding
#define ECONNRESET see below // freestanding
#define EDEADLK see below // freestanding
#define EDESTADDRREQ see below // freestanding
#define EEXIST see below // freestanding
#define EFAULT see below // freestanding
#define EFBIG see below // freestanding
#define EHOSTUNREACH see below // freestanding
#define EIDRM see below // freestanding
#define EILSEQ see below // freestanding
#define EINPROGRESS see below // freestanding
#define EINTR see below // freestanding
#define EINVAL see below // freestanding
#define EIO see below // freestanding
#define EISCONN see below // freestanding
#define EISDIR see below // freestanding
#define ELOOP see below // freestanding
#define EMFILE see below // freestanding
#define ENAMETOOLONG see below // freestanding
#define ENETDOWN see below // freestanding
#define ENETRESET see below // freestanding
#define ENETUNREACH see below // freestanding
#define ENFILE see below // freestanding
#define ENOBUFS see below // freestanding
#define ENODEV see below // freestanding
#define ENOENT see below // freestanding
#define ENOEXEC see below // freestanding
#define ENOLCK see below // freestanding
#define ENOLINK see below // freestanding
#define ENOMEM see below // freestanding
#define ENODEV see below // freestanding
#define ENOSPC see below // freestanding
#define ENOSYS see below // freestanding
#define ENOTCONN see below // freestanding
#define ENOTDIR see below // freestanding
```
1 The meaning of the macros in this header is defined by the POSIX standard.

**See also:** ISO/IEC 9899:2018, 7.5

---

### 19.5 System error support

#### 19.5.1 General

Subclause 19.5 describes components that the standard library and C++ programs may use to report error conditions originating from the operating system or other low-level application program interfaces.

Components described in 19.5 do not change the value of `errno` (19.4).

---

**Recommended practice:** Implementations should leave the error states provided by other libraries unchanged.

#### 19.5.2 Header `<system_error>` synopsis

```cpp
#include <compare> // see 17.11.1

namespace std {
  class error_category;
  const error_category& generic_category() noexcept;
  const error_category& system_category() noexcept;

  class error_code;
  class error_condition;
  class system_error;

  template<class T>
  struct is_error_code_enum : public false_type {};

  template<class T>
  struct is_error_condition_enum : public false_type {};

  enum class errc {
    address_family_not_supported, // EAFNOSUPPORT
    address_in_use, // EADDRINUSE
    address_not_available, // EADDRNOTAVAIL
    already_connected, // EISCONN
    argument_list_too_long, // E2BIG
    argument_out_of_domain, // EDOM
    bad_address, // EINVAL
    bad_file_descriptor, // EBADF
    bad_message, // EBADMSG
    broken_pipe, // EPIPE
  };
}
```

---

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592
N4986

};

template<> struct is_error_condition_enum<errc> : true_type {};

// 19.5.4.5, non-member functions
error_code make_error_code(errc e) noexcept;

template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const error_code& ec);

// 19.5.5.5, non-member functions
error_condition make_error_condition(errc e) noexcept;

// 19.5.6, comparison operator functions
bool operator==(const error_code& lhs, const error_code& rhs) noexcept;
bool operator==(const error_code& lhs, const error_condition& rhs) noexcept;
bool operator==(const error_condition& lhs, const error_code& rhs) noexcept;
strong_ordering operator<=>(const error_code& lhs, const error_code& rhs) noexcept;
strong_ordering operator<=>(const error_condition& lhs, const error_condition& rhs) noexcept;

// 19.5.7, hash support
template<class T> struct hash;

template<> struct hash<error_code>;

template<> struct hash<error_condition>;

// 19.5, system error support

1 The value of each enum errc enumerator is the same as the value of the <cerrno> macro shown in the above synopsis. Whether or not the <system_error> implementation exposes the <cerrno> macros is unspecified.

2 The is_error_code_enum and is_error_condition_enum templates may be specialized for program-defined types to indicate that such types are eligible for class error_code and class error_condition implicit conversions, respectively.

19.5.3 Class error_category [syserr.errcat]

19.5.3.1 Overview [syserr.errcat.overview]

The class error_category serves as a base class for types used to identify the source and encoding of a particular category of error code. Classes may be derived from error_category to support categories of errors in addition to those defined in this document. Such classes shall behave as specified in subclause 19.5.3.

[Note 1: error_category objects are passed by reference, and two such objects are equal if they have the same address. If there is more than a single object of a custom error_category type, such equality comparisons can evaluate to false even for objects holding the same value. — end note]
	namespace std {
    class error_category {
    public:
        constexpr error_category() noexcept;
        virtual ~error_category();
        error_category(const error_category&) = delete;
        error_category& operator=(const error_category&) = delete;
        virtual const char* name() const noexcept = 0;
        virtual bool equivalent(int ev, const error_condition& condition) const noexcept;
        virtual bool equivalent(const error_code& code, int condition) const noexcept;
        virtual string message(int ev) const = 0;
        bool operator==(const error_category& rhs) const noexcept;
        strong_ordering operator<=>(const error_category& rhs) const noexcept;
    }
19.5.3.2 Virtual members

virtual const char* name() const noexcept = 0;

Returns: A string naming the error category.

virtual error_condition default_error_condition(int ev) const noexcept;

Returns: error_condition(ev, *this).

virtual bool equivalent(int code, const error_condition& condition) const noexcept;

Returns: default_error_condition(code) == condition.

virtual bool equivalent(const error_code& code, int condition) const noexcept;

Returns: *this == code.category() && code.value() == condition.

virtual string message(int ev) const = 0;

Returns: A string that describes the error condition denoted by ev.

19.5.3.3 Non-virtual members

bool operator==(const error_category& rhs) const noexcept;

Returns: this == &rhs.

strong_ordering operator<=>(const error_category& rhs) const noexcept;

Returns: compare_three_way()(this, &rhs).

[Note 1: compare_three_way (22.10.8.8) provides a total ordering for pointers. — end note]

19.5.3.4 Program-defined classes derived from error_category

virtual const char* name() const noexcept = 0;

Returns: A string naming the error category.

virtual error_condition default_error_condition(int ev) const noexcept;

Returns: An object of type error_condition that corresponds to ev.

virtual bool equivalent(int code, const error_condition& condition) const noexcept;

Returns: true if, for the category of error represented by *this, code is considered equivalent to condition; otherwise, false.

virtual bool equivalent(const error_code& code, int condition) const noexcept;

Returns: true if, for the category of error represented by *this, code is considered equivalent to condition; otherwise, false.

19.5.3.5 Error category objects

const error_category& generic_category() noexcept;

Returns: A reference to an object of a type derived from class error_category. All calls to this function shall return references to the same object.

Remarks: The object’s default_error_condition and equivalent virtual functions shall behave as specified for the class error_category. The object’s name virtual function shall return a pointer to the string "generic".
const error_category& system_category() noexcept;

Returns: A reference to an object of a type derived from class error_category. All calls to this function shall return references to the same object.

Remarks: The object’s equivalent virtual functions shall behave as specified for class error_category. The object’s name virtual function shall return a pointer to the string "system". The object’s default_error_condition virtual function shall behave as follows:

If the argument ev is equal to 0, the function returns error_condition(0, generic_category()). Otherwise, if ev corresponds to a POSIX errno value pxv, the function returns error_condition(pxv, generic_category()). Otherwise, the function returns error_condition(ev, system_category()). What constitutes correspondence for any given operating system is unspecified.

[Note 1: The number of potential system error codes is large and unbounded, and some might not correspond to any POSIX errno value. Thus implementations are given latitude in determining correspondence. — end note]

19.5.4 Class error_code

19.5.4.1 Overview

The class error_code describes an object used to hold error code values, such as those originating from the operating system or other low-level application program interfaces.

[Note 1: Class error_code is an adjunct to error reporting by exception. — end note]

namespace std {

class error_code {

public:

// 19.5.4.2, constructors
error_code() noexcept;
error_code(int val, const error_category& cat) noexcept;
template<class ErrorCodeEnum>
error_code(ErrorCodeEnum e) noexcept;

// 19.5.4.3, modifiers
void assign(int val, const error_category& cat) noexcept;
template<class ErrorCodeEnum>
error_code& operator=(ErrorCodeEnum e) noexcept;
void clear() noexcept;

// 19.5.4.4, observers
int value() const noexcept;
const error_category& category() const noexcept;
error_condition default_error_condition() const noexcept;
string message() const;
explicit operator bool() const noexcept;

private:

int val_; // exposition only
const error_category* cat_; // exposition only

};

// 19.5.4.5, non-member functions
error_code make_error_code(errc e) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const error_code& ec);

}
template<class ErrorCodeEnum>
error_code(ErrorCodeEnum e) noexcept;

Constraints: is_error_code_enum_v<ErrorCodeEnum> is true.

Effects: Equivalent to:
error_code ec = make_error_code(e);
assign(ec.value(), ec.category());

19.5.4.3 Modifiers

void assign(int val, const error_category& cat) noexcept;

Postconditions: val_ == val and cat_ == &cat.

template<class ErrorCodeEnum>
error_code& operator=(ErrorCodeEnum e) noexcept;

Constraints: is_error_code_enum_v<ErrorCodeEnum> is true.

Effects: Equivalent to:
error_code ec = make_error_code(e);
assign(ec.value(), ec.category());

Returns: *this.

void clear() noexcept;

Postconditions: value() == 0 and category() == system_category().

19.5.4.4 Observers

int value() const noexcept;

Returns: val_.

const error_category& category() const noexcept;

Returns: *cat_.

error_condition default_error_condition() const noexcept;

Returns: category().default_error_condition(value()).

string message() const;

Returns: category().message(value()).

explicit operator bool() const noexcept;

Returns: value() != 0.

19.5.4.5 Non-member functions

error_code make_error_code(errc e) noexcept;

Returns: error_code(static_cast<int>(e), generic_category()).

template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const error_code& ec);

Effects: Equivalent to: return os << ec.category().name() << ':' << ec.value();

19.5.5 Class error_condition

19.5.5.1 Overview

The class error_condition describes an object used to hold values identifying error conditions.

[Note 1: error_condition values are portable abstractions, while error_code values (19.5.4) are implementation specific. — end note]
namespace std {
    class error_condition {
    public:
        // 19.5.5.2, constructors
        error_condition() noexcept;
        error_condition(int val, const error_category& cat) noexcept;
        template<class ErrorConditionEnum>
            error_condition(ErrorConditionEnum e) noexcept;

        // 19.5.5.3, modifiers
        void assign(int val, const error_category& cat) noexcept;
        template<class ErrorConditionEnum>
            error_condition& operator=(ErrorConditionEnum e) noexcept;
        void clear() noexcept;

        // 19.5.5.4, observers
        int value() const noexcept;
        const error_category& category() const noexcept;
        string message() const;
        explicit operator bool() const noexcept;
    private:
        int val_; // exposition only
        const error_category* cat_; // exposition only
    };
}

19.5.5.2 Constructors

*error_condition()* noexcept;

    *Effects*: Initializes *val_* with 0 and *cat_* with &generic_category().

*error_condition*(int val, const error_category& cat) noexcept;

    *Effects*: Initializes *val_* with *val* and *cat_* with &cat.

    template<class ErrorConditionEnum>
        error_condition(ErrorConditionEnum e) noexcept;

    *Constraints*: is_error_condition_enum_v<ErrorConditionEnum> is true.

    *Effects*: Equivalent to:
        error_condition ec = make_error_condition(e);
        assign(ec.value(), ec.category());

19.5.5.3 Modifiers

void assign(int val, const error_category& cat) noexcept;

    *Postconditions*: *val_* == *val* and *cat_* == &cat.

    template<class ErrorConditionEnum>
        error_condition& operator=(ErrorConditionEnum e) noexcept;

    *Constraints*: is_error_condition_enum_v<ErrorConditionEnum> is true.

    *Effects*: Equivalent to:
        error_condition ec = make_error_condition(e);
        assign(ec.value(), ec.category());

    *Returns*: *this.

void clear() noexcept;

    *Postconditions*: value() == 0 and category() == generic_category().

§ 19.5.5.3
19.5.5.4 Observers

int value() const noexcept;

Returns: val_.

const error_category& category() const noexcept;

Returns: *cat_.

string message() const;

Returns: category().message(value()).

explicit operator bool() const noexcept;

Returns: value() != 0.

19.5.5.5 Non-member functions

error_condition make_error_condition(errc e) noexcept;

Returns: error_condition(static_cast<int>(e), generic_category()).

19.5.6 Comparison operator functions

bool operator==(const error_code& lhs, const error_code& rhs) noexcept;

Returns:(lhs.category() == rhs.category() && lhs.value() == rhs.value())

bool operator==(const error_condition& lhs, const error_condition& rhs) noexcept;

Returns:(lhs.category() == rhs.category() && lhs.value() == rhs.value())

bool operator==(const error_condition& lhs, const error_condition& rhs) noexcept;

Returns:(lhs.category() == rhs.category() && lhs.value() == rhs.value())

strong_ordering operator<=>(const error_code& lhs, const error_code& rhs) noexcept;

Effects: Equivalent to:

if (auto c = lhs.category() <=> rhs.category(); c != 0) return c;

return lhs.value() <=> rhs.value();

strong_ordering operator<=>(const error_condition& lhs, const error_condition& rhs) noexcept;

Returns:

if (auto c = lhs.category() <=> rhs.category(); c != 0) return c;

return lhs.value() <=> rhs.value();

19.5.7 System error hash support

template<> struct hash<error_code>;
template<> struct hash<error_condition>;

The specializations are enabled (22.10.19).

19.5.8 Class system_error

19.5.8.1 Overview

The class system_error describes an exception object used to report error conditions that have an associated error code. Such error conditions typically originate from the operating system or other low-level application program interfaces.

[Note 1: If an error represents an out-of-memory condition, implementations are encouraged to throw an exception object of type bad_alloc (17.6.4.1) rather than system_error. — end note]
namespace std {
    class system_error : public runtime_error {
    public:
        system_error(error_code ec, const string& what_arg);
        system_error(error_code ec, const char* what_arg);
        system_error(error_code ec);
        system_error(int ev, const error_category& ecat, const string& what_arg);
        system_error(int ev, const error_category& ecat, const char* what_arg);
        system_error(int ev, const error_category& ecat);
        const error_code& code() const noexcept;
        const char* what() const noexcept override;
    }
}

19.5.8.2 Members

system_error(error_code ec, const string& what_arg);
1  Postconditions: code() == ec and
    string_view(what()).find(what_arg.c_str()) != string_view::npos.

system_error(error_code ec, const char* what_arg);
2  Postconditions: code() == ec and string_view(what()).find(what_arg) != string_view::npos.

system_error(error_code ec);
3  Postconditions: code() == ec.

system_error(int ev, const error_category& ecat, const string& what_arg);
4  Postconditions: code() == error_code(ev, ecat) and
    string_view(what()).find(what_arg.c_str()) != string_view::npos.

system_error(int ev, const error_category& ecat, const char* what_arg);
5  Postconditions: code() == error_code(ev, ecat) and
    string_view(what()).find(what_arg) != string_view::npos.

system_error(int ev, const error_category& ecat);
6  Postconditions: code() == error_code(ev, ecat).

const error_code& code() const noexcept;
7  Returns: ec or error_code(ev, ecat), from the constructor, as appropriate.

const char* what() const noexcept override;
8  Returns: An NTBS incorporating the arguments supplied in the constructor.
    [Note 1: The returned NTBS might be the contents of what_arg + ": " + code.message(). — end note]

19.6 Stacktrace

19.6.1 General

1 Subclause 19.6 describes components that C++ programs may use to store the stacktrace of the current thread of execution and query information about the stored stacktrace at runtime.

2 The invocation sequence of the current evaluation \( x_0 \) in the current thread of execution is a sequence \((x_0, \ldots, x_n)\) of evaluations such that, for \( i \geq 0, x_i \) is within the function invocation \( x_{i+1} \) (6.9.1).

3 A stacktrace is an approximate representation of an invocation sequence and consists of stacktrace entries. A stacktrace entry represents an evaluation in a stacktrace.

19.6.2 Header <stacktrace> synopsis

#include <compare> // see 17.11.1

namespace std {
    // 19.6.3, class stacktrace_entry
    class stacktrace_entry;
}
19.6.4, class template basic_stacktrace
template<class Allocator>
class basic_stacktrace;

basic_stacktrace typedef-name
using stacktrace = basic_stacktrace<allocator<stacktrace_entry>>;

19.6.4.6, non-member functions
template<class Allocator>
void swap(basic_stacktrace<Allocator>& a, basic_stacktrace<Allocator>& b)
noexcept(noexcept(a.swap(b)));

string to_string(const stacktrace_entry& f);

template<class Allocator>
string to_string(const basic_stacktrace<Allocator>& st);

ostream& operator<<(ostream& os, const stacktrace_entry& f);

template<class Allocator>
ostream& operator<<(ostream& os, const basic_stacktrace<Allocator>& st);

19.6.5, formatting support
template<> struct formatter<stacktrace_entry>;
template<class Allocator> struct formatter<basic_stacktrace<Allocator>>;

namespace pmr {
using stacktrace = basic_stacktrace<polymorphic_allocator<stacktrace_entry>>;
}

19.6.6, hash support
template<class T> struct hash;
template<> struct hash<stacktrace_entry>;
template<class Allocator> struct hash<basic_stacktrace<Allocator>>;

19.6.3 Class stacktrace_entry
19.6.3.1 Overview

namespace std {
class stacktrace_entry {
public:
  using native_handle_type = implementation-defined;

  // 19.6.3.2, constructors
  constexpr stacktrace_entry() noexcept;
  constexpr stacktrace_entry(const stacktrace_entry& other) noexcept;
  constexpr stacktrace_entry& operator=(const stacktrace_entry& other) noexcept;
  ~stacktrace_entry();

  // 19.6.3.3, observers
  constexpr native_handle_type native_handle() const noexcept;
  constexpr explicit operator bool() const noexcept;

  // 19.6.3.4, query
  string description() const;
  string source_file() const;
  uint_least32_t source_line() const;

  // 19.6.3.5, comparison
  friend constexpr bool operator==(const stacktrace_entry& x,
                                   const stacktrace_entry& y) noexcept;
  friend constexpr strong_ordering operator<=>(const stacktrace_entry& x,
                                               const stacktrace_entry& y) noexcept;
}
An object of type `stacktrace_entry` is either empty, or represents a stacktrace entry and provides operations for querying information about it. The class `stacktrace_entry` models regular (18.6) and three-way-comparable<strong_ordering> (17.11.4).

### 19.6.3.2 Constructors

```cpp
constexpr stacktrace_entry() noexcept;
```

*Postconditions:* `*this` is empty.

### 19.6.3.3 Observers

```cpp
constexpr native_handle_type native_handle() const noexcept;
```

*Remarks:* Successive invocations of the `native_handle` function for an unchanged `stacktrace_entry` object return identical values.

```cpp
constexpr explicit operator bool() const noexcept;
```

*Returns:* `false` if and only if `*this` is empty.

### 19.6.3.4 Query

1. `[Note 1: All the stacktrace_entry query functions treat errors other than memory allocation errors as “no information available” and do not throw in that case. — end note]`

```cpp
string description() const;
```

*Returns:* A description of the evaluation represented by `*this`, or an empty string.

```cpp
string source_file() const;
```

*Returns:* The presumed or actual name of the source file (15.11) that lexically contains the expression or statement whose evaluation is represented by `*this`, or an empty string.

```cpp
uint_least32_t source_line() const;
```

*Returns:* 0, or a 1-based line number that lexically relates to the evaluation represented by `*this`. If `source_file` returns the presumed name of the source file, returns the presumed line number; if `source_file` returns the actual name of the source file, returns the actual line number.

### 19.6.3.5 Comparison

```cpp
friend constexpr bool operator==(const stacktrace_entry& x, const stacktrace_entry& y) noexcept;
```

*Returns:* `true` if and only if `x` and `y` represent the same stacktrace entry or both `x` and `y` are empty.

### 19.6.4 Class template basic_stacktrace

### 19.6.4.1 Overview

```cpp
namespace std {

template<class Allocator>

class basic_stacktrace {

using value_type = stacktrace_entry;

using const_reference = const value_type&;

using reference = value_type&;

using const_iterator = implementation-defined; // see 19.6.4.3

using iterator = const_iterator;

using reverse_iterator = std::reverse_iterator<iterator>;

}```

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602
using const_reverse_iterator = std::reverse_iterator<const_iterator>;
using difference_type = implementation-defined;
using size_type = implementation-defined;
using allocator_type = Allocator;

// 19.6.4.2, creation and assignment
static basic_stacktrace current(const allocator_type& alloc = allocator_type()) noexcept;
static basic_stacktrace current(size_type skip, const allocator_type& alloc = allocator_type()) noexcept;
static basic_stacktrace current(size_type skip, size_type max_depth, const allocator_type& alloc = allocator_type()) noexcept;
basic_stacktrace() noexcept(is_nothrow_default_constructible_v<allocator_type>);
explicit basic_stacktrace(const allocator_type& alloc) noexcept;
basic_stacktrace(const basic_stacktrace& other);
basic_stacktrace(basic_stacktrace&& other) noexcept;
basic_stacktrace(const basic_stacktrace& other, const allocator_type& alloc);
basic_stacktrace(basic_stacktrace&& other, const allocator_type& alloc);
basic_stacktrace& operator=(const basic_stacktrace& other);
basic_stacktrace& operator=(basic_stacktrace&& other) noexcept(noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value || allocator_traits<Allocator>::is_always_equal::value));
~basic_stacktrace();

// 19.6.4.3, observers
allocator_type get_allocator() const noexcept;
const_iterator begin() const noexcept;
const_iterator end() const noexcept;
const_reverse_iterator rbegin() const noexcept;
const_reverse_iterator rend() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;
const_reference operator[](size_type) const;
const_reference at(size_type) const;

// 19.6.4.4, comparisons
template<class Allocator2>
friend bool operator==(const basic_stacktrace& x, const basic_stacktrace<Allocator2>& y) noexcept;
template<class Allocator2>
friend strong_ordering operator<=>(const basic_stacktrace& x, const basic_stacktrace<Allocator2>& y) noexcept;

// 19.6.4.5, modifiers
void swap(basic_stacktrace& other) noexcept(allocator_traits<Allocator>::propagate_on_container_swap::value || allocator_traits<Allocator>::is_always_equal::value);

private:
  vector<value_type, allocator_type> frames_; // exposition only
};
The class template `basic_stacktrace` satisfies the requirements of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), and of a sequence container (24.2.4), except that

1. only move, assignment, swap, and operations defined for const-qualified sequence containers are supported and,
2. the semantics of comparison functions are different from those required for a container.

19.6.4.2 Creation and assignment

```
static basic_stacktrace current(const allocator_type& alloc = allocator_type()) noexcept;
```

Returns: A `basic_stacktrace` object with `frames_` storing the stacktrace of the current evaluation in the current thread of execution, or an empty `basic_stacktrace` object if the initialization of `frames_` failed. `alloc` is passed to the constructor of the `frames_` object.

[Note 1: If the stacktrace was successfully obtained, then `frames_.front()` is the `stacktrace_entry` representing approximately the current evaluation, and `frames_.back()` is the `stacktrace_entry` representing approximately the initial function of the current thread of execution. —end note]

```
static basic_stacktrace current(size_type skip, const allocator_type& alloc = allocator_type()) noexcept;
```

Let `t` be a stacktrace as-if obtained via `basic_stacktrace::current(alloc)`. Let `n` be `t.size()`.

Returns: A `basic_stacktrace` object where `frames_` is direct-non-list-initialized from arguments `t.begin() + min(n, skip)`, `t.end()`, and `alloc`, or an empty `basic_stacktrace` object if the initialization of `frames_` failed.

```
static basic_stacktrace current(size_type skip, size_type max_depth, const allocator_type& alloc = allocator_type()) noexcept;
```

Let `t` be a stacktrace as-if obtained via `basic_stacktrace::current(alloc)`. Let `n` be `t.size()`.

Preconditions: `skip <= skip + max_depth` is true.

Returns: A `basic_stacktrace` object where `frames_` is direct-non-list-initialized from arguments `t.begin() + min(n, skip)`, `t.begin() + min(n, skip + max_depth)`, and `alloc`, or an empty `basic_stacktrace` object if the initialization of `frames_` failed.

```
basic_stacktrace() noexcept(is_nothrow_default_constructible_v<allocator_type>);
```

Postconditions: `empty()` is true.

```
explicit basic_stacktrace(const allocator_type& alloc) noexcept;
```

Effects: `alloc` is passed to the `frames_` constructor.

```
basic_stacktrace(const basic_stacktrace& other);
```

```
basic_stacktrace(const basic_stacktrace& other, const allocator_type& alloc);
```

```
basic_stacktrace(basic_stacktrace&& other, const allocator_type& alloc);
```

```
basic_stacktrace& operator=(const basic_stacktrace& other);
```

```
basic_stacktrace& operator=(basic_stacktrace&& other) noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value || allocator_traits<Allocator>::is_always_equal::value);
```

Remarks: Implementations may strengthen the exception specification for these functions (16.4.6.13) by ensuring that `empty()` is `true` on failed allocation.

19.6.4.3 Observers

```
using const_iterator = implementation-defined;
```

The type models `random_access_iterator` (25.3.4.13) and meets the `Cpp17RandomAccessIterator` requirements (25.3.5.7).

```
allocator_type get_allocator() const noexcept;
```

Returns: `frames_.get_allocator()`.
const_iterator begin() const noexcept;
const_iterator cbegin() const noexcept;

Returns: An iterator referring to the first element in `frames_`. If `empty()` is true, then it returns the same value as `end()`.

const_iterator end() const noexcept;
const_iterator cend() const noexcept;

Returns: The end iterator.

const_reverse_iterator rbegin() const noexcept;
const_reverse_iterator crbegin() const noexcept;

Returns: reverse_iterator(cend()).

const_reverse_iterator rend() const noexcept;
const_reverse_iterator crend() const noexcept;

Returns: reverse_iterator(cbegin()).

[[nodiscard]] bool empty() const noexcept;

size_type size() const noexcept;

size_type max_size() const noexcept;

Returns: `frames_.size()`.

const_reference operator[](size_type frame_no) const;

Returns: `frames_[frame_no]`.

10

Throws: Nothing.

11

const_reference at(size_type frame_no) const;

Returns: `frames_[frame_no]`.

12

 Throws: `out_of_range` if `frame_no >= size()`.

13

19.6.4.4 Comparisons [stacktrace.basic.cmp]

template<class Allocator2>
friend bool operator==(const basic_stacktrace& x, const basic_stacktrace<Allocator2>& y) noexcept;

Returns: `equal(x.begin(), x.end(), y.begin(), y.end())`.

1

template<class Allocator2>
friend strong_ordering
operator<=>(const basic_stacktrace& x, const basic_stacktrace<Allocator2>& y) noexcept;

Returns: `x.size() <=> y.size()` if `x.size() != y.size()`; lexicographical_compare_three-way(x.begin(), x.end(), y.begin(), y.end()) otherwise.

2

19.6.4.5 Modifiers [stacktrace.basic.mod]

void swap(basic_stacktrace& other)

noexcept(allocation_traits<Allocator>::propagate_on_container_swap::value ||
allocation_traits<Allocator>::is_always_equal::value);

1

Effects: Exchanges the contents of *this and other.

19.6.4.6 Non-member functions [stacktrace.basic.nonmem]
template<class Allocator>
void swap(basic_stacktrace<Allocator>& a, basic_stacktrace<Allocator>& b)
   noexcept(noexcept(a.swap(b)));

 Effects: Equivalent to a.swap(b).

string to_string(const stacktrace_entry& f);

 Returns: A string with a description of f.

 Recommended practice: The description should provide information about the contained evaluation,
 including information from f.source_file() and f.source_line().

template<class Allocator>
string to_string(const basic_stacktrace<Allocator>& st);

 Returns: A string with a description of st.

 [Note 1: The number of lines is not guaranteed to be equal to st.size(). — end note]

ostream& operator<<(ostream& os, const stacktrace_entry& f);

 Effects: Equivalent to: return os << to_string(f);

template<class Allocator>
ostream& operator<<(ostream& os, const basic_stacktrace<Allocator>& st);

 Effects: Equivalent to: return os << to_string(st);

19.6.5 Formatting support [stacktrace.format]

template<> struct formatter<stacktrace_entry>;

 formatter<stacktrace_entry> interprets format-spec as a stacktrace-entry-format-spec. The syntax of
 format specifications is as follows:

 stacktrace-entry-format-spec:

 fill-and-align opt width opt

 [Note 1: The productions fill-and-align and width are described in 22.14.2.2. — end note]

 A stacktrace_entry object se is formatted as if by copying to_string(se) through the output
 iterator of the context with additional padding and adjustments as specified by the format specifiers.

template<class Allocator> struct formatter.basic_stacktrace<Allocator>;

 For formatter<basic_stacktrace<Allocator>>, format-spec is empty.

 A basic_stacktrace<Allocator> object s is formatted as if by copying to_string(s) through the
 output iterator of the context.

19.6.6 Hash support [stacktrace.basic.hash]

template<> struct hash<stacktrace_entry>;

template<class Allocator> struct hash<basic_stacktrace<Allocator>>;

 The specializations are enabled (22.10.19).
20 Memory management library [mem]

20.1 General [mem.general]
1 This Clause describes components for memory management.
2 The following subclauses describe general memory management facilities, smart pointers, memory resources, and scoped allocators, as summarized in Table 47.

Table 47 — Memory management library summary [tab:mem.summary]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.2 Memory</td>
<td><code>&lt;cstdlib&gt;</code>, <code>&lt;memory&gt;</code></td>
</tr>
<tr>
<td>20.3 Smart pointers</td>
<td><code>&lt;memory&gt;</code></td>
</tr>
<tr>
<td>20.4 Memory resources</td>
<td><code>&lt;memory_resource&gt;</code></td>
</tr>
<tr>
<td>20.5 Scoped allocators</td>
<td><code>&lt;scoped_allocator&gt;</code></td>
</tr>
</tbody>
</table>

20.2 Memory [memory]
20.2.1 General [memory.general]
1 Subclause 20.2 describes the contents of the header `<memory>` (20.2.2) and some of the contents of the header `<cstdlib>` (17.2.2).

20.2.2 Header `<memory>` synopsis [memory.syn]
1 The header `<memory>` defines several types and function templates that describe properties of pointers and pointer-like types, manage memory for containers and other template types, destroy objects, and construct objects in uninitialized memory buffers (20.2.3–20.2.11 and 27.11). The header also defines the templates `unique_ptr`, `shared_ptr`, `weak_ptr`, `out_ptr_t`, `inout_ptr_t`, and various function templates that operate on objects of these types (20.3).

2 Let `POINTER_OF(T)` denote a type that is

- (2.1) `T::pointer` if the qualified-id `T::pointer` is valid and denotes a type,
- (2.2) `T::element_type*` if the qualified-id `T::element_type` is valid and denotes a type,
- (2.3) otherwise, `pointer_traits<T>::element_type*`.

3 Let `POINTER_OF_OR(T, U)` denote a type that is:

- (3.1) `POINTER_OF(T)` if `POINTER_OF(T)` is valid and denotes a type,
- (3.2) otherwise, `U`.

```cpp
#include <compare>
// see 17.11.1
namespace std {

   // 20.2.3, pointer traits
   template<class Ptr> struct pointer_traits; // freestanding
   template<class T> struct pointer_traits<T*>; // freestanding

   // 20.2.4, pointer conversion
   template<class T>
   constexpr T* to_address(T* p) noexcept; // freestanding
   template<class Ptr>
   constexpr auto to_address(const Ptr& p) noexcept; // freestanding

   // 20.2.5, pointer alignment
   void* align(size_t alignment, size_t size, void*& ptr, size_t& space); // freestanding
   template <size_t N, class T>
   [[nodiscard]] constexpr T* assume_aligned(T* ptr); // freestanding

```

§ 20.2.2 ©ISO/IEC 607
// 20.2.6, explicit lifetime management

template<class T>
    T* start_lifetime_as(void* p) noexcept; // freestanding

template<class T>
    const T* start_lifetime_as(const void* p) noexcept; // freestanding

template<class T>
    volatile T* start_lifetime_as(volatile void* p) noexcept; // freestanding

template<class T>
    const volatile T* start_lifetime_as(const volatile void* p) noexcept; // freestanding

template<class T>
    T* start_lifetime_as_array(void* p, size_t n) noexcept; // freestanding

template<class T>
    const T* start_lifetime_as_array(const void* p, size_t n) noexcept; // freestanding

template<class T>
    volatile T* start_lifetime_as_array(volatile void* p, size_t n) noexcept; // freestanding

template<class T>
    const volatile T* start_lifetime_as_array(const volatile void* p, size_t n) noexcept; // freestanding

// 20.2.7, allocator argument tag

struct allocator_arg_t { explicit allocator_arg_t() = default; }; // freestanding

inline constexpr allocator_arg_t allocator_arg{}; // freestanding

// 20.2.8, uses_allocator

template<class T, class Alloc> struct uses_allocator; // freestanding

// 20.2.8.1, uses_allocator

template<class T, class Alloc>
    constexpr bool uses_allocator_v = uses_allocator<T, Alloc>::value; // freestanding

// 20.2.8.2, uses-allocator construction

template<class T, class Alloc, class... Args>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        Arg&&... args) noexcept; // freestanding

template<class T, class Alloc, class Tuple1, class Tuple2>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        piecewise_construct_t,
        Tuple1&& x, Tuple2&& y) noexcept; // freestanding

template<class T, class Alloc>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc) noexcept; // freestanding

template<class T, class Alloc, class U, class V>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        pair<U, V>& pr) noexcept; // freestanding

template<class T, class Alloc, class U, class V>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        const pair<U, V>& pr) noexcept; // freestanding

template<class T, class Alloc, class U, class V>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        pair<U, V>&& pr) noexcept; // freestanding

template<class T, class Alloc, class U, class V>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        const pair<U, V>&& pr) noexcept; // freestanding

// freestanding

template<class T, class Alloc, class P>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        P&& p) noexcept; // freestanding

template<class T, class Alloc, class U>
    constexpr auto uses_allocator_construction_args(const Alloc& alloc,
        U&& u) noexcept; // freestanding

// freestanding

template<class T, class Alloc, class Arg...>
    constexpr T make_obj_using_allocator(const Alloc& alloc, Arg&&... args); // freestanding
template<class T, class Alloc, class... Args>
constexpr T* uninitialized_construct_using_allocator(T* p, // freestanding
cast Alloc alloc, Args&&... args);

// 20.2.9, allocator traits
template<class Alloc> struct allocator_traits; // freestanding

// freestanding
template<class Pointer, class SizeType = size_t>
struct allocation_result {
  Pointer ptr;
  SizeType count;
};

// 20.2.9, allocator traits
template<class Alloc> struct allocator_traits;

// freestanding
template<class Pointer, class SizeType = size_t>
struct allocation_result {
  Pointer ptr;
  SizeType count;
};

// 20.2.10, the default allocator
template<class T> class allocator;

template<class T, class U>
constexpr bool operator==(const allocator<T>&, const allocator<U>&) noexcept;

// 20.2.11, addressof
template<class T>
constexpr T* addressof(T& r) noexcept; // freestanding

template<class T>
const T* addressof(const T&&) = delete; // freestanding

// 27.11, specialized algorithms
// 27.11.2, special memory concepts

namespace ranges {
  template<nothrow-forward-iterator I, noexcept-sentinel-for I> S>
  requires default_initializable<iter_value_t<I>>
  I uninitialized_default_construct(I first, S last);

  template<class ExecutionPolicy, class NoThrowForwardIterator>
  void uninitialized_default_construct(ExecutionPolicy&& exec,
                                      NoThrowForwardIterator first,
                                      NoThrowForwardIterator last);

  template<class NoThrowForwardIterator, class Size>
  NoThrowForwardIterator
  uninitialized_default_construct_n(NoThrowForwardIterator first, Size n); // freestanding

  template<class ExecutionPolicy, class NoThrowForwardIterator, class Size>
  NoThrowForwardIterator
  uninitialized_default_construct_n(ExecutionPolicy&& exec,
                                  NoThrowForwardIterator first, Size n); // see 27.3.5

  namespace ranges {
    template<nothrow-forward-iterator I, noexcept-sentinel-for I> S>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_default_construct(I first, S last);

    template<nothrow-forward-range R>
    requires default_initializable<range_value_t<R>>
    borrowed_iterator_t<R> uninitialized_default_construct(R&& r); // freestanding

    template<nothrow-forward-iterator I>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_default_construct_n(I first, iter_difference_t<I> n); // freestanding
  }
}

§ 20.2.2 ©ISO/IEC 690
template<class NoThrowForwardIterator>
void uninitialized_value_construct(NoThrowForwardIterator first,
NoThrowForwardIterator last);  // freestanding

template<class ExecutionPolicy, class NoThrowForwardIterator>
void uninitialized_value_construct(ExecutionPolicy&& exec,
NoThrowForwardIterator first,
NoThrowForwardIterator last);  // see 27.3.5

namespace ranges {
    template<nothrow-forward-iterator I, noexcept-sentinel-for<I> S>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_value_construct(I first, S last);  // freestanding

    template<nothrow-forward-range R>
    requires default_initializable<range_value_t<R>>
    borrowed_iterator_t<R> uninitialized_value_construct(R&& r);  // freestanding

    template<nothrow-forward-iterator I>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_value_construct_n(I first, iter_difference_t<I> n);  // freestanding
}

template<class InputIterator, class NoThrowForwardIterator>
NoThrowForwardIterator uninitialized_copy(InputIterator first,
InputIterator last,
NoThrowForwardIterator result);  // freestanding

template<class ExecutionPolicy, class ForwardIterator, class NoThrowForwardIterator>
NoThrowForwardIterator uninitialized_copy(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last,
NoThrowForwardIterator result);  // see 27.3.5

namespace ranges {
    template<input_iterator I, sentinel_for<I> S1,
             nothrow-forward-iterator O, noexcept-sentinel-for<O> S2>
    requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
    uninitialized_copy_result<I, O>
    uninitialized_copy(I ifirst, S1 ilast, O ofirst, S2 olast);  // freestanding

    template<input_range IR, noexcept-forward-range OR>
    requires constructible_from<range_value_t<OR>, range_reference_t<IR>>
    uninitialized_copy_result<borrowed_iterator_t<IR>, borrowed_iterator_t<OR>>
    uninitialized_copy(IR&& in_range, OR&& out_range);  // freestanding
}

§ 20.2.2 © ISO/IEC 610
ofirst, S olast);

} // freestanding

// see 27.3.5


namespace ranges {
  template<class I, class O>
  using uninitialized_move_result = in_out_result<I, O>; // freestanding

  template<input_iterator I, sentinel_for<I> S1, noexcept-forward_iterator O, noexcept-sentinel_for<O> S2>
  requires constructible_from<iter_value_t<O>, iter_rvalue_reference_t<I>>
  uninitialized_move_result<I, O>
  uninitialized_move(I ifirst, S1 ilast, O ofirst, S2 olast);

  template<input_range IR, noexcept-forward-range OR>
  requires constructible_from<range_value_t<OR>, range_rvalue_reference_t<IR>>
  uninitialized_move_result<borrowed_iterator_t<IR>, borrowed_iterator_t<OR>>
  uninitialized_move(IR&& in_range, OR&& out_range);

  template<class I, class O>
  using uninitialized_move_n_result = in_out_result<I, O>; // freestanding

  template<input_iterator I, noexcept-forward_iterator O, noexcept-sentinel_for<O> S>
  requires constructible_from<iter_value_t<O>, const T&>
  uninitialized_move_n_result<I, O, T>
  uninitialized_move_n(I ifirst, iter_difference_t<I> n, O ofirst, S olast);

  template<class NoThrowForwardIterator, class T>
  void uninitialized_fill(NoThrowForwardIterator first, NoThrowForwardIterator last, const T& x); // freestanding

  template<class ExecutionPolicy, class NoThrowForwardIterator, class T>
  void uninitialized_fill(ExecutionPolicy&& exec, NoThrowForwardIterator first, NoThrowForwardIterator last, const T& x); // see 27.3.5

  template<class NoThrowForwardIterator, class Size, class T>
  NoThrowForwardIterator uninitialized_fill_n(NoThrowForwardIterator first, Size n, const T& x); // freestanding

  template<class ExecutionPolicy, class NoThrowForwardIterator, class Size, class T>
  NoThrowForwardIterator uninitialized_fill_n(ExecutionPolicy&& exec, NoThrowForwardIterator first, Size n, const T& x); // see 27.3.5

  namespace ranges {
    template<nothrow-forward_iterator I, noexcept-sentinel_for<I> S, class T>
    requires constructible_from<iter_value_t<I>, const T&>
    I uninitialized_fill(I first, S last, const T& x); // freestanding
  
} // freestanding
template<nothrow-forward-range R, class T>
    requires constructible_from<range_value_t<R>, const T&>
    borrowed_iterator_t<R> uninitialized_fill(R&& r, const T& x); // freestanding

template<nothrow-forward-iterator I, class T>
    requires constructible_from<iter_value_t<I>, const T&>
    I uninitialized_fill_n(I first, iter_difference_t<I> n, const T& x); // freestanding

// 27.11.8, construct_at
template<class T, class... Args>
    constexpr T* construct_at(T* location, Args&&... args); // freestanding
namespace ranges {
    template<class T, class... Args>
        constexpr T* construct_at(T* location, Args&&... args); // freestanding
}

// 27.11.9, destroy
template<class T>
    constexpr void destroy_at(T* location); // freestanding
template<class NoThrowForwardIterator>
    constexpr void destroy(NoThrowForwardIterator first, NoThrowForwardIterator last); // freestanding
template<class ExecutionPolicy, class NoThrowForwardIterator>
    void destroy(ExecutionPolicy&& exec, NoThrowForwardIterator first, NoThrowForwardIterator last); // see 27.3.5
template<class NoThrowForwardIterator, class Size>
    constexpr NoThrowForwardIterator destroy_n(NoThrowForwardIterator first, Size n); // freestanding
namespace ranges {
    template<destructible T>
        constexpr void destroy_at(T* location) noexcept; // freestanding
    template<nothrow-input-iterator I, nothrow-sentinel-for<I> S>
        requires destructible<iter_value_t<I>>
        constexpr I destroy(I first, S last) noexcept; // freestanding
    template<nothrow-input-range R>
        requires destructible<range_value_t<R>>
        constexpr borrowed_iterator_t<R> destroy(R&& r) noexcept; // freestanding
    template<nothrow-input-iterator I>
        requires destructible<iter_value_t<I>>
        constexpr I destroy_n(I first, iter_difference_t<I> n) noexcept; // freestanding
}

// 20.3.1, class template unique_ptr
template<class T> struct default_delete;
template<class T> struct default_delete<T[]>; // freestanding
template<class T, class D = default_delete<T[]>> class unique_ptr;
template<class T, class D> class unique_ptr<T[], D>; // freestanding

template<class T, class... Args>
    constexpr unique_ptr<T> make_unique(Args&&... args); // T is not array
template<class T>
    constexpr unique_ptr<T> make_unique(size_t n); // T is U[]
template<class T, class... Args>
    unspecified make_unique(Args&&...) = delete; // T is U[N]
template<class T>
constexpr unique_ptr<T> make_unique_for_overwrite(); // T is not array

template<class T>
constexpr unique_ptr<T> make_unique_for_overwrite(size_t n); // T is U[]

template<class T, class... Args>
unspecified make_unique_for_overwrite(Args&&...); // T is U[N]

template<class T, class D>
constexpr void swap(unique_ptr<T, D>& x, unique_ptr<T, D>& y) noexcept; // freestanding

template<class T1, class D1, class T2, class D2>
constexpr bool operator==(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y); // freestanding

template<class T1, class D1, class T2, class D2>
bool operator<(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y); // freestanding

template<class T1, class D1, class T2, class D2>
bool operator>(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y); // freestanding

template<class T1, class D1, class T2, class D2>
bool operator<=(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y); // freestanding

template<class T1, class D1, class T2, class D2>
requires three_way_comparable_with<typename unique_ptr<T1, D1>::pointer, typename unique_ptr<T2, D2>::pointer>
operator<=>(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y); // freestanding

template<class T, class D>
constexpr bool operator==(const unique_ptr<T, D>& x, nullptr_t) noexcept; // freestanding

template<class T, class D>
constexpr bool operator<(const unique_ptr<T, D>& x, nullptr_t); // freestanding

template<class T, class D>
constexpr bool operator<(nullptr_t, const unique_ptr<T, D>& y); // freestanding

template<class T, class D>
constexpr bool operator>(const unique_ptr<T, D>& x, nullptr_t); // freestanding

template<class T, class D>
constexpr bool operator>(nullptr_t, const unique_ptr<T, D>& y); // freestanding

template<class T, class D>
constexpr bool operator<=(const unique_ptr<T, D>& x, nullptr_t); // freestanding

template<class T, class D>
constexpr bool operator<=(nullptr_t, const unique_ptr<T, D>& y); // freestanding

template<class T, class D>
requires three_way_comparable<typename unique_ptr<T, D>::pointer>
constexpr compare_three_way_result_t<typename unique_ptr<T, D>::pointer> operator<=>(const unique_ptr<T, D>& x, nullptr_t); // freestanding

template<class E, class T, class Y, class D>
basic_ostream<E, T>& operator<<(basic_ostream<E, T>& os, const unique_ptr<Y, D>& p); // § 20.2.2

// 20.3.2.1, class bad_weak_ptr
class bad_weak_ptr;

// 20.3.2.2, class template shared_ptr
template<T> class shared_ptr;

// 20.3.2.2.7, shared_ptr creation
template<class T, class... Args>
shared_ptr<T> make_shared(Args&&... args); // T is not array
template<class T, class A, class... Args>
    shared_ptr<T> allocate_shared(const A& a, Args&&... args); // T is not array

template<class T>
    shared_ptr<T> make_shared(size_t N); // T is U[N]
template<class T, class A>
    shared_ptr<T> allocate_shared(const A& a, size_t N); // T is U[N]

template<class T>
    shared_ptr<T> make_shared(); // T is U[N]
template<class T, class A>
    shared_ptr<T> allocate_shared(const A& a); // T is U[N]

template<class T>
    shared_ptr<T> make_shared(size_t N, const remove_extent_t<T>& u); // T is U[N]
template<class T, class A>
    shared_ptr<T> allocate_shared(const A& a, size_t N,
                                const remove_extent_t<T>& u); // T is U[N]

template<class T>
    shared_ptr<T> make_shared(const remove_extent_t<T>& u); // T is U[N]
template<class T, class A>
    shared_ptr<T> allocate_shared(const A& a, const remove_extent_t<T>& u); // T is U[N]

template<class T>
    shared_ptr<T> make_shared_for_overwrite(); // T is not U[N]
template<class T, class A>
    shared_ptr<T> allocate_shared_for_overwrite(const A& a); // T is not U[N]

template<class T>
    shared_ptr<T> make_shared_for_overwrite(size_t N); // T is U[N]
template<class T, class A>
    shared_ptr<T> allocate_shared_for_overwrite(const A& a, size_t N); // T is U[N]

// 20.3.2.2.8, shared_ptr comparisons
template<class T, class U>
    bool operator==(const shared_ptr<T>& a, const shared_ptr<U>& b) noexcept;
template<class T, class U>
    strong_ordering operator<=>(const shared_ptr<T>& a, const shared_ptr<U>& b) noexcept;

template<class T>
    bool operator==(const shared_ptr<T>& x, nullptr_t) noexcept;
template<class T>
    strong_ordering operator<=>(const shared_ptr<T>& x, nullptr_t) noexcept;

// 20.3.2.2.9, shared_ptr specialized algorithms
template<class T>
    void swap(shared_ptr<T>& a, shared_ptr<T>& b) noexcept;

// 20.3.2.2.10, shared_ptr casts
template<class T, class U>
    shared_ptr<T> static_pointer_cast(const shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> static_pointer_cast(shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> dynamic_pointer_cast(const shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> dynamic_pointer_cast(shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> const_pointer_cast(const shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> const_pointer_cast(shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> reinterpret_pointer_cast(const shared_ptr<U>& r) noexcept;
template<class T, class U>
    shared_ptr<T> reinterpret_pointer_cast(shared_ptr<U>&& r) noexcept;

// 20.3.2.2.11, shared_ptr get_deleter
template<class D, class T>
    D* get_deleter(const shared_ptr<T>& p) noexcept;

// 20.3.2.2.12, shared_ptr I/O
template<class E, class T, class Y>
    basic_ostream<E, T>& operator<<(basic_ostream<E, T>& os, const shared_ptr<Y>& p);

// 20.3.2.3, class template weak_ptr
template<class T> class weak_ptr;

// 20.3.2.3.7, weak_ptr specialized algorithms
template<class T> void swap(weak_ptr<T>& a, weak_ptr<T>& b) noexcept;

// 20.3.2.4, class template owner_less
template<class T = void> struct owner_less;

// 20.3.2.5, struct owner_hash
struct owner_hash;

// 20.3.2.6, struct owner_equal
struct owner_equal;

// 20.3.2.7, class template enable_shared_from_this
template<class T> class enable_shared_from_this;

// 20.3.3, hash support
template<class T> struct hash; // freestanding
template<class T, class D> struct hash<unique_ptr<T, D>>; // freestanding
template<class T> struct hash<shared_ptr<T>>;

// 33.5.8.7, atomic smart pointers
template<class T> struct atomic; // freestanding
template<class T> struct atomic<unique_ptr<T, D>>; // freestanding
template<class T> struct atomic<shared_ptr<T>>;

// 20.3.4.1, class template out_ptr_t
template<class Smart, class Pointer, class... Args>
    class out_ptr_t; // freestanding

// 20.3.4.2, function template out_ptr
template<class Pointer = void, class Smart, class... Args>
    auto out_ptr(Smart& s, Args&&... args); // freestanding

// 20.3.4.3, class template inout_ptr_t
template<class Smart, class Pointer, class... Args>
    class inout_ptr_t; // freestanding

// 20.3.4.4, function template inout_ptr
template<class Pointer = void, class Smart, class... Args>
    auto inout_ptr(Smart& s, Args&&... args); // freestanding

20.2.3 Pointer traits

20.2.3.1 General

The class template pointer_traits supplies a uniform interface to certain attributes of pointer-like types.

namespace std {
    template<class Ptr> struct pointer_traits {
        see below;
    };
}
template<class T> struct pointer_traits<T*> {
    using pointer = T*;
    using element_type = T;
    using difference_type = ptrdiff_t;

    template<class U> using rebind = U*;

    static constexpr pointer pointer_to(r) noexcept
    { return std::addressof(r); }
};

20.2.3.2 Member types

The definitions in this subclause make use of the following exposition-only class template and concept:

```cpp
template<class T>
struct ptr-traits-elem  // exposition only
{
};
```

```cpp
template<class T> requires requires { typename T::element_type; }
struct ptr-traits-elem<T>{ using type = typename T::element_type; };
```

```cpp
template<template<class...> class SomePointer, class T, class... Args>
requires (!requires { typename SomePointer<T, Args...>::element_type; })
struct ptr-traits-elem<SomePointer<T, Args...>>
{ using type = T; };
```

```cpp
template<class Ptr>
concept has-elem-type =   // exposition only
    requires { typename ptr-traits-elem<Ptr>::type; }
```

If `Ptr` satisfies `has-elem-type`, a specialization `pointer_traits<Ptr>` generated from the `pointer_traits` primary template has the following members as well as those described in 20.2.3.3; otherwise, such a specialization has no members by any of those names.

```cpp
using pointer = see below;
```

**Type:** `Ptr`.

```cpp
using element_type = see below;
```

**Type:** `typename ptr-traits-elem<Ptr>::type`.

```cpp
using difference_type = see below;
```

**Type:** `Ptr::difference_type` if the qualified-id `Ptr::difference_type` is valid and denotes a type (13.10.3); otherwise, `ptrdiff_t`.

```cpp
template<class U> using rebind = see below;
```

**Alias template:** `Ptr::rebind<U>` if the qualified-id `Ptr::rebind<U>` is valid and denotes a type (13.10.3); otherwise, `SomePointer<U, Args>` if `Ptr` is a class template instantiation of the form `SomePointer<T, Args>`, where `Args` is zero or more type arguments; otherwise, the instantiation of `rebind` is ill-formed.

20.2.3.3 Member functions

```cpp
static pointer pointer_traits::pointer_to(see below r);
static constexpr pointer pointer_traits<T*>::pointer_to(see below r) noexcept;
```

**Mandates:** For the first member function, `Ptr::pointer_to(r)` is well-formed.

**Preconditions:** For the first member function, `Ptr::pointer_to(r)` returns a pointer to `r` through which indirection is valid.

**Returns:** The first member function returns `Ptr::pointer_to(r)`. The second member function returns `addressof(r)`.

**Remarks:** If `element_type` is `cv void`, the type of `r` is unspecified; otherwise, it is `element_type`.
20.2.3.4 Optional members [pointer.traits.optmem]

Specializations of `pointer_traits` may define the member declared in this subclause to customize the behavior of the standard library. A specialization generated from the `pointer_traits` primary template has no member by this name.

```cpp
static element_type* to_address(pointer p) noexcept;
```

1 Returns: A pointer of type `element_type*` that references the same location as the argument `p`.

[Note 1: This function is intended to be the inverse of `pointer_to`. If defined, it customizes the behavior of the non-member function `to_address` (20.2.4). — end note]

20.2.4 Pointer conversion [pointer.conversion]

```cpp
template<class T> constexpr T* to_address(T* p) noexcept;
```

1 Mandates: `T` is not a function type.

2 Returns: `p`.

```cpp
template<class Ptr> constexpr auto to_address(const Ptr& p) noexcept;
```

3 Returns: `pointer_traits<Ptr>::to_address(p)` if that expression is well-formed (see 20.2.3.4), otherwise `to_address(p.operator->())`.

20.2.5 Pointer alignment [ptr.align]

```cpp
void* align(size_t alignment, size_t size, void*& ptr, size_t& space);
```

1 Preconditions:

(1.1) `alignment` is a power of two

(1.2) `ptr` represents the address of contiguous storage of at least `space` bytes

2 Effects: If it is possible to fit `size` bytes of storage aligned by `alignment` into the buffer pointed to by `ptr` with length `space`, the function updates `ptr` to represent the first possible address of such storage and decreases `space` by the number of bytes used for alignment. Otherwise, the function does nothing.

3 Returns: A null pointer if the requested aligned buffer would not fit into the available space, otherwise the adjusted value of `ptr`.

4 [Note 1: The function updates its `ptr` and `space` arguments so that it can be called repeatedly with possibly different `alignment` and `size` arguments for the same buffer. — end note]

```cpp
template<size_t N, class T> [[nodiscard]] constexpr T* assume_aligned(T* ptr);
```

5 Mandates: `N` is a power of two.

6 Preconditions: `ptr` points to an object `X` of a type similar (7.3.6) to `T`, where `X` has alignment `N` (6.7.6).

7 Returns: `ptr`.

8 Throws: Nothing.

9 [Note 2: The alignment assumption on an object `X` expressed by a call to `assume_aligned` might result in generation of more efficient code. It is up to the program to ensure that the assumption actually holds. The call does not cause the implementation to verify or enforce this. An implementation might only make the assumption for those operations on `X` that access `X` through the pointer returned by `assume_aligned`. — end note]

20.2.6 Explicit lifetime management [obj.lifetime]

```cpp
template<class T>
T* start_lifetime_as(void* p) noexcept;
```

1 Mandates: `T` is an implicit-lifetime type (6.8.1) and not an incomplete type (6.8.1).

```cpp
template<class T>
const T* start_lifetime_as(const void* p) noexcept;
```

```cpp
template<class T>
volatile T* start_lifetime_as(volatile void* p) noexcept;
```

```cpp
template<class T>
const volatile T* start_lifetime_as(const volatile void* p) noexcept;
```

§ 20.2.6 © ISO/IEC 617
Preconditions: \([p, (char*)p + \text{sizeof}(T))\) denotes a region of allocated storage that is a subset of the region of storage reachable through (6.8.4) \(p\) and suitably aligned for the type \(T\).

Effects: Implicitly creates objects (6.7.2) within the denoted region consisting of an object \(a\) of type \(T\) whose address is \(p\), and objects nested within \(a\), as follows: The object representation of \(a\) is the contents of the storage prior to the call to \textit{start\_lifetime\_as}. The value of each created object \(o\) of trivially copyable type (6.8.1) \(U\) is determined in the same manner as for a call to \texttt{bit\_cast<\(U\)>}(\(E\)) (22.15.3), where \(E\) is an lvalue of type \(U\) denoting \(a\), except that the storage is not accessed. The value of any other created object is unspecified.

[Note 1: The unspecified value can be indeterminate. —end note]

Returns: A pointer to the \(a\) defined in the Effects paragraph.

```cpp
template<class T>
T* start_lifetime_as_array(void* p, size_t n) noexcept;
template<class T>
const T* start_lifetime_as_array(const void* p, size_t n) noexcept;
template<class T>
volatile T* start_lifetime_as_array(volatile void* p, size_t n) noexcept;
template<class T>
const volatile T* start_lifetime_as_array(const volatile void* p, size_t n) noexcept;
```

Mandates: \(T\) is a complete type.

Preconditions: \(p\) is suitably aligned for an array of \(T\) or is null. \(n \leq \text{size\_t}(-1) / \text{sizeof}(T)\) is true.

Effects: If \(n > 0\) is true, equivalent to \textit{start\_lifetime\_as<\(U\)>}(\(p\)) where \(U\) is the type “array of \(n\ T\)”.

Otherwise, there are no effects.

Returns: A pointer to the first element of the created array, if any; otherwise, a pointer that compares equal to \(p\) (7.6.10).

20.2.7 Allocator argument tag

namespace std {
    struct allocator_arg_t { explicit allocator_arg_t() = default; }; inline constexpr allocator_arg_t allocator_arg{};
}

The \texttt{allocator\_arg\_t} struct is an empty class type used as a unique type to disambiguate constructor and function overloading. Specifically, several types (see \texttt{tuple} 22.4) have constructors with \texttt{allocator\_arg\_t} as the first argument, immediately followed by an argument of a type that meets the \texttt{Cpp17Allocator} requirements (16.4.4.6.1).

20.2.8 uses_allocator

20.2.8.1 uses_allocator trait

```cpp
template<class T, class Alloc> struct uses_allocator;
```

Remarks: Automatically detects whether \(T\) has a nested \texttt{allocator\_type} that is convertible from \texttt{Alloc}. Meets the \texttt{Cpp17BinaryTypeTrait} requirements (21.3.2). The implementation shall provide a definition that is derived from \texttt{true\_type} if the \texttt{qualified\_id T::allocator\_type} is valid and denotes a type (13.10.3) and \texttt{is\_convertible\_v<Alloc, T::allocator\_type> !=} \texttt{false}, otherwise it shall be derived from \texttt{false\_type}. A program may specialize this template to derive from \texttt{true\_type} for a program-defined type \(T\) that does not have a nested \texttt{allocator\_type} but nonetheless can be constructed with an allocator where either:

(1.1) — the first argument of a constructor has type \texttt{allocator\_arg\_t} and the second argument has type \texttt{Alloc} or

(1.2) — the last argument of a constructor has type \texttt{Alloc}.

20.2.8.2 Uses-allocator construction

Uses-allocator construction with allocator \texttt{alloc} and constructor arguments \texttt{args}... refers to the construction of an object of type \(T\) such that \texttt{alloc} is passed to the constructor of \(T\) if \(T\) uses an allocator type compatible
with alloc. When applied to the construction of an object of type T, it is equivalent to initializing it with the value of the expression make_obj_using_allocator<T>(alloc, args...), described below.

The following utility functions support three conventions for passing alloc to a constructor:

1. If T does not use an allocator compatible with alloc, then alloc is ignored.
2. Otherwise, if T has a constructor invocable as T(allocator_arg, alloc, args...) (leading-allocator convention), then uses-allocator construction chooses this constructor form.
3. Otherwise, if T has a constructor invocable as T(args..., alloc) (trailing-allocator convention), then uses-allocator construction chooses this constructor form.

The uses_allocator_construction_args function template takes an allocator and argument list and produces (as a tuple) a new argument list matching one of the above conventions. Additionally, overloads are provided that treat specializations of pair such that uses-allocator construction is applied individually to the first and second data members. The make_obj_using_allocator and uninitialized_construct_using_allocator function templates apply the modified constructor arguments to construct an object of type T as a return value or in-place, respectively.

[Note 1: For uses_allocator_construction_args and make_obj_using_allocator, type T is not deduced and must therefore be specified explicitly by the caller. — end note]

template<class T, class Alloc, class... Args>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, Args&&... args) noexcept;

Constraints: remove_cv_t<T> is not a specialization of pair.

Returns: A tuple value determined as follows:

1. If uses_allocator_v<remove_cv_t<T>, Alloc> is false and is_constructible_v<T, Args...> is true, return forward_as_tuple(std::forward<Args>(args)...).
2. Otherwise, if uses_allocator_v<remove_cv_t<T>, Alloc> is true and is_constructible_v<T, allocator_arg_t, const Alloc&, Args...> is true, return tuple<allocator_arg_t, const Alloc&, Args&&...>({allocator_arg, alloc, std::forward<Args>(args)...})
3. Otherwise, if uses_allocator_v<remove_cv_t<T>, Alloc> is true and is_constructible_v<T, Args..., const Alloc&> is true, return forward_as_tuple(std::forward<Args>(args)..., alloc).
4. Otherwise, the program is ill-formed.

[Note 2: This definition prevents a silent failure to pass the allocator to a constructor of a type for which uses_allocator_v<T, Alloc> is true. — end note]

template<class T, class Alloc, class Tuple1, class Tuple2>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, piecewise_construct_t, Tuple1&& x, Tuple2&& y) noexcept;

Constraints: remove_cv_t<T> is a specialization of pair.

Effects: Equivalent to:

return make_tuple(
    piecewise_construct,
    apply([&alloc](auto&&... args1) {
        return uses_allocator_construction_args<T1>(alloc, std::forward<decltype(args1)>(args1)...);
    }, std::forward<Tuple1>(x)),
    apply([&alloc](auto&&... args2) {
        return uses_allocator_construction_args<T2>(alloc, std::forward<decltype(args2)>(args2)...);
    }, std::forward<Tuple2>(y)));

template<class T, class Alloc>
constexpr auto uses_allocator_construction_args(const Alloc& alloc) noexcept;

Constraints: remove_cv_t<T> is a specialization of pair.
Effects: Equivalent to:

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, U&& u, V&& v) noexcept;
```

Constraints: remove_cv_t<T> is a specialization of pair.

Effects: Equivalent to:

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, piecewise_construct,
                                                      forward_as_tuple(std::forward<U>(u)),
                                                      forward_as_tuple(std::forward<V>(v)));
```

Constraints: remove_cv_t<T> is a specialization of pair.

Effects: Equivalent to:

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, pair<U, V>& pr) noexcept;
```

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, const pair<U, V>& pr) noexcept;
```

Constraints: remove_cv_t<T> is a specialization of pair.

Effects: Equivalent to:

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, pair<U, V>&& pr) noexcept;
```

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, const pair<U, V>&& pr) noexcept;
```

Constraints: remove_cv_t<T> is a specialization of pair.

Effects: Equivalent to:

```cpp
template<class T, class Alloc, class U, class V>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, pair-like P)
```

Constraints: remove_cv_t<T> is a specialization of pair and remove_cvref_t<P> is not a specialization of ranges::subrange.

Effects: Equivalent to:

```cpp
template<class T, class Alloc, class U>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, U&& u) noexcept;
```

Let `FUN` be the function template:

```cpp
template<class A, class B>
void FUN(const pair<A, B>&);
```

Constraints: remove_cv_t<T> is a specialization of pair, and either:

(20.1) remove_cvref_t<T> is a specialization of ranges::subrange, or

(20.2) `U` does not satisfy `pair-like` and the expression `FUN(u)` is not well-formed when considered as an unevaluated operand.

§ 20.2.8.2 ©ISO/IEC
Let \texttt{pair-constructor} be an exposition-only class defined as follows:

```cpp
class pair-constructor {
  using pair-type = remove_cv_t<T>; // exposition only

  constexpr auto do-construct(const pair-type& p) const {
    return make_obj_using_allocator<pair-type>(alloc_, p);
  }

  constexpr auto do-construct(pair-type&& p) const {
    return make_obj_using_allocator<pair-type>(alloc_, std::move(p));
  }

  const Alloc& alloc_; // exposition only
  U& u_; // exposition only

public:
  constexpr operator pair-type() const {
    return do-construct(std::forward<U>(u_));
  }
};
```

Returns: \texttt{make_tuple(pc)}, where \texttt{pc} is a \texttt{pair-constructor} object whose \texttt{alloc_} member is initialized with \texttt{alloc} and whose \texttt{u_} member is initialized with \texttt{u}.

```cpp
template<class T, class Alloc, class... Args>
constexpr T make_obj_using_allocator(const Alloc& alloc, Args&&... args);
```

Effects: Equivalent to:

```
return make_from_tuple<T>(uses_allocator_construction_args<T>(
  alloc, std::forward<Args>(args)...));
```

```cpp
template<class T, class Alloc, class... Args>
constexpr T* uninitialized_construct_using_allocator(T* p, const Alloc& alloc, Args&&... args);
```

Effects: Equivalent to:

```
return apply([&]<class... U>(U&&... xs) {
  return construct_at(p, std::forward<U>(xs)...);
}, uses_allocator_construction_args<T>(alloc, std::forward<Args>(args)...));
```

### 20.2.9 Allocator traits

#### [allocator.traits]

#### [allocator.traits.general]

The class template \texttt{allocator_traits} supplies a uniform interface to all allocator types. An allocator cannot be a non-class type, however, even if \texttt{allocator_traits} supplies the entire required interface.

[Note 1: Thus, it is always possible to create a derived class from an allocator. — end note]

If a program declares an explicit or partial specialization of \texttt{allocator_traits}, the program is ill-formed, no diagnostic required.

```cpp
namespace std {
  template<class Alloc> struct allocator_traits {
    using allocator_type = Alloc;

    using value_type = typename Alloc::value_type;

    using pointer = see below;
    using const_pointer = see below;
    using void_pointer = see below;
    using const_void_pointer = see below;

    using difference_type = see below;
    using size_type = see below;

    using propagate_on_container_copy_assignment = see below;
    using propagate_on_container_move_assignment = see below;
    using propagate_on_container_swap = see below;
  }
}
```
using is_always_equal = see below;

template<class T> using rebind_alloc = see below;
template<class T> using rebind_traits = allocator_traits<rebind_alloc<T>>;

[[nodiscard]] static constexpr pointer allocate(Alloc& a, size_type n);
[[nodiscard]] static constexpr pointer allocate(Alloc& a, size_type n, const_void_pointer hint);
[[nodiscard]] static constexpr allocation_result<pointer, size_type> allocate_at_least(Alloc& a, size_type n);
static constexpr void deallocate(Alloc& a, pointer p, size_type n);
template<class T, class... Args>
static constexpr void construct(Alloc& a, T* p, Args&&... args);
template<class T>
static constexpr void destroy(Alloc& a, T* p);
static constexpr size_type max_size(const Alloc& a) noexcept;
static constexpr Alloc select_on_container_copy_construction(const Alloc& rhs);
};

```cpp
20.2.9.2 Member types

[allocator.traits.types]
using pointer = see below;

1 Type: Alloc::pointer if the qualified-id Alloc::pointer is valid and denotes a type (13.10.3); otherwise, value_type*.

using const_pointer = see below;

2 Type: Alloc::const_pointer if the qualified-id Alloc::const_pointer is valid and denotes a type (13.10.3); otherwise, pointer_traits<pointer>::rebind<const value_type>.

using void_pointer = see below;

3 Type: Alloc::void_pointer if the qualified-id Alloc::void_pointer is valid and denotes a type (13.10.3); otherwise, pointer_traits<pointer>::rebind<void>.

using const_void_pointer = see below;

4 Type: Alloc::const_void_pointer if the qualified-id Alloc::const_void_pointer is valid and denotes a type (13.10.3); otherwise, pointer_traits<pointer>::rebind<const void>.

using difference_type = see below;

5 Type: Alloc::difference_type if the qualified-id Alloc::difference_type is valid and denotes a type (13.10.3); otherwise, pointer_traits<pointer>::rebind<difference_type>.

using size_type = see below;

6 Type: Alloc::size_type if the qualified-id Alloc::size_type is valid and denotes a type (13.10.3); otherwise, make_unsigned_t<difference_type>.

using propagate_on_container_copy_assignment = see below;

7 Type: Alloc::propagate_on_container_copy_assignment if the qualified-id Alloc::propagate_on_container_copy_assignment is valid and denotes a type (13.10.3); otherwise false_type.

using propagate_on_container_move_assignment = see below;

8 Type: Alloc::propagate_on_container_move_assignment if the qualified-id Alloc::propagate_on_container_move_assignment is valid and denotes a type (13.10.3); otherwise false_type.
```
using propagate_on_container_swap = see below;

Type: Alloc::propagate_on_container_swap if the qualified-id Alloc::propagate_on_container_swap is valid and denotes a type (13.10.3); otherwise false_type.

using is_always_equal = see below;

Type: Alloc::is_always_equal if the qualified-id Alloc::is_always_equal is valid and denotes a type (13.10.3); otherwise is_empty<Alloc>::type.

template<class T> using rebind_alloc = see below;

Alias template: Alloc::rebind<T>::other if the qualified-id Alloc::rebind<T>::other is valid and denotes a type (13.10.3); otherwise, Alloc<T, Args> if Alloc is a class template instantiation of the form Alloc<U, Args>, where Args is zero or more type arguments; otherwise, the instantiation of rebind_alloc is ill-formed.

20.2.9.3 Static member functions [allocator.traits.members]

[[nodiscard]] static constexpr pointer allocate(Alloc& a, size_type n);

Returns: a.allocate(n).

[[nodiscard]] static constexpr pointer allocate(Alloc& a, size_type n, const_void_pointer hint);

Returns: a.allocate(n, hint) if that expression is well-formed; otherwise, a.allocate(n).

[[nodiscard]] static constexpr allocation_result<pointer, size_type> allocate_at_least(Alloc& a, size_type n);

Returns: a.allocate_at_least(n) if that expression is well-formed; otherwise, {a.allocate(n), n}.

static constexpr void deallocate(Alloc& a, pointer p, size_type n);

Effects: Calls a.deallocate(p, n).

Throws: Nothing.

template<class T, class... Args>
static constexpr void construct(Alloc& a, T* p, Args&&... args);

Effects: Calls a.construct(p, std::forward<Args>(args)...) if that call is well-formed; otherwise, invokes construct_at(p, std::forward<Args>(args)....).

template<class T>
static constexpr void destroy(Alloc& a, T* p);

Effects: Calls a.destroy(p) if that call is well-formed; otherwise, invokes destroy_at(p).

static constexpr size_type max_size(const Alloc& a) noexcept;

Returns: a.max_size() if that expression is well-formed; otherwise, numeric_limits<size_type>::max()/sizeof(value_type).

static constexpr Alloc select_on_container_copy_construction(const Alloc& rhs);

Returns: rhs.select_on_container_copy_construction() if that expression is well-formed; otherwise, rhs.

20.2.9.4 Other [allocator.traits.other]

The class template allocation_result has the template parameters, data members, and special members specified above. It has no base classes or members other than those specified.

20.2.10 The default allocator [default.allocator]

20.2.10.1 General [default.allocator.general]

All specializations of the default allocator meet the allocator completeness requirements (16.4.4.6.2).
using size_type = size_t;
using difference_type = ptrdiff_t;
using propagate_on_container_move_assignment = true_type;

constexpr allocator() noexcept;
constexpr allocator(const allocator&) noexcept;
template<class U> constexpr allocator(const allocator<U>&) noexcept;
constexpr ~allocator();
constexpr allocator& operator=(const allocator&) = default;

[[nodiscard]] constexpr T* allocate(size_t n);
[[nodiscard]] constexpr allocation_result<T*> allocate_at_least(size_t n);
constexpr void deallocate(T* p, size_t n);
};

2 allocator_traits<allocator<T>>::is_always_equal::value is true for any T.

20.2.10.2 Members

Except for the destructor, member functions of the default allocator shall not introduce data races (6.9.2) as a result of concurrent calls to those member functions from different threads. Calls to these functions that allocate or deallocate a particular unit of storage shall occur in a single total order, and each such deallocation call shall happen before the next allocation (if any) in this order.

[[nodiscard]] constexpr T* allocate(size_t n);

1 Mandates: T is not an incomplete type (6.8.1).

2 Returns: A pointer to the initial element of an array of n T.

3 Throws: bad_array_new_length if numeric_limits<size_t>::max() / sizeof(T) < n, or bad_alloc if the storage cannot be obtained.

4 Remarks: The storage for the array is obtained by calling ::operator new (17.6.3), but it is unspecified when or how often this function is called. This function starts the lifetime of the array object, but not that of any of the array elements.

[[nodiscard]] constexpr allocation_result<T*> allocate_at_least(size_t n);

5 Mandates: T is not an incomplete type (6.8.1).

6 Returns: allocation_result<T*>{ptr, count}, where ptr is a pointer to the initial element of an array of count T and count ≥ n.

7 Throws: bad_array_new_length if numeric_limits<size_t>::max() / sizeof(T) < n, or bad_alloc if the storage cannot be obtained.

8 Remarks: The storage for the array is obtained by calling ::operator new, but it is unspecified when or how often this function is called. This function starts the lifetime of the array object, but not that of any of the array elements.

constexpr void deallocate(T* p, size_t n);

9 Preconditions:

10.1 If p is memory that was obtained by a call to allocate_at_least, let ret be the value returned and req be the value passed as the first argument to that call. p is equal to ret.ptr and n is a value such that req ≤ n ≤ ret.count.

10.2 Otherwise, p is a pointer value obtained from allocate. n equals the value passed as the first argument to the invocation of allocate which returned p.

11 Effects: Deallocates the storage referenced by p.

12 Remarks: Uses ::operator delete (17.6.3), but it is unspecified when this function is called.

20.2.10.3 Operators

§ 20.2.10.3 ©ISO/IEC 624
template<class T, class U>
constexpr bool operator==(const allocator<T>&, const allocator<U>&) noexcept;

Returns: true.

20.2.11 addressof

template<class T> constexpr T* addressof(T& r) noexcept;

Returns: The actual address of the object or function referenced by r, even in the presence of an overloaded operator&.
Remarks: An expression addressof(E) is a constant subexpression (3.14) if E is an lvalue constant subexpression.

20.2.12 C library memory allocation

void* aligned_alloc(size_t alignment, size_t size);
void* calloc(size_t nmemb, size_t size);
void* malloc(size_t size);
void* realloc(void* ptr, size_t size);

Effects: These functions have the semantics specified in the C standard library.
Remarks: These functions do not attempt to allocate storage by calling ::operator new() (17.6.3).
These functions implicitly create objects (6.7.2) in the returned region of storage and return a pointer to a suitable created object. In the case of calloc and realloc, the objects are created before the storage is zeroed or copied, respectively.
void free(void* ptr);

Effects: This function has the semantics specified in the C standard library.
Remarks: This function does not attempt to deallocate storage by calling ::operator delete().

See also: ISO/IEC 9899:2018, 7.22.3

20.3 Smart pointers

20.3.1 Unique-ownership pointers

20.3.1.1 General

A unique pointer is an object that owns another object and manages that other object through a pointer. More precisely, a unique pointer is an object u that stores a pointer to a second object p and will dispose of p when u is itself destroyed (e.g., when leaving block scope (8.8)). In this context, u is said to own p.

The mechanism by which u disposes of p is known as p’s associated deleter, a function object whose correct invocation results in p’s appropriate disposition (typically its deletion).

Let the notation u.p denote the pointer stored by u, and let u.d denote the associated deleter. Upon request, u can reset (replace) u.p and u.d with another pointer and deleter, but properly disposes of its owned object via the associated deleter before such replacement is considered completed.

Each object of a type U instantiated from the unique_ptr template specified in 20.3.1 has the strict ownership semantics, specified above, of a unique pointer. In partial satisfaction of these semantics, each such U is Cpp17MoveConstructible and Cpp17MoveAssigneble, but is not Cpp17CopyConstructible nor Cpp17CopyAssigneble. The template parameter T of unique_ptr may be an incomplete type.

[Note 1: The uses of unique_ptr include providing exception safety for dynamically allocated memory, passing ownership of dynamically allocated memory to a function, and returning dynamically allocated memory from a function. — end note]

20.3.1.2 Default deleters

20.3.1.2.1 General

The class template default_delete serves as the default deleter (destruction policy) for the class template unique_ptr.

The template parameter T of default_delete may be an incomplete type.
20.3.1.2.2 default_delete

namespace std {
    template<class T> struct default_delete {
        constexpr default_delete() noexcept = default;
        template<class U> constexpr default_delete(const default_delete<U>&) noexcept;
        constexpr void operator()(T* const); 
    };
}

template<class U> constexpr default_delete(const default_delete<U>& other) noexcept;

1 Constraints: U* is implicitly convertible to T*.
2 Effects: Constructs a default_delete object from another default_delete<U> object.
3 Mandates: T is a complete type.
4 Effects: Calls delete on ptr.

20.3.1.2.3 default_delete<T[]>

namespace std {
    template<class T> struct default_delete<T[]> {
        constexpr default_delete() noexcept = default;
        template<class U> constexpr default_delete(const default_delete<U[]>&) noexcept;
        template<class U> constexpr void operator()(U* ptr) const;
    };
}

template<class U> constexpr default_delete(const default_delete<U[]>& other) noexcept;

1 Constraints: U(*)[] is convertible to T(*)[].
2 Effects: Constructs a default_delete object from another default_delete<U[]> object.
3 Constraints: U(*)[] is convertible to T(*)[].
4 Mandates: U is a complete type.
5 Effects: Calls delete[] on ptr.

20.3.1.3 unique_ptr for single objects

20.3.1.3.1 General

namespace std {
    template<class T, class D = default_delete<T>> class unique_ptr {
        public:
            using pointer = see below;
            using element_type = T;
            using deleter_type = D;

            // 20.3.1.3.2, constructors
            constexpr unique_ptr() noexcept;
            constexpr explicit unique_ptr(type_identity_t<pointer> p) noexcept;
            constexpr unique_ptr<T>(type_identity_t<pointer> p, see below d1) noexcept;
            constexpr unique_ptr<T>(type_identity_t<pointer> p, see below d2) noexcept;
            constexpr unique_ptr<T>(unique_ptr&& u) noexcept;
            constexpr unique_ptr<T>(nullptr_t) noexcept;
            template<class U, class E>
                constexpr unique_ptr<T>(unique_ptr<T<U, E>> u) noexcept;
            template<class U, class E>
                constexpr unique_ptr<T>(unique_ptr<U, E>&& u) noexcept;

            // 20.3.1.3.3, destructor
            constexpr ~unique_ptr();

            // 20.3.1.3.4, assignment
            constexpr unique_ptr& operator=(unique_ptr&& u) noexcept;
    }
}
template<class U, class E>
    constexpr unique_ptr& operator=(unique_ptr<U, E>&& u) noexcept;
    constexpr unique_ptr& operator=(nullptr_t) noexcept;

    // 20.3.1.3.5, observers
    constexpr add_lvalue_reference_t<T> operator*() const noexcept;
    constexpr pointer operator->() const noexcept;
    constexpr pointer get() const noexcept;
    constexpr deleter_type& get_deleter() noexcept;
    constexpr const deleter_type& get_deleter() const noexcept;
    constexpr explicit operator bool() const noexcept;

    // 20.3.1.3.6, modifiers
    constexpr pointer release() noexcept;
    constexpr void reset(pointer p = pointer()) noexcept;
    constexpr void swap(unique_ptr& u) noexcept;

    // disable copy from lvalue
    unique_ptr(const unique_ptr&) = delete;
    unique_ptr& operator=(const unique_ptr&) = delete;
}

1 The default type for the template parameter D is default_delete. A client-supplied template argument D shall be a function object type (22.10), lvalue reference to function, or lvalue reference to function object type for which, given a value d of type D and a value ptr of type unique_ptr<T, D>::pointer, the expression d(ptr) is valid and has the effect of disposing of the pointer as appropriate for that deleter.

2 If the deleter’s type D is not a reference type, D shall meet the Cpp17Destructible requirements (Table 35).

3 If the qualified-id remove_reference_t<D>::pointer is valid and denotes a type (13.10.3), then unique_ptr<T, D>::pointer shall be a synonym for remove_reference_t<D>::pointer. Otherwise unique_ptr<T, D>::pointer shall be a synonym for element_type*. The type unique_ptr<T, D>::pointer shall meet the Cpp17NullablePointer requirements (Table 36).

4 [Example 1: Given an allocator type X (16.4.4.6.1) and letting A be a synonym for allocator_traits<X>, the types A::pointer, A::const_pointer, A::void_pointer, and A::const_void_pointer may be used as unique_ptr<T, D>::pointer. —end example]

20.3.1.3.2 Constructors

constexpr unique_ptr() noexcept;
constexpr unique_ptr(nullptr_t) noexcept;

Constraints: is_pointer_v<deleter_type> is false and is_default_constructible_v<deleter_type> is true.

Preconditions: D meets the Cpp17DefaultConstructible requirements (Table 30), and that construction does not throw an exception.

Effects: Constructs a unique_ptr object that owns nothing, value-initializing the stored pointer and the stored deleter.

Postconditions: get() == nullptr. get_deleter() returns a reference to the stored deleter.

constexpr explicit unique_ptr(type_identity_t<pointer> p) noexcept;

Constraints: is_pointer_v<deleter_type> is false and is_default_constructible_v<deleter_type> is true.

Preconditions: D meets the Cpp17DefaultConstructible requirements (Table 30), and that construction does not throw an exception.

Effects: Constructs a unique_ptr which owns p, initializing the stored pointer with p and value-initializing the stored deleter.

Postconditions: get() == p. get_deleter() returns a reference to the stored deleter.

constexpr unique_ptr(type_identity_t<pointer> p, const D& d) noexcept;
constexpr unique_ptr(type_identity_t<pointer> p, remove_reference_t<D>&& d) noexcept;

**Constraints:** is_constructible_v<D, decltype(d)> is true.

**Preconditions:** For the first constructor, if D is not a reference type, D meets the Cpp17CopyConstructible requirements and such construction does not exit via an exception. For the second constructor, if D is not a reference type, D meets the Cpp17MoveConstructible requirements and such construction does not exit via an exception.

**Effects:** Constructs a unique_ptr object which owns p, initializing the stored pointer with p and initializing the deleter from std::forward<decltype(d)>(d).

**Postconditions:** get() == p. get_deleter() returns a reference to the stored deleter. If D is a reference type then get_deleter() returns a reference to the lvalue d.

**Remarks:** If D is a reference type, the second constructor is defined as deleted.

**Example 1:**
```cpp
d D;
d unique_ptr<int, D> p1(new int, D()); // D must be Cpp17MoveConstructible
d unique_ptr<int, D> p2(new int, d); // D must be Cpp17CopyConstructible
d unique_ptr<int, D&> p3(new int, d); // p3 holds a reference to d
unique_ptr<int, const D&> p4(new int, D()); // error: rvalue deleter object combined // with reference deleter type
```

```text
— end example
```

constexpr unique_ptr(unique_ptr&& u) noexcept;

**Constraints:** is_move_constructible_v<D> is true.

**Preconditions:** If D is not a reference type, D meets the Cpp17MoveConstructible requirements (Table 31). Construction of the deleter from an rvalue of type D does not throw an exception.

**Effects:** Constructs a unique_ptr from u. If D is a reference type, this deleter is copy constructed from u’s deleter; otherwise, this deleter is move constructed from u’s deleter.

[Note 1: The construction of the deleter can be implemented with std::forward<D>. — end note]

**Postconditions:** get() yields the value u.get() yielded before the construction. u.get() == nullptr. get_deleter() returns a reference to the stored deleter that was constructed from u.get_deleter(). If D is a reference type then get_deleter() and u.get_deleter() both reference the same lvalue deleter.

**Example 2:**
```cpp
template<class U, class E> constexpr unique_ptr(unique_ptr<U, E>&& u) noexcept;
```

**Constraints:**

1. unique_ptr<U, E>::pointer is implicitly convertible to pointer,
2. U is not an array type, and
3. either D is a reference type and E is the same type as D, or D is not a reference type and E is implicitly convertible to D.

**Preconditions:** If E is not a reference type, construction of the deleter from an rvalue of type E is well-formed and does not throw an exception. Otherwise, E is a reference type and construction of the deleter from an lvalue of type E is well-formed and does not throw an exception.

**Effects:** Constructs a unique_ptr from u. If E is a reference type, this deleter is copy constructed from u’s deleter; otherwise, this deleter is move constructed from u’s deleter.

[Note 2: The deleter constructor can be implemented with std::forward<E>. — end note]

**Postconditions:** get() yields the value u.get() yielded before the construction. u.get() == nullptr. get_deleter() returns a reference to the stored deleter that was constructed from u.get_deleter().

### 20.3.1.3.3 Destructor

```cpp
constexpr ~unique_ptr();
```

**Effects:** Equivalent to: if (get()) get_deleter()(get());

[Note 1: The use of default_delete requires T to be a complete type. — end note]
Remarks: The behavior is undefined if the evaluation of `get_deleter()(get())` throws an exception.

20.3.1.3.4 Assignment

```cpp
constexpr unique_ptr& operator=(unique_ptr&& u) noexcept;
```

Constraints: `is_move_assignable_v<D>` is true.

Preconditions: If `D` is not a reference type, `D` meets the `Cpp17MoveAssignable` requirements (Table 33) and assignment of the deleter from an rvalue of type `D` does not throw an exception. Otherwise, `D` is a reference type; `remove_reference_t<D>` meets the `Cpp17CopyAssignable` requirements and assignment of the deleter from an lvalue of type `D` does not throw an exception.

Effects: Calls `reset(u.release())` followed by `get_deleter() = std::forward<D>(u.get_deleter())`.

Postconditions: If `this != addressof(u)`, `u.get() == nullptr`, otherwise `u.get()` is unchanged.

Returns: `*this`.

```cpp
template<class U, class E> constexpr unique_ptr& operator=(unique_ptr<U, E>&& u) noexcept;
```

Constraints:

- (6.1) `unique_ptr<U, E>::pointer` is implicitly convertible to `pointer`, and
- (6.2) `U` is not an array type, and
- (6.3) `is_assignable_v<D&, E&&>` is true.

Preconditions: If `E` is not a reference type, assignment of the deleter from an rvalue of type `E` is well-formed and does not throw an exception. Otherwise, `E` is a reference type and assignment of the deleter from an lvalue of type `E` is well-formed and does not throw an exception.

Effects: Calls `reset(u.release())` followed by `get_deleter() = std::forward<E>(u.get_deleter())`.

Postconditions: `u.get() == nullptr`.

Returns: `*this`.

```cpp
constexpr unique_ptr& operator=(nullptr_t) noexcept;
```

Effects: As if by `reset()`.

Postconditions: `get() == nullptr`.

Returns: `*this`.

20.3.1.3.5 Observers

```cpp
constexpr add_lvalue_reference_t<T> operator*() const noexcept(noexcept(*declval<pointer>()));
```

Preconditions: `get() != nullptr`.

Returns: `*get()`.

```cpp
constexpr pointer operator->() const noexcept;
```

Preconditions: `get() != nullptr`.

Returns: `get()`.

[Note 1: The use of this function typically requires that T be a complete type. — end note]

```cpp
constexpr pointer get() const noexcept;
```

Returns: The stored pointer.

```cpp
constexpr deleter_type& get_deleter() noexcept;
```

```cpp
constexpr const deleter_type& get_deleter() const noexcept;
```

Returns: A reference to the stored deleter.

```cpp
constexpr explicit operator bool() const noexcept;
```

Returns: `get() != nullptr`. 

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20.3.1.3.6 Modifiers

constexpr pointer release() noexcept;

1  Postconditions: get() == nullptr.

Returns: The value get() had at the start of the call to release.

constexpr void reset(pointer p = pointer()) noexcept;

3  Effects: Assigns p to the stored pointer, and then, with the old value of the stored pointer, old_p, evaluates if (old_p) get_deleter()(old_p);

[Note 1: The order of these operations is significant because the call to get_deleter() might destroy *this. —end note]

4  Postconditions: get() == p.

[Note 2: The postcondition does not hold if the call to get_deleter() destroys *this since this->get() is no longer a valid expression. — end note]

5  Remarks: The behavior is undefined if the evaluation of get_deleter()(old_p) throws an exception.

constexpr void swap(unique_ptr& u) noexcept;

6  Preconditions: get_deleter() is swappable (16.4.4.3) and does not throw an exception under swap.

7  Effects: Invokes swap on the stored pointers and on the stored deleters of *this and u.

20.3.1.4 unique_ptr for array objects with a runtime length

20.3.1.4.1 General

namespace std {
  template<class T, class D> class unique_ptr<T[], D> {
    public:
      using pointer = see below;
      using element_type = T;
      using deleter_type = D;

      // 20.3.1.4.2, constructors
      constexpr unique_ptr() noexcept;
      template<class U> constexpr explicit unique_ptr(U p) noexcept;
      template<class U> constexpr unique_ptr(U p, see below d) noexcept;
      template<class U> constexpr unique_ptr(unique_ptr<U>&& u) noexcept;
      template<class U, class E>
        constexpr unique_ptr(unique_ptr<U, E>&& u) noexcept;
      constexpr unique_ptr(nullptr_t) noexcept;

      // destructor
      constexpr ~unique_ptr();

      // assignment
      constexpr unique_ptr& operator=(unique_ptr&& u) noexcept;
      template<class U, class E>
        constexpr unique_ptr& operator=(unique_ptr<U, E>&& u) noexcept;
      constexpr unique_ptr& operator=(nullptr_t) noexcept;

      // 20.3.1.4.4, observers
      constexpr T& operator[](size_t i) const;
      constexpr pointer get() const noexcept;
      constexpr deleter_type& get_deleter() noexcept;
      constexpr deleter_type const& get_deleter() const noexcept;
      constexpr explicit operator bool() const noexcept;

      // 20.3.1.4.5, modifiers
      constexpr pointer release() noexcept;
      template<class U> constexpr void reset(U p) noexcept;
      constexpr void reset(nullptr_t = nullptr) noexcept;
      constexpr void swap(unique_ptr& u) noexcept;
  }
}
A specialization for array types is provided with a slightly altered interface.

(1.1) Conversions between different types of `unique_ptr<T[], D>` that would be disallowed for the corresponding pointer-to-array types, and conversions to or from the non-array forms of `unique_ptr`, produce an ill-formed program.

(1.2) Pointers to types derived from `T` are rejected by the constructors, and by `reset`.

(1.3) The observers `operator*` and `operator->` are not provided.

(1.4) The indexing observer `operator[]` is provided.

(1.5) The default deleter will call `delete[]`.

2 Descriptions are provided below only for members that differ from the primary template.

The template argument `T` shall be a complete type.

20.3.1.4.2 Constructors

```cpp
template<class U> constexpr explicit unique_ptr(U p) noexcept;
```

1 This constructor behaves the same as the constructor in the primary template that takes a single parameter of type `pointer`.

2 Constraints:

(2.1) `U` is the same type as `pointer`, or

(2.2) `pointer` is the same type as `element_type*`, `U` is a pointer type `V*`, and `V(*)[]` is convertible to `element_type(*)(*)[]`.

```cpp
template<class U> constexpr unique_ptr(U p, see below d) noexcept;
template<class U> constexpr unique_ptr(U p, see below d) noexcept;
```

3 These constructors behave the same as the constructors in the primary template that take a parameter of type `pointer` and a second parameter.

4 Constraints:

(4.1) `U` is the same type as `pointer`,

(4.2) `U` is `nullptr_t`, or

(4.3) `pointer` is the same type as `element_type*`, `U` is a pointer type `V*`, and `V(*)[]` is convertible to `element_type(*)(*)[]`.

```cpp
template<class U, class E> constexpr unique_ptr(unique_ptr<U, E>&& u) noexcept;
```

5 This constructor behaves the same as in the primary template.

6 Constraints: Where `UP` is `unique_ptr<U, E>`:

(6.1) `U` is an array type, and

(6.2) `pointer` is the same type as `element_type*`, and

(6.3) `UP::pointer` is the same type as `UP::element_type*`, and

(6.4) `UP::element_type(*)(*)[]` is convertible to `element_type(*)(*)[]`, and

(6.5) either `D` is a reference type and `E` is the same type as `D`, or `D` is not a reference type and `E` is implicitly convertible to `D`.

[Note 1: This replaces the Constraints: specification of the primary template. — end note]

20.3.1.4.3 Assignment

```cpp
template<class U, class E> constexpr unique_ptr& operator=(unique_ptr<U, E>&& u) noexcept;
```

1 This operator behaves the same as in the primary template.

2 Constraints: Where `UP` is `unique_ptr<U, E>`:
— \( U \) is an array type, and
— `pointer` is the same type as `element_type*`, and
— `UP::pointer` is the same type as `UP::element_type*`, and
— `UP::element_type(*)[]` is convertible to `element_type(*)[]`, and
— `is_assignable_v<D&, E&&>` is true.

[Note 1: This replaces the `Constraints`: specification of the primary template. — end note]

### 20.3.1.4.4 Observers

```cpp
constexpr T& operator[](size_t i) const;
```

1. **Preconditions**: \( i < \) the number of elements in the array to which the stored pointer points.
2. **Returns**: `get()[i]`.

### 20.3.1.4.5 Modifiers

```cpp
constexpr void reset(nullptr_t p = nullptr) noexcept;
```

1. **Effects**: Equivalent to `reset(pointer())`.
2. **Returns**: This function behaves the same as the `reset` member of the primary template.
3. **Constraints**:
   - (3.1) `U` is the same type as `pointer`, or
   - (3.2) `pointer` is the same type as `element_type*`, `U` is a pointer type `V*`, and `V(*)[]` is convertible to `element_type(*)(*)[]`.

### 20.3.1.5 Creation

```cpp
template<class T, class... Args> constexpr unique_ptr<T> make_unique(Args&&... args);
```

1. **Constraints**: `T` is not an array type.
2. **Returns**: `unique_ptr<T>(new T(std::forward<Args>(args)...))`.

```cpp
template<class T> constexpr unique_ptr<T> make_unique(size_t n);
```

3. **Constraints**: `T` is an array of unknown bound.
4. **Returns**: `unique_ptr<T>(new remove_extent_t<T>[n]())`.

```cpp
template<class T, class... Args> unspecified make_unique_for_overwrite();
```

5. **Constraints**: `T` is an array of known bound.
6. **Returns**: `unique_ptr<T>(new T)`.

```cpp
template<class T> unspecified make_unique_for_overwrite(size_t n);
```

7. **Constraints**: `T` is an array of known bound.
8. **Returns**: `unique_ptr<T>(new remove_extent_t<T>[n])`.

```cpp
template<class T, class... Args> unspecified make_unique_for_overwrite(Arg&&... = delete);
```

### 20.3.1.5 Specialized algorithms

```cpp
template<class T, class D> constexpr void swap(unique_ptr<T, D>& x, unique_ptr<T, D>& y) noexcept;
```

1. **Constraints**: `is_swappable_v<D>` is true.
2. **Effects**: Calls `x.swap(y)`.
template<class T1, class D1, class T2, class D2>
constexpr bool operator==(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);

Returns: x.get() == y.get().

template<class T1, class D1, class T2, class D2>
bool operator<(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);

Let CT denote

common_type_t<typename unique_ptr<T1, D1>::pointer,
    typename unique_ptr<T2, D2>::pointer>

Mandates:
(5.1) — unique_ptr<T1, D1>::pointer is implicitly convertible to CT and
(5.2) — unique_ptr<T2, D2>::pointer is implicitly convertible to CT.

Preconditions: The specialization less<CT> is a function object type (22.10) that induces a strict weak ordering (27.8) on the pointer values.

Returns: less<CT>()(x.get(), y.get()).

template<class T1, class D1, class T2, class D2>
bool operator<=(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);

Returns: !(y < x).

template<class T1, class D1, class T2, class D2>
bool operator>=(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);

Returns: !(x < y).

requires three_way_comparable_with<typename unique_ptr<T1, D1>::pointer,
    typename unique_ptr<T2, D2>::pointer>
compare_three_way_result_t<typename unique_ptr<T1, D1>::pointer,
    typename unique_ptr<T2, D2>::pointer>
operator<=>(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);

Returns: compare_three_way()(x.get(), y.get()).

template<class T, class D>
constexpr bool operator==(const unique_ptr<T, D>& x, nullptr_t) noexcept;

Returns: !x.

template<class T, class D>
constexpr bool operator<(const unique_ptr<T, D>& x, nullptr_t);
template<class T, class D>
constexpr bool operator<(nullptr_t, const unique_ptr<T, D>& x);

Preconditions: The specialization less<unique_ptr<T, D>::pointer> is a function object type (22.10) that induces a strict weak ordering (27.8) on the pointer values.

Returns: The first function template returns
less<unique_ptr<T, D>::pointer>()(x.get(), nullptr)
The second function template returns
less<unique_ptr<T, D>::pointer>()(nullptr, x.get())

template<class T, class D>
constexpr bool operator>(const unique_ptr<T, D>& x, nullptr_t);
template<class T, class D>
constexpr bool operator>(nullptr_t, const unique_ptr<T, D>& x);
constexpr bool operator>(nullptr_t, const unique_ptr<T, D>& x);

Returns: The first function template returns nullptr < x. The second function template returns x < nullptr.

template<class T, class D>
constexpr bool operator<=(const unique_ptr<T, D>& x, nullptr_t);
template<class T, class D>
constexpr bool operator<=(nullptr_t, const unique_ptr<T, D>& x);

Returns: The first function template returns !(nullptr < x). The second function template returns !(x < nullptr).

template<class T, class D>
constexpr bool operator>=(const unique_ptr<T, D>& x, nullptr_t);
template<class T, class D>
constexpr bool operator>=(nullptr_t, const unique_ptr<T, D>& x);

Returns: The first function template returns !(x < nullptr). The second function template returns !(nullptr < x).

template<class T, class D>
requires three_way_comparable<typename unique_ptr<T, D>::pointer>
constexpr compare_three_way_result_t<typename unique_ptr<T, D>::pointer>
operator<=>(const unique_ptr<T, D>& x, nullptr_t);

Returns: compare_three_way(x.get(), static_cast<typename unique_ptr<T, D>::pointer>(nullptr)).

20.3.1.7 I/O
[unique.ptr.io]

template<class E, class T, class Y, class D>
basic_ostream<E, T>& operator<<(basic_ostream<E, T>& os, const unique_ptr<Y, D>& p);

Constraints: os << p.get() is a valid expression.

Effects: Equivalent to: os << p.get();

Returns: os.

20.3.2 Shared-ownership pointers
[util.sharedptr]

20.3.2.1 Class bad_weak_ptr
[util.smartptr.weak.bad]

namespace std {
    class bad_weak_ptr : public exception {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    }
}

An exception of type bad_weak_ptr is thrown by the shared_ptr constructor taking a weak_ptr.

const char* what() const noexcept override;

Returns: An implementation-defined NTBS.

20.3.2.2 Class template shared_ptr
[util.sharedptr.shared]

20.3.2.2.1 General
[util.sharedptr.shared.general]

The shared_ptr class template stores a pointer, usually obtained via new. shared_ptr implements semantics of shared ownership; the last remaining owner of the pointer is responsible for destroying the object, or otherwise releasing the resources associated with the stored pointer. A shared_ptr is said to be empty if it does not own a pointer.

namespace std {
    template<class T> class shared_ptr {
        public:
            using element_type = remove_extent_t<T>;
            using weak_type = weak_ptr<T>;
    }
}

§ 20.3.2.2.1
// 20.3.2.2.1, constructors
constexpr shared_ptr() noexcept;
constexpr shared_ptr(nullptr_t) noexcept : shared_ptr() {}
N4986

template<class U>
bool owner_equal(const shared_ptr<U>& b) const noexcept;
template<class U>
bool owner_equal(const weak_ptr<U>& b) const noexcept;
}

template<class T>
shared_ptr(weak_ptr<T>) -> shared_ptr<T>;
template<class T, class D>
shared_ptr(unique_ptr<T, D>) -> shared_ptr<T>;

2 Specializations of shared_ptr shall be Cpp17CopyConstructible, Cpp17CopyAssignable, and Cpp17LessThanComparable, allowing their use in standard containers. Specializations of shared_ptr shall be contextually convertible to bool, allowing their use in boolean expressions and declarations in conditions.

3 The template parameter T of shared_ptr may be an incomplete type.

[Note 1: T can be a function type. — end note]

4 [Example 1:]
   if (shared_ptr<X> px = dynamic_pointer_cast<X>(py)) {
       // do something with px
   }
   —end example

5 For purposes of determining the presence of a data race, member functions shall access and modify only the shared_ptr and weak_ptr objects themselves and not objects they refer to. Changes in use_count() do not reflect modifications that can introduce data races.

6 For the purposes of 20.3, a pointer type Y* is said to be compatible with a pointer type T* when either Y* is convertible to T* or Y is U[N] and T is cv U[].

20.3.2.2.2 Constructors [util.smartptr.shared.const]

1 In the constructor definitions below, enables shared_from_this with p, for a pointer p of type T*, means that if Y has an unambiguous and accessible base class that is a specialization of enable_shared_from_this (20.3.2.7), then remove_cv_t<Y>** shall be implicitly convertible to T* and the constructor evaluates the statement:

   if (p != nullptr && p->weak_this.expired())
   p->weak_this = shared_ptr<remove_cv_t<T>>(*this, const_cast<remove_cv_t<T>*>(p));

The assignment to the weak_this member is not atomic and conflicts with any potentially concurrent access to the same object (6.9.2).

constexpr shared_ptr() noexcept;

2 Postconditions: use_count() == 0 && get() == nullptr.

template<class Y> explicit shared_ptr(Y* p);

3 Constraints: When T is an array type, the expression delete[] p is well-formed and either T is U[N] and Y(*)[N] is convertible to T*, or T is U[] and Y(*)[] is convertible to T*. When T is not an array type, the expression delete p is well-formed and Y* is convertible to T*.

4 Mandates: Y is a complete type.

5 Preconditions: The expression delete[] p, when T is an array type, or delete p, when T is not an array type, has well-defined behavior, and does not throw exceptions.

6 Effects: When T is not an array type, constructs a shared_ptr object that owns the pointer p. Otherwise, constructs a shared_ptr that owns p and a deleter of an unspecified type that calls delete[] p. When T is not an array type, enables shared_from_this with p. If an exception is thrown, delete p is called when T is not an array type, delete[] p otherwise.

7 Postconditions: use_count() == 1 && get() == p.

8 Throws: bad_alloc, or an implementation-defined exception when a resource other than memory cannot be obtained.
template<
    class Y,
    class D>
shared_ptr(Y* p, D d);

template<
    class Y,
    class D,
    class A>
shared_ptr(Y* p, D d, A a);

template<
    class D>
shared_ptr(nullptr_t p, D d);

template<
    class D,
    class A>
shared_ptr(nullptr_t p, D d, A a);

Constraints:

is_move_constructible_v<D> is true, and \( \text{d}(p) \) is a well-formed expression. For the first two overloads:

9.1 If \( T \) is an array type, then either \( T \) is \( U[N] \) and \( Y(*)[N] \) is convertible to \( T* \), or \( T \) is \( U[] \) and \( Y(*)[] \) is convertible to \( T* \).

9.2 If \( T \) is not an array type, then \( Y* \) is convertible to \( T* \).

Preconditions:

Construction of \( d \) and a deleter of type \( D \) initialized with \( \text{std::move}(d) \) do not throw exceptions. The expression \( \text{d}(p) \) has well-defined behavior and does not throw exceptions. \( A \) meets the Cpp17Allocator requirements (16.4.4.6.1).

Effects: Constructs a \( \text{shared_ptr} \) object that owns the object \( p \) and the deleter \( d \). When \( T \) is not an array type, the first and second constructors enable \( \text{shared_from_this} \) with \( p \). The second and fourth constructors shall use a copy of \( a \) to allocate memory for internal use. If an exception is thrown, \( \text{d}(p) \) is called.

Postconditions: \( \text{use_count}() == 1 \) \&\& \( \text{get}() == p \).

Throws: \( \text{bad_alloc} \), or an implementation-defined exception when a resource other than memory cannot be obtained.

template<
    class Y>
shared_ptr(const shared_ptr<Y>& r, element_type* p) noexcept;

template<
    class Y>
shared_ptr(shared_ptr<Y>&& r, element_type* p) noexcept;

Effects: Constructs a \( \text{shared_ptr} \) instance that stores \( p \) and shares ownership with the initial value of \( r \).

Postconditions: \( \text{get}() == p \). For the second overload, \( r \) is empty and \( r.\text{get}() == \text{nullptr} \).

[Note 1: Use of this constructor leads to a dangling pointer unless \( p \) remains valid at least until the ownership group of \( r \) is destroyed. —end note]

[Note 2: This constructor allows creation of an empty \( \text{shared_ptr} \) instance with a non-null stored pointer. —end note]

shared_ptr(const shared_ptr& r) noexcept;

template<
    class Y>
shared_ptr(const shared_ptr<Y>& r) noexcept;

Constraints: For the second constructor, \( Y* \) is compatible with \( T* \).

Effects: If \( r \) is empty, constructs an empty \( \text{shared_ptr} \) object; otherwise, constructs a \( \text{shared_ptr} \) object that shares ownership with \( r \).

Postconditions: \( \text{get}() == r.\text{get}() \) \&\& \( \text{use_count}() == r.\text{use_count}() \).

shared_ptr(shared_ptr&& r) noexcept;

template<
    class Y>
shared_ptr(shared_ptr<Y>&& r) noexcept;

Constraints: For the second constructor, \( Y* \) is compatible with \( T* \).

Effects: Move constructs a \( \text{shared_ptr} \) instance from \( r \).

Postconditions: \( \ast \text{this contains the old value of } r. r \) is empty, and \( r.\text{get}() == \text{nullptr} \).

template<
    class Y>
explicit shared_ptr(const weak_ptr<Y>& r);

Constraints: \( Y* \) is compatible with \( T* \).

Effects: Constructs a \( \text{shared_ptr} \) object that shares ownership with \( r \) and stores a copy of the pointer stored in \( r \). If an exception is thrown, the constructor has no effect.

Postconditions: \( \text{use_count}() == r.\text{use_count}() \).

Throws: \( \text{bad_weak_ptr} \) when \( r.\text{expired}() \).

template<
    class Y, class D>
shared_ptr(unique_ptr<Y, D>&& r);

Constraints: \( Y* \) is compatible with \( T* \) and \( \text{unique_ptr}<Y, D>::\text{pointer} \) is convertible to \( \text{element_type}* \).
Effects: If \( \text{r.get()} == \text{nullptr} \), equivalent to \text{shared_ptr()}\). Otherwise, if \( D \) is not a reference type, equivalent to \text{shared_ptr(r.release(), std::move(r.get_deleter())\)}. Otherwise, equivalent to \text{shared_ptr(r.release(), ref(r.get_deleter())\)}. If an exception is thrown, the constructor has no effect.

20.3.2.2.3 Destructor

\[ \text{~shared_ptr();} \]

Effects:

1. If \( \star\text{this} \) is empty or shares ownership with another \text{shared_ptr} instance (\text{use_count()} > 1), there are no side effects.
2. Otherwise, if \( \star\text{this} \) owns an object \( p \) and a deleter \( d(p) \) is called.
3. Otherwise, \( \star\text{this} \) owns a pointer \( p \), and \text{delete } p \) is called.

\[ \text{[Note 1: Since the destruction of } \star\text{this} \text{ decreases the number of instances that share ownership with } \star\text{this} \text{ by one, after } \star\text{this} \text{ has been destroyed all } \text{shared_ptr} \text{ instances that shared ownership with } \star\text{this} \text{ will report a } \text{use_count()} \text{ that is one less than its previous value. ~end note]} \]

20.3.2.2.4 Assignment

\[ \text{shared_ptr\& operator=(const shared_ptr\& r) noexcept;} \]

Effects: Equivalent to \text{shared_ptr(r).swap(*this)}.

Returns: \text{*this}.

\[ \text{[Note 1: The use count updates caused by the temporary object construction and destruction are not observable side effects, so the implementation can meet the effects (and the implied guarantees) via different means, without creating a temporary. In particular, in the example:} \]

\[ \text{shared_ptr<\text{int}> p(new int);} \]
\[ \text{shared_ptr<\text{void}> q(p);} \]
\[ \text{p = p;} \]
\[ \text{q = p;} \]

\[ \text{both assignments can be no-ops. ~end note]} \]

\[ \text{shared_ptr\& operator=(shared_ptr\&\& r) noexcept;} \]

Effects: Equivalent to \text{shared_ptr(std::move(r)).swap(*this)}.

Returns: \text{*this}.

\[ \text{template<class Y> shared_ptr\& operator=(shared_ptr<Y>&& r) noexcept;} \]

Effects: Equivalent to \text{shared_ptr(std::move(r)).swap(*this)}.

Returns: \text{*this}.

\[ \text{template<class Y, class D> shared_ptr\& operator=(unique_ptr<Y, D>&& r);} \]

Effects: Equivalent to \text{shared_ptr(std::move(r)).swap(*this)}.

Returns: \text{*this}.

20.3.2.2.5 Modifiers

\[ \text{void swap(shared_ptr\& r) noexcept;} \]

Effects: Exchanges the contents of \( \star\text{this} \) and \( r \).

\[ \text{void reset() noexcept;} \]

Effects: Equivalent to \text{shared_ptr().swap(*this)}.

\[ \text{template<class Y> void reset(Y\* p);} \]

Effects: Equivalent to \text{shared_ptr(p).swap(*this)}.

\[ \text{template<class Y, class D> void reset(Y\* p, D d);} \]

Effects: Equivalent to \text{shared_ptr(p, d).swap(*this)}.

\[ \text{template<class Y, class D, class A> void reset(Y\* p, D d, A a);} \]

Effects: Equivalent to \text{shared_ptr(p, d, a).swap(*this)}.
20.3.2.2.6 Observers

\[ \text{util.smartptr.shared.obs} \]

\begin{verbatim}

element_type* get() const noexcept;

Returns: The stored pointer.

T& operator*() const noexcept;

Preconditions: get() != nullptr.

Returns: *get().

Remarks: When \( T \) is an array type or cv void, it is unspecified whether this member function is declared. If it is declared, it is unspecified what its return type is, except that the declaration (although not necessarily the definition) of the function shall be well-formed.

T* operator->() const noexcept;

Preconditions: get() != nullptr.

Returns: get().

Remarks: When \( T \) is an array type, it is unspecified whether this member function is declared. If it is declared, it is unspecified what its return type is, except that the declaration (although not necessarily the definition) of the function shall be well-formed.

element_type& operator[](ptrdiff_t i) const;

Preconditions: get() != nullptr && i >= 0. If \( T \) is \( U[N] \), \( i < N \).

Returns: get()[i].

Throws: Nothing.

Remarks: When \( T \) is not an array type, it is unspecified whether this member function is declared. If it is declared, it is unspecified what its return type is, except that the declaration (although not necessarily the definition) of the function shall be well-formed.

long use_count() const noexcept;

Synchronization: None.

Returns: The number of \( \text{shared_ptr} \) objects, \(*\text{this} \) included, that share ownership with \(*\text{this} \), or 0 when \(*\text{this} \) is empty.

[Note 1: get() == nullptr does not imply a specific return value of use_count(). — end note]

[Note 2: weak_ptr<U>::lock() can affect the return value of use_count(). — end note]

[Note 3: When multiple threads might affect the return value of use_count(), the result is approximate. In particular, use_count() == 1 does not imply that accesses through a previously destroyed \( \text{shared_ptr} \) have in any sense completed. — end note]

explicit operator bool() const noexcept;

Returns: get() != nullptr.

template<class U> bool owner_before(const shared_ptr<U>& b) const noexcept;

template<class U> bool owner_before(const weak_ptr<U>& b) const noexcept;

Returns: An unspecified value such that

- owner_before(b) defines a strict weak ordering as defined in 27.8;

- !owner_before(b) && !b.owner_before(*this) is true if and only if owner_equal(b) is true.

size_t owner_hash() const noexcept;

Returns: An unspecified value such that, for any object \( x \) where owner_equal(x) is true, owner_hash() == x.owner_hash() is true.

template<class U>
bool owner_equal(const shared_ptr<U>& b) const noexcept;

template<class U>
bool owner_equal(const weak_ptr<U>& b) const noexcept;

Returns: true if and only if *this and b share ownership or are both empty. Otherwise returns false.
\end{verbatim}
Remarks: owner_equal is an equivalence relation.

20.3.2.2.7 Creation
The common requirements that apply to all make_shared, allocate_shared, make_shared_for_overwrite, and allocate_shared_for_overwrite overloads, unless specified otherwise, are described below.

\begin{verbatim}
template<class T, ...>
    shared_ptr<T> make_shared(args);

template<class T, class A, ...>
    shared_ptr<T> allocate_shared(const A& a, args);

template<class T, ...>
    shared_ptr<T> make_shared_for_overwrite(args);

template<class T, class A, ...>
    shared_ptr<T> allocate_shared_for_overwrite(const A& a, args);
\end{verbatim}

Preconditions: A meets the Cpp17Allocator requirements (16.4.4.6.1).

Effects: Allocates memory for an object of type T (or U[N] when T is U[], where N is determined from args as specified by the concrete overload). The object is initialized from args as specified by the concrete overload. The allocate_shared and allocate_shared_for_overwrite templates use a copy of a (rebound for an unspecified value_type) to allocate memory. If an exception is thrown, the functions have no effect.

Postconditions: r.get() != nullptr && r.use_count() == 1, where r is the return value.

Returns: A shared_ptr instance that stores and owns the address of the newly constructed object.

Remarks:

(7.1) — Implementations should perform no more than one memory allocation.

[Note 1: This provides efficiency equivalent to an intrusive smart pointer. — end note]

(7.2) — When an object of an array type U is specified to have an initial value of u (of the same type), this shall be interpreted to mean that each array element of the object has as its initial value the corresponding element from u.

(7.3) — When an object of an array type is specified to have a default initial value, this shall be interpreted to mean that each array element of the object has a default initial value.

(7.4) — When a (sub)object of a non-array type U is specified to have an initial value of v, or U(1...), where 1... is a list of constructor arguments, make_shared shall initialize this (sub)object via the expression ::new(pv) U(v) or ::new(pv) U(1...) respectively, where pv has type void* and points to storage suitable to hold an object of type U.

(7.5) — When a (sub)object of a non-array type U is specified to have an initial value of v, or U(1...), where 1... is a list of constructor arguments, allocate_shared shall initialize this (sub)object via the expression

(7.5.1) — allocator_traits<A2>::construct(a2, pv, v) or

(7.5.2) — allocator_traits<A2>::construct(a2, pv, 1...)

respectively, where pv points to storage suitable to hold an object of type U and a2 of type A2 is a rebound copy of the allocator a passed to allocate_shared such that its value_type is remove_cv_t<U>.

(7.6) — When a (sub)object of non-array type U is specified to have a default initial value, make_shared shall initialize this (sub)object via the expression ::new(pv) U(), where pv has type void* and points to storage suitable to hold an object of type U.

(7.7) — When a (sub)object of non-array type U is specified to have a default initial value, allocate_shared shall initialize this (sub)object via the expression allocator_traits<A2>::construct(a2, pv), where pv points to storage suitable to hold an object of type U and a2 of type A2 is a rebound copy of the allocator a passed to allocate_shared such that its value_type is remove_cv_t<U>.

(7.8) — When a (sub)object of non-array type U is initialized by make_shared_for_overwrite or allocate_shared_for_overwrite, it is initialized via the expression ::new(pv) U, where pv has type void* and points to storage suitable to hold an object of type U.
— Array elements are initialized in ascending order of their addresses.

— When the lifetime of the object managed by the return value ends, or when the initialization of an array element throws an exception, the initialized elements are destroyed in the reverse order of their original construction.

— When a (sub)object of non-array type $U$ that was initialized by `make_shared` is to be destroyed, it is destroyed via the expression $pv->U()$ where $pv$ points to that object of type $U$.

— When a (sub)object of non-array type $U$ that was initialized by `allocate_shared` is to be destroyed, it is destroyed via the expression `allocator_traits<A2>::destroy(a2, pv)` where $pv$ points to that object of type `remove_cv_t<U>` and $a2$ of type $A2$ is a rebound copy of the allocator $a$ passed to `allocate_shared` such that its `value_type` is `remove_cv_t<U>`.

[Note 2: These functions will typically allocate more memory than `sizeof(T)` to allow for internal bookkeeping structures such as reference counts. — end note]

```
template<class T, class... Args>
shared_ptr<T> make_shared(Args&&... args); // T is not array

template<class T, class A, class... Args>
shared_ptr<T> allocate_shared(const A& a, Args&&... args); // T is not array
```

Constraints: $T$ is not an array type.

Returns: A `shared_ptr` to an object of type $T$ with an initial value $T$(std::forward<Args>(args)...).

Remarks: The `shared_ptr` constructors called by these functions enable `shared_from_this` with the address of the newly constructed object of type $T$.

[Example 1:

```
shared_ptr<int> p = make_shared<int>(); // shared_ptr to int()
shared_ptr<vector<int>> q = make_shared<vector<int>>(16, 1);
// shared_ptr to vector of 16 elements with value 1
```
— end example]

```
template<class T> shared_ptr<T> make_shared(size_t N); // T is U[]

template<class T, class A>
shared_ptr<T> allocate_shared(const A& a, size_t N); // T is U[]
```

Constraints: $T$ is of the form $U[]$.

Returns: A `shared_ptr` to an object of type $U[N]$ with a default initial value, where $U$ is `remove_extent_t<T>`.

[Example 2:

```
shared_ptr<double[]> p = make_shared<double[]>(1024);
// shared_ptr to a value-initialized double[1024]
shared_ptr<double[][2][2]> q = make_shared<double[][2][2]>(6);
// shared_ptr to a value-initialized double[6][2][2]
```
— end example]

```
template<class T>
shared_ptr<T> make_shared(); // T is U[N]

template<class T, class A>
shared_ptr<T> allocate_shared(const A& a); // T is U[N]
```

Constraints: $T$ is of the form $U[N]$.

Returns: A `shared_ptr` to an object of type $T$ with a default initial value.

[Example 3:

```
shared_ptr<double[1024]> p = make_shared<double[1024]>();
// shared_ptr to a value-initialized double[1024]
shared_ptr<double[][2][2]> q = make_shared<double[][2][2]>();
// shared_ptr to a value-initialized double[6][2][2]
```
— end example]
template<class T>
shared_ptr<T> make_shared(size_t N, const remove_extent_t<T>& u); // T is U[N]

Constraints: T is of the form U[].

Returns: A shared_ptr to an object of type U[N], where U is remove_extent_t<T> and each array element has an initial value of u.

Example 4:

shared_ptr<double[]> p = make_shared<double[]>(1024, 1.0);
// shared_ptr to a double[1024], where each element is 1.0
shared_ptr<double[]> q = make_shared<double[]>(6, {1.0, 0.0});
// shared_ptr to a double[6], where each double[2] element is {1.0, 0.0}
shared_ptr<vector<int>[]> r = make_shared<vector<int>[]>(4, {1, 2});
// shared_ptr to a vector<int>[4], where each vector has contents {1, 2}
— end example

template<class T>
shared_ptr<T> make_shared_for_overwrite();

template<class T, class A>
shared_ptr<T> allocate_shared_for_overwrite(const A& a);

Constraints: T is not an array of unknown bound.

Returns: A shared_ptr to an object of type T.

Example 6:

struct X { double data[1024]; }; 
shared_ptr<X> p = make_shared_for_overwrite<X>();
// shared_ptr to a default-initialized X, where each element in X::data has an indeterminate value
shared_ptr<double[]> q = make_shared_for_overwrite<double[]>(1024, 0);
// shared_ptr to a default-initialized double[1024], where each element has an indeterminate value
— end example

template<class T>
shared_ptr<T> make_shared_for_overwrite(size_t N);

template<class T, class A>
shared_ptr<T> allocate_shared_for_overwrite(const A& a, size_t N);

Constraints: T is an array of unknown bound.

Returns: A shared_ptr to an object of type U[N], where U is remove_extent_t<T>.
Example 7:

```cpp
shared_ptr<double[]> p = make_shared_for_overwrite<double[]>(1024);
// shared_ptr to a default-initialized double[1024], where each element has an indeterminate value
```

---

20.3.2.2.8 Comparison

```cpp
template<class T, class U>
bool operator==(const shared_ptr<T>& a, const shared_ptr<U>& b) noexcept;
Returns: a.get() == b.get().
```

```cpp
template<class T>
bool operator==(const shared_ptr<T>& a, nullptr_t) noexcept;
Returns: !a.
```

```cpp
template<class T, class U>
strong_ordering operator<=>(const shared_ptr<T>& a, const shared_ptr<U>& b) noexcept;
Returns: compare_three_way()(a.get(), b.get()).
[Note 1: Defining a comparison operator function allows shared_ptr objects to be used as keys in associative containers. —end note]
```

```cpp
template<class T>
strong_ordering operator<=>(const shared_ptr<T>& a, nullptr_t) noexcept;
Returns: compare_three_way()(a.get(), static_cast<typename shared_ptr<T>::element_type*>(nullptr))
```

20.3.2.2.9 Specialized algorithms

```cpp
template<class T>
void swap(shared_ptr<T>& a, shared_ptr<T>& b) noexcept;
Effects: Equivalent to a.swap(b).
```

20.3.2.2.10 Casts

```cpp
template<class T, class U>
shared_ptr<T> static_pointer_cast(const shared_ptr<U>& r) noexcept;
```

```cpp
template<class T, class U>
shared_ptr<T> static_pointer_cast(shared_ptr<U>&& r) noexcept;
Mandates: The expression static_cast<T*>(static_cast<typename shared_ptr<T>::element_type*>(r.get()))
where R is r for the first overload, and std::move(r) for the second.
```

```cpp
template<class T, class U>
shared_ptr<T> dynamic_pointer_cast(const shared_ptr<U>& r) noexcept;
```

```cpp
template<class T, class U>
shared_ptr<T> dynamic_pointer_cast(shared_ptr<U>&& r) noexcept;
Mandates: The expression dynamic_cast<T*>(static_cast<typename shared_ptr<T>::element_type*>(r.get())) has well-defined behavior.
Preconditions: The expression dynamic_cast<typename shared_ptr<T>::element_type*>(r.get()) returns a non-null value p, shared_ptr<T>(R, p), where R is r for the first overload, and std::move(r) for the second.
```

---

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Otherwise, \texttt{shared\_ptr<T>}. 

[Note 2: The seemingly equivalent expression \texttt{shared\_ptr<T>(dynamic\_cast<T*>(r.get()))} can result in undefined behavior, attempting to delete the same object twice. —end note]

\begin{verbatim}
template<class T, class U>
shared_ptr<T> const_pointer_cast(const shared_ptr<U>& r) noexcept;

Mandates: The expression \texttt{const\_cast<T*>(U*)nullptr)} is well-formed.

Returns:
\begin{verbatim}
shared_ptr<T>(R, const_cast<typename shared_ptr<T>::element_type*>(r.get()))
\end{verbatim}
where \texttt{R} is \texttt{r} for the first overload, and \texttt{std::move(r)} for the second.

[Note 3: The seemingly equivalent expression \texttt{shared\_ptr<T>(const\_cast<T*>(r.get()))} can result in undefined behavior, attempting to delete the same object twice. —end note]

\begin{verbatim}
template<class T, class U>
shared_ptr<T> reinterpret_pointer_cast(const shared_ptr<U>& r) noexcept;

Mandates: The expression \texttt{reinterpret\_cast<T*>(U*)nullptr)} is well-formed.

Returns:
\begin{verbatim}
shared_ptr<T>(R, reinterpret_cast<typename shared_ptr<T>::element_type*>(r.get()))
\end{verbatim}
where \texttt{R} is \texttt{r} for the first overload, and \texttt{std::move(r)} for the second.

[Note 4: The seemingly equivalent expression \texttt{shared\_ptr<T>(reinterpret\_cast<T*>(r.get()))} can result in undefined behavior, attempting to delete the same object twice. —end note]
\end{verbatim}

20.3.2.2.11 get_deleter

\begin{verbatim}
template<class D, class T>
D* get_deleter(const shared_ptr<T>& p) noexcept;

Returns: If \texttt{p} owns a deleter \texttt{d} of type cv-unqualified \texttt{D}, returns \texttt{addressof(d)}; otherwise returns \texttt{nullptr}. The returned pointer remains valid as long as there exists a \texttt{shared\_ptr} instance that owns \texttt{d}.

[Note 1: It is unspecified whether the pointer remains valid longer than that. This can happen if the implementation doesn’t destroy the deleter until all \texttt{weak\_ptr} instances that share ownership with \texttt{p} have been destroyed. —end note]
\end{verbatim}

20.3.2.2.12 I/O

\begin{verbatim}
template<class E, class T, class Y>
basic_ostream<E, T>& operator<<(basic_ostream<E, T>& os, const shared_ptr<Y>& p);

Effects: As if by: \texttt{os << p.get();}

Returns: \texttt{os}.
\end{verbatim}

20.3.2.3 Class template weak_ptr

20.3.2.3.1 General

The \texttt{weak\_ptr} class template stores a weak reference to an object that is already managed by a \texttt{shared\_ptr}. To access the object, a \texttt{weak\_ptr} can be converted to a \texttt{shared\_ptr} using the member function \texttt{lock}.

```cpp
namespace std {
    template<class T> class weak_ptr {
        public:
            using element_type = remove_extent_t<T>;

            // 20.3.2.3.2, constructors
            constexpr weak_ptr() noexcept;
            template<class Y>
            weak_ptr(const shared_ptr<Y>& r) noexcept;

            // 20.3.2.3.3, members
```
weak_ptr(const weak_ptr& r) noexcept;
    template<class Y>
        weak_ptr(const weak_ptr<Y>& r) noexcept;
    weak_ptr(weak_ptr&& r) noexcept;
    template<class Y>
        weak_ptr(weak_ptr<Y>&& r) noexcept;

    // 20.3.2.3.3, destructor
    ~weak_ptr() noexcept;

    // 20.3.2.3.4, assignment
    weak_ptr& operator=(const weak_ptr& r) noexcept;
    template<class Y>
        weak_ptr& operator=(const weak_ptr<Y>& r) noexcept;
    template<class Y>
        weak_ptr& operator=(const shared_ptr<Y>& r) noexcept;
    weak_ptr& operator=(weak_ptr&& r) noexcept;
    template<class Y>
        weak_ptr& operator=(weak_ptr<Y>&& r) noexcept;

    // 20.3.2.3.5, modifiers
    void swap(weak_ptr& r) noexcept;
    void reset() noexcept;

    // 20.3.2.3.6, observers
    long use_count() const noexcept;
    bool expired() const noexcept;
    shared_ptr<T> lock() const noexcept;
    template<class U>
        bool owner_before(const shared_ptr<U>& b) const noexcept;
    template<class U>
        bool owner_before(const weak_ptr<U>& b) const noexcept;
    size_t owner_hash() const noexcept;
    template<class U>
        bool owner_equal(const shared_ptr<U>& b) const noexcept;
    template<class U>
        bool owner_equal(const weak_ptr<U>& b) const noexcept;
    
    template<class T>
        weak_ptr(shared_ptr<T>) -> weak_ptr<T>;
};

Specializations of weak_ptr shall be Cpp17CopyConstructible and Cpp17CopyAssignable, allowing their use in standard containers. The template parameter T of weak_ptr may be an incomplete type.

20.3.2.3.2 Constructors

    constexpr weak_ptr() noexcept;

    Effects: Constructs an empty weak_ptr object that stores a null pointer value.
    Postconditions: use_count() == 0.

    weak_ptr(const weak_ptr& r) noexcept;
    template<class Y> weak_ptr(const weak_ptr<Y>& r) noexcept;
    template<class Y> weak_ptr(const shared_ptr<Y>& r) noexcept;

    Constraints: For the second and third constructors, Y* is compatible with T*.

    Effects: If r is empty, constructs an empty weak_ptr object that stores a null pointer value; otherwise, constructs a weak_ptr object that shares ownership with r and stores a copy of the pointer stored in r.
    Postconditions: use_count() == r.use_count().

    weak_ptr(weak_ptr&& r) noexcept;
template<class Y> weak_ptr(weak_ptr<Y>&& r) noexcept;

Constraints: For the second constructor, Y* is compatible with T*.

Effects: Move constructs a weak_ptr instance from r.

Postconditions: *this contains the old value of r. r is empty, stores a null pointer value, and r.use_count() == 0.

20.3.2.3.3 Destructor

~weak_ptr();

Effects: Destroys this weak_ptr object but has no effect on the object its stored pointer points to.

20.3.2.3.4 Assignment

weak_ptr& operator=(const weak_ptr& r) noexcept;

Effects: Equivalent to weak_ptr(r).swap(*this).

Returns: *this.

Remarks: The implementation may meet the effects (and the implied guarantees) via different means, without creating a temporary object.

weak_ptr& operator=(weak_ptr&& r) noexcept;

Effects: Equivalent to weak_ptr(std::move(r)).swap(*this).

Returns: *this.

20.3.2.3.5 Modifiers

void swap(weak_ptr& r) noexcept;

Effects: Exchanges the contents of *this and r.

void reset() noexcept;

Effects: Equivalent to weak_ptr().swap(*this).

20.3.2.3.6 Observers

long use_count() const noexcept;

Returns: 0 if *this is empty; otherwise, the number of shared_ptr instances that share ownership with *this.

bool expired() const noexcept;

Returns: use_count() == 0.

shared_ptr<T> lock() const noexcept;

Returns: expired() ? shared_ptr<T>(*this), executed atomically.

template<class U> bool owner_before(const shared_ptr<U>& b) const noexcept;

template<class U> bool owner_before(const weak_ptr<U>& b) const noexcept;

Returns: An unspecified value such that

(4.1) — owner_before(b) defines a strict weak ordering as defined in 27.8;

(4.2) — !owner_before(b) && !b.owner_before(*this) is true if and only if owner_equal(b) is true.

size_t owner_hash() const noexcept;

Returns: An unspecified value such that, for any object x where owner_equal(x) is true, owner_hash() == x.owner_hash() is true.
template<class U>
bool owner_equal(const shared_ptr<U>& b) const noexcept;
template<class U>
bool owner_equal(const weak_ptr<U>& b) const noexcept;

Returns: true if and only if *this and b share ownership or are both empty. Otherwise returns false.
Remarks: owner_equal is an equivalence relation.

20.3.2.3.7 Specialized algorithms

template<class T>
void swap(weak_ptr<T>& a, weak_ptr<T>& b) noexcept;

Effects: Equivalent to a.swap(b).

20.3.2.4 Class template owner_less

The class template owner_less allows ownership-based mixed comparisons of shared and weak pointers.

namespace std {
    template<class T = void> struct owner_less;
    template<class T> struct owner_less<shared_ptr<T>> {
        bool operator()(const shared_ptr<T>&, const shared_ptr<T>&) const noexcept;
        bool operator()(const shared_ptr<T>&, const weak_ptr<T>&) const noexcept;
        bool operator()(const weak_ptr<T>&, const shared_ptr<T>&) const noexcept;
    };
    template<class T> struct owner_less<weak_ptr<T>> {
        bool operator()(const weak_ptr<T>&, const weak_ptr<T>&) const noexcept;
        bool operator()(const shared_ptr<T>&, const weak_ptr<T>&) const noexcept;
        bool operator()(const weak_ptr<T>&, const shared_ptr<T>&) const noexcept;
    };
    template<> struct owner_less<void> {
        template<class T, class U>
        bool operator()(const shared_ptr<T>&, const shared_ptr<U>&) const noexcept;
        template<class T, class U>
        bool operator()(const shared_ptr<T>&, const weak_ptr<U>&) const noexcept;
        template<class T, class U>
        bool operator()(const weak_ptr<T>&, const shared_ptr<U>&) const noexcept;
        template<class T, class U>
        bool operator()(const weak_ptr<T>&, const weak_ptr<U>&) const noexcept;
        using is_transparent = unspecified;
    };
}

operator()(x, y) returns x.owner_before(y).

[Note 1: Note that
(2.1) — operator() defines a strict weak ordering as defined in 27.8;
(2.2) — !operator()(a, b) && !operator()(b, a) is true if and only if a.owner_equal(b) is true.
—end note]

20.3.2.5 Struct owner_hash

The class owner_hash provides ownership-based hashing.

namespace std {
    struct owner_hash {
        template<class T>
        size_t operator()(const shared_ptr<T>&) const noexcept;
        template<class T>
        size_t operator()(const weak_ptr<T>&) const noexcept;
    };
}
using is_transparent = unspecified;
};
}

template<class T>
size_t operator()(const shared_ptr<T>& x) const noexcept;

template<class T>
size_t operator()(const weak_ptr<T>& x) const noexcept;

2 Returns: x.owner_hash().

3
[Note 1: For any object y where x.owner_equal(y) is true, x.owner_hash() == y.owner_hash() is true.
—end note]

20.3.2.6 Struct owner_equal [util.smartptr.owner.equal]

1 The class owner_equal provides ownership-based mixed equality comparisons of shared and weak pointers.

namespace std {
    struct owner_equal {
        template<class T, class U>
        bool operator()(const shared_ptr<T>&, const shared_ptr<U>&) const noexcept;
        template<class T, class U>
        bool operator()(const shared_ptr<T>&, const weak_ptr<U>&) const noexcept;
        template<class T, class U>
        bool operator()(const weak_ptr<T>&, const shared_ptr<U>&) const noexcept;
        template<class T, class U>
        bool operator()(const weak_ptr<T>&, const weak_ptr<U>&) const noexcept;

        using is_transparent = unspecified;
    };
}

template<class T, class U>
bool operator()(const shared_ptr<T>& x, const shared_ptr<U>& y) const noexcept;

template<class T, class U>
bool operator()(const shared_ptr<T>& x, const weak_ptr<U>& y) const noexcept;

template<class T, class U>
bool operator()(const weak_ptr<T>& x, const shared_ptr<U>& y) const noexcept;

template<class T, class U>
bool operator()(const weak_ptr<T>& x, const weak_ptr<U>& y) const noexcept;

2 Returns: x.owner_equal(y).

3
[Note 1: x.owner_equal(y) is true if and only if x and y share ownership or are both empty. —end note]

20.3.2.7 Class template enable_shared_from_this [util.smartptr.enab]

1 A class T can inherit from enable_shared_from_this<T> to inherit the shared_from_this member functions that obtain a shared_ptr instance pointing to *this.

2 [Example 1]:

struct X: public enable_shared_from_this<X> { }; int main() {
    shared_ptr<X> p(new X);
    shared_ptr<X> q = p->shared_from_this();
    assert(p == q);
    assert(p.owner_equal(q)); // p and q share ownership
}

—end example]

namespace std {
    template<class T> class enable_shared_from_this {
        protected:
            constexpr enable_shared_from_this() noexcept;
            enable_shared_from_this(const enable_shared_from_this&) noexcept;
            enable_shared_from_this& operator=(const enable_shared_from_this&) noexcept;
            ~enable_shared_from_this();
    };
}

§ 20.3.2.7 ©ISO/IEC 648
public:
    shared_ptr<T> shared_from_this();
    shared_ptr<T const> shared_from_this() const;
    weak_ptr<T> weak_from_this() noexcept;
    weak_ptr<T const> weak_from_this() const noexcept;
private:
    mutable weak_ptr<T> weak_this; // exposition only
};

3 The template parameter T of enable_shared_from_this may be an incomplete type.

constexpr enable_shared_from_this() noexcept;
enable_shared_from_this(const enable_shared_from_this<T>&) noexcept;

4 Effects: Value-initializes weak_this.

enable_shared_from_this<T>& operator=(const enable_shared_from_this<T>&) noexcept;

5 Returns: *this.

[Note 1: weak_this is not changed. — end note]

shared_ptr<T> shared_from_this();
shared_ptr<T const> shared_from_this() const;

6 Returns: shared_ptr<T>(weak_this).

weak_ptr<T> weak_from_this() noexcept;
weak_ptr<T const> weak_from_this() const noexcept;

7 Returns: weak_this.

20.3.3 Smart pointer hash support [util.smartptr.hash]

template<class T, class D> struct hash<unique_ptr<T, D>>;

1 Letting UP be unique_ptr<T, D>, the specialization hash<UP> is enabled (22.10.19) if and only if
hash<typename UP::pointer> is enabled. When enabled, for an object p of type UP, hash<UP>()(p)
evaluates to the same value as hash<typename UP::pointer>()(p.get()). The member functions
are not guaranteed to be noexcept.

template<class T> struct hash<shared_ptr<T>>;

2 For an object p of type shared_ptr<T>, hash<shared_ptr<T>>()(p) evaluates to the same value as
hash<typename shared_ptr<T>::element_type*>()(p.get()).

20.3.4 Smart pointer adaptors [smartptr.adapt]

20.3.4.1 Class template out_ptr_t [out.ptr.t]

out_ptr_t is a class template used to adapt types such as smart pointers (20.3) for functions that use output
pointer parameters.

2 [Example 1]:

#include <memory>
#include <cstdio>

int fopen_s(std::FILE** f, const char* name, const char* mode);

struct fclose_deleter {
    void operator()(std::FILE* f) const noexcept {
        std::fclose(f);
    }
};

int main(int, char*[]) {
    constexpr const char* file_name = "ow.o";
    std::unique_ptr<std::FILE, fclose_deleter> file_ptr;

    // Further code...
}
int err = fopen_s(std::out_ptr<std::FILE*>(file_ptr), file_name, "r+b");
if (err != 0)
    return 1;
// *file_ptr is valid
return 0;
}

unique_ptr can be used with out_ptr to be passed into an output pointer-style function, without needing to hold onto an intermediate pointer value and manually delete it on error or failure. — end example

namespace std {
    template<class Smart, class Pointer, class... Args>
    class out_ptr_t {
        public:
            explicit out_ptr_t(Smart&, Args...);
            out_ptr_t(const out_ptr_t&) = delete;
            ~out_ptr_t();
            operator Pointer*() const noexcept;
            operator void**() const noexcept;
        private:
            Smart& s;    // exposition only
            tuple<Args...> a;    // exposition only
            Pointer p;    // exposition only
    };
}

Pointer shall meet the Cpp17NullablePointer requirements. If Smart is a specialization of shared_ptr and sizeof...(Args) == 0, the program is ill-formed.

[Note 1: It is typically a user error to reset a shared_ptr without specifying a deleter, as shared_ptr will replace a custom deleter upon usage of reset, as specified in 20.3.2.2.5. — end note]

Program-defined specializations of out_ptr_t that depend on at least one program-defined type need not meet the requirements for the primary template.

Evaluations of the conversion functions on the same object may conflict (6.9.2.2).

explicit out_ptr_t(Smart& smart, Args... args);

Effects: Initializes s with smart, a with std::forward<Args>(args)..., and value-initializes p. Then, equivalent to:

(6.1)  —  s.reset();
       if the expression s.reset() is well-formed;
(6.2)  —  otherwise,
       s = Smart();
       if is_constructible_v<Smart> is true;
(6.3)  —  otherwise, the program is ill-formed.

[Note 2: The constructor is not noexcept to allow for a variety of non-terminating and safe implementation strategies. For example, an implementation can allocate a shared_ptr’s internal node in the constructor and let implementation-defined exceptions escape safely. The destructor can then move the allocated control block in directly and avoid any other exceptions. — end note]

~out_ptr_t();

Let SP be POINTER_OF_OR(Smart, Pointer) (20.2.1).

Effects: Equivalent to:

(9.1)  —  if (p) {
         apply([&](auto&&... args) {
            s.reset(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
        }

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if the expression `s.reset(static_cast<SP>(p), std::forward<Args>(args)...)` is well-formed;
— otherwise,

(9.2) if (p) {
    apply([&](auto&&... args) {
        s = Smart(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
}
if `is_constructible_v<Smart, SP, Args...>` is true;
— otherwise, the program is ill-formed.

operator Pointer*() const noexcept;
10 Preconditions: operator void**() has not been called on *this.
    Returns: addressof(const_cast<Pointer&>(p)).

operator void**() const noexcept;
12 Constraints: `is_same_v<Pointer, void*>` is false.
    Mandates: `is_pointer_v<Pointer>` is true.
    Preconditions: operator Pointer*() has not been called on *this.
    Returns: A pointer value `v` such that:

(15.1) the initial value *v* is equivalent to `static_cast<void*>(p)` and

(15.2) any modification of *v* that is not followed by a subsequent modification of *this* affects the value of *v* during the destruction of *this*, such that `static_cast<void*>(p) == *v`.
    Remarks: Accessing *v* outside the lifetime of *this* has undefined behavior.
[Note 3: reinterpret_cast<void**>(static_cast<Pointer*>(*this)) can be a viable implementation strategy for some implementations. — end note]

20.3.4.2 Function template out_ptr

`template<class Pointer = void, class Smart, class... Args>`
`auto out_ptr(Smart& s, Args&&... args);`
1 Let P be Pointer if `is_void_v<Pointer>` is false, otherwise `POINTER_OF(Smart)`.
2 Returns: `out_ptr_t<Smart, P, Args&&...>(s, std::forward<Args>(args)...)`

20.3.4.3 Class template inout_ptr_t

`inout_ptr_t` is a class template used to adapt types such as smart pointers (20.3) for functions that use output pointer parameters whose dereferenced values may first be deleted before being set to another allocated value.

[Example 1:]

```cpp
#include <memory>

struct star_fish* star_fish_alloc();
int star_fish_populate(struct star_fish** ps, const char* description);

struct star_fish_deleter {
    void operator() (struct star_fish* c) const noexcept;
};

using star_fish_ptr = std::unique_ptr<star_fish, star_fish_deleter>;

int main(int, char*[]) {
    star_fish_ptr peach(star_fish_alloc());
    // ...
    // used, need to re-make
    int err = star_fish_populate(std::inout_ptr(peach), "caring clown-fish liker");
    return err;
}
```
A `unique_ptr` can be used with `inout_ptr` to be passed into an output pointer-style function. The original value will be properly deleted according to the function it is used with and a new value reset in its place. —end example

```cpp
namespace std {
    template<class Smart, class Pointer, class... Args>
    class inout_ptr_t {
    public:
        explicit inout_ptr_t(Smart&, Args...);
        inout_ptr_t(const inout_ptr_t&) = delete;
        ~inout_ptr_t();
        operator Pointer*() const noexcept;
        operator void**() const noexcept;
    private:
        Smart& s; // exposition only
        tuple<Args...> a; // exposition only
        Pointer p; // exposition only
    };
}
```

3 Pointer shall meet the Cpp17NullablePointer requirements. If `Smart` is a specialization of `shared_ptr`, the program is ill-formed.

[Note 1: It is impossible to properly acquire unique ownership of the managed resource from a `shared_ptr` given its shared ownership model. —end note]

4 Program-defined specializations of `inout_ptr_t` that depend on at least one program-defined type need not meet the requirements for the primary template.

5 Evaluations of the conversion functions on the same object may conflict (6.9.2.2).

```cpp
explicit inout_ptr_t(Smart& smart, Args... args);
```

6 

Effects: Initializes `s` with `smart`, `a` with `std::forward<Args>(args)...`, and `p` to either

(6.1) — `smart` if `is_pointer_v<Smart>` is true,

(6.2) — otherwise, `smart.get()`.

7 Remarks: An implementation can call `s.release()`.

[Note 2: The constructor is not `noexcept` to allow for a variety of non-terminating and safe implementation strategies. For example, an intrusive pointer implementation with a control block can allocate in the constructor and safely fail with an exception. —end note]

```cpp
~inout_ptr_t();
```

9 Let `SP` be `POINTER_OF_OR(Smart, Pointer)` (20.2.1).

10 Let `release-statement` be `s.release()`; if an implementation does not call `s.release()` in the constructor. Otherwise, it is empty.

11 Effects: Equivalent to:

(11.1) — `apply([&](auto&&... args) {
    s = Smart(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));`

if `is_pointer_v<Smart>` is true;

(11.2) — otherwise,

```
release-statement;
```

if `(p)` {

```
apply([&](auto&&... args) {
    s.reset(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
```

if the expression `s.reset(static_cast<SP>(p), std::forward<Args>(args)...)` is well-formed;

(11.3) — otherwise,

```
release-statement;
```
if (p) {
    apply([&](auto&&... args) {
        s = Smart(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
}

if is_constructible_v<Smart, SP, Args...> is true:
    — otherwise, the program is ill-formed.

operator Pointer*() const noexcept;

Preconditions: operator void**() has not been called on *this.

Returns: addressof(const_cast<Pointer&>(p)).

operator void**() const noexcept;

Constraints: is_same_v<Pointer, void*> is false.

Mandates: is_pointer_v<Pointer> is true.

Preconditions: operator Pointer*() has not been called on *this.

Returns: A pointer value v such that:
    — the initial value *v is equivalent to static_cast<void*>(p) and
    — any modification of *v that is not followed by subsequent modification of *this affects the value of p during the destruction of *this, such that static_cast<void*>(p) == *v.

Remarks: Accessing *v outside the lifetime of *this has undefined behavior.

[Note 3: reinterpret_cast<void**>(static_cast<Pointer*>(*this)) can be a viable implementation strategy for some implementations. —end note]

20.3.4.4 Function template inout_ptr

template<class Pointer = void, class Smart, class... Args>
auto inout_ptr(Smart& s, Args&&... args);

Let P be Pointer if is_void_v<Pointer> is false, otherwise POINTER_OF(Smart).

Returns: inout_ptr_t<Smart, P, Args&&...>(s, std::forward<Args>(args)...).

20.4 Memory resources

20.4.1 Header <memory_resource> synopsis

namespace std::pmr {
    // 20.4.2, class memory_resource
    class memory_resource;

    bool operator==(const memory_resource& a, const memory_resource& b) noexcept;

    // 20.4.3, class template polymorphic_allocator
    template<classTp = byte> class polymorphic_allocator;

    template<class T1, class T2>
    bool operator==(const polymorphic_allocator<T1>& a, const polymorphic_allocator<T2>& b) noexcept;

    // 20.4.4, global memory resources
    memory_resource* new_delete_resource() noexcept;
    memory_resource* null_memory_resource() noexcept;
    memory_resource* set_default_resource(memory_resource* r) noexcept;
    memory_resource* get_default_resource() noexcept;

    // 20.4.5, pool resource classes
    struct pool_options;
    class synchronized_pool_resource;
    class unsynchronized_pool_resource;
    class monotonic_buffer_resource;
}
20.4.2 Class memory_resource

20.4.2.1 General

The `memory_resource` class is an abstract interface to an unbounded set of classes encapsulating memory resources.

```cpp
namespace std::pmr {
    class memory_resource {
        static constexpr size_t max_align = alignof(max_align_t); // exposition only

        public:
            memory_resource() = default;
            memory_resource(const memory_resource&) = default;
            virtual ~memory_resource();

            memory_resource& operator=(const memory_resource&) = default;

            [[nodiscard]] void* allocate(size_t bytes, size_t alignment = max_align);
            void deallocate(void* p, size_t bytes, size_t alignment = max_align);
            bool is_equal(const memory_resource& other) const noexcept;

        private:
            virtual void* do_allocate(size_t bytes, size_t alignment) = 0;
            virtual void do_deallocate(void* p, size_t bytes, size_t alignment) = 0;
            virtual bool do_is_equal(const memory_resource& other) const noexcept = 0;
    };
}
```

20.4.2.2 Public member functions

~memory_resource();

Effects: Destroys this `memory_resource`.

```cpp
[[nodiscard]] void* allocate(size_t bytes, size_t alignment = max_align);
```

Effects: Allocates storage by calling `do_allocate(bytes, alignment)` and implicitly creates objects within the allocated region of storage.

Returns: A pointer to a suitable created object (6.7.2) in the allocated region of storage.

Throws: What and when the call to `do_allocate` throws.

```cpp
void deallocate(void* p, size_t bytes, size_t alignment = max_align);
```

Effects: Equivalent to `do_deallocate(p, bytes, alignment)`.

```cpp
bool is_equal(const memory_resource& other) const noexcept;
```

Effects: Equivalent to: `return do_is_equal(other);`

20.4.2.3 Private virtual member functions

```cpp
virtual void* do_allocate(size_t bytes, size_t alignment) = 0;
```

Preconditions: `alignment` is a power of two.

Returns: A derived class shall implement this function to return a pointer to allocated storage (6.7.5.5.2) with a size of at least `bytes`, aligned to the specified `alignment`.

Throws: A derived class implementation shall throw an appropriate exception if it is unable to allocate memory with the requested size and alignment.

```cpp
virtual void do_deallocate(void* p, size_t bytes, size_t alignment) = 0;
```

Preconditions: `p` was returned from a prior call to `allocate(bytes, alignment)` on a memory resource equal to `*this`, and the storage at `p` has not yet been deallocated.

Effects: A derived class shall implement this function to dispose of allocated storage.
virtual bool do_is_equal(const memory_resource& other) const noexcept = 0;

Returns: A derived class shall implement this function to return true if memory allocated from *this
can be deallocated from other and vice-versa, otherwise false.

[Note 1: It is possible that the most-derived type of other does not match the type of *this. For a derived
class B, an implementation of this function can immediately return false if dynamic_cast<const D*>(&other)
== nullptr. —end note]

20.4.2.4 Equality [mem.res.eq]

bool operator==(const memory_resource& a, const memory_resource& b) noexcept;

Returns: &a == &b || a.is_equal(b).

20.4.3 Class template polymorphic_allocator [mem.polyallocator.class]

20.4.3.1 General [mem.polyallocator.class.general]

A specialization of class template pmr::polymorphic_allocator meets the Cpp17Allocator requirements
(16.4.4.6.1) if its template argument is a cv-unqualified object type. Constructed with different memory
resources, different instances of the same specialization of pmr::polymorphic_allocator can exhibit entirely
different allocation behavior. This runtime polymorphism allows objects that use polymorphic_allocator
to behave as if they used different allocator types at run time even though they use the same static allocator
type.

A specialization of class template pmr::polymorphic_allocator meets the allocator completeness require-
ments (16.4.4.6.2) if its template argument is a cv-unqualified object type.

namespace std::pmr {

    template<class Tp = byte> class polymorphic_allocator {
        memory_resource* memory_rsrc; // exposition only

    public:
        using value_type = Tp;

        // 20.4.3.2, constructors
        polymorphic_allocator() noexcept;
        polymorphic_allocator(memory_resource* r);

        polymorphic_allocator(const polymorphic_allocator& other) = default;

        template<class U>
        polymorphic_allocator(const polymorphic_allocator<U>& other) noexcept;

        polymorphic_allocator& operator=(const polymorphic_allocator&) = delete;

        // 20.4.3.3, member functions
        [[nodiscard]] Tp* allocate(size_t n);
        void deallocate(Tp* p, size_t n);

        [[nodiscard]] void* allocate_bytes(size_t nbytes, size_t alignment = alignof(max_align_t));
        void deallocate_bytes(void* p, size_t nbytes, size_t alignment = alignof(max_align_t));

        template<class T> [[nodiscard]] T* allocate_object(size_t n = 1);
        template<class T> void deallocate_object(T* p, size_t n = 1);
        template<class T, class... CtorArgs> [[nodiscard]] T* new_object(CtorArgs&&... ctor_args);
        template<class T> void delete_object(T* p);
        template<class T, class... Args>
        void construct(T* p, Args&&... args);

        template<class T>
        void destroy(T* p);

        polymorphic_allocator select_on_container_copy_construction() const;
    }

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§ 20.4.3.1
memory_resource* resource() const;

// friends
friend bool operator==(const polymorphic_allocator& a,
                     const polymorphic_allocator& b) noexcept {
    return *a.resource() == *b.resource();
}
};

20.4.3.2 Constructors

polymorphic_allocator() noexcept;
1
   Effects: Sets memory_rsrc to get_default_resource().

polymorphic_allocator(memory_resource* r);
2    Preconditions: r is non-null.
3    Effects: Sets memory_rsrc to r.
4    Throws: Nothing.
5 [Note 1: This constructor provides an implicit conversion from
6      memory_resource*. — end note]

template<class U> polymorphic_allocator(const polymorphic_allocator<U>& other) noexcept;
6    Effects: Sets memory_rsrc to other.resource().

20.4.3.3 Member functions

[[nodiscard]] Tp* allocate(size_t n);
1    Effects: If numeric_limits<size_t>::max() / sizeof(Tp) < n, throws bad_array_new_length.
          Otherwise equivalent to:
          return static_cast<Tp*>(memory_rsrc->allocate(n * sizeof(Tp), alignof(Tp)));

void deallocate(Tp* p, size_t n);
2    Preconditions: p was allocated from a memory resource x, equal to *memory_rsrc, using
3                  x.allocate(n * sizeof(Tp), alignof(Tp)).
4    Effects: Equivalent to memory_rsrc->deallocate(p, n * sizeof(Tp), alignof(Tp)).
5    Throws: Nothing.

[[nodiscard]] void* allocate_bytes(size_t nbytes, size_t alignment = alignof(max_align_t));
5    Effects: Equivalent to: return memory_rsrc->allocate(nbytes, alignment);
6    [Note 1: The return type is void* (rather than, e.g., byte*) to support conversion to an
7      arbitrary pointer type U* by static_cast<U*>, thus facilitating construction of a U
8      object in the allocated memory. — end note]

void deallocate_bytes(void* p, size_t nbytes, size_t alignment = alignof(max_align_t));
7    Effects: Equivalent to memory_rsrc->deallocate(p, nbytes, alignment).

template<class T>
[[nodiscard]] T* allocate_object(size_t n = 1);
8    Effects: Allocates memory suitable for holding an array of n objects of type T, as follows:
9    (8.1) if numeric_limits<size_t>::max() / sizeof(T) < n, throws bad_array_new_length,
9    (8.2) otherwise equivalent to:
9          return static_cast<T*>(allocate_bytes(n*sizeof(T), alignof(T)));
10   [Note 2: T is not deduced and must therefore be provided as a template argument. — end note]

template<class T>
void deallocate_object(T* p, size_t n = 1);
10    Effects: Equivalent to deallocate_bytes(p, n*sizeof(T), alignof(T)).
**template<class T, class... CtorArgs>**

```cpp
[[nodiscard]] T* new_object(CtorArgs&&... ctor_args);
```

**Effects**: Allocates and constructs an object of type `T`, as follows. Equivalent to:

```cpp
T* p = allocate_object<T>();
try {
    construct(p, std::forward<CtorArgs>(ctor_args)...);
} catch (...) {
    deallocate_object(p);
    throw;
}
return p;
```

**Note 3**: `T` is not deduced and must therefore be provided as a template argument. — end note

**template<class T>**

```cpp
void delete_object(T* p);
```

**Effects**: Equivalent to:

```cpp
destroy(p);
deleallocate_object(p);
```

**template<class T, class... Args>**

```cpp
void construct(T* p, Args&&... args);
```

**Mandates**: Uses-allocator construction of `T` with allocator `*this` (see 20.2.8.2) and constructor arguments `std::forward<Args>(args)`... is well-formed.

**Effects**: Construct a `T` object in the storage whose address is represented by `p` by uses-allocator construction with allocator `*this` and constructor arguments `std::forward<Args>(args)`...

**Throws**: Nothing unless the constructor for `T` throws.

**template<class T>**

```cpp
void destroy(T* p);
```

**Effects**: Equivalent to `p->~T()`.

**polymorphic_allocator select_on_container_copy_construction()**

```cpp
const;
```

**Returns**: `polymorphic_allocator()`.

**Note 4**: The memory resource is not propagated. — end note

**memory_resource* resource()**

```cpp
const;
```

**Returns**: `memory_rsrc`.

### 20.4.3.4 Equality

**template<class T1, class T2>**

```cpp
bool operator==(const polymorphic_allocator<T1>& a,
               const polymorphic_allocator<T2>& b) noexcept;
```

**Returns**: `*a.resource() == *b.resource()`.

### 20.4.4 Access to program-wide memory_resource objects

**memory_resource* new_delete_resource()**

```cpp
noexcept;
```

**Returns**: A pointer to a static-duration object of a type derived from `memory_resource` that can serve as a resource for allocating memory using `::operator new` and `::operator delete`. The same value is returned every time this function is called. For a return value `p` and a memory resource `r`, `p->is_equal(r)` returns `&r == p`.

**memory_resource* null_memory_resource()**

```cpp
noexcept;
```

**Returns**: A pointer to a static-duration object of a type derived from `memory_resource` for which `allocate()` always throws `bad_alloc` and for which `deallocate()` has no effect. The same value is
returned every time this function is called. For a return value p and a memory resource r, p->is_equal(r) returns &r == p.

3 The default memory resource pointer is a pointer to a memory resource that is used by certain facilities when an explicit memory resource is not supplied through the interface. Its initial value is the return value of new_delete_resource().

memory_resource* set_default_resource(memory_resource* r) noexcept;

4 Effects: If r is non-null, sets the value of the default memory resource pointer to r, otherwise sets the default memory resource pointer to new_delete_resource().

5 Returns: The previous value of the default memory resource pointer.

6 Remarks: Calling the set_default_resource and get_default_resource functions shall not incur a data race. A call to the set_default_resource function shall synchronize with subsequent calls to the set_default_resource and get_default_resource functions.

memory_resource* get_default_resource() noexcept;

7 Returns: The current value of the default memory resource pointer.

20.4.5 Pool resource classes [mem.res.pool]

20.4.5.1 Classes synchronized_pool_resource and unsynchronized_pool_resource [mem.res.pool.overview]

1 The synchronized_pool_resource and unsynchronized_pool_resource classes (collectively called pool resource classes) are general-purpose memory resources having the following qualities:

(1.1) — Each resource frees its allocated memory on destruction, even if deallocate has not been called for some of the allocated blocks.

(1.2) — A pool resource consists of a collection of pools, serving requests for different block sizes. Each individual pool manages a collection of chunks that are in turn divided into blocks of uniform size, returned via calls to do_allocate. Each call to do_allocate(size, alignment) is dispatched to the pool serving the smallest blocks accommodating at least size bytes.

(1.3) — When a particular pool is exhausted, allocating a block from that pool results in the allocation of an additional chunk of memory from the upstream allocator (supplied at construction), thus replenishing the pool. With each successive replenishment, the chunk size obtained increases geometrically.

[Note 1: By allocating memory in chunks, the pooling strategy increases the chance that consecutive allocations will be close together in memory. — end note]

(1.4) — Allocation requests that exceed the largest block size of any pool are fulfilled directly from the upstream allocator.

(1.5) — A pool_options struct may be passed to the pool resource constructors to tune the largest block size and the maximum chunk size.

2 A synchronized_pool_resource may be accessed from multiple threads without external synchronization and may have thread-specific pools to reduce synchronization costs. An unsynchronized_pool_resource class may not be accessed from multiple threads simultaneously and thus avoids the cost of synchronization entirely in single-threaded applications.

namespace std::pmr {
    struct pool_options {
        size_t max_blocks_per_chunk = 0;
        size_t largest_required_pool_block = 0;
    };

    class synchronized_pool_resource : public memory_resource {
    public:
        synchronized_pool_resource(const pool_options& opts, memory_resource* upstream);

        synchronized_pool_resource() : synchronized_pool_resource(pool_options(), get_default_resource()) {};

        explicit synchronized_pool_resource(memory_resource* upstream) : synchronized_pool_resource(pool_options(), upstream) {};
    }
explicit synchronized_pool_resource(const pool_options& opts)  
  : synchronized_pool_resource(opts, get_default_resource()) {}  

synchronized_pool_resource(const synchronized_pool_resource&) = delete;  
virtual ~synchronized_pool_resource();  
synchronized_pool_resource& operator=(const synchronized_pool_resource&) = delete;  

void release();  
memory_resource* upstream_resource() const;  
pool_options options() const;  

protected:  
  void* do_allocate(size_t bytes, size_t alignment) override;  
  void do_deallocate(void* p, size_t bytes, size_t alignment) override;  

  bool do_is_equal(const memory_resource& other) const noexcept override;  
};  

class unsynchronized_pool_resource : public memory_resource {  
public:  
  unsynchronized_pool_resource(const pool_options& opts, memory_resource* upstream);  
  
unsynchronized_pool_resource(const unsynchronized_pool_resource&) = delete;  
virtual ~unsynchronized_pool_resource();  

unsynchronized_pool_resource& operator=(const unsynchronized_pool_resource&) = delete;  

void release();  
memory_resource* upstream_resource() const;  
pool_options options() const;  

protected:  
  void* do_allocate(size_t bytes, size_t alignment) override;  
  void do_deallocate(void* p, size_t bytes, size_t alignment) override;  

  bool do_is_equal(const memory_resource& other) const noexcept override;  
};  

20.4.5.2 pool_options data members

The members of pool_options comprise a set of constructor options for pool resources. The effect of each option on the pool resource behavior is described below:

- size_t max_blocks_per_chunk;  
The maximum number of blocks that will be allocated at once from the upstream memory resource (20.4.6) to replenish a pool. If the value of max_blocks_per_chunk is zero or is greater than an implementation-defined limit, that limit is used instead. The implementation may choose to use a smaller value than is specified in this member and may use different values for different pools.

- size_t largest_required_pool_block;  
The largest allocation size that is required to be fulfilled using the pooling mechanism. Attempts to allocate a single block larger than this threshold will be allocated directly from the upstream memory resource. If largest_required_pool_block is zero or is greater than an implementation-defined limit,
that limit is used instead. The implementation may choose a pass-through threshold larger than specified in this member.

### 20.4.5.3 Constructors and destructors

```cpp
synchronized_pool_resource(const pool_options& opts, memory_resource* upstream);
unsynchronized_pool_resource(const pool_options& opts, memory_resource* upstream);
```

**Preconditions:** `upstream` is the address of a valid memory resource.

**Effects:** Constructs a pool resource object that will obtain memory from `upstream` whenever the pool resource is unable to satisfy a memory request from its own internal data structures. The resulting object will hold a copy of `upstream`, but will not own the resource to which `upstream` points.

*[Note 1: The intention is that calls to `upstream->allocate()` will be substantially fewer than calls to `this->allocate()` in most cases. — end note]*

The behavior of the pooling mechanism is tuned according to the value of the `opts` argument.

**Throws:** Nothing unless `upstream->allocate()` throws. It is unspecified if, or under what conditions, this constructor calls `upstream->allocate()`.

```cpp
virtual ~synchronized_pool_resource();
virtual ~unsynchronized_pool_resource();
```

**Effects:** Calls `release()`.

### 20.4.5.4 Members

```cpp
void release();
```

**Effects:** Calls `upstream_resource()->deallocate()` as necessary to release all allocated memory.

*[Note 1: The memory is released back to `upstream_resource()` even if `deallocate` has not been called for some of the allocated blocks. — end note]*

**Returns:** The value of the `upstream` argument provided to the constructor of this object.

```cpp
memory_resource* upstream_resource() const;
```

**Returns:** The value of the `upstream` argument provided to the constructor of this object.

```cpp
pool_options options() const;
```

**Returns:** The options that control the pooling behavior of this resource. The values in the returned struct may differ from those supplied to the pool resource constructor in that values of zero will be replaced with implementation-defined defaults, and sizes may be rounded to unspecified granularity.

```cpp
void* do_allocate(size_t bytes, size_t alignment) override;
```

**Effects:** If the pool selected for a block of size `bytes` is unable to satisfy the memory request from its own internal data structures, it will call `upstream_resource()->allocate()` to obtain more memory. If `bytes` is larger than that which the largest pool can handle, then memory will be allocated using `upstream_resource()->allocate()`.

**Returns:** A pointer to allocated storage (6.7.5.5.2) with a size of at least `bytes`. The size and alignment of the allocated memory shall meet the requirements for a class derived from `memory_resource` (20.4.2).

**Throws:** Nothing unless `upstream_resource()->allocate()` throws.

```cpp
void do_deallocate(void* p, size_t bytes, size_t alignment) override;
```

**Effects:** Returns the memory at `p` to the pool. It is unspecified if, or under what circumstances, this operation will result in a call to `upstream_resource()->deallocate()`.

**Throws:** Nothing.

```cpp
bool do_is_equal(const memory_resource& other) const noexcept override;
```

**Returns:** `this` == `&other`. 

§ 20.4.5.4 © ISO/IEC 660
20.4.6 Class monotonic_buffer_resource

20.4.6.1 General

A monotonic_buffer_resource is a special-purpose memory resource intended for very fast memory allocations in situations where memory is used to build up a few objects and then is released all at once when the memory resource object is destroyed.

namespace std::pmr {
    class monotonic_buffer_resource : public memory_resource {
        memory_resource* upstream_rsrc; // exposition only
        void* current_buffer;           // exposition only
        size_t next_buffer_size;        // exposition only

        public:
            explicit monotonic_buffer_resource(memory_resource* upstream);
            monotonic_buffer_resource(size_t initial_size, memory_resource* upstream);
            monotonic_buffer_resource(void* buffer, size_t buffer_size, memory_resource* upstream);

            monotonic_buffer_resource()
                : monotonic_buffer_resource(get_default_resource()) {}
            explicit monotonic_buffer_resource(size_t initial_size)
                : monotonic_buffer_resource(initial_size, get_default_resource()) {}
            monotonic_buffer_resource(void* buffer, size_t buffer_size)
                : monotonic_buffer_resource(buffer, buffer_size, get_default_resource()) {}

            monotonic_buffer_resource(const monotonic_buffer_resource&) = delete;
            virtual ~monotonic_buffer_resource();
            monotonic_buffer_resource& operator=(const monotonic_buffer_resource&) = delete;
            void release();
            memory_resource* upstream_resource() const;

        protected:
            void* do_allocate(size_t bytes, size_t alignment) override;
            void do_deallocate(void* p, size_t bytes, size_t alignment) override;

            bool do_is_equal(const memory_resource& other) const noexcept override;
    };
}

20.4.6.2 Constructors and destructor

explicit monotonic_buffer_resource(memory_resource* upstream);
monotonic_buffer_resource(size_t initial_size, memory_resource* upstream);

1 Preconditions: upstream is the address of a valid memory resource. initial_size, if specified, is greater than zero.

2 Effects: Sets upstream_rsrc to upstream and current_buffer to nullptr. If initial_size is specified, sets next_buffer_size to at least initial_size; otherwise sets next_buffer_size to an implementation-defined size.

monotonic_buffer_resource(void* buffer, size_t buffer_size, memory_resource* upstream);

3 Preconditions: upstream is the address of a valid memory resource. buffer_size is no larger than the number of bytes in buffer.

4 Effects: Sets upstream_rsrc to upstream, current_buffer to buffer, and next_buffer_size to buffer_size (but not less than 1), then increases next_buffer_size by an implementation-defined growth factor (which need not be integral).

~monotonic_buffer_resource();

5 Effects: Calls release().
20.4.6.3 Members

```cpp
void release();
```

1. **Effects**: Calls `upstream_rsrc->deallocate()` as necessary to release all allocated memory. Resets `current_buffer` and `next_buffer_size` to their initial values at construction.

2. **Note 1**: The memory is released back to `upstream_rsrc` even if some blocks that were allocated from `*this` have not been deallocated from `*this`. — end note

```cpp
memory_resource* upstream_resource() const;
```

3. **Returns**: The value of `upstream_rsrc`.

```cpp
void* do_allocate(size_t bytes, size_t alignment) override;
```

4. **Effects**: If the unused space in `current_buffer` can fit a block with the specified `bytes` and `alignment`, then allocate the return block from `current_buffer`; otherwise set `current_buffer` to `upstream_rsrc->allocate(n, m)`, where `n` is not less than `max(bytes, next_buffer_size)` and `m` is not less than `alignment`, and increase `next_buffer_size` by an implementation-defined growth factor (which need not be integral), then allocate the return block from the newly-allocated `current_buffer`.

5. **Returns**: A pointer to allocated storage (6.7.5.5.2) with a size of at least `bytes`. The size and alignment of the allocated memory shall meet the requirements for a class derived from `memory_resource` (20.4.2).

6. **Throws**: Nothing unless `upstream_rsrc->allocate()` throws.

```cpp
void do_deallocate(void* p, size_t bytes, size_t alignment) override;
```

7. **Effects**: None.

8. **Throws**: Nothing.

9. **Remarks**: Memory used by this resource increases monotonically until its destruction.

```cpp
bool do_is_equal(const memory_resource& other) const noexcept override;
```

10. **Returns**: `this == &other`.

## 20.5 Class template `scoped_allocator_adaptor`

### 20.5.1 Header `<scoped_allocator>`

```cpp
namespace std {
    // class template scoped_allocator_adaptor
    template<class OuterAlloc, class... InnerAllocs>
    class scoped_allocator_adaptor;

    // 20.5.5, scoped allocator operators
    template<class OuterA1, class OuterA2, class... InnerAllocs>
    bool operator==(const scoped_allocator_adaptor<OuterA1, InnerAllocs...>& a, const scoped_allocator_adaptor<OuterA2, InnerAllocs...>& b) noexcept;
}
```

1. The class template `scoped_allocator_adaptor` is an allocator template that specifies an allocator resource (the outer allocator) to be used by a container (as any other allocator does) and also specifies an inner allocator resource to be passed to the constructor of every element within the container. This adaptor is instantiated with one outer and zero or more inner allocator types. If instantiated with only one allocator type, the inner allocator becomes the `scoped_allocator_adaptor` itself, thus using the same allocator resource for the container and every element within the container and, if the elements themselves are containers, each of their elements recursively. If instantiated with more than one allocator, the first allocator is the outer allocator for use by the container, the second allocator is passed to the constructors of the container’s elements, and, if the elements themselves are containers, the third allocator is passed to the elements’ elements, and so on. If containers are nested to a depth greater than the number of allocators, the last allocator is used repeatedly, as in the single-allocator case, for any remaining recursions.

2. **Note 1**: The `scoped_allocator_adaptor` is derived from the outer allocator type so it can be substituted for the outer allocator type in most expressions. — end note
namespace std {
    template<class OuterAlloc, class... InnerAllocs>
    class scoped_allocator_adaptor : public OuterAlloc {
    private:
        using OuterTraits = allocator_traits<OuterAlloc>;    // exposition only
        scoped_allocator_adaptor<InnerAllocs...> inner;     // exposition only
    public:
        using outer_allocator_type = OuterAlloc;
        using inner_allocator_type = see below;
        using value_type = typename OuterTraits::value_type;
        using size_type = typename OuterTraits::size_type;
        using difference_type = typename OuterTraits::difference_type;
        using pointer = typename OuterTraits::pointer;
        using const_pointer = typename OuterTraits::const_pointer;
        using void_pointer = typename OuterTraits::void_pointer;
        using const_void_pointer = typename OuterTraits::const_void_pointer;
        using propagate_on_container_copy_assignment = see below;
        using propagate_on_container_move_assignment = see below;
        using propagate_on_container_swap = see below;
        using is_always_equal = see below;

        template<class Tp> struct rebind {
            using other = scoped_allocator_adaptor<
                OuterTraits::template rebind_alloc<Tp>, InnerAllocs...>;
        };

        scoped_allocator_adaptor();
        template<class OuterA2>
        scoped_allocator_adaptor(OuterA2&& outerAlloc,
            const InnerAllocs&... innerAllocs) noexcept;

        scoped_allocator_adaptor(const scoped_allocator_adaptor& other) noexcept;
        scoped_allocator_adaptor(scoped_allocator_adaptor&& other) noexcept;

        template<class OuterA2>
        scoped_allocator_adaptor(const scoped_allocator_adaptor<OuterA2, InnerAllocs...>& other) noexcept;
        template<class OuterA2>
        scoped_allocator_adaptor(scoped_allocator_adaptor<OuterA2, InnerAllocs...>&& other) noexcept;

        scoped_allocator_adaptor& operator=(const scoped_allocator_adaptor&) = default;
        scoped_allocator_adaptor& operator=(scoped_allocator_adaptor&&) = default;

        ~scoped_allocator_adaptor();

        inner_allocator_type& inner_allocator() noexcept;
        const inner_allocator_type& inner_allocator() const noexcept;

        outer_allocator_type& outer_allocator() noexcept;
        const outer_allocator_type& outer_allocator() const noexcept;

        [[nodiscard]] pointer allocate(size_type n);
        [[nodiscard]] pointer allocate(size_type n, const_void_pointer hint);
        void deallocate(pointer p, size_type n);

        size_type max_size() const;

        template<class T, class... Args>
        void construct(T* p, Args&&... args);

        template<class T>
        void destroy(T* p);
    };
}
```cpp
scoped_allocator_adaptor select_on_container_copy_construction() const;
}

template<class OuterAlloc, class... InnerAllocs>
scoped_allocator_adaptor(OuterAlloc, InnerAllocs...) -> scoped_allocator_adaptor<OuterAlloc, InnerAllocs...>;
}

20.5.2 Member types

using inner_allocator_type = see below;

1 Type: scoped_allocator_adaptor<OuterAlloc> if sizeof...(InnerAllocs) is zero; otherwise, scoped_allocator_adaptor<InnerAllocs...>.

using propagate_on_container_copy_assignment = see below;

2 Type: true_type if allocator_traits<A>::propagate_on_container_copy_assignment::value is true for any A in the set of OuterAlloc and InnerAllocs...; otherwise, false_type.

using propagate_on_container_move_assignment = see below;

3 Type: true_type if allocator_traits<A>::propagate_on_container_move_assignment::value is true for any A in the set of OuterAlloc and InnerAllocs...; otherwise, false_type.

using propagate_on_container_swap = see below;

4 Type: true_type if allocator_traits<A>::propagate_on_container_swap::value is true for any A in the set of OuterAlloc and InnerAllocs...; otherwise, false_type.

using is_always_equal = see below;

5 Type: true_type if allocator_traits<A>::is_always_equal::value is true for every A in the set of OuterAlloc and InnerAllocs...; otherwise, false_type.

20.5.3 Constructors

scoped_allocator_adaptor();

1 Effects: Value-initializes the OuterAlloc base class and the inner allocator object.

template<class OuterA2>
scoped_allocator_adaptor(OuterA2& outerAlloc, const InnerAllocs&... innerAllocs) noexcept;

2 Constraints: is_constructible_v<OuterAlloc, OuterA2> is true.

3 Effects: Initializes the OuterAlloc base class with std::forward<OuterA2>(outerAlloc) and inner with innerAllocs... (hence recursively initializing each allocator within the adaptor with the corresponding allocator from the argument list).

scoped_allocator_adaptor(const scoped_allocator_adaptor& other) noexcept;

4 Effects: Initializes each allocator within the adaptor with the corresponding allocator from other.

scoped_allocator_adaptor(scoped_allocator_adaptor&& other) noexcept;

5 Effects: Move constructs each allocator within the adaptor with the corresponding allocator from other.

template<class OuterA2>
scoped_allocator_adaptor(
    const scoped_allocator_adaptor<OuterA2, InnerAllocs...>& other) noexcept;

6 Constraints: is_constructible_v<OuterAlloc, const OuterA2&> is true.

7 Effects: Initializes each allocator within the adaptor with the corresponding allocator from other.

template<class OuterA2>
scoped_allocator_adaptor(scoped_allocator_adaptor<OuterA2, InnerAllocs...>&& other) noexcept;

8 Constraints: is_constructible_v<OuterAlloc, OuterA2> is true.
```
Effects: Initializes each allocator within the adaptor with the corresponding allocator rvalue from other.

20.5.4 Members

In the construct member functions, OUTERMOST(x) is OUTERMOST(x.outer_allocator()) if the expression x.outer_allocator() is valid (13.10.3) and x otherwise; OUTERMOST_ALLOC_TRAITS(x) is allocator_traits<remove_reference_t<decltype(OUTERMOST(x))>>.

[Note 1: OUTERMOST(x) and OUTERMOST_ALLOC_TRAITS(x) are recursive operations. It is incumbent upon the definition of outer_allocator() to ensure that the recursion terminates. It will terminate for all instantiations of scoped_allocator_adaptor. — end note]

inner_allocator_type& inner_allocator() noexcept;
const inner_allocator_type& inner_allocator() const noexcept;

Returns: *this if sizeof...(InnerAllocs) is zero; otherwise, inner.

outer_allocator_type& outer_allocator() noexcept;

Returns: static_cast<OuterAlloc&>(*this).

const outer_allocator_type& outer_allocator() const noexcept;

Returns: static_cast<const OuterAlloc&>(*this).

[[nodiscard]] pointer allocate(size_type n);

Returns: allocator_traits<OuterAlloc>::allocate(outer_allocator(), n).

[[nodiscard]] pointer allocate(size_type n, const_void_pointer hint);

Returns: allocator_traits<OuterAlloc>::allocate(outer_allocator(), n, hint).

void deallocate(pointer p, size_type n) noexcept;

Effects: As if by: allocator_traits<OuterAlloc>::deallocate(outer_allocator(), p, n);

size_type max_size() const;

Returns: allocator_traits<OuterAlloc>::max_size(outer_allocator()).

template<class T, class... Args>

void construct(T* p, Args&&... args);

Effects: Equivalent to:

apply([p, this](auto&&... newargs) {
  OUTERMOST_ALLOC_TRAITS(*this)::construct(
    OUTERMOST(*this), p,
    std::forward<decltype(newargs)>(newargs)...);
},
uses_allocator_construction_args<T>{inner_allocator(),
  std::forward<Args>(args)...});

template<class T>

void destroy(T* p);

Effects: Calls OUTERMOST_ALLOC_TRAITS(*this)::destroy(OUTERMOST(*this), p).

scoped_allocator_adaptor select_on_container_copy_construction() const;

Returns: A new scoped_allocator_adaptor object where each allocator a1 within the adaptor is initialized with allocator_traits<A1>::select_on_container_copy_construction(a2), where A1 is the type of a1 and a2 is the corresponding allocator in *this.

20.5.5 Operators

bool operator==(const scoped_allocator_adaptor<OuterA1, InnerAllocs>& a,
  const scoped_allocator_adaptor<OuterA2, InnerAllocs>& b) noexcept;

Returns: If sizeof...(InnerAllocs) is zero,
a.outer_allocator() == b.outer_allocator()
otherwise
   a.outer_allocator() == b.outer_allocator() && a.inner_allocator() == b.inner_allocator()
21 Metaprogramming library [meta]

21.1 General [meta.general]

This Clause describes metaprogramming facilities. These facilities are summarized in Table 48.

Table 48 — Metaprogramming library summary [tab:meta.summary]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.2</td>
<td>&lt;utility&gt;</td>
</tr>
<tr>
<td>21.3</td>
<td>&lt;type_traits&gt;</td>
</tr>
<tr>
<td>21.4</td>
<td>&lt;ratio&gt;</td>
</tr>
</tbody>
</table>

21.2 Compile-time integer sequences [intseq]

21.2.1 General [intseq.general]

The library provides a class template that can represent an integer sequence. When used as an argument to a function template the template parameter pack defining the sequence can be deduced and used in a pack expansion.

[Note 1: The index_sequence alias template is provided for the common case of an integer sequence of type size_t; see also 22.4.6. — end note]

21.2.2 Class template integer_sequence [intseq.intseq]

```cpp
namespace std {
    template<class T, T... I> struct integer_sequence {
        using value_type = T;
        static constexpr size_t size() noexcept { return sizeof...(I); } 
    };
}
```

Mandates: T is an integer type.

21.2.3 Alias template make_integer_sequence [intseq.make]

```cpp
template<class T, T N>
    using make_integer_sequence = integer_sequence<T, see below>;
```

Mandates: N ≥ 0.

The alias template make_integer_sequence denotes a specialization of integer_sequence with N non-type template arguments. The type make_integer_sequence<T, N> is an alias for the type integer_sequence<T, 0, 1, ..., N-1>.

[Note 1: make_integer_sequence<int, 0> is an alias for the type integer_sequence<int>. — end note]

21.3 Metaprogramming and type traits [type.traits]

21.3.1 General [type.traits.general]

Subclause 21.3 describes components used by C++ programs, particularly in templates, to support the widest possible range of types, optimize template code usage, detect type related user errors, and perform type inference and transformation at compile time. It includes type classification traits, type property inspection traits, and type transformations. The type classification traits describe a complete taxonomy of all possible C++ types, and state where in that taxonomy a given type belongs. The type property inspection traits allow important characteristics of types or of combinations of types to be inspected. The type transformations allow certain properties of types to be manipulated.

All functions specified in 21.3 are signal-safe (17.13.5).
21.3.2 Requirements [meta rqmts]

A `Cpp17UnaryTypeTrait` describes a property of a type. It shall be a class template that takes one template type argument and, optionally, additional arguments that help define the property being described. It shall be `Cpp17DefaultConstructible`, `Cpp17CopyConstructible`, and publicly and unambiguously derived, directly or indirectly, from its base characteristic, which is a specialization of the template `integral_constant` (21.3.4), with the arguments to the template `integral_constant` determined by the requirements for the particular property being described. The member names of the base characteristic shall not be hidden and shall be unambiguously available in the `Cpp17UnaryTypeTrait`.

A `Cpp17BinaryTypeTrait` describes a relationship between two types. It shall be a class template that takes two template type arguments and, optionally, additional arguments that help define the relationship being described. It shall be `Cpp17DefaultConstructible`, `Cpp17CopyConstructible`, and publicly and unambiguously derived, directly or indirectly, from its base characteristic, which is a specialization of the template `integral_constant` (21.3.4), with the arguments to the template `integral_constant` determined by the requirements for the particular relationship being described. The member names of the base characteristic shall not be hidden and shall be unambiguously available in the `Cpp17BinaryTypeTrait`.

A `Cpp17TransformationTrait` modifies a property of a type. It shall be a class template that takes one template type argument and, optionally, additional arguments that help define the modification. It shall define a publicly accessible nested type named `type`, which shall be a synonym for the modified type.

Unless otherwise specified, the behavior of a program that adds specializations for any of the templates specified in 21.3 is undefined.

Unless otherwise specified, an incomplete type may be used to instantiate a template specified in 21.3. The behavior of a program is undefined if

- an instantiation of a template specified in 21.3 directly or indirectly depends on an incompletely-defined object type `T`, and
- that instantiation could yield a different result were `T` hypothetically completed.

21.3.3 Header `<type_traits>` synopsis [meta type synop]

```cpp
// all freestanding
namespace std {
  // 21.3.4, helper class
  template<class T, T v> struct integral_constant;
  
  template<bool B>
    using bool_constant = integral_constant<bool, B>;
  using true_type = bool_constant<true>;
  using false_type = bool_constant<false>;

  // 21.3.5.2, primary type categories
  template<class T> struct is_void;
  template<class T> struct is_null_pointer;
  template<class T> struct is_integral;
  template<class T> struct is_floating_point;
  template<class T> struct is_array;
  template<class T> struct is_pointer;
  template<class T> struct is_lvalue_reference;
  template<class T> struct is_rvalue_reference;
  template<class T> struct is_member_object_pointer;
  template<class T> struct is_member_function_pointer;
  template<class T> struct is_enum;
  template<class T> struct is_union;
  template<class T> struct is_class;
  template<class T> struct is_function;

  // 21.3.5.3, composite type categories
  template<class T> struct is_reference;
  template<class T> struct is_arithmetic;
  template<class T> struct is_fundamental;
  template<class T> struct is_object;
  template<class T> struct is_scalar;
```
template<class T> struct is_compound;
template<class T> struct is_member_pointer;

// 21.3.5.4, type properties
template<class T> struct is_const;
template<class T> struct is_volatile;
template<class T> struct is_trivial;
template<class T> struct is_trivially_copyable;
template<class T> struct is_standard_layout;
template<class T> struct is_empty;
template<class T> struct is_polymorphic;
template<class T> struct is_abstract;
template<class T> struct is_final;
template<class T> struct is_aggregate;

template<class T> struct is_signed;
template<class T> struct is_unsigned;
template<class T> struct is_bounded_array;
template<class T> struct is_unbounded_array;
template<class T> struct isScoped_enum;

template<class T, class... Args> struct is_constructible;
template<class T> struct is_default_constructible;
template<class T> struct is_copy_constructible;
template<class T> struct is_move_constructible;

template<class T> struct is_assignable;
template<class T> struct is_copy_assignable;
template<class T> struct is_move_assignable;

template<class T, class U> struct is_swappable_with;
template<class T> struct is_swappable;

template<class T> struct is_destructible;
template<class T, class... Args> struct is_trivially_constructible;
template<class T> struct is_trivially_default_constructible;
template<class T> struct is_trivially_copy_constructible;
template<class T> struct is_trivially_move_constructible;

template<class T, class U> struct is_trivially_assignable;
template<class T> struct is_trivially_copy_assignable;
template<class T> struct is_trivially_move_assignable;
template<class T> struct is_trivially_destructible;

template<class T, class... Args> struct is_nothrow_constructible;
template<class T> struct is_nothrow_default_constructible;
template<class T> struct is_nothrow_copy_constructible;
template<class T> struct is_nothrow_move_constructible;

template<class T, class U> struct is_nothrow_assignable;
template<class T> struct is_nothrow_copy_assignable;
template<class T> struct is_nothrow_move_assignable;

template<class T, class U> struct is_nothrow_swappable_with;
template<class T> struct is_nothrow_swappable;

template<class T> struct is_nothrow_destructible;

template<class T> struct is_implicit_lifetime;

template<class T> struct has_virtual_destructor;

template<class T> struct has_unique_object_representations;
template<class T, class U> struct reference_constructs_from_temporary;
template<class T, class U> struct reference_converts_from_temporary;

// 21.3.6, type property queries
template<class T> struct alignment_of;
template<class T> struct rank;
template<class T, unsigned I = 0> struct extent;

// 21.3.7, type relations
template<class T, class U> struct is_same;
template<class Base, class Derived> struct is_base_of;
template<class Base, class Derived> struct is_virtual_base_of;
template<class From, class To> struct is_convertible;
template<class T, class U> struct is_layout_compatible;
template<class Base, class Derived> struct is_pointer_interconvertible_base_of;

template<class Fn, class... ArgTypes> struct is_invocable;
template<class R, class Fn, class... ArgTypes> struct is_invocable_r;

template<class Fn, class... ArgTypes> struct is_nothrow_invocable;
template<class R, class Fn, class... ArgTypes> struct is_nothrow_invocable_r;

// 21.3.8.2, const-volatile modifications
template<class T> struct remove_const;
template<class T> struct remove_volatile;
template<class T> struct remove_cv;
template<class T> struct add_const;
template<class T> struct add_volatile;
template<class T> struct add_cv;

using remove_const_t = typename remove_const<T>::type;
using remove_volatile_t = typename remove_volatile<T>::type;
using remove_cv_t = typename remove_cv<T>::type;
using add_const_t = typename add_const<T>::type;
using add_volatile_t = typename add_volatile<T>::type;
using add_cv_t = typename add_cv<T>::type;

// 21.3.8.3, reference modifications
template<class T> struct remove_reference;
template<class T> struct add_lvalue_reference;
template<class T> struct add_rvalue_reference;

using remove_reference_t = typename remove_reference<T>::type;
using add_lvalue_reference_t = typename add_lvalue_reference<T>::type;
using add_rvalue_reference_t = typename add_rvalue_reference<T>::type;

// 21.3.8.4, sign modifications
template<class T> struct make_signed;
template<class T> struct make_unsigned;

using make_signed_t = typename make_signed<T>::type;
using make_unsigned_t = typename make_unsigned<T>::type;
// 21.3.8.5, array modifications
template<class T> struct remove_extent;
template<class T> struct remove_all_extents;

template<class T>
    using remove_extent_t = typename remove_extent<T>::type;
template<class T>
    using remove_all_extents_t = typename remove_all_extents<T>::type;

// 21.3.8.6, pointer modifications
template<class T> struct remove_pointer;
template<class T> struct add_pointer;

template<class T>
    using remove_pointer_t = typename remove_pointer<T>::type;
template<class T>
    using add_pointer_t = typename add_pointer<T>::type;

// 21.3.8.7, other transformations
template<class T> struct type_identity;
template<class T> struct remove_cvref;
template<class T> struct decay;
template<bool, class T = void> struct enable_if;
template<bool, class T, class F> struct conditional;
template<class... T> struct common_type;
template<class T, class U, template<class> class TQual, template<class> class UQual>
    struct basic_common_reference
        { 
        }; 
template<class... T> struct common_reference;
template<class T> struct underlying_type;
template<class Fn, class... ArgTypes> struct invoke_result;
template<class T> struct unwrap_reference;
template<class T> struct unwrap_ref_decay;

template<class T>
    using type_identity_t = typename type_identity<T>::type;
template<class T>
    using remove_cvref_t = typename remove_cvref<T>::type;
template<class T>
    using decay_t = typename decay<T>::type;
template<bool B, class T = void>
    using enable_if_t = typename enable_if<B, T>::type;
template<bool B, class T, class F>
    using conditional_t = typename conditional<B, T, F>::type;
template<class... T>
    using common_type_t = typename common_type<T...>::type;
template<class... T>
    using common_reference_t = typename common_reference<T...>::type;
template<class T>
    using underlying_type_t = typename underlying_type<T>::type;
template<class Fn, class... ArgTypes>
    using invoke_result_t = typename invoke_result<Fn, ArgTypes...>::type;
template<class T>
    using unwrap_reference_t = typename unwrap_reference<T>::type;
template<class T>
    using unwrap_ref_decay_t = typename unwrap_ref_decay<T>::type;
template<class T>
    using void_t = void;

// 21.3.9, logical operator traits
template<class... B> struct conjunction;
template<class... B> struct disjunction;
template<class B> struct negation;
// 21.3.5.2, primary type categories
template<class T>
constexpr bool is_void_v = is_void<T>::value;
template<class T>
constexpr bool is_null_pointer_v = is_null_pointer<T>::value;
template<class T>
constexpr bool is_integral_v = is_integral<T>::value;
template<class T>
constexpr bool is_floating_point_v = is_floating_point<T>::value;
template<class T>
constexpr bool is_array_v = is_array<T>::value;
template<class T>
constexpr bool is_pointer_v = is_pointer<T>::value;
template<class T>
constexpr bool is_lvalue_reference_v = is_lvalue_reference<T>::value;
template<class T>
constexpr bool is_rvalue_reference_v = is_rvalue_reference<T>::value;
template<class T>
constexpr bool is_member_object_pointer_v = is_member_object_pointer<T>::value;
template<class T>
constexpr bool is_member_function_pointer_v = is_member_function_pointer<T>::value;
template<class T>
constexpr bool is_enum_v = is_enum<T>::value;
template<class T>
constexpr bool is_union_v = is_union<T>::value;
template<class T>
constexpr bool is_class_v = is_class<T>::value;
template<class T>
constexpr bool is_function_v = is_function<T>::value;

// 21.3.5.3, composite type categories
template<class T>
constexpr bool is_reference_v = is_reference<T>::value;
template<class T>
constexpr bool is_arithmetic_v = is_arithmetic<T>::value;
template<class T>
constexpr bool is_fundamental_v = is_fundamental<T>::value;
template<class T>
constexpr bool is_object_v = is_object<T>::value;
template<class T>
constexpr bool is_scalar_v = is_scalar<T>::value;
template<class T>
constexpr bool is_compound_v = is_compound<T>::value;
template<class T>
constexpr bool is_member_pointer_v = is_member_pointer<T>::value;

// 21.3.5.4, type properties
template<class T>
constexpr bool is_const_v = is_const<T>::value;
template<class T>
constexpr bool is_volatile_v = is_volatile<T>::value;
template<class T>
constexpr bool is_trivial_v = is_trivial<T>::value;
template<class T>
constexpr bool is_trivially_copyable_v = is_trivially_copyable<T>::value;
template<class T>
constexpr bool is_standard_layout_v = is_standard_layout<T>::value;
template<class T>
constexpr bool is_empty_v = is_empty<T>::value;
template<class T>
constexpr bool is_polymorphic_v = is_polymorphic<T>::value;
template<class T>
constexpr bool is_abstract_v = is_abstract<T>::value;
template<class T>
    constexpr bool is_final_v = is_final<T>::value;

template<class T>
    constexpr bool is_aggregate_v = is_aggregate<T>::value;

template<class T>
    constexpr bool is_signed_v = is_signed<T>::value;

template<class T>
    constexpr bool is_unsigned_v = is_unsigned<T>::value;

template<class T>
    constexpr bool is_bounded_array_v = is_bounded_array<T>::value;

template<class T>
    constexpr bool is_unbounded_array_v = is_unbounded_array<T>::value;

template<class T>
    constexpr bool is_scoped_enum_v = is_scoped_enum<T>::value;

template<class T, class... Args>
    constexpr bool is_constructible_v = is_constructible<T, Args...>::value;

template<class T>
    constexpr bool is_default_constructible_v = is_default_constructible<T>::value;

template<class T>
    constexpr bool is_copy_constructible_v = is_copy_constructible<T>::value;

template<class T>
    constexpr bool is_move_constructible_v = is_move_constructible<T>::value;

template<class T, class U>
    constexpr bool is_assignable_v = is_assignable<T, U>::value;

template<class T>
    constexpr bool is_copy_assignable_v = is_copy_assignable<T>::value;

template<class T>
    constexpr bool is_move_assignable_v = is_move_assignable<T>::value;

template<class T, class U>
    constexpr bool is_swappable_with_v = is_swappable_with<T, U>::value;

template<class T>
    constexpr bool is_swappable_v = is_swappable<T>::value;

template<class T>
    constexpr bool is_destructible_v = is_destructible<T>::value;

template<class T, class... Args>
    constexpr bool is_trivially_constructible_v
        = is_trivially_constructible<T, Args...>::value;

template<class T>
    constexpr bool is_trivially_default_constructible_v
        = is_trivially_default_constructible<T>::value;

template<class T>
    constexpr bool is_trivially_copy_constructible_v
        = is_trivially_copy_constructible<T>::value;

template<class T>
    constexpr bool is_trivially_move_constructible_v
        = is_trivially_move_constructible<T>::value;

template<class T, class U>
    constexpr bool is_trivially_assignable_v
        = is_trivially_assignable<T, U>::value;

template<class T>
    constexpr bool is_trivially_copy_assignable_v
        = is_trivially_copy_assignable<T>::value;

template<class T>
    constexpr bool is_trivially_move_assignable_v
        = is_trivially_move_assignable<T>::value;

template<class T>
    constexpr bool is_trivially_destructible_v
        = is_trivially_destructible<T>::value;

template<class T, class... Args>
    constexpr bool is_nothrow_constructible_v
        = is_nothrow_constructible<T, Args...>::value;

template<class T>
    constexpr bool is_nothrow_default_constructible_v
        = is_nothrow_default_constructible<T>::value;

template<class T, class... Args>
    constexpr bool is_nothrow_constructible_v
        = is_nothrow_constructible<T, Args...>::value;

template<class T>
    constexpr bool is_nothrow_default_constructible_v
        = is_nothrow_default_constructible<T>::value;
template<class T>
constexpr bool is_nothrow_copy_constructible_v
    = is_nothrow_copy_constructible<T>::value;

template<class T>
constexpr bool is_nothrow_move_constructible_v
    = is_nothrow_move_constructible<T>::value;

template<class T, class U>
constexpr bool is_nothrow_assignable_v = is_nothrow_assignable<T, U>::value;

template<class T>
constexpr bool is_nothrow_copy_assignable_v = is_nothrow_copy_assignable<T>::value;

template<class T>
constexpr bool is_nothrow_move_assignable_v = is_nothrow_move_assignable<T>::value;

template<class T, class U>
constexpr bool is_nothrow_swappable_with_v = is_nothrow_swappable_with<T, U>::value;

template<class T>
constexpr bool is_nothrow_swappable_v = is_nothrow_swappable<T>::value;

template<class T>
constexpr bool is_nothrow_destructible_v = is_nothrow_destructible<T>::value;

template<class T>
constexpr bool has_virtualDestructor_v = has_virtual_destructor<T>::value;

template<class T>
constexpr bool has_unique_object_representations_v
    = has_unique_object_representations<T>::value;

template<class T, class U>
constexpr bool reference_constructs_from_temporary_v
    = reference_constructs_from_temporary<T, U>::value;

template<class T, class U>
constexpr bool reference_converts_from_temporary_v
    = reference_converts_from_temporary<T, U>::value;

// 21.3.6, type property queries
template<class T>
constexpr size_t alignment_of_v = alignment_of<T>::value;

template<class T>
constexpr size_t rank_v = rank<T>::value;

template<class T, unsigned I = 0>
constexpr size_t extent_v = extent<T, I>::value;

// 21.3.7, type relations
template<class T, class U>
constexpr bool is_same_v = is_same<T, U>::value;

template<class Base, class Derived>
constexpr bool is_base_of_v = is_base_of<Base, Derived>::value;

template<class Base, class Derived>
constexpr bool is_virtual_base_of_v = is_virtual_base_of<Base, Derived>::value;

template<class From, class To>
constexpr bool is_convertible_v = is_convertible<From, To>::value;

template<class From, class To>
constexpr bool is_nothrow_convertible_v = is_nothrow_convertible<From, To>::value;

template<class T, class U>
constexpr bool is_layout_compatible_v = is_layout_compatible<T, U>::value;

template<class Base, class Derived>
constexpr bool is_pointer_interconvertible_base_of_v
    = is_pointer_interconvertible_base_of<Base, Derived>::value;

template<class Fn, class... ArgTypes>
constexpr bool is_invocable_v = is_invocable<Fn, ArgTypes...>::value;

template<class R, class Fn, class... ArgTypes>
constexpr bool is_invocable_r_v = is_invocable_r<R, Fn, ArgTypes...>::value;

template<class Fn, class... ArgTypes>
constexpr bool is_nothrow_invocable_v = is_nothrow_invocable<Fn, ArgTypes...>::value;
template<class R, class Fn, class... ArgTypes>
constexpr bool is_nothrow_invocable_r_v
    = is_nothrow_invocable_r<R, Fn, ArgTypes...>::value;

// 21.3.9, logical operator traits
template<class... B>
constexpr bool conjunction_v = conjunction<B...>::value;
template<class... B>
constexpr bool disjunction_v = disjunction<B...>::value;
template<class B>
constexpr bool negation_v = negation<B>::value;

// 21.3.10, member relationships
template<class S, class M>
constexpr bool is_pointer_interconvertible_with_class(M S::*m) noexcept;
template<class S1, class S2, class M1, class M2>
constexpr bool is_corresponding_member(M1 S1::*m1, M2 S2::*m2) noexcept;

// 21.3.11, constant evaluation context
constexpr bool is_constant_evaluated() noexcept;
consteval bool is_within_lifetime(const auto*) noexcept;

21.3.4 Helper classes

namespace std {
    template<class T, T v> struct integral_constant {
        static constexpr T value = v;
        using value_type = T;
        using type = integral_constant<T, v>;

        constexpr operator value_type() const noexcept { return value; }
        constexpr value_type operator()() const noexcept { return value; }
    };
}

The class template `integral_constant`, alias template `bool_constant`, and its associated `typedef-names` `true_type` and `false_type` are used as base classes to define the interface for various type traits.

21.3.5 Unary type traits

21.3.5.1 General

Subclause 21.3.5 contains templates that may be used to query the properties of a type at compile time.

Each of these templates shall be a `Cpp17UnaryTypeTrait` (21.3.2) with a base characteristic of `true_type` if the corresponding condition is `true`, otherwise `false_type`.

21.3.5.2 Primary type categories

The primary type categories specified in Table 49 correspond to the descriptions given in subclause 6.8 of the C++ standard.

For any given type `T`, the result of applying one of these templates to `T` and to `cv T` shall yield the same result.

[Note 1: For any given type `T`, exactly one of the primary type categories has a `value` member that evaluates to `true`. — end note]

Table 49 — Primary type category predicates

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_void;</td>
<td><code>T is void</code></td>
<td></td>
</tr>
</tbody>
</table>
### Table 49 — Primary type category predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_null_pointer;</td>
<td>T is <code>nullptr_t</code> (6.8.2)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_integral;</td>
<td>T is an integral type (6.8.2)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_floating_point;</td>
<td>T is a floating-point type (6.8.2)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_array;</td>
<td>T is an array type (6.8.4) of known or unknown extent Class template <code>array</code> (24.3.8) is not an array type.</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_pointer;</td>
<td>T is a pointer type (6.8.4) Includes pointers to functions but not pointers to non-static members.</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_lvalue_reference;</td>
<td>T is an lvalue reference type (9.3.4.3)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_rvalue_reference;</td>
<td>T is an rvalue reference type (9.3.4.3)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_object_pointer;</td>
<td>T is a pointer to data member</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_function_pointer;</td>
<td>T is a pointer to member function</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_enum;</td>
<td>T is an enumeration type (6.8.4)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_union;</td>
<td>T is a union type (6.8.4)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_class;</td>
<td>T is a non-union class type (6.8.4)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_function;</td>
<td>T is a function type (6.8.4)</td>
<td></td>
</tr>
</tbody>
</table>

### 21.3.5.3 Composite type traits

The templates specified in Table 50 provide convenient compositions of the primary type categories, corresponding to the descriptions given in subclause 6.8.

For any given type `T`, the result of applying one of these templates to `T` and to `cv T` shall yield the same result.

### Table 50 — Composite type category predicates

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_reference;</td>
<td>T is an lvalue reference or an rvalue reference</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_arithmetic;</td>
<td>T is an arithmetic type (6.8.2)</td>
<td></td>
</tr>
</tbody>
</table>
Table 50 — Composite type category predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_fundamental;</td>
<td>T is a fundamental type (6.8.2)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_object;</td>
<td>T is an object type (6.8.1)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_scalar;</td>
<td>T is a scalar type (6.8.1)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_compound;</td>
<td>T is a compound type (6.8.4)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_pointer;</td>
<td>T is a pointer-to-member type (6.8.4)</td>
<td></td>
</tr>
</tbody>
</table>

21.3.5.4 Type properties

1 The templates specified in Table 51 provide access to some of the more important properties of types.

2 It is unspecified whether the library defines any full or partial specializations of any of these templates.

3 For all of the class templates X declared in this subclause, instantiating that template with a template-argument that is a class template specialization may result in the implicit instantiation of the template argument if and only if the semantics of X require that the argument is a complete type.

4 For the purpose of defining the templates in this subclause, a function call expression declval<T>() for any type T is considered to be a trivial (6.8.1, 11.4.4) function call that is not an odr-use (6.3) of declval in the context of the corresponding definition notwithstanding the restrictions of 22.2.6.

5 For the purpose of defining the templates in this subclause, let VAL<T> for some type T be an expression defined as follows:

\[(5.1)\]  
- If T is a reference or function type, VAL<T> is an expression with the same type and value category as declval<T>().

\[(5.2)\]  
- Otherwise, VAL<T> is a prvalue that initially has type T.

[Note 1: If T is cv-qualified, the cv-qualification is subject to adjustment (7.2.2). — end note]

Table 51 — Type property predicates

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_const;</td>
<td>T is const-qualified (6.8.5)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_volatile;</td>
<td>T is volatile-qualified (6.8.5)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_trivial;</td>
<td>T is a trivial type (6.8.1)</td>
<td>remove_all_extents_t&lt;T&gt; shall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>be a complete type or cv void.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_trivially_copyable;</td>
<td>T is a trivially copyable type (6.8.1)</td>
<td>remove_all_extents_t&lt;T&gt; shall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>be a complete type or cv void.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_standard_layout;</td>
<td>T is a standard-layout type (6.8.1)</td>
<td>remove_all_extents_t&lt;T&gt; shall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>be a complete type or cv void.</td>
</tr>
</tbody>
</table>

§ 21.3.5.4 © ISO/IEC 677
<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>template&lt;class T&gt; struct is_empty;</code></td>
<td>T is a class type, but not a union type, with no non-static data members other than subobjects of zero size, no virtual member functions, no virtual base classes, and no base class B for which <code>is_empty_v&lt;B&gt;</code> is false.</td>
<td>If T is a non-union class type, T shall be a complete type.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_polymorphic;</code></td>
<td>T is a polymorphic class (11.7.3)</td>
<td>If T is a non-union class type, T shall be a complete type.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_abstract;</code></td>
<td>T is a class type marked with the <code>class-virt-specifier final</code> (11.1). [Note 2: A union is a class type that can be marked with <code>final</code>. — end note]</td>
<td>If T is a class type, T shall be a complete type.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_final;</code></td>
<td>T is an aggregate type (9.4.2)</td>
<td>T shall be an array type, a complete type, or <code>cv void</code>.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_aggregate;</code></td>
<td>T is an array type of known bound (9.3.4.5)</td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_bounded_array;</code></td>
<td>T is an array type of unknown bound (9.3.4.5)</td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_scoped_enum;</code></td>
<td>T is a scoped enumeration (9.7.1)</td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T, class... Args&gt; struct is_constructible;</code></td>
<td>For a function type T or for a <code>cv void</code> type T, <code>is_constructible_v&lt;T, Args...&gt;</code> is false, otherwise see below</td>
<td>T and all types in the template parameter pack <code>Args</code> shall be complete types, <code>cv void</code>, or arrays of unknown bound.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_default_constructible;</code></td>
<td><code>is_constructible_v&lt;T&gt;</code> is true.</td>
<td>T shall be a complete type, <code>cv void</code>, or an array of unknown bound.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_copy_constructible;</code></td>
<td>For a referenceable type T (3.44), the same result as <code>is_constructible_v&lt;T, const T&amp;&gt;</code>, otherwise false.</td>
<td>T shall be a complete type, <code>cv void</code>, or an array of unknown bound.</td>
</tr>
</tbody>
</table>
Table 51 — Type property predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_move_constructible;</td>
<td>For a referenceable type T, the same result as is_constructible_v&lt;T, T&amp;&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T, class U&gt; struct is_assignable;</td>
<td>The expression declval&lt;T&gt;() = declval&lt;U&gt;() is well-formed when treated as an unevaluated operand (7.2.3). Access checking is performed as if in a context unrelated to T and U. Only the validity of the immediate context of the assignment expression is considered. [Note 3: The compilation of the expression can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the “immediate context” and can result in the program being ill-formed. — end note]</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_copy_assignable;</td>
<td>For a referenceable type T, the same result as is_assignable_v&lt;T&amp;, const T&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_move_assignable;</td>
<td>For a referenceable type T, the same result as is_assignable_v&lt;T&amp;, T&amp;&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
</tbody>
</table>
### Table 51 — Type property predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>template&lt;class T, class U&gt; struct is_swappable_with;</code></td>
<td>The expressions <code>swap(declval&lt;T&gt;(), declval&lt;U&gt;())</code> and <code>swap(declval&lt;T&gt;(), declval&lt;U&gt;())</code> are each well-formed when treated as an unevaluated operand (7.2.3) in an overload-resolution context for swappable values (16.4.4.3). Access checking is performed as if in a context unrelated to T and U. Only the validity of the immediate context of the swap expressions is considered.</td>
<td></td>
</tr>
</tbody>
</table>

  **Note 4:** The compilation of the expressions can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the “immediate context” and can result in the program being ill-formed. — end note |

| T and U shall be complete types, cv void, or arrays of unknown bound. |
|-----------------------|-------------------------------------------------|----------------------------------------------------------------|
| `template<class T> struct is_swappable;` | For a referenceable type T, the same result as is_swappable_with_v<T&, T&>, otherwise false. | T shall be a complete type, cv void, or an array of unknown bound. |

| `template<class T> struct is_destructible;` | Either T is a reference type, or T is a complete object type for which the expression `declval<U&>() . ~U()` is well-formed when treated as an unevaluated operand (7.2.3), where U is remove_all_extents_t<T>. | T shall be a complete type, cv void, or an array of unknown bound. |

| `template<class T, class... Args> struct is_trivially_constructible;` | `is_constructible_v<T, Args...>` is true and the variable definition for `is_constructible`, as defined below, is known to call no operation that is not trivial (6.8.1, 11.4.4). | T and all types in the template parameter pack Args shall be complete types, cv void, or arrays of unknown bound. |

<p>| <code>template&lt;class T&gt; struct is_trivially_default_constructible;</code> | <code>is_trivially_constructible_v&lt;T&gt;</code> is true. | T shall be a complete type, cv void, or an array of unknown bound. |</p>
<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct is_trivially_copy_constructible;</td>
<td>For a referenceable type T, the same result as is_trivially_constructible_v&lt;T, const T&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_trivially_move_constructible;</td>
<td>For a referenceable type T, the same result as is_trivially_constructible_v&lt;T, T&amp;&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T, class U&gt; struct is_trivially_assignable;</td>
<td>is_assignable_v&lt;T, U&gt; is true and the assignment, as defined by is_assignable, is known to call no operation that is not trivial (6.8.1, 11.4.4).</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_trivially_copy_assignable;</td>
<td>For a referenceable type T, the same result as is_trivially_assignable_v&lt;T&amp;, const T&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_trivially_move_assignable;</td>
<td>For a referenceable type T, the same result as is_trivially_assignable_v&lt;T&amp;, T&amp;&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_trivially_destructible;</td>
<td>is_destructible_v&lt;T&gt; is true and remove_all_extents_t&lt;T&gt; is either a non-class type or a class type with a trivial destructor.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T, class... Args&gt; struct is_nothrow_constructible;</td>
<td>is_constructible_v&lt;T, Args...&gt; is true and the variable definition for is_constructible, as defined below, is known not to throw any exceptions (7.6.2.7).</td>
<td>T and all types in the template parameter pack Args shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_nothrow_default_constructible;</td>
<td>is_nothrow_constructible_v&lt;T&gt; is true.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_nothrow_copy_constructible;</td>
<td>For a referenceable type T, the same result as is_nothrow_constructible_v&lt;T, const T&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_nothrow_move_constructible;</td>
<td>For a referenceable type T, the same result as is_nothrow_constructible_v&lt;T, T&amp;&amp;&gt;, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>Template</td>
<td>Condition</td>
<td>Preconditions</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-----------------------------------------------------</td>
<td>----------------------------------------------------</td>
</tr>
<tr>
<td>template&lt;class T, class U&gt;</td>
<td>is_assignable_v&lt;T, U&gt; is true and the assignment is known not to throw any exceptions (7.6.2.7).</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>struct is_nothrow_assignable;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct is_nothrow_copy_assignable;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct is_nothrow_move_assignable;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct is_nothrow_swappable_with;</td>
<td>is_swappable_with_v&lt;T, U&gt; is true and each swap expression of the definition of is_swappable_with&lt;T, U&gt; is known not to throw any exceptions (7.6.2.7).</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct is_nothrow_swappable;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct is_nothrow_destructible;</td>
<td>is_destructible_v&lt;T&gt; is true and the indicated destructor is known not to throw any exceptions (7.6.2.7).</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct is_implicit_lifetime;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct has_virtualDestructor;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>struct has_uniqueObjectRepresentations;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Template</td>
<td>Condition</td>
<td>Preconditions</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>---------------</td>
</tr>
<tr>
<td>template&lt;class T, class U&gt; struct reference_constructs_from_temporary;</td>
<td>T is a reference type, and the initialization T t(VAL&lt;U&gt;); is well-formed and binds t to a temporary object whose lifetime is extended (6.7.7). Access checking is performed as if in a context unrelated to T and U. Only the validity of the immediate context of the variable initialization is considered. [Note 5: The initialization can result in effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such effects are not in the “immediate context” and can result in the program being ill-formed. — end note]</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T, class U&gt; struct reference_converts_from_temporary;</td>
<td>T is a reference type, and the initialization T t = VAL&lt;U&gt;; is well-formed and binds t to a temporary object whose lifetime is extended (6.7.7). Access checking is performed as if in a context unrelated to T and U. Only the validity of the immediate context of the variable initialization is considered. [Note 6: The initialization can result in effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such effects are not in the “immediate context” and can result in the program being ill-formed. — end note]</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
</tbody>
</table>

6 [Example 1:}
is_const_v<const volatile int>  // true
is_const_v<const int*>       // false
is_const_v<const int&>       // false
is_const_v<int[3]>           // false
is_const_v<const int[3]>     // true
— end example

[Example 2:
remove_const_t<const volatile int>  // volatile int
remove_const_t<const int* const>    // const int*
remove_const_t<const int&>          // const int&
— end example

[Example 3:
// Given:
struct P final { };  
union U1 { };  
union U2 final { };  

// the following assertions hold:
static_assert(!is_final_v<int>);  
static_assert(is_final_v<P>);  
static_assert(!is_final_v<U1>);  
static_assert(is_final_v<U2>);  
— end example

The predicate condition for a template specialization is_constructible<T, Args...> shall be satisfied if and only if the following variable definition would be well-formed for some invented variable t:

\[ T(t(\text{declval<Args>()...}) \) ; \]

[Note 7: These tokens are never interpreted as a function declaration. — end note]

Access checking is performed as if in a context unrelated to T and any of the Args. Only the validity of the immediate context of the variable initialization is considered.

[Note 8: The evaluation of the initialization can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the “immediate context” and can result in the program being ill-formed. — end note]

The predicate condition for a template specialization has_unique_object_representations<T> shall be satisfied if and only if

\( (10.1) \quad \text{T is trivially copyable, and} \)

\( (10.2) \quad \text{any two objects of type T with the same value have the same object representation, where} \)

\( (10.2.1) \quad \text{two objects of array or non-union class type are considered to have the same value if their respective} \)

\( \text{sequences of direct subobjects have the same values, and} \)

\( (10.2.2) \quad \text{two objects of union type are considered to have the same value if they have the same active} \)

\( \text{member and the corresponding members have the same value.} \)

The set of scalar types for which this condition holds is implementation-defined.

[Note 9: If a type has padding bits, the condition does not hold; otherwise, the condition holds true for integral types. — end note]

21.3.6 Type property queries

The templates specified in Table 52 may be used to query properties of types at compile time.

<table>
<thead>
<tr>
<th>Template</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt;</td>
<td>alignof(T).</td>
</tr>
<tr>
<td>struct alignment_of;</td>
<td>Mandates: alignof(T) is a valid expression (7.6.2.6)</td>
</tr>
</tbody>
</table>
Table 52 — Type property queries (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct rank;</td>
<td>If T is an array type, an integer value representing the number of</td>
</tr>
<tr>
<td></td>
<td>dimensions of T; otherwise, 0.</td>
</tr>
<tr>
<td>template&lt;class T, unsigned I = 0&gt; struct extent;</td>
<td>If T is not an array type, or if it has rank less than or equal to</td>
</tr>
<tr>
<td></td>
<td>I, or if I is 0 and T has type “array of unknown bound of U”, then</td>
</tr>
<tr>
<td></td>
<td>0; otherwise, the bound (9.3.4.5) of the Ith dimension of T, where</td>
</tr>
<tr>
<td></td>
<td>indexing of I is zero-based.</td>
</tr>
</tbody>
</table>

2 Each of these templates shall be a Cpp17UnaryTypeTrait (21.3.2) with a base characteristic of integral_constant<size_t, Value>.

3 [Example 1:

// the following assertions hold:
static_assert(rank_v<int> == 0);
static_assert(rank_v<int[2]> == 1);
static_assert(rank_v<int[][4]> == 2);
—end example]

4 [Example 2:

// the following assertions hold:
static_assert(extent_v<int> == 0);
static_assert(extent_v<int[2]> == 2);
static_assert(extent_v<int[2][4]> == 2);
static_assert(extent_v<int[][4]> == 0);
static_assert(extent_v<int[2], 1> == 0);
static_assert(extent_v<int[2][4], 1> == 4);
static_assert(extent_v<int[][4], 1> == 4);
—end example]

21.3.7 Relationships between types

1 The templates specified in Table 53 may be used to query relationships between types at compile time.

2 Each of these templates shall be a Cpp17BinaryTypeTrait (21.3.2) with a base characteristic of true_type if the corresponding condition is true, otherwise false_type.

Table 53 — Type relationship predicates

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T, class U&gt; struct is_same;</td>
<td>T and U name the same type with the same cv-qualifications</td>
<td></td>
</tr>
<tr>
<td>template&lt;class Base, class Derived&gt; struct is_base_of;</td>
<td>Base is a base class of Derived (11.7) without regard to cv-qualifiers or Base and Derived are not unions and name the same class type without regard to cv-qualifiers</td>
<td>If Base and Derived are non-union class types and are not (possibly cv-qualified versions of) the same type, Derived shall be a complete type. [Note 1: Base classes that are private, protected, or ambiguous are, nonetheless, base classes. —end note]</td>
</tr>
<tr>
<td>Template</td>
<td>Condition</td>
<td>Comments</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>template&lt;class Base, class Derived&gt; struct is_virtual_base_of;</td>
<td>Base is a virtual base class of Derived (11.7.2) without regard to cv-qualifiers.</td>
<td>If Base and Derived are non-union class types, Derived shall be a complete type. [Note 2: Virtual base classes that are private, protected, or ambiguous are, nonetheless, virtual base classes. — end note] [Note 3: A class is never a virtual base class of itself. — end note]</td>
</tr>
<tr>
<td>template&lt;class From, class To&gt; struct is_convertible;</td>
<td>see below</td>
<td>From and To shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class From, class To&gt; struct is_nothrow_convertible;</td>
<td>is_convertible_v&lt;From, To&gt; is true and the conversion, as defined by is_convertible, is known not to throw any exceptions (7.6.2.7)</td>
<td>From and To shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T, class U&gt; struct is_layout_compatible;</td>
<td>T and U are layout-compatible (6.8.1)</td>
<td>T and U shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class Base, class Derived&gt; struct is_pointer_interconvertible_base_of;</td>
<td>Derived is unambiguously derived from Base without regard to cv-qualifiers, and each object of type Derived is pointer-interconvertible (6.8.4) with its Base subobject, or Base and Derived are not unions and name the same class type without regard to cv-qualifiers.</td>
<td>If Base and Derived are non-union class types and are not (possibly cv-qualified versions of) the same type, Derived shall be a complete type.</td>
</tr>
<tr>
<td>template&lt;class Fn, class... ArgTypes&gt; struct is_invocable;</td>
<td>The expression INVOKE(declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...) (22.10.4) is well-formed when treated as an unevaluated operand (7.2.3)</td>
<td>Fn and all types in the template parameter pack ArgTypes shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class R, class Fn, class... ArgTypes&gt; struct is_invocable_r;</td>
<td>The expression INVOKE&lt;R&gt;(declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...) is well-formed when treated as an unevaluated operand</td>
<td>Fn, R, and all types in the template parameter pack ArgTypes shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class Fn, class... ArgTypes&gt; struct is_nothrow_invocable;</td>
<td>is_invocable_v&lt;Fn, ArgTypes...&gt; is true and the expression INVOKE(declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...) is known not to throw any exceptions (7.6.2.7)</td>
<td>Fn and all types in the template parameter pack ArgTypes shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class R, class Fn, class... ArgTypes&gt; struct is_nothrow_invocable_r;</td>
<td>is_invocable_v&lt;r, Fn, ArgTypes...&gt; is true and the expression INVOKE&lt;R&gt;(declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...) is known not to throw any exceptions (7.6.2.7)</td>
<td>Fn, R, and all types in the template parameter pack ArgTypes shall be complete types, cv void, or arrays of unknown bound.</td>
</tr>
</tbody>
</table>
For the purpose of defining the templates in this subclause, a function call expression `declval<T>()` for any type `T` is considered to be a trivial (6.8.1, 11.4.4) function call that is not an odr-use (6.3) of `declval` in the context of the corresponding definition notwithstanding the restrictions of 22.2.6.

Example 1:

```cpp
struct B {};
struct B1 : B {};
struct B2 : B {};
struct D : private B1, private B2 {};
```

- `is_base_of_v<B, D>` // true
- `is_base_of_v<const B, D>` // true
- `is_base_of_v<B, const D>` // true
- `is_base_of_v<int, D>` // false
- `is_base_of_v<int[3], D[3]>` // false
- `is_base_of_v<int, int>` // false

The predicate condition for a template specialization `is_convertible<From, To>` shall be satisfied if and only if the return expression in the following code would be well-formed, including any implicit conversions to the return type of the function:

```cpp
To test() {
    return declval<From>();
}
```

Note 4: This requirement gives well-defined results for reference types, array types, function types, and `cv` void.

Access checking is performed in a context unrelated to `To` and `From`. Only the validity of the immediate context of the expression of the return statement (8.7.4) (including initialization of the returned object or reference) is considered.

Note 5: The initialization can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the “immediate context” and can result in the program being ill-formed.

21.3.8 Transformations between types

21.3.8.1 General

Subclause 21.3.8 contains templates that may be used to transform one type to another following some predefined rule.

2. Each of the templates in 21.3.8 shall be a `Cpp17TransformationTrait` (21.3.2).

21.3.8.2 Const-volatile modifications

The templates specified in Table 54 add or remove `cv`-qualifications (6.8.5).

Table 54 — Const-volatile modifications

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>template&lt;class T&gt;</code></td>
<td>The member typedef <code>type</code> denotes the type formed by removing any top-level <code>const</code>-qualifier from <code>T</code>.</td>
</tr>
<tr>
<td><code>struct remove_const;</code></td>
<td><code>[Example 1: </code>remove_const_t&lt;const volatile int&gt;<code>evaluates to</code>volatile int<code>, whereas </code>remove_const_t&lt;const int*&gt;<code>evaluates to</code>const int*<code>. — end example]</code></td>
</tr>
</tbody>
</table>
21.3.8.3 Reference modifications

The templates specified in Table 55 add or remove references.

Table 55 — Reference modifications

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct remove_reference;</td>
<td>If T has type “reference to T1” then the member typedef type denotes T1; otherwise, type denotes T.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct add_lvalue_reference;</td>
<td>If T is a referenceable type (3.44) then the member typedef type denotes T&amp;; otherwise, type denotes T.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct add_rvalue_reference;</td>
<td>If T is a referenceable type then the member typedef type denotes T&amp;&amp;; otherwise, type denotes T.</td>
</tr>
</tbody>
</table>

21.3.8.4 Sign modifications

The templates specified in Table 56 convert an integer type to its corresponding signed or unsigned type.

Table 56 — Sign modifications

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct make_signed;</td>
<td>If T is a (possibly cv-qualified) signed integer type (6.8.2) then the member typedef type denotes T; otherwise, if T is a (possibly cv-qualified) unsigned integer type then type denotes the corresponding signed integer type, with the same cv-qualifiers as T; otherwise, type denotes the signed integer type with smallest rank (6.8.6) for which sizeof(T) == sizeof(type), with the same cv-qualifiers as T.</td>
</tr>
</tbody>
</table>

Mandates: T is an integral or enumeration type other than cv bool.
Table 56 — Sign modifications (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
</table>
| template<class T>
struct make_unsigned; | If T is a (possibly cv-qualified) unsigned integer type (6.8.2) then the member typedef type denotes T; otherwise, if T is a (possibly cv-qualified) signed integer type then type denotes the corresponding unsigned integer type, with the same cv-qualifiers as T; otherwise, type denotes the unsigned integer type with smallest rank (6.8.6) for which sizeof(T) == sizeof(type), with the same cv-qualifiers as T. Mandates: T is an integral or enumeration type other than cv bool. |

21.3.8.5 Array modifications [meta.trans.arr]

The templates specified in Table 57 modify array types.

Table 57 — Array modifications [tab:meta.trans.arr]

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
</table>
| template<class T>
struct remove_extent; | If T is a type “array of U”, the member typedef type denotes U, otherwise T. 

[Note 1: For multidimensional arrays, only the first array dimension is removed. For a type “array of const U”, the resulting type is const U. — end note] |
| template<class T>
struct remove_all_extents; | If T is “multidimensional array of U”, the resulting member typedef type denotes U, otherwise T. |

2 [Example 1]:

// the following assertions hold:
static_assert(is_same_v<remove_extent_t<int>, int>);
static_assert(is_same_v<remove_extent_t<int[2]>, int>);
static_assert(is_same_v<remove_extent_t<int[2][3]>, int[3]>>);
static_assert(is_same_v<remove_extent_t<int[2][3][2]>, int[3]>>);
— end example |

3 [Example 2]:

// the following assertions hold:
static_assert(is_same_v<remove_all_extents_t<int>, int>);
static_assert(is_same_v<remove_all_extents_t<int[2]>, int>);
static_assert(is_same_v<remove_all_extents_t<int[2][3]>, int>);
static_assert(is_same_v<remove_all_extents_t<int[2][3][2]>, int>);
— end example |

21.3.8.6 Pointer modifications [meta.trans.ptr]

The templates specified in Table 58 add or remove pointers.

Table 58 — Pointer modifications [tab:meta.trans.ptr]

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
</table>
| template<class T>
struct remove_pointer; | If T has type “(possibly cv-qualified) pointer to T1” then the member typedef type denotes T1; otherwise, it denotes T. |
| template<class T>
struct add_pointer; | If T is a referenceable type (3.44) or a cv void type then the member typedef type denotes remove_reference_t<T*>; otherwise, type denotes T. |
### 21.3.8.7 Other transformations

The templates specified in Table 59 perform other modifications of a type.

**Table 59 — Other transformations**

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct type_identity;</td>
<td>The member typedef type denotes T.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct remove_cvref;</td>
<td>The member typedef type denotes remove_cv_t&lt;remove_reference_t&lt;T&gt;&gt;.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct decay;</td>
<td>Let U be remove_reference_t&lt;T&gt;. If is_array_v&lt;U&gt; is true, the member typedef type denotes remove_extent_t&lt;U&gt;*. If is_function_v&lt;U&gt; is true, the member typedef type denotes add_pointer_t&lt;U&gt;. Otherwise the member typedef type denotes remove_cv_t&lt;T&gt;. [Note 1: This behavior is similar to the lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) conversions applied when an lvalue is used as an rvalue, but also strips cv-qualifiers from class types in order to more closely model by-value argument passing. — end note]</td>
</tr>
<tr>
<td>template&lt;bool B, class T = void&gt; struct enable_if;</td>
<td>If B is true, the member typedef type denotes T; otherwise, there shall be no member type.</td>
</tr>
<tr>
<td>template&lt;bool B, class T, class F&gt; struct conditional;</td>
<td>If B is true, the member typedef type denotes T. If B is false, the member typedef type denotes F.</td>
</tr>
<tr>
<td>template&lt;class... T&gt; struct common_type;</td>
<td>Unless this trait is specialized, the member typedef is defined or omitted as specified below. If it is omitted, there shall be no member type. Each type in the template parameter pack T shall be complete, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class, class, template&lt;class&gt; class, template&lt;class&gt; class&gt; struct basic_common_reference;</td>
<td>Unless this trait is specialized, there shall be no member type.</td>
</tr>
<tr>
<td>template&lt;class... T&gt; struct common_reference;</td>
<td>The member typedef-name type is defined or omitted as specified below. Each type in the parameter pack T shall be complete or cv void.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct underlying_type;</td>
<td>If T is an enumeration type, the member typedef type denotes the underlying type of T (9.7.1); otherwise, there is no member type. Mandates: T is not an incomplete enumeration type.</td>
</tr>
<tr>
<td>template&lt;class Fn, class... ArgTypes&gt; struct invoke_result;</td>
<td>If the expression INVOKE(declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...) (22.10.4) is well-formed when treated as an unevaluated operand (7.2.3), the member typedef type denotes the type decltype(INVOKE(declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...)); otherwise, there shall be no member type. Access checking is performed as if in a context unrelated to Fn and ArgTypes. Only the validity of the immediate context of the expression is considered. [Note 2: The compilation of the expression can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the “immediate context” and can result in the program being ill-formed. — end note] Preconditions: Fn and all types in the template parameter pack ArgTypes are complete types, cv void, or arrays of unknown bound.</td>
</tr>
</tbody>
</table>
2 In addition to being available via inclusion of the `<type_traits>` header, the templates `unwrap_reference`, `unwrap_ref_decay`, `unwrap_reference_t`, and `unwrap_ref_decay_t` are available when the header `<functional>` (22.10.2) is included.

3 Let:

(3.1) — `CREF(A)` be `add_lvalue_reference_t<const remove_reference_t<A>>`,

(3.2) — `XREF(A)` denote a unary alias template `T` such that `T<U>` denotes the same type as `U` with the addition of `A`'s cv and reference qualifiers, for a non-reference cv-unqualified type `U`,

(3.3) — `COPYCV(FROM, TO)` be an alias for type `TO` with the addition of `FROM`'s top-level cv-qualifiers,

[Example 1: `COPYCV(const int, volatile short)` is an alias for `const volatile short` — end example]

(3.4) — `COND-RES(X, Y)` be `decltype(false ? declval<X(&)()>()() : declval<Y(&)()>()())`.

Given types `A` and `B`, let `X` be `remove_reference_t<A>`, let `Y` be `remove_reference_t<B>`, and let `COMMON-REF(A, B)` be:

(3.5) — If `A` and `B` are both lvalue reference types, `COMMON-REF(A, B)` is `COND-RES(COPYCV(X, Y) &, COPYCV(Y, X) &)`) if that type exists and is a reference type.

(3.6) — Otherwise, let `C` be `remove_reference_t<COMMON-REF(X, Y) &> &`. If `A` and `B` are both rvalue reference types, `C` is well-formed, and `is_convertible_v<C, A> & & is_convertible_v<C, B>` is true, then `COMMON-REF(A, B)` is `C`.

(3.7) — Otherwise, let `D` be `COMMON-REF(const X&, Y&)`. If `A` is an rvalue reference and `B` is an lvalue reference and `D` is well-formed and `is_convertible_v<A, D>` is true, then `COMMON-REF(A, B)` is `D`.

(3.8) — Otherwise, if `A` is an lvalue reference and `B` is an rvalue reference, then `COMMON-REF(A, B)` is `COMMON-REF(B, A)`.

(3.9) — Otherwise, `COMMON-REF(A, B)` is ill-formed.

If any of the types computed above is ill-formed, then `COMMON-REF(A, B)` is ill-formed.

4 For the `common_type` trait applied to a template parameter pack `T` of types, the member `type` shall be either defined or not present as follows:

(4.1) — If `sizeof...(T)` is zero, there shall be no member `type`.

(4.2) — If `sizeof...(T)` is one, let `T0` denote the sole type constituting the pack `T`. The member `typedef-name` type shall denote the same type, if any, as `common_type_t<T0, T0>`; otherwise there shall be no member `type`.

(4.3) — If `sizeof...(T)` is two, let the first and second types constituting `T` be denoted by `T1` and `T2`, respectively, and let `D1` and `D2` denote the same types as `decay_t<T1>` and `decay_t<T2>`, respectively.

(4.3.1) — If `is_same_v<T1, D1>` is false or `is_same_v<T2, D2>` is false, let `C` denote the same type, if any, as `common_type_t<D1, D2>`.

(4.3.2) — [Note 3: None of the following will apply if there is a specialization `common_type_t<D1, D2>` — end note]

(4.3.3) — Otherwise, if

\[\text{decay_t<decltype(false ? declval<D1>() : declval<D2>())>}

denotes a valid type, let `C` denote that type.

(4.3.4) — Otherwise, if `COND-RES(CREF(D1), CREF(D2))` denotes a type, let `C` denote the type `decay_t<COND-RES(CREF(D1), CREF(D2))>`. 

---

N4986

Table 59 — Other transformations (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt; struct unwrap_reference;</td>
<td>If <code>T</code> is a specialization <code>reference_wrapper&lt;X&gt;</code> for some type <code>X</code>, the member typedef <code>type</code> of <code>unwrap_reference&lt;T&gt;</code> denotes <code>X&amp;</code>, otherwise <code>type</code> denotes <code>T</code>.</td>
</tr>
<tr>
<td>template&lt;class T&gt; unwrap_ref_decay;</td>
<td>The member typedef <code>type</code> of <code>unwrap_ref_decay&lt;T&gt;</code> denotes the type <code>unwrap_reference_t&lt;decay_t&lt;T&gt;&gt;</code>.</td>
</tr>
</tbody>
</table>
In either case, the member *typedef-name type* shall denote the same type, if any, as C. Otherwise, there shall be no member type.

(4.4) — If sizeof...(T) is greater than two, let T1, T2, and R, respectively, denote the first, second, and (pack of) remaining types constituting T. Let C denote the same type, if any, as common_type_t<T1, T2>. If there is such a type C, the member *typedef-name type* shall denote the same type, if any, as common_type_t<C, R,...>. Otherwise, there shall be no member type.

Notwithstanding the provisions of 21.3.3, and pursuant to 16.4.5.2.1, a program may specialize common_type<T1, T2> for types T1 and T2 such that is_same_v<T1, decay_t<T1>> and is_same_v<T2, decay_t<T2>> are each true.

[Note 4: Such specializations are needed when only explicit conversions are desired between the template arguments. — end note]

Such a specialization need not have a member named type, but if it does, the qualified-id common_type<T1, T2>::type shall denote a cv-unqualified non-reference type to which each of the types T1 and T2 is explicitly convertible. Moreover, common_type_t<T1, T2> shall denote the same type, if any, as does common_type_t<T2, T1>. No diagnostic is required for a violation of this Note’s rules.

For the common_reference trait applied to a parameter pack T of types, the member type shall be either defined or not present as follows:

(6.1) — If sizeof...(T) is zero, there shall be no member type.

(6.2) — Otherwise, if sizeof...(T) is one, let T0 denote the sole type in the pack T. The member typedef type shall denote the same type as T0.

(6.3) — Otherwise, if sizeof...(T) is two, let T1 and T2 denote the two types in the pack T. Then

(6.3.1) — Let R be COMMON-REF(T1, T2). If T1 and T2 are reference types, R is well-formed, and is_convertible_v<add_pointer_t<T1>, add_pointer_t<R>> && is_convertible_v<add_pointer_t<T2>, add_pointer_t<R>> is true, then the member typedef type denotes R.

(6.3.2) — Otherwise, if basic_common_reference<remove_cvref_t<T1>, remove_cvref_t<T2>, XREF(T1), XREF(T2)>::type is well-formed, then the member typedef type denotes that type.

(6.3.3) — Otherwise, if COND-RES(T1, T2) is well-formed, then the member typedef type denotes that type.

(6.3.4) — Otherwise, if common_type_t<T1, T2> is well-formed, then the member typedef type denotes that type.

(6.3.5) — Otherwise, there shall be no member type.

(6.4) — Otherwise, if sizeof...(T) is greater than two, let T1, T2, and Rest, respectively, denote the first, second, and (pack of) remaining types comprising T. Let C be the type common_reference_t<T1, T2>. Then:

(6.4.1) — If there is such a type C, the member typedef type shall denote the same type, if any, as common_reference_t<C, Rest,...>.

(6.4.2) — Otherwise, there shall be no member type.

Notwithstanding the provisions of 21.3.3, and pursuant to 16.4.5.2.1, a program may partially specialize basic_common_reference<T, U, TQual, UQual> for types T and U such that is_same_v<T, decay_t<T>> and is_same_v<U, decay_t<U>> are each true.

[Note 5: Such specializations can be used to influence the result of common_reference, and are needed when only explicit conversions are desired between the template arguments. — end note]

Such a specialization need not have a member named type, but if it does, the qualified-id basic_common_reference<T, U, TQual, UQual>::type shall denote a type to which each of the types TQual<T> and UQual<U> is convertible. Moreover, basic_common_reference<T, U, TQual, UQual>::type shall denote the same type, if any, as does basic_common_reference<U, T, UQual, TQual>::type. No diagnostic is required for a violation of these rules.

[Example 2: Given these definitions:

```c++
using PF1 = bool (*)(long);
using PF2 = short (*)(long);

struct S {
    operator PF2() const;
```
double operator()(char, int&);
void fn(long) const;
char data;
};

using PMF = void (S::*)(long) const;
using PMD = char S::*;

the following assertions will hold:
static_assert(is_same_v<invoke_result_t<S, int>, short>);
static_assert(is_same_v<invoke_result_t<S&, unsigned char, int&>, double>);
static_assert(is_same_v<invoke_result_t<PF1>, bool>);
static_assert(is_same_v<invoke_result_t<PMF, unique_ptr<S>, int, void>);
static_assert(is_same_v<invoke_result_t<PMD, S>, char&&>);
static_assert(is_same_v<invoke_result_t<PMD, const S*>, const char&>);

—end example

21.3.9 Logical operator traits [meta.logical]

This subclause describes type traits for applying logical operators to other type traits.

template<class... B> struct conjunction : see below {
};

The class template conjunction forms the logical conjunction of its template type arguments.

For a specialization conjunction<B1, ..., BN>, if there is a template type argument Bi for which
bool(Bi::value) is false, then instantiating conjunction<B1, ..., BN>::value does not require
the instantiation of Bj::value for j > i.

[Note 1: This is analogous to the short-circuiting behavior of the built-in operator &&. — end note]

Every template type argument for which Bi::value is instantiated shall be usable as a base class and
shall have a member value which is convertible to bool, is not hidden, and is unambiguously available
in the type.

The specialization conjunction<B1, ..., BN> has a public and unambiguous base that is either
— the first type Bi in the list true_type, B1, ..., BN for which bool(Bi::value) is false, or
— if there is no such Bi, the last type in the list.

[Note 2: This means a specialization of conjunction does not necessarily inherit from either true_type or
false_type. — end note]

The member names of the base class, other than conjunction and operator=, shall not be hidden
and shall be unambiguously available in conjunction.

template<class... B> struct disjunction : see below {
};

The class template disjunction forms the logical disjunction of its template type arguments.

For a specialization disjunction<B1, ..., BN>, if there is a template type argument Bi for which
bool(Bi::value) is true, then instantiating disjunction<B1, ..., BN>::value does not require
the instantiation of Bj::value for j > i.

[Note 3: This is analogous to the short-circuiting behavior of the built-in operator ||. — end note]

Every template type argument for which Bi::value is instantiated shall be usable as a base class and
shall have a member value which is convertible to bool, is not hidden, and is unambiguously available
in the type.

The specialization disjunction<B1, ..., BN> has a public and unambiguous base that is either
— the first type Bi in the list false_type, B1, ..., BN for which bool(Bi::value) is true, or
— if there is no such Bi, the last type in the list.

[Note 4: This means a specialization of disjunction does not necessarily inherit from either true_type or
false_type. — end note]

The member names of the base class, other than disjunction and operator=, shall not be hidden
and shall be unambiguously available in disjunction.
template<class B> struct negation : see below { }; 

12 The class template negation forms the logical negation of its template type argument. The type
negation<B> is a Cpp17UnaryTypeTrait with a base characteristic of bool_constant<!bool(B::
value)>.

21.3.10 Member relationships

template<class S, class M>
constexpr bool is_pointer_interconvertible_with_class(M S::*m) noexcept;

1 Mandates: S is a complete type.
2 Returns: true if and only if S is a standard-layout type, M is an object type, m is not null, and each
object s of type S is pointer-interconvertible (6.8.4) with its subobject s.*m.

template<class S1, class S2, class M1, class M2>
constexpr bool is_corresponding_member(M1 S1::*m1, M2 S2::*m2) noexcept;

3 Mandates: S1 and S2 are complete types.
4 Returns: true if and only if S1 and S2 are standard-layout struct (11.2) types, M1 and M2 are object
types, m1 and m2 are not null, and m1 and m2 point to corresponding members of the common initial
sequence (11.4) of S1 and S2.

5 [Note 1: The type of a pointer-to-member expression &C::b is not always a pointer to member of C, leading to
potentially surprising results when using these functions in conjunction with inheritance.

[Example 1:]
struct A { int a; }; // a standard-layout class
struct B { int b; }; // a standard-layout class
struct C: public A, public B { }; // not a standard-layout class

static_assert( is_pointer_interconvertible_with_class( &C::b ) );
// Succeeds because, despite its appearance, &C::b has type
// “pointer to member of B of type int”.
static_assert( is_pointer_interconvertible_with_class<C>( &C::b ) );
// Forces the use of class C, and fails.
static_assert( is_corresponding_member( &C::a, &C::b ) );
// Succeeds because, despite its appearance, &C::a and &C::b have types
// “pointer to member of A of type int” and
// “pointer to member of B of type int”, respectively.
static_assert( is_corresponding_member<C, C>( &C::a, &C::b ) );
// Forces the use of class C, and fails.
— end example]
— end note]

21.3.11 Constant evaluation context

constexpr bool is_constant_evaluated() noexcept;

1 Effects: Equivalent to:
    if constexpr { 
    return true;
} else {
    return false;
}

2 [Example 1:]
constexpr void f(unsigned char *p, int n) {
    if (std::is_constant_evaluated()) {
        // should not be a constexpr if statement
        for (int k = 0; k<n; ++k) p[k] = 0;
    } else {
        memset(p, 0, n);  // not a core constant expression
    }
}
consteval bool is_within_lifetime(const auto* p) noexcept;

Returns: true if p is a pointer to an object that is within its lifetime (6.7.3); otherwise, false.

Remarks: During the evaluation of an expression E as a core constant expression, a call to this function is ill-formed unless p points to an object that is usable in constant expressions or whose complete object’s lifetime began within E.

[Example 2:

```cpp
struct OptBool {
    union { bool b; char c; };

    // note: this assumes common implementation properties for bool and char:
    // * sizeof(bool) == sizeof(char), and
    // * the value representations for true and false are distinct
    // from the value representation for 2
    constexpr OptBool() : c(2) { }
    constexpr OptBool(bool b) : b(b) { }

    constexpr OptBool disengaged;
    constexpr OptBool engaged(true);
    static_assert(!disengaged.has_value());
    static_assert(engaged.has_value());
    static_assert(*engaged);
};
```

— end example]
// 21.4.5, ratio comparison
template<class R1, class R2> struct ratio_equal;
template<class R1, class R2> struct ratio_not_equal;
template<class R1, class R2> struct ratio_less;
template<class R1, class R2> struct ratio_less_equal;
template<class R1, class R2> struct ratio_greater;
template<class R1, class R2> struct ratio_greater_equal;

template<class R1, class R2>
constexpr bool ratio_equal_v = ratio_equal<R1, R2>::value;
template<class R1, class R2>
constexpr bool ratio_not_equal_v = ratio_not_equal<R1, R2>::value;
template<class R1, class R2>
constexpr bool ratio_less_v = ratio_less<R1, R2>::value;
template<class R1, class R2>
constexpr bool ratio_less_equal_v = ratio_less_equal<R1, R2>::value;
template<class R1, class R2>
constexpr bool ratio_greater_v = ratio_greater<R1, R2>::value;
template<class R1, class R2>
constexpr bool ratio_greater_equal_v = ratio_greater_equal<R1, R2>::value;

// 21.4.6, convenience SI typedefs
using quecto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using ronto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using yocto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using zepto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using atto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using femto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using pico = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using nano = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using micro = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using milli = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using centi = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using deci = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using deca = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using hecto = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using kilo = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using mega = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using giga = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using tera = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using peta = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using exa = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
using zetta = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using yotta = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using ronna = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below
using quetta = ratio<1, 1'000'000'000'000'000'000'000'000'000'000>;
// see below

21.4.3 Class template ratio

namespace std {
    template<intmax_t N, intmax_t D = 1> class ratio {
        public:
            static constexpr intmax_t num;
            static constexpr intmax_t den;
            using type = ratio<num, den>;
    };
}

1 If the template argument D is zero or the absolute values of either of the template arguments N and D is not representable by type intmax_t, the program is ill-formed.

[Note 1: These rules ensure that infinite ratios are avoided and that for any negative input, there exists a representable value of its absolute value which is positive. This excludes the most negative value. — end note]
The static data members \texttt{num} and \texttt{den} shall have the following values, where \texttt{gcd} represents the greatest common divisor of the absolute values of \texttt{N} and \texttt{D}:

\begin{enumerate}
\item \texttt{num} shall have the value \texttt{sgn(N) \times sgn(D) \times abs(N) / gcd}.
\item \texttt{den} shall have the value \texttt{abs(D) / gcd}.
\end{enumerate}

### 21.4.4 Arithmetic on ratios

Each of the alias templates \texttt{ratio_add}, \texttt{ratio_subtract}, \texttt{ratio_multiply}, and \texttt{ratio_divide} denotes the result of an arithmetic computation on two \texttt{ratio}s \texttt{R1} and \texttt{R2}. With \texttt{X} and \texttt{Y} computed (in the absence of arithmetic overflow) as specified by Table 60, each alias denotes a \texttt{ratio}

\begin{itemize}
\item \texttt{ratio_add<R1, R2>}
\item \texttt{ratio_subtract<R1, R2>}
\item \texttt{ratio_multiply<R1, R2>}
\item \texttt{ratio_divide<R1, R2>}
\end{itemize}

\texttt{R1} shall denote \texttt{ratio\langle X, Y\rangle::num} and \texttt{V} shall denote \texttt{ratio\langle X, Y\rangle::den}.

If it is not possible to represent \texttt{U} or \texttt{V} with \texttt{intmax_t}, the program is ill-formed. Otherwise, an implementation should yield correct values of \texttt{U} and \texttt{V}. If it is not possible to represent \texttt{X} or \texttt{Y} with \texttt{intmax_t}, the program is ill-formed unless the implementation yields correct values of \texttt{U} and \texttt{V}.

### Table 60 — Expressions used to perform ratio arithmetic

<table>
<thead>
<tr>
<th>Type</th>
<th>Value of X</th>
<th>Value of Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{ratio_add}</td>
<td>\texttt{R1::num \times R2::den + R1::den \times R2::den}</td>
<td>\texttt{R2::num \times R1::den}</td>
</tr>
<tr>
<td>\texttt{ratio_subtract}</td>
<td>\texttt{R1::num \times R2::den - R1::den \times R2::den}</td>
<td>\texttt{R2::num \times R1::den}</td>
</tr>
<tr>
<td>\texttt{ratio_multiply}</td>
<td>\texttt{R1::num \times R2::num}</td>
<td>\texttt{R1::den \times R2::den}</td>
</tr>
<tr>
<td>\texttt{ratio_divide}</td>
<td>\texttt{R1::num \times R2::den}</td>
<td>\texttt{R1::den \times R2::num}</td>
</tr>
</tbody>
</table>

\[\text{Example 1:}\]

\begin{verbatim}
static assert(ratio_add<ratio<1, 3>, ratio<1, 6>>::num == 1, "1/3+1/6 == 1/2");
static assert(ratio_add<ratio<1, 3>, ratio<1, 6>>::den == 2, "1/3+1/6 == 1/2");
static assert(ratio_multiply<ratio<1, 3>, ratio<3, 2>>::num == 1, "1/3*3/2 == 1/2");
static assert(ratio_multiply<ratio<1, 3>, ratio<3, 2>>::den == 2, "1/3*3/2 == 1/2");

// The following cases may cause the program to be ill-formed under some implementations
static assert(ratio_add<ratio<1, INT_MAX>, ratio<1, INT_MAX>>::num == 2, "1/MAX+1/MAX == 2/MAX");
static assert(ratio_add<ratio<1, INT_MAX>, ratio<1, INT_MAX>>::den == INT_MAX, "1/MAX+1/MAX == 2/MAX");
static assert(ratio_multiply<ratio<1, INT_MAX>, ratio<INT_MAX, 2>>::num == 1, "1/MAX * MAX/2 == 1/2");
static assert(ratio_multiply<ratio<1, INT_MAX>, ratio<INT_MAX, 2>>::den == 2, "1/MAX * MAX/2 == 1/2");
\end{verbatim}

--- end example]

### 21.4.5 Comparison of ratios

\begin{verbatim}
template<class R1, class R2>
struct ratio_equal : bool_constant<R1::num == R2::num && R1::den == R2::den> { };
template<class R1, class R2>
struct ratio_not_equal : bool_constant<!ratio_equal_v<R1, R2>> { };
template<class R1, class R2>
struct ratio_less : bool_constant<see below> { };

1 If \texttt{R1::num \times R2::den} is less than \texttt{R2::num \times R1::den}, \texttt{ratio_less<R1, R2>} shall be derived from \texttt{bool_constant<true>}; otherwise it shall be derived from \texttt{bool_constant<false>}. Implementations may use other algorithms to compute this relationship to avoid overflow. If overflow occurs, the program is ill-formed.
\end{verbatim}
template<class R1, class R2>
struct ratio_less_equal : bool_constant<!ratio_less_v<R2, R1>> { };  

template<class R1, class R2>
struct ratio_greater : bool_constant<ratio_less_v<R2, R1>> { };  

template<class R1, class R2>
struct ratio_greater_equal : bool_constant<!ratio_less_v<R1, R2>> { };  

21.4.6 SI types for ratio

For each of the typedef-names quecto, ronto, yocto, zepto, zetta, yotta, ronna, and quetta, if both of the constants used in its specification are representable by intmax_t, the typedef is defined; if either of the constants is not representable by intmax_t, the typedef is not defined.
22 General utilities library

22.1 General

This Clause describes utilities that are generally useful in C++ programs; some of these utilities are used by other elements of the C++ standard library. These utilities are summarized in Table 61.

Table 61 — General utilities library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.2</td>
<td>Utility components &lt;utility&gt;</td>
</tr>
<tr>
<td>22.3</td>
<td>Pairs &lt;tuple&gt;</td>
</tr>
<tr>
<td>22.4</td>
<td>Tuples &lt;optional&gt;</td>
</tr>
<tr>
<td>22.5</td>
<td>Optional objects &lt;optional&gt;</td>
</tr>
<tr>
<td>22.6</td>
<td>Variants &lt;variant&gt;</td>
</tr>
<tr>
<td>22.7</td>
<td>Storage for any type &lt;any&gt;</td>
</tr>
<tr>
<td>22.8</td>
<td>Expected objects &lt;expected&gt;</td>
</tr>
<tr>
<td>22.9</td>
<td>Fixed-size sequences of bits &lt;bitset&gt;</td>
</tr>
<tr>
<td>22.10</td>
<td>Function objects &lt;functional&gt;</td>
</tr>
<tr>
<td>22.11</td>
<td>Type indexes &lt;typeindex&gt;</td>
</tr>
<tr>
<td>22.12</td>
<td>Execution policies &lt;execution&gt;</td>
</tr>
<tr>
<td>22.13</td>
<td>Primitive numeric conversions &lt;charconv&gt;</td>
</tr>
<tr>
<td>22.14</td>
<td>Formatting &lt;format&gt;</td>
</tr>
<tr>
<td>22.15</td>
<td>Bit manipulation &lt;bit&gt;</td>
</tr>
<tr>
<td>22.16</td>
<td>Debugging &lt;debugging&gt;</td>
</tr>
</tbody>
</table>

22.2 Utility components

22.2.1 Header <utility> synopsis

The header <utility> contains some basic function and class templates that are used throughout the rest of the library.

```cpp
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 22.2.2, swap
    template<class T>
    constexpr void swap(T& a, T& b) noexcept(see below);
    template<class T, size_t N>
    constexpr void swap(T (&a)[N], T (&b)[N]) noexcept(is_nothrow_swappable_v<T>);

    // 22.2.3, exchange
    template<class T, class U = T>
    constexpr T exchange(T& obj, U&& new_val) noexcept(see below);

    // 22.2.4, forward/move
    template<class T>
    constexpr T&& forward(remove_reference_t<T>& t) noexcept;
    template<class T>
    constexpr T&& forward(remove_reference_t<T>&& t) noexcept;
    template<class T, class U>
    [[nodiscard]] constexpr auto forward_like(U&& x) noexcept -> see below;
    template<class T>
    constexpr remove_reference_t<T>&& move(T&&) noexcept;
```

§ 22.1
template<class T>
constexpr conditional_t<!is_nothrow_move_constructible_v<T> && is_copy_constructible_v<T>, const T&, T&&>
move_if_noexcept(T& x) noexcept;

// 22.2.5, as_const
template<class T>
constexpr add_const_t<T>& as_const(T& t) noexcept;
template<class T>
void as_const(const T& t) = delete;

// 22.2.6, declval
template<class T>
add_rvalue_reference_t<T> declval() noexcept; // as unevaluated operand

// 22.2.7, integer comparison functions
template<class T, class U>
constexpr bool cmp_equal(T t, U u) noexcept;
template<class T, class U>
constexpr bool cmp_not_equal(T t, U u) noexcept;

template<class T, class U>
constexpr bool cmp_less(T t, U u) noexcept;
template<class T, class U>
constexpr bool cmp_greater(T t, U u) noexcept;
template<class T, class U>
constexpr bool cmp_less_equal(T t, U u) noexcept;
template<class T, class U>
constexpr bool cmp_greater_equal(T t, U u) noexcept;

template<class R, class T>
constexpr underlying_type_t<T> to_underlying(T value) noexcept;

// 22.2.8, to_underlying
template<class T>
constexpr underlying_type_t<T> to_underlying(T value) noexcept;

[[noreturn]] void unreachable();

// 21.2, compile-time integer sequences
template<class T, T...>
struct integer_sequence;
template<
size_t..., I>
using index_sequence = integer_sequence<size_t, I,...>;

template<class T, T N>
using make_index_sequence = integer_sequence<T, see below>;
template<
size_t N>
using make_index_sequence = make_integer_sequence<size_t, N>;

template<class... T>
using index_sequence_for = make_index_sequence<sizeof...(T)>;

// 22.3, class template pair
template<class T1, class T2>
struct pair;

template<class T1, class T2, class U1, class U2,
    template<class> class TQual, template<class> class UQual>
requires requires {
    typename pair<common_reference_t<TQual<T1>>, UQual<U1>>,
    common_reference_t<TQual<T2>>, UQual<U2>>;
}
struct basic_common_reference<pair<T1, T2>, pair<U1, U2>, TQual, UQual> {
    using type = pair<
        common_reference_t<TQual<T1>, UQual<U1>>,
        common_reference_t<TQual<T2>, UQual<U2>>;
};

template<class T1, class T2, class U1, class U2>
requires requires { typename pair<
    common_type_t<T1, U1>, common_type_t<T2, U2>>; }
struct common_type<pair<T1, T2>, pair<U1, U2>> {
    using type = pair<
        common_type_t<T1, U1>, common_type_t<T2, U2>>;
};

// 22.3.3, pair specialized algorithms
template<class T1, class T2, class U1, class U2>
constexpr bool operator==(const pair<T1, T2>&, const pair<U1, U2>&);

template<class T1, class T2, class U1, class U2>
constexpr common_comparison_category_t<
    synth-three-way-result<T1, U1>,
    synth-three-way-result<T2, U2>>
operator<=>(const pair<T1, T2>&, const pair<U1, U2>&);

template<class T1, class T2>
constexpr void swap(pair<T1, T2>&, pair<T1, T2>& y) noexcept(noexcept(x.swap(y)));

template<class T1, class T2>
constexpr void swap(const pair<T1, T2>&, const pair<T1, T2>& y)
noexcept(noexcept(x.swap(y)));

// 22.3.4, tuple-like access to pair
template<class T> struct tuple_size;

template<size_t I, class T> struct tuple_element;

template<class T1, class T2> struct tuple_size<pair<T1, T2>>;

template<size_t I, class T1, class T2> struct tuple_element<I, pair<T1, T2>>;

template<size_t I, class T1, class T2>
constexpr tuple_element_t<I, pair<T1, T2>>& get(pair<T1, T2>&) noexcept;

template<size_t I, class T1, class T2>
constexpr tuple_element_t<I, pair<T1, T2>>&& get(pair<T1, T2>&&) noexcept;

template<size_t I, class T1, class T2>
constexpr const tuple_element_t<I, pair<T1, T2>>& get(const pair<T1, T2>&) noexcept;

template<size_t I, class T1, class T2>
constexpr const tuple_element_t<I, pair<T1, T2>>&& get(const pair<T1, T2>&&) noexcept;

template<class T1, class T2>
constexpr T1& get(pair<T1, T2>& p) noexcept;

template<class T1, class T2>
constexpr const T1& get(const pair<T1, T2>& p) noexcept;

template<class T1, class T2>
constexpr T1&& get(pair<T1, T2>&& p) noexcept;

template<class T1, class T2>
constexpr const T1&& get(const pair<T1, T2>&& p) noexcept;

template<class T2, class T1>
constexpr T2& get(pair<T1, T2>& p) noexcept;

template<class T2, class T1>
constexpr const T2& get(const pair<T1, T2>& p) noexcept;

template<class T2, class T1>
constexpr T2&& get(pair<T1, T2>&& p) noexcept;

template<class T2, class T1>
constexpr const T2&& get(const pair<T1, T2>&& p) noexcept;

// 22.3.5, pair piecewise construction
struct piecewise_construct_t {
    explicit piecewise_construct_t() = default;
};
inline constexpr piecewise_construct_t piecewise_construct{};

template<class... Types> class tuple;  // defined in <tuple> (22.4.2)

// in-place construction
struct in_place_t {
    explicit in_place_t() = default;
};
inline constexpr in_place_t in_place{};

template<class T>
struct in_place_type_t {
    explicit in_place_type_t() = default;
};
template<class T> constexpr in_place_type_t<T> in_place_type{};

template<size_t I>
struct in_place_index_t {
    explicit in_place_index_t() = default;
};
template<size_t I> constexpr in_place_index_t<I> in_place_index{};

// nontype argument tag
template<auto V>
struct nontype_t {
    explicit nontype_t() = default;
};
template<auto V> constexpr nontype_t<V> nontype{};

22.2.2 swap

template<class T>
constexpr void swap(T& a, T& b) noexcept(see below);

1 Constraints: is_move_constructible_v<T> is true and is_move_assignable_v<T> is true.
2 Preconditions: Type T meets the Cpp17MoveConstructible (Table 31) and Cpp17MoveAssignable (Table 33) requirements.
3 Effects: Exchanges values stored in two locations.
4 Remarks: The exception specification is equivalent to:
   is_nothrow_move_constructible_v<T> && is_nothrow_move_assignable_v<T>

template<class T, size_t N>
constexpr void swap(T (&a)[N], T (&b)[N]) noexcept(is_nothrow_swappable_v<T>);

5 Constraints: is_swappable_v<T> is true.
6 Preconditions: a[i] is swappable with (16.4.4.3) b[i] for all i in the range [0, N).
7 Effects: As if by swap_ranges(a, a + N, b).

22.2.3 exchange

template<class T, class U = T>
constexpr T exchange(T& obj, U&& new_val) noexcept(see below);

1 Effects: Equivalent to:
   T old_val = std::move(obj);
   obj = std::forward<U>(new_val);
   return old_val;
2 Remarks: The exception specification is equivalent to:
   is_nothrow_move_constructible_v<T> && is_nothrow_assignable_v<T&, U>
22.2.4  Forward/move helpers

The library provides templated helper functions to simplify applying move semantics to an lvalue and to simplify the implementation of forwarding functions. All functions specified in this subclause are signal-safe (17.13.5).

```
template<class T> constexpr T&& forward(remove_reference_t<T>& t) noexcept;
template<class T> constexpr T&& forward(remove_reference_t<T>&& t) noexcept;
```

*Mandates:* For the second overload, `is_lvalue_reference_v<T>` is false.

*Returns:* `static_cast<T&&>(t)`.

*[Example 1:]*

```
template<class T, class A1, class A2>
shared_ptr<T> factory(A1&& a1, A2&& a2) {
    return shared_ptr<T>(new T(std::forward<A1>(a1), std::forward<A2>(a2)));
}
```

```
struct A {
    A(int&, const double&);
};
```

```
void g() {
    shared_ptr<A> sp1 = factory<A>(2, 1.414); // error: 2 will not bind to int&
    int i = 2;
    shared_ptr<A> sp2 = factory<A>(i, 1.414); // OK
}
```

In the first call to `factory`, `A1` is deduced as `int`, so 2 is forwarded to `A`'s constructor as an rvalue. In the second call to `factory`, `A1` is deduced as `int&`, so i is forwarded to `A`'s constructor as an lvalue. In both cases, `A2` is deduced as `double`, so 1.414 is forwarded to `A`'s constructor as an rvalue.

*[end example]*

```
template<class T, class U>
[[nodiscard]] constexpr auto forward_like(U&& x) noexcept -> see below;
```

*Mandates:* `T` is a referenceable type (3.44).

(5.1) — Let `COPY_CONST(A, B)` be `const B` if `A` is a const type, otherwise `B`.

(5.2) — Let `OVERRIDE_REF(A, B)` be `remove_reference_t<B>&&` if `A` is an rvalue reference type, otherwise `B&`.

(5.3) — Let `V` be

```
OVERRIDE_REF(T&&, COPY_CONST(remove_reference_t<T>, remove_reference_t<U>))
```

*Returns:* `static_cast<V>(x)`.

*Remarks:* The return type is `V`.

*[Example 2:]*

```
struct accessor {
    vector<string>* container;
    decltype(auto) operator[](this auto&& self, size_t i) { return std::forward_like<decltype(self)>(*container)[i]; }
};
```

```
void g() {
    vector v{"a"s, "b"s};
    accessor a{&v};
    string& x = a[0]; // OK, binds to lvalue reference
    string&& y = std::move(a)[0]; // OK, is rvalue reference
    string const& z = std::move(as_const(a))[1]; // OK, is const&&
    string& w = as_const(a)[1]; // error: will not bind to non-const
}
```

*[end example]*

```
template<class T> constexpr remove_reference_t<T>&& move(T&& t) noexcept;
```

*Returns:* `static_cast<remove_reference_t<T>&&>(t)`.

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[Example 3:
  template<class T, class A1>
  shared_ptr<T> factory(A1&& a1) {
    return shared_ptr<T>(new T(std::forward<A1>(a1)));}

  struct A {
    A();
    A(const A&); // copies from lvalues
    A(A&&); // moves from rvalues
  };

  void g() {
    A a;
    shared_ptr<A> sp1 = factory<A>(a); // "a" binds to A(const A&)
    shared_ptr<A> sp2 = factory<A>(std::move(a)); // "a" binds to A(A&&)
  }

  In the first call to factory, A1 is deduced as A&, so a is forwarded as a non-const lvalue. This binds to the constructor A(const A&), which copies the value from a. In the second call to factory, because of the call std::move(a), A1 is deduced as A, so a is forwarded as an rvalue. This binds to the constructor A(A&&), which moves the value from a. — end example]

  template<class T> constexpr conditional_t<
    !is_nothrow_move_constructible_v<T> && is_copy_constructible_v<T>, const T&, T&&> move_if_noexcept(T& x) noexcept;

  Returns: std::move(x).

22.2.5 Function template as_const [utility.as.const]

  template<class T> constexpr add_const_t<T> as_const(T& t) noexcept;

  Returns: t.

22.2.6 Function template declval [declval]

  template<class T> constexpr add_rvalue_reference_t<T> declval() noexcept;

  // as unevaluated operand

  Mandates: This function is not odr-used (6.3).

  Remarks: The template parameter T of declval may be an incomplete type.

  [Example 1:
   template<class To, class From> decltype(static_cast<To>(declval<From>())()) convert(From&&);
  
  declares a function template convert which only participates in overload resolution if the type From can be explicitly converted to type To. For another example see class template common_type (21.3.8.7). — end example]

22.2.7 Integer comparison functions [utility.intcmp]

  template<class T, class U>
  constexpr bool cmp_equal(T t, U u) noexcept;

  Mandates: Both T and U are standard integer types or extended integer types (6.8.2).

  Effects: Equivalent to:

  using UT = make_unsigned_t<T>;
  using UU = make_unsigned_t<U>;
  if constexpr (is_signed_v<T> == is_signed_v<U>)
    return t == u;
  else if constexpr (is_signed_v<T>)
    return t < 0 ? false : UT(t) == u;
  else
    return u < 0 ? false : t == UU(u);
template<class T, class U>
constexpr bool cmp_not_equal(T t, U u) noexcept;

Effects: Equivalent to: return !cmp_equal(t, u);

template<class T, class U>
constexpr bool cmp_less(T t, U u) noexcept;

Mandates: Both T and U are standard integer types or extended integer types (6.8.2).

Effects: Equivalent to:
  using UT = make_unsigned_t<T>;
  using UU = make_unsigned_t<U>;
  if constexpr (is_signed_v<T> == is_signed_v<U>)
    return t < u;
  else if constexpr (is_signed_v<T>)
    return t < 0 ? true : UT(t) < u;
  else
    return u < 0 ? false : t < UU(u);

template<class T, class U>
constexpr bool cmp_greater(T t, U u) noexcept;

Effects: Equivalent to: return cmp_less(u, t);

template<class T, class U>
constexpr bool cmp_less_equal(T t, U u) noexcept;

Effects: Equivalent to: return !cmp_greater(t, u);

template<class T, class U>
constexpr bool cmp_greater_equal(T t, U u) noexcept;

Effects: Equivalent to: return !cmp_less(t, u);

template<class R, class T>
constexpr bool in_range(T t) noexcept;

Mandates: Both T and R are standard integer types or extended integer types (6.8.2).

Effects: Equivalent to:
  return cmp_greater_equal(t, numeric_limits<R>::min()) &&
  cmp_less_equal(t, numeric_limits<R>::max());

[Note 1: These function templates cannot be used to compare byte, char, char8_t, char16_t, char32_t, wchar_t, and bool. — end note]

22.2.8 Function template to_underlying

template<class T>
constexpr underlying_type_t<T> to_underlying(T value) noexcept;

Returns: static_cast<underlying_type_t<T>>(value).

22.2.9 Function unreachable

[[noreturn]] void unreachable();

Preconditions: false is true.

[Note 1: This precondition cannot be satisfied, thus the behavior of calling unreachable is undefined. — end note]

[Example 1:
  int f(int x) {
    switch (x) {
      case 0:
      case 1:
        return x;
      default:
        std::unreachable();
```cpp
int a = f(1); // OK, a has value 1
int b = f(3); // undefined behavior
```

---

### 22.3 Pairs

#### 22.3.1 General

The library provides a template for heterogeneous pairs of values. The library also provides a matching function template to simplify their construction and several templates that provide access to `pair` objects as if they were `tuple` objects (see 22.4.7 and 22.4.8).

#### 22.3.2 Class template pair

```cpp
namespace std {
    template<class T1, class T2>
    struct pair {
        using first_type = T1;
        using second_type = T2;
        T1 first;
        T2 second;
        pair(const pair&) = default;
        pair(pair&&) = default;
        constexpr explicit(pair());
        constexpr explicit(pair(const T1& x, const T2& y));
        template<class U1 = T1, class U2 = T2>
        constexpr explicit(pair(U1&& x, U2&& y));
        template<class U1, class U2>
        constexpr explicit(pair(const pair<U1, U2>& p));
        template<class U1, class U2>
        constexpr explicit(pair(U1, U2&& p));
        template<class U1, class U2>
        constexpr explicit(pair(U1&& p, const pair<U1, U2>& p));
        template<class U1, class U2>
        constexpr explicit(pair(U1&& p, pair<U1, U2>& p));
        template<class U1, class U2>
        constexpr explicit(pair(U1&& p, pair<U1, U2>&& p));
        template<class U1, class U2>
        constexpr explicit(pair(U1&& p, const pair<U1, U2>&& p));
        constexpr void swap(pair&) noexcept;
        constexpr void swap(const pair&) const noexcept;
    }

    template<class... Args1, class... Args2>
    constexpr pair(piecewise_construct_t,
                   tuple<Args1...> first_args, tuple<Args2...> second_args);
}
```
template<class T1, class T2>
pair(T1, T2) -> pair<T1, T2>;

Constructors and member functions of pair do not throw exceptions unless one of the element-wise operations specified for that operation throws an exception.

The defaulted move and copy constructor, respectively, of pair is a constexpr function if and only if all required element-wise initializations for move and copy, respectively, would be constexpr-suitable (9.2.6).

If (is_trivially_destructible_v<T1> && is_trivially_destructible_v<T2>) is true, then the destructor of pair is trivial.

pair<T, U> is a structural type (13.2) if T and U are both structural types. Two values p1 and p2 of type pair<T, U> are template-argument-equivalent (13.6) if and only if p1.first and p2.first are template-argument-equivalent and p1.second and p2.second are template-argument-equivalent.

constexpr explicit(see below) pair();

Constraints:
(1.1) is_default_constructible_v<T1> is true and
(1.2) is_default_constructible_v<T2> is true.

Effects: Value-initializes first and second.

Remarks: The expression inside explicit evaluates to true if and only if either T1 or T2 is not implicitly default-constructible.

[Note 1: This behavior can be implemented with a trait that checks whether a const T1& or a const T2& can be initialized with {}. — end note]

constexpr explicit(see below) pair(const T1& x, const T2& y);

Constraints:
(2.1) is_copy_constructible_v<T1> is true and
(2.2) is_copy_constructible_v<T2> is true.

Effects: Initializes first with x and second with y.

Remarks: The expression inside explicit is equivalent to:
!is_convertible_v<const T1&, T1> || !is_convertible_v<const T2&, T2>

template<class U1 = T1, class U2 = T2> constexpr explicit(see below) pair(U1&& x, U2&& y);

Constraints:
(3.1) is_constructible_v<T1, U1> is true and
(3.2) is_constructible_v<T2, U2> is true.

Effects: Initializes first with std::forward<U1>(x) and second with std::forward<U2>(y).

Remarks: The expression inside explicit is equivalent to:
!is_convertible_v<const U1&, T1> || !is_convertible_v<const U2&, T2>

This constructor is defined as deleted if reference_constructs_from_temporary_v<first_type, U1&&> is true or reference_constructs_from_temporary_v<second_type, U2&&> is true.

template<class T1, class T2> constexpr explicit(see below) pair(T1, T2) -> pair<T1, T2>;

}
Effects: Initializes first with get<0>(FWD(p)) and second with get<1>(FWD(p)).

Remarks: The expression inside explicit is equivalent to:

!is_convertible_v<decltype(get<0>(FWD(p))), T1> ||
!is_convertible_v<decltype(get<1>(FWD(p))), T2>

The constructor is defined as deleted if

reference_constructs_from_temporary_v<first_type, decltype(get<0>(FWD(p)))> ||
reference_constructs_from_temporary_v<second_type, decltype(get<1>(FWD(p)))>

is true.

template<class... Args1, class... Args2>
constexpr pair(piecewise_construct_t,
        tuple<Args1...> first_args, tuple<Args2...> second_args);

Mandates:
(18.1) is_constructible_v<T1, Args1...> is true and
(18.2) is_constructible_v<T2, Args2...> is true.

Effects: Initializes first with arguments of types Args1... obtained by forwarding the elements of first_args and initializes second with arguments of types Args2... obtained by forwarding the elements of second_args. (Here, forwarding an element x of type U within a tuple object means calling std::forward<U>(x).) This form of construction, whereby constructor arguments for first and second are each provided in a separate tuple object, is called piecewise construction.

[Note 2: If a data member of pair is of reference type and its initialization binds it to a temporary object, the program is ill-formed (11.9.3). — end note]

constexpr pair& operator=(const pair& p);

Effects: Assigns p.first to first and p.second to second.

Returns: *this.

Remarks: This operator is defined as deleted unless is_copy_assignable_v<T1> is true and is_copy_assignable_v<T2> is true.

constexpr const pair& operator=(const pair& p) const;

Effects: Assigns p.first to first and p.second to second.

Returns: *this.

template<class U1, class U2> constexpr pair& operator=(const pair<U1, U2>& p);

Constraints:
(26.1) is_assignable_v<T1&, const U1&> is true and
(26.2) is_assignable_v<T2&, const U2&> is true.

Effects: Assigns p.first to first and p.second to second.

Returns: *this.

Constraints:
(29.1) is_assignable_v<const T1&, const U1&> is true, and
(29.2) is_assignable_v<const T2&, const U2&> is true.

Effects: Assigns p.first to first and p.second to second.

Returns: *this.
constexpr pair& operator=(pair&& p) noexcept(see below);

32 Constraints:
32.1 — is_move_assignable_v<T1> is true and
32.2 — is_move_assignable_v<T2> is true.
33 Effects: Assigns std::forward<T1>(p.first) to first and std::forward<T2>(p.second) to second.
34 Returns: *this.
35 Remarks: The exception specification is equivalent to:
            is_nothrow_move_assignable_v<T1> && is_nothrow_move_assignable_v<T2>

constexpr const pair& operator=(pair&& p) const;

36 Constraints:
36.1 — is_assignable_v<const T1&, T1> is true and
36.2 — is_assignable_v<const T2&, T2> is true.
37 Effects: Assigns std::forward<T1>(p.first) to first and std::forward<T2>(p.second) to second.
38 Returns: *this.

template<class U1, class U2> constexpr pair& operator=(pair<U1, U2>&& p);

39 Constraints:
39.1 — is_assignable_v<T1&, U1> is true and
39.2 — is_assignable_v<T2&, U2> is true.
40 Effects: Assigns std::forward<U1>(p.first) first and std::forward<U2>(p.second) to second.
41 Returns: *this.

template<pair-like P> constexpr pair& operator=(P&& p);

42 Constraints:
42.1 — different-from<P, pair> (26.5.2) is true,
42.2 — remove_cvref_t<P> is not a specialization of ranges::subrange,
42.3 — is_assignable_v<T1&, decltype(get<0>(std::forward<P>(p)))> is true, and
42.4 — is_assignable_v<T2&, decltype(get<1>(std::forward<P>(p)))> is true.
43 Effects: Assigns get<0>(std::forward<P>(p)) to first and get<1>(std::forward<P>(p)) to second.
44 Returns: *this.

template<pair-like P> constexpr const pair& operator=(P&& p) const;

45 Constraints:
45.1 — different-from<P, pair> (26.5.2) is true,
45.2 — remove_cvref_t<P> is not a specialization of ranges::subrange,
45.3 — is_assignable_v<const T1&, decltype(get<0>(std::forward<P>(p)))> is true, and
45.4 — is_assignable_v<const T2&, decltype(get<1>(std::forward<P>(p)))> is true.
46 Effects: Assigns get<0>(std::forward<P>(p)) to first and get<1>(std::forward<P>(p)) to second.
47 Returns: *this.

template<class U1, class U2> constexpr const pair& operator=(pair<U1, U2>&& p) const;

48 Constraints:
48.1 — is_assignable_v<const T1&, U1> is true, and
48.2 — is_assignable_v<const T2&, U2> is true.
Effects: Assigns std::forward<U1>(p.first) to first and std::forward<U2>(u.second) to second.

Returns: *this.

costexpr void swap(pair& p) noexcept(see below);
costexpr void swap(const pair& p) const noexcept(see below);

Mandates:
— For the first overload, is_swappable_v<T1> is true and is_swappable_v<T2> is true.
— For the second overload, is_swappable_v<const T1> is true and is_swappable_v<const T2> is true.

Preconditions: first is swappable with (16.4.4.3) p.first and second is swappable with p.second.

Effects: Swaps first with p.first and second with p.second.

Remarks: The exception specification is equivalent to:
— is_nothrow_swappable_v<T1> && is_nothrow_swappable_v<T2> for the first overload, and
— is_nothrow_swappable_v<const T1> && is_nothrow_swappable_v<const T2> for the second overload.

### 22.3.3 Specialized algorithms

**template<class T1, class T2, class U1, class U2>**

    constexpr bool operator==(const pair<T1, T2>& x, const pair<U1, U2>& y);

**Constraints:** x.first == y.first and x.second == y.second are valid expressions and each of
decltype(x.first == y.first) and decltype(x.second == y.second) models boolean-testable.

**Returns:** x.first == y.first && x.second == y.second.

**template<class T1, class T2, class U1, class U2>**

    constexpr common_comparison_category_t<
        synth-three-way-result<T1, U1>,
        synth-three-way-result<T2, U2>>
    operator<=>(const pair<T1, T2>& x, const pair<U1, U2>& y);

**Effects:** Equivalent to:

    if (auto c = synth-three-way(x.first, y.first); c != 0) return c;
    return synth-three-way(x.second, y.second);

**template<class T1, class T2>**

    constexpr void swap(pair<T1, T2>& x, pair<T1, T2>& y) noexcept(noexcept(x.swap(y)));

**Constraints:**
— For the first overload, is_swappable_v<T1> is true and is_swappable_v<T2> is true.
— For the second overload, is_swappable_v<const T1> is true and is_swappable_v<const T2> is true.

**Effects:** Equivalent to x.swap(y).

**template<class T1, class T2>**

    constexpr pair<unwrap_ref_decay_t<T1>, unwrap_ref_decay_t<T2>>
    make_pair(T1&& x, T2&& y);

**Returns:**

    pair<unwrap_ref_decay_t<T1>,
        unwrap_ref_decay_t<T2>>((std::forward<T1>(x), std::forward<T2>(y))

**Example 1:** In place of:

    return pair<int, double>(5, 3.1415926); // explicit types

a C++ program may contain:

    return make_pair(5, 3.1415926); // types are deduced

— end example]
22.3.4 Tuple-like access to pair

```cpp
template<class T1, class T2>
struct tuple_size<pair<T1, T2>> : integral_constant<size_t, 2> { }

template<size_t I, class T1, class T2>
struct tuple_element<I, pair<T1, T2>> {
    using type = see below ;
};
```

1. **Mandates:** \( I < 2 \).
2. **Type:** The type \( T_1 \) if \( I \) is 0, otherwise the type \( T_2 \).

```cpp
template<size_t I, class T1, class T2>
constexpr tuple_element_t<I, pair<T1, T2>>& get(pair<T1, T2>& p) noexcept;
```

(4.1) — If \( I \) is 0, returns a reference to \( p\.\text{first} \).
(4.2) — If \( I \) is 1, returns a reference to \( p\.\text{second} \).

```cpp
template<class T1, class T2>
constexpr T1& get(pair<T1, T2>& p) noexcept;
```

5. **Mandates:** \( T_1 \) and \( T_2 \) are distinct types.
6. **Returns:** A reference to \( p\.\text{first} \).

```cpp
template<class T2, class T1>
constexpr T2& get(pair<T1, T2>& p) noexcept;
```

7. **Mandates:** \( T_1 \) and \( T_2 \) are distinct types.
8. **Returns:** A reference to \( p\.\text{second} \).

22.3.5 Piecewise construction

```cpp
struct piecewise_construct_t {
    explicit piecewise_construct_t() = default;
};
inline constexpr piecewise_construct_t piecewise_construct{};
```

1. The `struct piecewise_construct_t` is an empty class type used as a unique type to disambiguate constructor and function overloading. Specifically, `pair` has a constructor with `piecewise_construct` as the first argument, immediately followed by two `tuple` (22.4) arguments used for piecewise construction of the elements of the `pair` object.
22.4 Tuples [tuple]

22.4.1 General [tuple.general]

Subclause 22.4 describes the tuple library that provides a tuple type as the class template `tuple` that can be instantiated with any number of arguments. Each template argument specifies the type of an element in the `tuple`. Consequently, tuples are heterogeneous, fixed-size collections of values. An instantiation of `tuple` with two arguments is similar to an instantiation of `pair` with the same two arguments. See 22.3.

In addition to being available via inclusion of the `<tuple>` header, `ignore` (22.4.2) is available when `<utility>` (22.2) is included.

22.4.2 Header `<tuple>` synopsis [tuple.syn]

```cpp
#include <compare>  // see 17.11.1
namespace std {
    // 22.4.4, class template tuple
    template<class... Types>
    class tuple;
    // 22.4.3, concept tuple-like
    template<class T>
    concept tuple-like = see below;  // exposition only
    template<class T>
    concept pair-like =  // exposition only
        tuple-like<T> && tuple_size_v<remove_cvref_t<T>> == 2;
    // 22.4.10, common_reference related specializations
    template<tuple-like TTuple, tuple-like UTuple, template<class> class TQual, template<class> class UQual>
    struct basic_common_reference<TTuple, UTuple, TQual, UQual>;
    template<tuple-like TTuple, tuple-like UTuple>
    struct common_type<TTuple, UTuple>;
    // ignore
    struct ignore-type {  // exposition only
        constexpr const ignore-type
            operator=(const auto &) const noexcept { return *this; }  
    };
    inline constexpr ignore-type ignore;
    // 22.4.5, tuple creation functions
    template<class... TTypes>
    constexpr tuple<unwrap_ref_decay_t<TTypes>...> make_tuple(TTypes&&...);
    template<class... TTypes>
    constexpr tuple<TTypes&&...> forward_as_tuple(TTypes&&...) noexcept;
    template<class... TTypes>
    constexpr tuple<TTypes&...> tie(TTypes&...) noexcept;
    template<tuple-like... Tuples>
    constexpr tuple<CTypes...> tuple_cat(Tuples&&...);  // 22.4.6, calling a function with a tuple of arguments
    template<class F, tuple-like Tuple>
    constexpr decltype(auto) apply(F&& f, Tuple&& t) noexcept(see below);
    template<class T, tuple-like Tuple>
    constexpr T make_from_tuple(Tuple&& t);
    // 22.4.7, tuple helper classes
    template<class T> struct tuple_size;  // not defined
    template<class T> struct tuple_size<const T>;
}
```

§ 22.4 © ISO/IEC 712
template<class... Types> struct tuple_size<tuple<Types...>>;

template<
size_t I, class T
>
struct

tuple_element;
  // not defined

template<
size_t I, class T
>
struct
tuple_element<I, tuple<Types...>>;


template<
size_t I, class T
>
using
tuple_element_t = typename
tuple_element<I, T>::type;

// 22.4.8, element access

template<
size_t I, class... Types
>
constexpr
tuple_element_t<I, tuple<Types...>> &
get(tuple<Types...>&) noexcept;

template<
size_t I, class... Types
>
constexpr
tuple_element_t<I, tuple<Types...>> &
&
get(tuple<Types...>&&) noexcept;

template<
size_t I, class... Types
>
constexpr
tuple_element_t<I, const tuple<Types...>> &
&
get(const tuple<Types...>&) noexcept;

template<
size_t I, class... Types
>
constexpr
tuple_element_t<I, const tuple<Types...>> &
&
get(const tuple<Types...>&&) noexcept;

template<
class T, class... Types
>
constexpr
T &
get(tuple<Types...>& t) noexcept;

template<
class T, class... Types
>
constexpr
T &
&
get(tuple<Types...>&& t) noexcept;

template<
class T, class... Types
>
constexpr
const T &
get(const tuple<Types...>& t) noexcept;

template<
class T, class... Types
>
constexpr
const T &
&
get(const tuple<Types...>&& t) noexcept;

// 22.4.9, relational operators

template<class... TTypes, class... UTypes>
constexpr
bool operator==(const tuple<TTypes...>&, const tuple<UTypes...>&);

template<class... TTypes, class... UTypes>
constexpr
common_comparison_category_t<
synth-three-way-result<TTypes, UTypes>...>
operator<=>(const tuple<TTypes...>&, const tuple<UTypes...>&);

// 22.4.11, allocator-related traits

template<class... Types, class Alloc>
struct uses_allocator<tuple<Types...>, Alloc>;

// 22.4.12, specialized algorithms

template<class... Types>
constexpr
void swap(tuple<Types...>& x, tuple<Types...>& y) noexcept;

template<class... Types>
constexpr
void swap(const tuple<Types...>& x, const tuple<Types...>& y) noexcept;

// 22.4.7, tuple helper classes

template<class T>
constexpr
size_t
size_t
&
tuple_size_v = tuple_size<T>::value;

22.4.3 Concept

tuple-like

// exposition only

template<class T>
concept
tuple-like = see below;

A type T models and satisfies the exposition-only concept tuple-like if remove_cvref_t<T> is a specialization of array, complex, pair, tuple, or ranges::subrange.
22.4.4 Class template `tuple`

22.4.4.1 General

```cpp	namespace std {
    template<class... Types>
    class tuple {
    public:
      // 22.4.4.2, tuple construction
      constexpr explicit(see below) tuple();
      constexpr explicit(see below) tuple(const Types&...); // only if sizeof...(Types) >= 1
      template<class... UTypes>
      constexpr explicit(see below) tuple(UTypes&&...); // only if sizeof...(Types) >= 1
      tuple(const tuple&) = default;
      tuple(tuple&&) = default;
      template<class... UTypes>
      constexpr explicit(see below) tuple(UTypes&&...);

      template<class U1, class U2>
      constexpr explicit(see below) tuple(pair<U1, U2>&);
      template<class U1, class U2>
      constexpr explicit(see below) tuple(const pair<U1, U2>&);
      template<class U1, class U2>
      constexpr explicit(see below) tuple(pair<U1, U2>&&);
      template<class U1, class U2>
      constexpr explicit(see below) tuple(const pair<U1, U2>&&);
      template<class U1, class U2>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a);
      template<class Alloc>
      constexpr tuple(allocator_arg_t, const Alloc& a, const Types&...);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, UTypes&&...);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, const UTypes&...);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, UTypes&&...);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, tuple<UTypes...>&);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, const tuple<UTypes...>&);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, tuple<UTypes...>&&);
      template<class Alloc, class... UTypes>
      constexpr explicit(see below) tuple(allocator_arg_t, const Alloc& a, const tuple<UTypes...>&&);
```
template<class Alloc, class U1, class U2>
    constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, pair<U1, U2>&);

// 22.4.4.3, tuple assignment
    constexpr tuple& operator=(const tuple&);
    constexpr const tuple& operator=(const tuple&) const;
    constexpr tuple& operator=(tuple&&) noexcept(see below);
    constexpr const tuple& operator=(tuple&&) const;

template<class... UTypes>
    constexpr tuple& operator=(const tuple<UTypes...>&);
    constexpr const tuple& operator=(const tuple<UTypes...>&) const;
    constexpr tuple& operator=(tuple<UTypes...>&&);
    constexpr const tuple& operator=(tuple<UTypes...>&&) const;

template<class U1, class U2>
    constexpr tuple& operator=(const pair<U1, U2>&);  // only if sizeof...(Types) == 2
    constexpr const tuple& operator=(const pair<U1, U2>&) const;  // only if sizeof...(Types) == 2
    constexpr tuple& operator=(pair<U1, U2>&&);  // only if sizeof...(Types) == 2
    constexpr const tuple& operator=(pair<U1, U2>&&) const;  // only if sizeof...(Types) == 2

template<tuple-like UTuple>
    constexpr tuple& operator=(UTuple&&);
    constexpr const tuple& operator=(UTuple&&) const;

// 22.4.4.4, tuple swap
    constexpr void swap(tuple&) noexcept(see below);
    constexpr void swap(const tuple&) const noexcept(see below);
};

template<class... UTypes>
    tuple(UTypes...) -> tuple<UTypes...>;
template<class T1, class T2>
    tuple(pair<T1, T2>) -> tuple<T1, T2>;
template<class Alloc, class... UTypes>
    tuple(allocator_arg_t, Alloc, UTypes...) -> tuple<UTypes...>;
template<class Alloc, class T1, class T2>
    tuple(allocator_arg_t, Alloc, pair<T1, T2>) -> tuple<T1, T2>;

If a program declares an explicit or partial specialization of `tuple`, the program is ill-formed, no diagnostic required.

22.4.4.2 Construction

In the descriptions that follow, let `i` be in the range `[0, sizeof...(Types))` in order, `T_i` be the `i`th type in `Types`, and `U_i` be the `i`th type in a template parameter pack named `UTypes`, where indexing is zero-based.

For each `tuple` constructor, an exception is thrown only if the construction of one of the types in `Types` throws an exception.

The defaulted move and copy constructor, respectively, of `tuple` is a constexpr function if and only if all required element-wise initializations for move and copy, respectively, would be constexpr-suitable (9.2.6). The defaulted move and copy constructor of `tuple<>` are constexpr functions.

If `is_trivially_destructible_v<T_i>` is true for all `T_i`, then the destructor of `tuple` is trivial.

The default constructor of `tuple<>` is trivial.

```cpp
cconstexpr explicit(see below) tuple();
```

**Constraints:** `is_default_constructible_v<T_i>` is true for all `i`.

**Effects:** Value-initializes each element.

**Remarks:** The expression inside `explicit` evaluates to `true` if and only if `T_i` is not copy-list-initializable from an empty list for at least one `i`.

[Note 1: This behavior can be implemented with a trait that checks whether a `const T_i`& can be initialized with `{}`. — end note]

```cpp
cconstexpr explicit(see below) tuple(const Types&...);
```

**Constraints:** `sizeof...(Types) ≥ 1` and `is_copy_constructible_v<T_i>` is true for all `i`.

**Effects:** Initializes each element with the value of the corresponding parameter.

**Remarks:** The expression inside `explicit` is equivalent to:

```cpp!
!conjunction_v<is_convertible<const Types&, Types>...>
```

```cpp
template<class... UTypes> constexpr explicit(see below) tuple(UTypes&&... u);
```

Let `disambiguating-constraint` be:

1. `— negation<is_same<remove_cvref_t<U_0>, tuple>>, tuple>>` if `sizeof...(Types)` is 1;
2. `— otherwise, bool constexpr!!is_same_v<remove_cvref_t<U_0>, alloc_arg_t> || is_same_v<remove_cvref_t<T_0>, alloc_arg_t>>` if `sizeof...(Types)` is 2 or 3;
3. `— otherwise, true_type`.

**Constraints:**

1. `— sizeof...(Types) equals sizeof...(UTypes),`
2. `— sizeof...(Types) ≥ 1, and`
3. `— conjunction_v<disambiguating-constraint, is_constructible<Types, UTypes>,...> is true.`

**Effects:** Initializes the elements in the tuple with the corresponding value in `std::forward<UTypes>(u)`. 

**Remarks:** The expression inside `explicit` is equivalent to:

```cpp!
!conjunction_v<is_convertible<UTypes, Types>...>
```

This constructor is defined as deleted if

```cpp
(reference_constructs_from_temporary_v<Types, UTypes&&> || ...)
```

is true.

```cpp
tuple(const tuple& u) = default;
```

**Mandates:** `is_copy_constructible_v<T_i>` is true for all `i`.

**Effects:** Initializes each element of `*this` with the corresponding element of `u`.

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tuple(tuple&& u) = default;

18 Constraints: is_move_constructible_v<T_i> is true for all i.

19 Effects: For all i, initializes the i-th element of *this with std::forward<T_i>(get<i>(u)).

template<class... UTypes> constexpr explicit(see below) tuple(tuple<UTypes...>& u);
template<class... UTypes> constexpr explicit(see below) tuple(const tuple<UTypes...>& u);
template<class... UTypes> constexpr explicit(see below) tuple(tuple<UTypes...>&& u);
template<class... UTypes> constexpr explicit(see below) tuple(const tuple<UTypes...>&& u);

20 Let I be the pack 0, 1, ..., (sizeof...(Types) - 1).
Let FWD (u) be static_cast< decltype(u) >(u).

21 Constraints:
(21.1) sizeof...(Types) equals sizeof...(UTypes), and
(21.2) (is_constructible_v<T_i, decltype(get<I>(FWD (u)))> && ...) is true, and
(21.3) either sizeof...(Types) is not 1, or (when Types... expands to T and UTypes... expands to U)
    is_convertible_v<decltype(u), T>, is_constructible_v<T, decltype(u)>, and is_same_v<T, U>
    are all false.

22 Effects: For all i, initializes the i-th element of *this with get<i>(FWD (u)).

23 Remarks: The expression inside explicit is equivalent to:

!(is_convertible_v<decltype(get<I>(FWD (u))), Types> && ...)

The constructor is defined as deleted if

(reference_constructs_from_temporary_v<Types, decltype(get<I>(FWD (u)))> || ...)

is true.

24 Let FWD (u) be static_cast< decltype(u) >(u).

25 Constraints:
(25.1) sizeof...(Types) is 2,
(25.2) is_constructible_v<T0, decltype(get<0>(FWD (u)))> is true, and
(25.3) is_constructible_v<T1, decltype(get<1>(FWD (u)))> is true.

26 Effects: Initializes the first element with get<0>(FWD (u)) and the second element with get<1>(FWD (u)).

27 Remarks: The expression inside explicit is equivalent to:

!is_convertible_v<decltype(get<0>(FWD (u))), T0> ||
!is_convertible_v<decltype(get<1>(FWD (u))), T1>

The constructor is defined as deleted if

reference_constructs_from_temporary_v<T0, decltype(get<0>(FWD (u)))> ||
reference_constructs_from_temporary_v<T1, decltype(get<1>(FWD (u)))>

is true.

28 template<tuple-like UTuple>
constexpr explicit(see below) tuple(UTuple&& u);

29 Let I be the pack 0, 1, ..., (sizeof...(Types) - 1).

29 Constraints:
(29.1) different_from<UTuple, tuple> (26.5.2) is true,
(29.2) remove_cvref_t<UTuple> is not a specialization of ranges::subrange,
(29.3) sizeof...(Types) equals tuple_size_v<remove_cvref_t<UTuple>>,
— (is_constructible_v<Types, decltype(get<I>(std::forward<UTuple>(u)))) && ...) is true, and
— either sizeof...(Types) is not 1, or (when Types... expands to T) is_convertible_v<UTuple, T> and is_constructible_v<T, UTuple> are both false.

**Effects:** For all i, initializes the i th element of *this with get<i>(std::forward<UTuple>(u)).

**Remarks:** The expression inside explicit is equivalent to:

( !is_convertible_v<decltype(get<I>(std::forward<UTuple>(u))), Types> && ... )

The constructor is defined as deleted if

( reference_constructs_from_temporary_v<Types, decltype(get<I>(std::forward<UTuple>(u)))> || ... )

is true.

```cpp
template<class Alloc>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a);
template<class Alloc>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, const Types&...);
template<class Alloc, class... UTypes>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, UTypes&&...);
template<class Alloc>
constexpr tuple(allocator_arg_t, const Alloc& a, const tuple&);
template<class Alloc>
constexpr tuple(allocator_arg_t, const Alloc& a, tuple&&);
template<class Alloc, class... UTypes>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, const tuple<UTypes...>&);
template<class Alloc, class... UTypes>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, const tuple<UTypes...>&&);
template<class Alloc, class U1, class U2>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, pair<U1, U2>&);
template<class Alloc, class U1, class U2>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, const pair<U1, U2>&);
template<class Alloc, class U1, class U2>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, pair<U1, U2>&&);
template<class Alloc, class U1, class U2>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, const pair<U1, U2>&&);
template<class Alloc, class U1, class U2>
constexpr explicit(see below)
    tuple(allocator_arg_t, const Alloc& a, UTuple);
template<class Alloc, class U1, class U2>
constexpr explicit(see below)
    tuple<like UTuple>
```
in order, $T_i$ be the $i^{th}$ type in $\text{Types}$, and $U_i$ be the $i^{th}$ type in a template parameter pack named $\text{UTypes}$, where indexing is zero-based.

```cpp
constexpr tuple& operator=(const tuple& u);
```

**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: This operator is defined as deleted unless $\text{is\_copy\_assignable\_v}\langle T_i \rangle$ is true for all $i$.

```cpp
constexpr const tuple& operator=(const tuple& u) const;
```

**Constraints**: $\text{is\_copy\_assignable\_v}\langle \text{const Types} \rangle \&\& \ldots$ is true.  
**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: The exception specification is equivalent to the logical AND of the following expressions:  
$$\text{is\_nothrow\_move\_assignable\_v}\langle T_i \rangle$$  
where $T_i$ is the $i^{th}$ type in $\text{Types}$.

```cpp
constexpr tuple& operator=(tuple&& u) noexcept;
```

**Constraints**:  
- $\text{sizeof}\ldots(\text{Types})$ equals $\text{sizeof}\ldots(\text{UTypes})$ and  
- $\text{is\_assignable\_v}\langle T_i, \text{const U}_i \rangle$ is true for all $i$.  
**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: The exception specification is equivalent to the logical AND of the following expressions:  
$$\text{is\_nothrow\_move\_assignable\_v}\langle T_i \rangle$$  
where $T_i$ is the $i^{th}$ type in $\text{Types}$.

```cpp
template<class... UTypes> constexpr tuple& operator=(const tuple<UTypes...>& u);
```

**Constraints**:  
- $\text{sizeof}\ldots(\text{Types})$ equals $\text{sizeof}\ldots(\text{UTypes})$ and  
- $\text{is\_assignable\_v}\langle \text{const Types}&, \text{const UTypes}& \rangle \&\& \ldots$ is true.  
**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: The exception specification is equivalent to the logical AND of the following expressions:  
$$\text{is\_nothrow\_move\_assignable\_v}\langle T_i \rangle$$  
where $T_i$ is the $i^{th}$ type in $\text{Types}$.

```cpp
template<class... UTypes> constexpr const tuple& operator=(const tuple<UTypes...>& u) const;
```

**Constraints**:  
- $\text{sizeof}\ldots(\text{Types})$ equals $\text{sizeof}\ldots(\text{UTypes})$ and  
- $(\text{is\_assignable\_v}\langle \text{const Types}&, \text{const UTypes}& \rangle \&\& \ldots)$ is true.  
**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: The exception specification is equivalent to the logical AND of the following expressions:  
$$\text{is\_nothrow\_move\_assignable\_v}\langle T_i \rangle$$  
where $T_i$ is the $i^{th}$ type in $\text{Types}$.

```cpp
template<class... UTypes> constexpr tuple& operator=(tuple<UTypes...>&& u);
```

**Constraints**:  
- $\text{sizeof}\ldots(\text{Types})$ equals $\text{sizeof}\ldots(\text{UTypes})$ and  
- $\text{is\_assignable\_v}\langle T_i, \text{U}_i \rangle$ is true for all $i$.  
**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: The exception specification is equivalent to the logical AND of the following expressions:  
$$\text{is\_nothrow\_move\_assignable\_v}\langle T_i \rangle$$  
where $T_i$ is the $i^{th}$ type in $\text{Types}$.

```cpp
template<class... UTypes> constexpr const tuple& operator=(tuple<UTypes...>&& u) const;
```

**Constraints**:  
- $\text{sizeof}\ldots(\text{Types})$ equals $\text{sizeof}\ldots(\text{UTypes})$ and  
- $(\text{is\_assignable\_v}\langle \text{const Types}&, \text{const UTypes}& \rangle \&\& \ldots)$ is true.  
**Effects**: Assigns each element of $u$ to the corresponding element of $*\text{this}$.  
**Returns**: $*\text{this}$.  
**Remarks**: The exception specification is equivalent to the logical AND of the following expressions:  
$$\text{is\_nothrow\_move\_assignable\_v}\langle T_i \rangle$$  
where $T_i$ is the $i^{th}$ type in $\text{Types}$.
(24.2) — (is_assignable_v<const Types &, UTypes> && ...) is true.

Effects: For all \( i \), assigns std::forward\:<U_i>(get\:<i>(u)) to get\:<i>(*this).

Returns: *this.

template<class U1, class U2> constexpr tuple& operator=(const pair<U1, U2>&& u);

Constraints:

(27.1) — sizeof...(Types) is 2 and
(27.2) — is_assignable_v<T_0 &, const U1 &> is true, and
(27.3) — is_assignable_v<T_1 &, const U2 &> is true.

Effects: Assigns u.first to the first element of *this and u.second to the second element of *this.

Returns: *this.

template<class U1, class U2> constexpr const tuple& operator=(const pair<U1, U2>& u) const;

Constraints:

(30.1) — sizeof...(Types) is 2,
(30.2) — is_assignable_v<const T_0 &, const U1 &> is true, and
(30.3) — is_assignable_v<const T_1 &, const U2 &> is true.

Effects: Assigns u.first to the first element and u.second to the second element.

Returns: *this.

template<class U1, class U2> constexpr tuple& operator=(pair<U1, U2>&& u);

Constraints:

(33.1) — sizeof...(Types) is 2 and
(33.2) — is_assignable_v<const T_0 &, U1> is true, and
(33.3) — is_assignable_v<const T_1 &, U2> is true.

Effects: Assigns std::forward<U_1>(u.first) to the first element of *this and std::forward<U_2>(u.second) to the second element of *this.

Returns: *this.

template<class U1, class U2> constexpr const tuple& operator=(pair<U1, U2>& u) const;

Constraints:

(36.1) — sizeof...(Types) is 2,
(36.2) — is_assignable_v<const T_0 &, U1> is true, and
(36.3) — is_assignable_v<const T_1 &, U2> is true.

Effects: Assigns std::forward<U_1>(u.first) to the first element and std::forward<U_2>(u.second) to the second element.

Returns: *this.

template<tuple-like UTuple>
constexpr tuple& operator=(UTuple&& u);

Constraints:

(39.1) — different-from<UTuple, tuple>(26.5.2) is true,
(39.2) — remove_cvref_t<UTuple> is not a specialization of ranges::subrange,
(39.3) — sizeof...(Types) equals tuple_size_v<remove_cvref_t<UTuple>>, and,
(39.4) — is_assignable_v<T_i &, decltype(get\:<i>(std::forward<UTuple>(u)))> is true for all \( i \).

Effects: For all \( i \), assigns get\:<i>(std::forward<UTuple>(u)) to get\:<i>(*this).

Returns: *this.
template<tuple-like UTuple>
constexpr const tuple& operator=(UTuple&& u) const;

Constraints:
(42.1) different-from<UTuple, tuple> (26.5.2) is true,
(42.2) remove_cvref_t<UTuple> is not a specialization of ranges::subrange,
(42.3) sizeof...(Types) equals tuple_size_v<remove_cvref_t<UTuple>>, and,
(42.4) is_assignable_v<const T, decltype(get<i>(std::forward<UTuple>(u)))) is true for all i.

Effects: For all i, assigns get<i>(std::forward<UTuple>(u)) to get<i>(*this).
Returns: *this.

22.4.4.4 swap [tuple.swap]

constexpr void swap(tuple& rhs) noexcept(see below);
constexpr void swap(const tuple& rhs) const noexcept(see below);

Let i be in the range \([0, \text{sizeof}...(\text{Types}))\) in order.

Mandates:
(2.1) For the first overload, \((\text{is_swappable_v<Types> \\ &k ...})\) is true.
(2.2) For the second overload, \((\text{is_swappable_v<const Types> \\ &k ...})\) is true.

Preconditions: For all i, get<i>(*this) is swappable with (16.4.4.3) get<i>(rhs).

Effects: For each i, calls swap for get<i>(*this) and get<i>(rhs).

Throws: Nothing unless one of the element-wise swap calls throws an exception.

Remarks: The exception specification is equivalent to
(6.1) \((\text{is_nothrow_swappable_v<Types> \\ &k ...})\) for the first overload and
(6.2) \((\text{is_nothrow_swappable_v<const Types> \\ &k ...})\) for the second overload.

22.4.5 Tuple creation functions [tuple.creation]

template<class... TTypes>
constexpr tuple<unwrap_ref_decay_t<TTypes>...> make_tuple(TTypes&&... t);

Returns: tuple<unwrap_ref_decay_t<TTypes>...>(std::forward<TTypes>(t)...).

[Example 1:
int i; float j;
make_tuple(1, ref(i), cref(j));
creates a tuple of type tuple<int, int&, const float&>. — end example]

template<class... TTypes>
constexpr tuple<TTypes&&...> forward_as_tuple(TTypes&&... t) noexcept;

Effects: Constructs a tuple of references to the arguments in t suitable for forwarding as arguments to a function. Because the result may contain references to temporary objects, a program shall ensure that the return value of this function does not outlive any of its arguments (e.g., the program should typically not store the result in a named variable).

Returns: tuple<TTypes&&...>(std::forward<TTypes>(t)...).

template<class... TTypes>
constexpr tuple<TTypes&...> tie(TTypes&... t) noexcept;

Returns: tuple<TTypes&...>(t...).

[Example 2: tie functions allow one to create tuples that unpack tuples into variables. ignore can be used for elements that are not needed:
int i; std::string s;
tie(i, ignore, s) = make_tuple(42, 3.14, "C++");
// i == 42, s == "C++"]
Let \( n \) be \( \text{sizeof} \ldots (\text{Tuples}) \). For every integer \( 0 \leq i < n \):

1. Let \( T_i \) be the \( i \)th type in \( \text{Tuples} \).
2. Let \( U_i \) be \( \text{remove\_cv\_ref\_t<T_i> } \).
3. Let \( tp_i \) be the \( i \)th element in the function parameter pack \( \text{tpls} \).
4. Let \( S_i \) be \( \text{tuple\_size\_v<U_i>} \).
5. Let \( E_i^k \) be \( \text{tuple\_element\_t<k, U_i>} \).
6. Let \( c_i^k \) be \( \text{get<k>(std::forward<T_i>(tp_i))}> \).
7. Let \( \text{Elems}_i \) be a pack of the types \( E_1^0, ..., E_i^{S_i-1} \).
8. Let \( \text{elems}_i \) be a pack of the expressions \( e_0^i, ..., e_{S_i-1}^i \).

The types in \( \text{CTypes} \) are equal to the ordered sequence of the expanded packs of types \( \text{Elems}_0, ..., \text{Elems}_1, ..., \text{Elems}_{n-1} \). Let \( \text{celems} \) be the ordered sequence of the expanded packs of expressions \( \text{elems}_0, ..., \text{elems}_{n-1} \).

**Mandates:** (\( \text{is\_constructible\_v<\text{CTypes}, decltype(\text{celems})>} \&\& \ldots \) ) is true.

**Returns:** \( \text{tuple<CTypes...>(celems...)} \).

### 22.4.6 Calling a function with a tuple of arguments

**Effects:** Given the exposition-only function template:

```cpp
namespace std {
    template<class F, tuple-like Tuple, size_t... I>
    constexpr decltype(auto) apply_impl(F&& f, Tuple&& t, index_sequence<I...>) {
        // exposition only
        return INVOKE(std::forward<F>(f), get<I>(std::forward<Tuple>(t))...); // see 22.10.4
    }
}
```

Equivalent to:

```cpp
return apply_impl(std::forward<F>(f), std::forward<Tuple>(t), make_index_sequence<tuple_size_v<remove_reference_t<Tuple>>>{});
```

**Remarks:** Let \( I \) be the pack \( 0, 1, ..., (\text{tuple\_size\_v<remove\_reference\_t<Tuple>>} - 1) \). The exception specification is equivalent to:

```cpp
noexcept(invoke(std::forward<F>(f), get<I>(std::forward<Tuple>(t))...))
```

**Mandates:** If \( \text{tuple\_size\_v<remove\_reference\_t<Tuple>>} \) is 1, then \( \text{reference\_constructs\_from\_temporary\_v<T, decltype(get<0>(declval<Tuple>()))}> \) is false.

**Effects:** Given the exposition-only function template:

```cpp
namespace std {
    template<class T, tuple-like Tuple, size_t... I>
    requires is_constructible_v<T, decltype(get<I>(declval<Tuple>()))>...
    constexpr T make-from-tuple_impl(Tuple&& t, index_sequence<I...>) { // exposition only
        return T(get<I>(std::forward<Tuple>(t))...);
    }
}
```

Equivalent to:
return make_from_tuple_impl<T>(
    std::forward<Tuple>(t),
    make_index_sequence<tuple_size_v<remove_reference_t<Tuple>>{});

[Note 1: The type of T must be supplied as an explicit template parameter, as it cannot be deduced from the argument list. — end note]

### 22.4.7 Tuple helper classes

```cpp
template<class T> struct tuple_size;
```

Except where specified otherwise, all specializations of `tuple_size` meet the `Cpp17UnaryTypeTrait` requirements (21.3.2) with a base characteristic of `integral_constant<size_t, N>` for some `N`.

```cpp
template<class... Types>
struct tuple_size<tuple<Types...>> : public integral_constant<size_t, sizeof...(Types)> { };
```

```cpp
template<size_t I, class... Types>
struct tuple_element<I, tuple<Types...>> {
    using type = TI;
};
```

**Mandates:** `I < sizeof...(Types)`.

**Type:** `TI` is the type of the `I`th element of `Types`, where indexing is zero-based.

```cpp
template<class T> struct tuple_size<const T>;
```

Let `TS` denote `tuple_size<T>` of the cv-unqualified type `T`. If the expression `TS::value` is well-formed when treated as an unevaluated operand (7.2.3), then each specialization of the template meets the `Cpp17UnaryTypeTrait` requirements (21.3.2) with a base characteristic of

```cpp
integral_constant<size_t, TS::value>
```

Otherwise, it has no member `value`.

Access checking is performed as if in a context unrelated to `TS` and `T`. Only the validity of the immediate context of the expression is considered.

[Note 1: The compilation of the expression can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the “immediate context” and can result in the program being ill-formed. — end note]

In addition to being available via inclusion of the `<tuple>` header, the template is available when any of the headers `<array>` (24.3.2), `<ranges>` (26.2), or `<utility>` (22.2.1) are included.

```cpp
template<size_t I, class T> struct tuple_element<I, const T>;
```

Let `TE` denote `tuple_element_t<I, T>` of the cv-unqualified type `T`. Then each specialization of the template meets the `Cpp17TransformationTrait` requirements (21.3.2) with a member typedef `type` that names the type `add_const_t<TE>`.

In addition to being available via inclusion of the `<tuple>` header, the template is available when any of the headers `<array>` (24.3.2), `<ranges>` (26.2), or `<utility>` (22.2.1) are included.

### 22.4.8 Element access

```cpp
template<size_t I, class... Types>
constexpr tuple_element_t<I, tuple<Types...>>&
    get(tuple<Types...>&& t) noexcept;
```

```cpp
template<size_t I, class... Types>
constexpr tuple_element_t<I, tuple<Types...>>&
    get(tuple<Types...>& t) noexcept;
```

```cpp
template<size_t I, class... Types>
constexpr const tuple_element_t<I, tuple<Types...>>&
    get(const tuple<Types...>& t) noexcept;
```

```cpp
template<size_t I, class... Types>
constexpr const tuple_element_t<I, tuple<Types...>>&
    get(const tuple<Types...>&& t) noexcept;
```

**Mandates:** `I < sizeof...(Types)`.
Returns: A reference to the \(i\)th element of \(t\), where indexing is zero-based.

[Note 1: For the overload marked \#1, if a type \(T\) in \(Types\) is some reference type \(X\&\), the return type is \(X\&\), not \(X&&\). However, if the element type is a non-reference type \(T\), the return type is \(T&&\). — end note]

[Note 2: Constness is shallow. For the overload marked \#2, if a type \(T\) in \(Types\) is some reference type \(X\&\), the return type is \(X\&\), not \(\text{const } X\&\). However, if the element type is a non-reference type \(T\), the return type is \(\text{const } T\&\). This is consistent with how constness is defined to work for non-static data members of reference type. — end note]

```
template<class T, class... Types>
constexpr T& get(tuple<Types...>& t) noexcept;
template<class T, class... Types>
constexpr T&& get(tuple<Types...>&& t) noexcept;
template<class T, class... Types>
constexpr const T& get(const tuple<Types...>& t) noexcept;
template<class T, class... Types>
constexpr const T&& get(const tuple<Types...>&& t) noexcept;
```

Mandates: The type \(T\) occurs exactly once in \(Types\).

Returns: A reference to the element of \(t\) corresponding to the type \(T\) in \(Types\).

[Example 1:

```cpp
const tuple<int, const int, double, double> t(1, 2, 3.4, 5.6);
cost int i1 = get<int>(t); // OK, i1 has value 1
cost int i2 = get<const int>(t); // OK, i2 has value 2
cost double d = get<double>(t); // error: type double is not unique within t
```
— end example]

[Note 3: The reason \(\text{get}\) is a non-member function is that if this functionality had been provided as a member function, code where the type depended on a template parameter would have required using the \texttt{template} keyword. — end note]

### 22.4.9 Relational operators

[\section{tuple.rel}]

```
template<class..., TTypes, class..., UTypes>
constexpr bool operator==(const tuple<TTypes...>& t, const tuple<UTypes...>& u);
template<class..., TTypes, tuple-like UTuple>
constexpr bool operator==(const tuple<TTypes...>& t, const UTuple& u);
```

For the first overload let UTuple be \(\text{tuple<UTypes...>...}\).

Constraints: For all \(i\), where \(0 \leq i < \text{sizeof...}(TTypes)\), \(\text{get<i>(t)} == \text{get<i>(u)}\) is a valid expression and \(\text{decltype(get<i>(t)} == \text{get<i>(u)}\) models \texttt{boolean-testable} \texttt{.sizeof...}(TTypes) equals \text{tuple_size_v<UTuple>}\).

Returns: \(\text{true}\) if \(\text{get<i>(t)} == \text{get<i>(u)}\) for all \(i\), otherwise \(\text{false}\).

[Note 1: If \(\text{sizeof...}(TTypes)\) equals \(0\), returns \(\text{true}\). — end note]

Remarks:

(4.1) — The elementary comparisons are performed in order from the zeroth index upwards. No comparisons or element accesses are performed after the first equality comparison that evaluates to \(\text{false}\).

(4.2) — The second overload is to be found via argument-dependent lookup (6.5.4) only.

```
template<class..., TTypes, class..., UTypes>
constexpr common_comparison_category_t<
\text{synth-three-way-result}<\text{TTypes, UTypes}...>
operator<\text{const tuple<TTypes...>&& t, const tuple<UTuple...>& u}>
```
return t_tail <=> u_tail;

where r_tail for some r is a tuple containing all but the first element of r.

Remarks: The second overload is to be found via argument-dependent lookup (6.5.4) only.

[Note 2: The above definition does not require t_tail (or u_tail) to be constructed. It might not even be possible, as t and u are not required to be copy constructible. Also, all comparison operator functions are short circuited; they do not perform element accesses beyond what is needed to determine the result of the comparison. — end note]

22.4.10 common_reference related specializations

In the descriptions that follow:

(1.1) — Let TTypes be a pack formed by the sequence of tuple_element_t<i, TTuple> for every integer 0 ≤ i < tuple_size_v<TTuple>.

(1.2) — Let UTypes be a pack formed by the sequence of tuple_element_t<i, UTuple> for every integer 0 ≤ i < tuple_size_v<UTuple>.

template<tuple-like TTuple, tuple-like UTuple,
         template<class> class TQual, template<class> class UQual>
struct basic_common_reference<TTuple, UTuple, TQual, UQual> {
    using type = see below;
};

Constraints:

(2.1) — TTuple is a specialization of tuple or UTuple is a specialization of tuple.

(2.2) — is_same_v<TTuple, decay_t<TTuple>> is true.

(2.3) — is_same_v<UTuple, decay_t<UTuple>> is true.

(2.4) — tuple_size_v<TTuple> equals tuple_size_v<UTuple>.

(2.5) — tuple<common_reference_t<TQual<TTypes>, UQual<UTypes>>...> denotes a type.

The member typedef-name type denotes the type tuple<common_reference_t<TQual<TTypes>, UQual<UTypes>>...>.

template<tuple-like TTuple, tuple-like UTuple>
struct common_type<TTuple, UTuple> {
    using type = see below;
};

Constraints:

(3.1) — TTuple is a specialization of tuple or UTuple is a specialization of tuple.

(3.2) — is_same_v<TTuple, decay_t<TTuple>> is true.

(3.3) — is_same_v<UTuple, decay_t<UTuple>> is true.

(3.4) — tuple_size_v<TTuple> equals tuple_size_v<UTuple>.

(3.5) — tuple<common_type_t<TTypes, UTypes>>...> denotes a type.

The member typedef-name type denotes the type tuple<common_type_t<TTypes, UTypes>>...>.

22.4.11 Tuple traits


template<class... Types, class Alloc>
struct uses_allocator<tuple<Types...>, Alloc> : true_type { };
template<class... Types>
constexpr void swap(const tuple<Types...>& x, const tuple<Types...>& y) noexcept(see below);

1
Constraints:
(1.1) For the first overload, (is_swappableView<Types> & ... is true.
(1.2) For the second overload, (is_swappableView<const Types> & ... is true.

2
Effects: As if by x.swap(y).

3
Remarks: The exception specification is equivalent to:
noexcept(x.swap(y))

22.5 Optional objects

22.5.1 General

Subclause 22.5 describes class template optional that represents optional objects. An optional object is an object that contains the storage for another object and manages the lifetime of this contained object, if any. The contained object may be initialized after the optional object has been initialized, and may be destroyed before the optional object has been destroyed. The initialization state of the contained object is tracked by the optional object.

22.5.2 Header <optional> synopsis

namespace std {
// mostly freestanding
#include <compare>
// see 17.11.1

// 22.5.3, class template optional
template<class T>
class optional;  // partially freestanding

template<class T>
constexpr bool ranges::enable_view<optional<T>> = true;
template<class T>
constexpr auto format_kind<optional<T>> = range_format::disabled;

template<class T>
concept is-derived-from-optional = requires(const T& t) {
// exposition only
[](class U>(const optional<U>&){ }());
};

// 22.5.4, no-value state indicator
struct nullopt_t{ see below};
inline constexpr nullopt_t nullopt(unspecified);

// 22.5.5, class bad_optional_access
class bad_optional_access;

// 22.5.6, relational operators
template<class T, class U>
constexpr bool operator==(optional<T>&, optional<U>&);
template<class T, class U>
constexpr bool operator!=(optional<T>&, optional<U>&);
template<class T, class U>
constexpr bool operator<(optional<T>&, optional<U>&);
template<class T, class U>
constexpr bool operator>(optional<T>&, optional<U>&);
template<class T, class U>
constexpr bool operator<=(optional<T>&, optional<U>&);
template<class T, class U>
constexpr bool operator>=(optional<T>&, optional<U>&);
template<class T, three_way_comparable_with<T> U>
constexpr compare_three_way_result_t<T, U>
operator<=>(optional<T>&, optional<U>&);
// 22.5.7, comparison with nullopt
template<class T> constexpr bool operator==(const optional<T>&, nullopt_t) noexcept;

template<class T> constexpr strong_ordering operator<=>(const optional<T>&, nullopt_t) noexcept;

// 22.5.8, comparison with T
template<class T, class U> constexpr bool operator==(const optional<T>&, const U&);

// 22.5.9, specialized algorithms
template<class T> constexpr void swap(optional<T>&, optional<T>&) noexcept(see below);

// 22.5.10, hash support
template<class T> struct hash;

22.5.3 Class template optional

22.5.3.1 General

namespace std {
    template<class T>
    class optional {
    public:
        using value_type = T;
        using iterator = implementation-defined; // see 22.5.3.6
        using const_iterator = implementation-defined; // see 22.5.3.6

    // 22.5.3.2, constructors
    constexpr optional() noexcept;
    constexpr optional(nullopt_t) noexcept;
    constexpr optional(const optional&) noexcept;
    template<class... Args>
    constexpr explicit optional(in_place_t, Args&&...);
    template<class U, class... Args>
    constexpr explicit optional(in_place_t, initializer_list<U>, Args&&...);
    template<class U = T>
    constexpr explicit(optional<U&&>);
    template<class U>
    constexpr explicit(optional<see below> optional(U&&));

} // namespace std
template<class U>
  constexpr explicit(see below) optional(optional<U>&&);

// 22.5.3.3, destructor
constexpr ~optional();

// 22.5.3.4, assignment
constexpr optional& operator=(nullopt_t) noexcept;
constexpr optional& operator=(const optional&);
constexpr optional& operator=(optional&&) noexcept(see below);
template<class U = T> constexpr optional& operator=(U&&);
template<class U> constexpr optional& operator=(const optional<U>&);
template<class U> constexpr optional& operator=(optional<U>&&);
template<class... Args> constexpr T& emplace(Args&&...);
template<class U, class... Args> constexpr T& emplace(initializer_list<U>, Args&&...);

  // 22.5.3.5, swap
constexpr void swap(optional&) noexcept(see below);

  // 22.5.3.6, iterator support
constexpr iterator begin() noexcept;
constexpr const_iterator begin() const noexcept;
constexpr iterator end() noexcept;
constexpr const_iterator end() const noexcept;

// 22.5.3.7, observers
constexpr const T* operator->() const noexcept;  // freestanding-deleted
constexpr T* operator->() noexcept;  // freestanding-deleted
constexpr const T& operator*() const & noexcept;  // freestanding-deleted
constexpr T& operator*() & noexcept;  // freestanding-deleted
constexpr T&& operator*() && noexcept;  // freestanding-deleted
constexpr explicit operator bool() const noexcept;
constexpr bool has_value() const noexcept;
constexpr const T& value() const &;
// freestanding-deleted
constexpr T& value() &;
// freestanding-deleted
constexpr T&& value() &&;
// freestanding-deleted
template<class U> constexpr T value_or(U&&) const &;
template<class U> constexpr T value_or(U&&) &&;

// 22.5.3.8, monadic operations
template<class F> constexpr auto and_then(F&& f) &;
template<class F> constexpr auto and_then(F&& f) &&;
template<class F> constexpr auto and_then(F&& f) const &;
template<class F> constexpr auto and_then(F&& f) const &&;
template<class F> constexpr auto transform(F&& f) &;
template<class F> constexpr auto transform(F&& f) &&;
template<class F> constexpr auto transform(F&& f) const &;
template<class F> constexpr auto transform(F&& f) const &&;
template<class F> constexpr optional or_else(F&& f) &;
template<class F> constexpr optional or_else(F&& f) &&;
template<class F> constexpr optional or_else(F&& f) const &;
template<class F> constexpr optional or_else(F&& f) const &&;

// 22.5.3.9, modifiers
constexpr void reset() noexcept;

private:
  T *val;  // exposition only
};

  template<class T>
  optional(T) -> optional<T>;
}
Any instance of \texttt{optional\textless{}T\textgreater{}} at any given time either contains a value or does not contain a value. When an instance of \texttt{optional\textless{}T\textgreater{}} contains a value, it means that an object of type \texttt{T}, referred to as the optional object’s contained value, is allocated within the storage of the optional object. Implementations are not permitted to use additional storage, such as dynamic memory, to allocate its contained value. When an object of type \texttt{optional\textless{}T\textgreater{}} is contextually converted to \texttt{bool}, the conversion returns \texttt{true} if the object contains a value; otherwise the conversion returns \texttt{false}.

When an \texttt{optional\textless{}T\textgreater{}} object contains a value, member \texttt{val} points to the contained value.

\texttt{T} shall be a type other than \texttt{cv\ in\ place\_t} or \texttt{cv\ nullopt\_t} that meets the \texttt{Cpp17Destructible} requirements (Table 35).

### 22.5.3.2 Constructors

The exposition-only variable template \texttt{converts-from-any-cvref} is used by some constructors for \texttt{optional}.

\begin{verbatim}
template<class T, class W>
constexpr bool converts-from-any-cvref = // exposition only
    disjunction_v<is_constructible<T, W&>, is_convertible<W&, T>,
             is_constructible<T, W>, is_convertible<W, T>,
             is_constructible<T, const W&>, is_convertible<const W&, T>,
             is_constructible<T, const W>, is_convertible<const W, T>>;

constexpr optional() noexcept;
constexpr optional(nullopt_t) noexcept;

Postconditions: *this does not contain a value.
Remarks: No contained value is initialized. For every object type \texttt{T} these constructors are constexpr constructors (9.2.6).

constexpr optional(const optional& rhs);
Effects: If \texttt{rhs} contains a value, direct-non-list-initializes the contained value with \texttt{*rhs}.
Postconditions: \texttt{rhs.has_value()} == \texttt{this->has_value()}.
Throws: Any exception thrown by the selected constructor of \texttt{T}.
Remarks: This constructor is defined as deleted unless \texttt{is\_copy\_constructible\_v\textless{}T\textgreater{}} is \texttt{true}. If \texttt{is\_trivially\_copy\_constructible\_v\textless{}T\textgreater{}} is \texttt{true}, this constructor is trivial.

constexpr optional(optional&& rhs) noexcept(see below);
Constraints: \texttt{is\_move\_constructible\_v\textless{}T\textgreater{}} is \texttt{true}.
Effects: If \texttt{rhs} contains a value, direct-non-list-initializes the contained value with \texttt{std::move(*rhs)}.
\texttt{rhs.has_value()} is unchanged.
Postconditions: \texttt{rhs.has_value()} == \texttt{this->has_value()}.
Throws: Any exception thrown by the selected constructor of \texttt{T}.
Remarks: The exception specification is equivalent to \texttt{is\_nothrow\_move\_constructible\_v\textless{}T\textgreater{}}. If \texttt{is\_trivially\_move\_constructible\_v\textless{}T\textgreater{}} is \texttt{true}, this constructor is trivial.

template<class... Args> constexpr explicit optional(in_place_t, Args&&... args);
Constraints: \texttt{is\_constructible\_v\textless{}T\textgreater{}} is \texttt{true}.
Effects: Direct-non-list-initializes the contained value with \texttt{std::forward<Args>(args)}... .
Postconditions: *this contains a value.
Throws: Any exception thrown by the selected constructor of \texttt{T}.
Remarks: If \texttt{T}’s constructor selected for the initialization is a constexpr constructor, this constructor is a constexpr constructor.

template<class U, class... Args>
constexpr explicit optional(in_place_t, initializer_list<U> il, Args&&... args);
Constraints: \texttt{is\_constructible\_v\textless{}T\textgreater{}, initializer_list<U>&, Args...} is \texttt{true}.
Effects: Direct-non-list-initializes the contained value with \texttt{il, std::forward<Args>(args)}... .
\end{verbatim}


Postconditions: *this contains a value.

Throws: Any exception thrown by the selected constructor of T.

Remarks: If T's constructor selected for the initialization is a constexpr constructor, this constructor is a constexpr constructor.

```cpp
template<class U = T> constexpr explicit(see below) optional(U&& v);
```

Constraints:

- **(23.1)** is_constructible_v<T, U> is true,
- **(23.2)** is_same_v<remove_cvref_t<U>, in_place_t> is false,
- **(23.3)** is_same_v<remove_cvref_t<U>, optional> is false, and
- **(23.4)** if T is cv bool, remove_cvref_t<U> is not a specialization of optional.

Effects: Direct-non-list-initializes the contained value with std::forward<U>(v).

Postconditions: *this contains a value.

Remarks: If T's selected constructor is a constexpr constructor, this constructor is a constexpr constructor.

```cpp
template<class U> constexpr explicit(see below) optional(const optional<U>& rhs);
```

Constraints:

- **(28.1)** is_constructible_v<T, const U&> is true, and
- **(28.2)** if T is not cv bool, converts-from-any-cvref<T, optional<U>> is false.

Effects: If rhs contains a value, direct-non-list-initializes the contained value with *rhs.

Postconditions: rhs.has_value() == this->has_value().

Remarks: The expression inside explicit is equivalent to:

```cpp
!is_convertible_v<U, T>
```

```cpp
template<class U> constexpr explicit(see below) optional(optional<U>&& rhs);
```

Constraints:

- **(33.1)** is_constructible_v<T, U> is true, and
- **(33.2)** if T is not cv bool, converts-from-any-cvref<T, optional<U>> is false.

Effects: If rhs contains a value, direct-non-list-initializes the contained value with std::move(*rhs). rhs.has_value() is unchanged.

Postconditions: rhs.has_value() == this->has_value().

Remarks: The expression inside explicit is equivalent to:

```cpp
!is_convertible_v<U, T>
```

### 22.5.3.3 Destructor [optional.dtor]

```cpp
constexpr ~optional();
```

Effects: If is_trivially_destructible_v<T> != true and *this contains a value, calls val->T::~T().

Remarks: If is_trivially_destructible_v<T> is true, then this destructor is trivial.

### 22.5.3.4 Assignment [optional.assign]

§ 22.5.4 ©ISO/IEC 730
constexpr optional<T>& operator=(nullopt_t) noexcept;  

Effects: If *this contains a value, calls val->T::~T() to destroy the contained value; otherwise no effect.

Postconditions: *this does not contain a value.

Returns: *this.

constexpr optional<T>& operator=(const optional& rhs);  

Effects: See Table 62.

Table 62 — optional::operator=(const optional&) effects  

<table>
<thead>
<tr>
<th>*this contains a value</th>
<th>*this does not contain a value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rhs contains a value</td>
<td>assigns *rhs to the contained value</td>
</tr>
<tr>
<td>rhs does not contain a value</td>
<td>destroys the contained value by calling val-&gt;T::~T()</td>
</tr>
</tbody>
</table>

Postconditions: rhs.has_value() == this->has_value().

Returns: *this.

Remarks: If any exception is thrown, the result of the expression this->has_value() remains unchanged.  
If an exception is thrown during the call to T’s copy constructor, no effect. If an exception is thrown during the call to T’s copy assignment, the state of its contained value is as defined by the exception safety guarantee of T’s copy assignment. This operator is defined as deleted unless is_copy_constructible_v<T> is true and is_copy_assignable_v<T> is true. If is_trivially_copy_constructible_v<T> && is_trivially_copy_assignable_v<T> && is_trivially_destructible_v<T> is true, this assignment operator is trivial.

constexpr optional& operator=(optional&& rhs) noexcept(see below);  

Constraints: is_move_constructible_v<T> is true and is_move_assignable_v<T> is true.

Effects: See Table 63. The result of the expression rhs.has_value() remains unchanged.

Table 63 — optional::operator=(optional&&) effects  

<table>
<thead>
<tr>
<th>*this contains a value</th>
<th>*this does not contain a value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rhs contains a value</td>
<td>assigns std::move(*rhs) to the contained value</td>
</tr>
<tr>
<td>rhs does not contain a value</td>
<td>destroys the contained value by calling val-&gt;T::~T()</td>
</tr>
</tbody>
</table>

Postconditions: rhs.has_value() == this->has_value().

Returns: *this.

Remarks: The exception specification is equivalent to:

is_nothrow_move_assignable_v<T> && is_nothrow_move_constructible_v<T>

If any exception is thrown, the result of the expression this->has_value() remains unchanged. If an exception is thrown during the call to T’s move constructor, the state of *rhs.val is determined by the exception safety guarantee of T’s move constructor. If an exception is thrown during the call to T’s move assignment, the state of *val and *rhs.val is determined by the exception safety guarantee of T’s move assignment. If is_trivially_move_constructible_v<T> && is_trivially_move_assignable_v<T> && is_trivially_destructible_v<T> is true, this assignment operator is trivial.
template<class U = T> constexpr optional<T>& operator=(U&& v);

**Constraints:**
is_same_v<remove_cvref_t<U>, optional> is false, conjunction_v<is_scalar<T>,
is_same<T, decay_t<U>>&> is false, is_constructible_v<T, U> is true, and is_assignable_v<T&, U> is true.

**Effects:** If *this contains a value, assigns std::forward<U>(v) to the contained value; otherwise direct-non-list-initializes the contained value with std::forward<U>(v).

**Postconditions:** *this contains a value.

**Returns:** *this.

**Remarks:** If any exception is thrown, the result of the expression this->has_value() remains unchanged. If an exception is thrown during the call to T’s constructor, the state of v is determined by the exception safety guarantee of T’s constructor. If an exception is thrown during the call to T’s assignment, the state of *val and v is determined by the exception safety guarantee of T’s assignment.

template<class U> constexpr optional<T>& operator=(const optional<U>& rhs);

**Constraints:**
- (19.1) is_constructible_v<T, const U&> is true,
- (19.2) is_assignable_v<T&, const U&> is true,
- (19.3) converts-from-any-cvref<T, optional<U>> is false,
- (19.4) is_assignable_v<T&, optional<U>&> is false,
- (19.5) is_assignable_v<T&, optional<U>&&> is false,
- (19.6) is_assignable_v<T&, const optional<U>&> is false, and
- (19.7) is_assignable_v<T&, const optional<U>&&> is false.

**Effects:** See Table 64.

<table>
<thead>
<tr>
<th>Table 64 — optional::operator=(const optional&lt;U&gt;&amp;) effects [tab:optional.assign.copy.templ]</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>rhs contains a value</code></td>
</tr>
<tr>
<td>assigns *rhs to the contained value</td>
</tr>
<tr>
<td><code>rhs does not contain a value</code></td>
</tr>
</tbody>
</table>

**Postconditions:** rhs.has_value() == this->has_value().

**Returns:** *this.

**Remarks:** If any exception is thrown, the result of the expression this->has_value() remains unchanged. If an exception is thrown during the call to T’s constructor, the state of *rhs.val is determined by the exception safety guarantee of T’s constructor. If an exception is thrown during the call to T’s assignment, the state of *val and *rhs.val is determined by the exception safety guarantee of T’s assignment.

template<class U> constexpr optional<T>& operator=(optional<U>&& rhs);

**Constraints:**
- (24.1) is_constructible_v<T, U> is true,
- (24.2) is_assignable_v<T&, U> is true,
- (24.3) converts-from-any-cvref<T, optional<U>> is false,
- (24.4) is_assignable_v<T&, optional<U>&> is false,
- (24.5) is_assignable_v<T&, optional<U>&&> is false,
- (24.6) is_assignable_v<T&, const optional<U>&> is false, and
- (24.7) is_assignable_v<T&, const optional<U>&&> is false.

§ 22.5.3.4 ISO/IEC 732
**Effects:** See Table 65. The result of the expression `rhs.has_value()` remains unchanged.

<table>
<thead>
<tr>
<th>*this contains a value</th>
<th>*this does not contain a value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>rhs contains a value</strong></td>
<td>assigns std::move(*rhs) to the contained value</td>
</tr>
<tr>
<td></td>
<td>direct-non-list-initializes the contained value with std::move(*rhs)</td>
</tr>
<tr>
<td><strong>rhs does not contain a value</strong></td>
<td>destroys the contained value by calling val-&gt;T::T()</td>
</tr>
<tr>
<td></td>
<td>no effect</td>
</tr>
</tbody>
</table>

**Postconditions:** `rhs.has_value() == this->has_value()`.

**Returns:** *this.

**Remarks:** If any exception is thrown, the result of the expression `this->has_value()` remains unchanged. If an exception is thrown during the call to T’s constructor, the state of *rhs.val is determined by the exception safety guarantee of T’s constructor. If an exception is thrown during the call to T’s assignment, the state of *val and *rhs.val is determined by the exception safety guarantee of T’s assignment.

```cpp
template<class... Args> constexpr T& emplace(Args&&... args);
```

**Mandates:** `is_constructible_v<T, Args...>` is true.

**Effects:** Calls *this = nullopt. Then direct-non-list-initializes the contained value with std::forward<Args>(args)....

**Postconditions:** *this contains a value.

**Returns:** A reference to the new contained value.

**Throws:** Any exception thrown by the selected constructor of T.

**Remarks:** If an exception is thrown during the call to T’s constructor, *this does not contain a value, and the previous *val (if any) has been destroyed.

```cpp
template<class U, class... Args> constexpr T& emplace(initializer_list<U> il, Args&&... args);
```

**Constraints:** `is_constructible_v<T, initializer_list<U>&, Args...>` is true.

**Effects:** Calls *this = nullopt. Then direct-non-list-initializes the contained value with il, std::forward<Args>(args)....

**Postconditions:** *this contains a value.

**Returns:** A reference to the new contained value.

**Throws:** Any exception thrown by the selected constructor of T.

**Remarks:** If an exception is thrown during the call to T’s constructor, *this does not contain a value, and the previous *val (if any) has been destroyed.

### 22.5.3.5 Swap

```cpp
constexpr void swap(optional& rhs) noexcept;
```

**Mandates:** `is_move_constructible_v<T>` is true.

**Preconditions:** T meets the Cpp17Swappable requirements (16.4.4.3).

**Effects:** See Table 66.

**Throws:** Any exceptions thrown by the operations in the relevant part of Table 66.

**Remarks:** The exception specification is equivalent to:

```
  is_nothrow_move_constructible_v<T> && is_nothrow_swappable_v<T>
```

If any exception is thrown, the results of the expressions `this->has_value()` and `rhs.has_value()` remain unchanged. If an exception is thrown during the call to function swap, the state of *val and
Table 66 — optional::swap(optional&) effects

<table>
<thead>
<tr>
<th>*this contains a value</th>
<th>*this does not contain a value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rhs contains a value</td>
<td>calls swap(*(*this), *rhs)</td>
</tr>
<tr>
<td></td>
<td>direct-non-list-initializes the contained value of *this with std::move(*rhs), followed by rhs.val-&gt;T::~T(); postcondition is that *this contains a value and rhs does not contain a value</td>
</tr>
<tr>
<td>rhs does not contain a value</td>
<td>direct-non-list-initializes the contained value of rhs with std::move(*(*this)), followed by val-&gt;T::~T(); postcondition is that *this does not contain a value and rhs contains a value</td>
</tr>
<tr>
<td></td>
<td>no effect</td>
</tr>
</tbody>
</table>

*rhs.val* is determined by the exception safety guarantee of swap for lvalues of *T*. If an exception is thrown during the call to T’s move constructor, the state of *val* and *rhs.val* is determined by the exception safety guarantee of T’s move constructor.

### 22.5.3.6 Iterator support

```cpp
using iterator = implementation-defined;
using const_iterator = implementation-defined;
```

1. These types model contiguous_iterator (25.3.4.14), meet the Cpp17RandomAccessIterator requirements (25.3.5.7), and meet the requirements for constexpr iterators (25.3.1), with value type remove_cv_t<T>. The reference type is T& for iterator and const T& for const_iterator.

2. All requirements on container iterators (24.2.2.2) apply to optional::iterator and optional::const_iterator as well.

3. Any operation that initializes or destroys the contained value of an optional object invalidates all iterators into that object.

```cpp
constexpr iterator begin() noexcept;
constexpr const_iterator begin() const noexcept;
```

4. Returns: If has_value() is true, an iterator referring to the contained value. Otherwise, a past-the-end iterator value.

```cpp
constexpr iterator end() noexcept;
constexpr const_iterator end() const noexcept;
```

5. Returns: begin() + has_value().

### 22.5.3.7 Observers

```cpp
constexpr const T* operator->() const noexcept;
constexpr T* operator->() noexcept;
```

1. Preconditions: *this contains a value.

2. Returns: val.

3. Remarks: These functions are constexpr functions.

```cpp
constexpr const T& operator*() const & noexcept;
constexpr T& operator*() & noexcept;
```

4. Preconditions: *this contains a value.

5. Returns: *val.
Remarks: These functions are constexpr functions.

```cpp
constexpr T&& operator*() && noexcept;
constexpr const T&& operator*() const && noexcept;
```

Preconditions: *this contains a value.

Effects: Equivalent to: return std::move(*val);

Returns: true if and only if *this contains a value.

Remarks: This function is a constexpr function.

```cpp
constexpr bool has_value() const noexcept;
```

Returns: true if and only if *this contains a value.

Remarks: This function is a constexpr function.

```cpp
constexpr const T& value() const &;
constexpr T& value() &;
```

Effects: Equivalent to:
```cpp
return has_value() ? *val : throw bad_optional_access();
```

```cpp
constexpr T&& value() &&;
constexpr const T&& value() const &&;
```

Effects: Equivalent to:
```cpp
return has_value() ? std::move(*val) : throw bad_optional_access();
```

22.5.3.8 Monadic operations

```cpp
template<class F> constexpr auto and_then(F&& f) &;
template<class F> constexpr auto and_then(F&& f) const &;
```

Let U be invoke_result_t<F, decltype(*val)>

Mandates: remove_cvref_t<U> is a specialization of optional.

Effects: Equivalent to:
```cpp
if (*this) {
    return invoke(std::forward<F>(f), *val);
} else {
    return remove_cvref_t<U>();
}
```

```cpp
template<class F> constexpr auto and_then(F&& f) &&;
template<class F> constexpr auto and_then(F&& f) const &&;
```

Let U be invoke_result_t<F, decltype(std::move(*val))>

Mandates: remove_cvref_t<U> is a specialization of optional.

Effects: Equivalent to:
if (*this) {
    return invoke(std::forward<F>(f), std::move(*val));
} else {
    return remove_cvref_t<U>();
}

template<class F> constexpr auto transform(F&& f) &;  
template<class F> constexpr auto transform(F&& f) const &;

Let U be remove_cv_t<invoke_result_t<F, decltype(*val)>>.

Mandates: U is a non-array object type other than in_place_t or nullopt_t. The declaration
    U u(invoke(std::forward<F>(f), *val));
is well-formed for some invented variable u.

[Note 1: There is no requirement that U is movable (9.4.1). — end note]

Returns: If *this contains a value, an optional<U> object whose contained value is direct-non-list-
initialized with invoke(std::forward<F>(f), *val); otherwise, optional<U>().

 template<class F> constexpr auto transform(F&& f) &&;  
 template<class F> constexpr auto transform(F&& f) const &&;

Let U be remove_cv_t<invoke_result_t<F, decltype(std::move(*val))>>.

Mandates: U is a non-array object type other than in_place_t or nullopt_t. The declaration
    U u(invoke(std::forward<F>(f), std::move(*val)));
is well-formed for some invented variable u.

[Note 2: There is no requirement that U is movable (9.4.1). — end note]

Returns: If *this contains a value, an optional<U> object whose contained value is direct-non-list-
initialized with invoke(std::forward<F>(f), std::move(*val)); otherwise, optional<U>().

 template<class F> constexpr optional or_else(F&& f) const &;  
 template<class F> constexpr optional or_else(F&& f) &&;

Constraints: F models invocable<> and T models copy_constructible.

Mandates: is_same_v<remove_cvref_t<invoke_result_t<F>>, optional> is true.

Effects: Equivalent to:
    if (*this) {
        return *this;
    } else {
        return std::forward<F>(f());
    }

 template<class F> constexpr optional or_else(F&& f) &&;

Constraints: F models invocable<> and T models move_constructible.

Mandates: is_same_v<remove_cvref_t<invoke_result_t<F>>, optional> is true.

Effects: Equivalent to:
    if (*this) {
        return std::move(*this);
    } else {
        return std::forward<F>(f());
    }

22.5.3.9 Modifiers [optional.mod]

constexpr void reset() noexcept;

Effects: If *this contains a value, calls val->T::~T() to destroy the contained value; otherwise no
effect.

Postconditions: *this does not contain a value.

22.5.4 No-value state indicator [optional.nullopt]
struct nullopt_t{see below};
inline constexpr nullopt_t nullopt(unspecified);

1 The struct nullopt_t is an empty class type used as a unique type to indicate the state of not containing a value for optional objects. In particular, optional<T> has a constructor with nullopt_t as a single argument; this indicates that an optional object not containing a value shall be constructed.

2 Type nullopt_t shall not have a default constructor or an initializer-list constructor, and shall not be an aggregate.

22.5.5 Class bad_optional_access [optional.bad.access]

namespace std {
    class bad_optional_access : public exception {
public:
        // see 17.9.3 for the specification of the special member functions
        const char* what() const noexcept override;
    };
}

1 The class bad_optional_access defines the type of objects thrown as exceptions to report the situation where an attempt is made to access the value of an optional object that does not contain a value.

const char* what() const noexcept override;

2 Returns: An implementation-defined ntbs.

22.5.6 Relational operators [optional.relops]

template<class T, class U> constexpr bool operator==(const optional<T>& x, const optional<U>& y);

1 Constraints: The expression *x == *y is well-formed and its result is convertible to bool.
[Note 1: T need not be Cpp17EqualityComparable. — end note]

2 Returns: If x.has_value() != y.has_value(), false; otherwise if x.has_value() == false, true; otherwise *x == *y.

3 Remarks: Specializations of this function template for which *x == *y is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator!=(const optional<T>& x, const optional<U>& y);

4 Constraints: The expression *x != *y is well-formed and its result is convertible to bool.

5 Returns: If x.has_value() != y.has_value(), true; otherwise, if x.has_value() == false, false; otherwise *x != *y.

6 Remarks: Specializations of this function template for which *x != *y is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator<(const optional<T>& x, const optional<U>& y);

7 Constraints: *x < *y is well-formed and its result is convertible to bool.

8 Returns: If !y, false; otherwise, if !x, true; otherwise *x < *y.

9 Remarks: Specializations of this function template for which *x < *y is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator>(const optional<T>& x, const optional<U>& y);

10 Constraints: The expression *x > *y is well-formed and its result is convertible to bool.

11 Returns: If !x, false; otherwise, if !y, true; otherwise *x > *y.

12 Remarks: Specializations of this function template for which *x > *y is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator<=(const optional<T>& x, const optional<U>& y);

13 Constraints: The expression *x <= *y is well-formed and its result is convertible to bool.

14 Returns: If !x, true; otherwise, if !y, false; otherwise *x <= *y.
Remarks: Specializations of this function template for which *x <= *y is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator>=(const optional<T>& x, const optional<U>& y);

Constraints: The expression *x >= *y is well-formed and its result is convertible to bool.

Returns: If !y, true; otherwise, if !x, false; otherwise *x >= *y.

Remarks: Specializations of this function template for which *x >= *y is a core constant expression are constexpr functions.

template<class T, three_way_comparable_with<T> U>
constexpr compare_three_way_result_t<T, U> operator<=>(const optional<T>& x, const optional<U>& y);

Returns: If x && y, *x <=> *y; otherwise x.has_value() <=> y.has_value().

Remarks: Specializations of this function template for which *x <=> *y is a core constant expression are constexpr functions.

22.5.7 Comparison with nullopt

[optional.nullops]

template<class T> constexpr bool operator==(const optional<T>& x, nullopt_t) noexcept;

Returns: !x.

template<class T> constexpr strong_ordering operator<=>(const optional<T>& x, nullopt_t) noexcept;

Returns: x.has_value() <=> false.

22.5.8 Comparison with T

[optional.comp.with.t]

template<class T, class U> constexpr bool operator==(const optional<T>& x, const U& v);

Constraints: The expression *x == v is well-formed and its result is convertible to bool.

[Note 1: T need not be Cpp17EqualityComparable. — end note]

Effects: Equivalent to: return x.has_value() ? *x == v : false;

template<class T, class U> constexpr bool operator==(const T& v, const optional<U>& x);

Constraints: The expression v == *x is well-formed and its result is convertible to bool.

Effects: Equivalent to: return x.has_value() ? v == *x : false;

template<class T, class U> constexpr bool operator!=(const optional<T>& x, const U& v);

Constraints: The expression *x != v is well-formed and its result is convertible to bool.

Effects: Equivalent to: return x.has_value() ? *x != v : true;

template<class T, class U> constexpr bool operator!=(const T& v, const optional<U>& x);

Constraints: The expression v != *x is well-formed and its result is convertible to bool.

Effects: Equivalent to: return x.has_value() ? v != *x : true;

template<class T, class U> constexpr bool operator<(const optional<T>& x, const U& v);

Constraints: The expression *x < v is well-formed and its result is convertible to bool.

Effects: Equivalent to: return x.has_value() ? *x < v : true;

template<class T, class U> constexpr bool operator<(const T& v, const optional<U>& x);

Constraints: The expression v < *x is well-formed and its result is convertible to bool.

Effects: Equivalent to: return x.has_value() ? v < *x : false;

template<class T, class U> constexpr bool operator>(const optional<T>& x, const U& v);

Constraints: The expression *x > v is well-formed and its result is convertible to bool.

Effects: Equivalent to: return x.has_value() ? *x > v : false;
template<class T, class U> constexpr bool operator>(const T& v, const optional<U>& x);

Constraints: The expression \( v > *x \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( return \ x.\text{has\_value}() \ ? \ v > *x : true; \)

template<class T, class U> constexpr bool operator<=(const optional<T>& x, const U& v);

Constraints: The expression \( *x <= v \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( return \ x.\text{has\_value}() \ ? \ *x <= v : true; \)

template<class T, class U> constexpr bool operator<=(const T& v, const optional<U>& x);

Constraints: The expression \( v <= *x \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( return \ x.\text{has\_value}() \ ? \ v <= *x : false; \)

template<class T, class U> constexpr bool operator>=(const optional<T>& x, const U& v);

Constraints: The expression \( *x >= v \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( return \ x.\text{has\_value}() \ ? \ *x >= v : false; \)

template<class T, class U> constexpr bool operator>=(const T& v, const optional<U>& x);

Constraints: The expression \( v >= *x \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( return \ x.\text{has\_value}() \ ? \ v >= *x : true; \)

template<class T, class U>
requires (!is-derived-from-optional<U> && three_way_comparable_with<T, U>)
constexpr compare_three_way_result_t<T, U> operator<=>(const optional<T>& x, const U& v);

Effects: Equivalent to: \( return \ x.\text{has\_value}() \ ? \ *x <=> v : \text{strong\_ordering::less}; \)

22.5.9 Specialized algorithms

22.5.10 Hash support

22.6 Variants

22.6.1 General
2 In 22.6, \textit{GET} denotes a set of exposition-only function templates (22.6.5).

22.6.2 Header \texttt{<variant\_synopsis\> synopsis} \cite{variant.syn]

\begin{verbatim}
// mostly freestanding
#include <compare> // see 17.11.1

namespace std {
    // 22.6.3, class template variant
template<class... Types>
    class variant;

    // 22.6.4, variant helper classes
template<class T> struct variant_size;
    // not defined

    template<class T> struct variant_size<const T>;
    template<class T>
    constexpr size_t variant_size_v = variant_size<T>::value;

    template<class... Types>
    struct variant_size<variant<Types...>>;

    template<size_t I, class T> struct variant_alternative;
    // not defined

    template<size_t I, class T> struct variant_alternative<I, const T>;
    template<size_t I, class T>
    using variant_alternative_t = typename variant_alternative<I, T>::type;

    template<size_t I, class... Types>
    struct variant_alternative<I, variant<Types...>>;

    inline constexpr size_t variant_npos = -1;

    // 22.6.5, value access
    template<class T, class... Types>
    constexpr bool holds_alternative(const variant<Types...>&) noexcept;

    template<size_t I, class... Types>
    constexpr variant_alternative_t<I, variant<Types...>>&
    get(variant<Types...>&); // freestanding-deleted

    template<size_t I, class... Types>
    constexpr variant_alternative_t<I, variant<Types...>>&
    get(const variant<Types...>&); // freestanding-deleted

    template<class T, class... Types>
    constexpr T& get(variant<Types...>&); // freestanding-deleted

    template<class T, class... Types>
    constexpr T&& get(variant<Types...>&&); // freestanding-deleted

    template<class T, class... Types>
    constexpr const T& get(const variant<Types...>&); // freestanding-deleted

    template<class T, class... Types>
    constexpr const T&& get(const variant<Types...>&&); // freestanding-deleted

    template<size_t I, class... Types>
    constexpr add_pointer_t<variant_alternative_t<I, variant<Types...>>>
    get_if(variant<Types...>*) noexcept;

    template<size_t I, class... Types>
    constexpr add_pointer_t<const variant_alternative_t<I, variant<Types...>>>
    get_if(const variant<Types...>*) noexcept;
\end{verbatim}
template<class T, class... Types>
constexpr add_pointer_t<T>
get_if(variant<Types...>*) noexcept;

// 22.6.6, relational operators
// see below

// 22.6.7, visitation

// 22.6.8, class monostate
struct monostate;

// 22.6.9, monostate relational operators

// 22.6.10, specialized algorithms

// 22.6.11, class bad_variant_access

// 22.6.12, hash support

}  

22.6.3 Class template variant

22.6.3.1 General

namespace std {
    template<class... Types>
    class variant {
        public:
            // 22.6.3.2, constructors
            constexpr variant() noexcept(see below);
            constexpr variant(const variant&);
            constexpr variant(variant&&) noexcept(see below);

            template<class T>
            constexpr variant(T&&) noexcept(see below);

            template<class T, class... Types>
            constexpr add_pointer_t<T>
            get_if(const variant<Types...>*) noexcept;
        }
    }  

§ 22.6.3.1
Any instance of `variant` at any given time either holds a value of one of its alternative types or holds no value. When an instance of `variant` holds a value of alternative type `T`, it means that a value of type `T`, referred to as the `variant` object’s `contained value`, is allocated within the storage of the `variant` object. Implementations are not permitted to use additional storage, such as dynamic memory, to allocate the contained value.

All types in `Types` shall meet the `Cpp17Destructible` requirements (Table 35).

A program that instantiates the definition of `variant` with no template arguments is ill-formed.

If a program declares an explicit or partial specialization of `variant`, the program is ill-formed, no diagnostic required.

### 22.6.3.2 Constructors

In the descriptions that follow, let `i` be in the range `[0, size_of...(Types))`, and `T_i` be the `i`th type in `Types`.

`constexpr variant() noexcept(see below);`

**Constraints:** `is_default_constructible_v<T_0>` is true.

**Effects:** Constructs a `variant` holding a value-initialized value of type `T_0`. 

---

1. Any instance of `variant` at any given time either holds a value of one of its alternative types or holds no value. When an instance of `variant` holds a value of alternative type `T`, it means that a value of type `T`, referred to as the `variant` object’s `contained value`, is allocated within the storage of the `variant` object. Implementations are not permitted to use additional storage, such as dynamic memory, to allocate the contained value.

2. All types in `Types` shall meet the `Cpp17Destructible` requirements (Table 35).

3. A program that instantiates the definition of `variant` with no template arguments is ill-formed.

4. If a program declares an explicit or partial specialization of `variant`, the program is ill-formed, no diagnostic required.
Postconditions: valueless_by_exception() is false and index() is 0.

Throws: Any exception thrown by the value-initialization of T0.

Remarks: This function is constexpr if and only if the value-initialization of the alternative type T0 would be constexpr-suitable (9.2.6). The exception specification is equivalent to is_nothrow_default_constructible_v<T0>.

[Note 1: See also class monostate. — end note]

constexpr variant(const variant& w);

Effects: If w holds a value, initializes the variant to hold the same alternative as w and direct-initializes the contained value with GET<j>(w), where j is w.index(). Otherwise, initializes the variant to not hold a value.

Throws: Any exception thrown by direct-initializing any Ti for all i.

Remarks: This constructor is defined as deleted unless is_copy_constructible_v<Ti> is true for all i. If is_trivially_copy_constructible_v<Ti> is true for all i, this constructor is trivial.

constexpr variant(variant& w) noexcept(see below);

Constraints: is_move_constructible_v<Ti> is true for all i.

Effects: If w holds a value, initializes the variant to hold the same alternative as w and direct-initializes the contained value with GET<j>(std::move(w)), where j is w.index(). Otherwise, initializes the variant to not hold a value.

Throws: Any exception thrown by move-constructing any Ti for all i.

Remarks: The exception specification is equivalent to the logical and of is_nothrow_move_constructible_v<Ti> for all i. If is_trivially_move_constructible_v<Ti> is true for all i, this constructor is trivial.

template<class T> constexpr variant(T&& t) noexcept(see below);

Let T be a type that is determined as follows: build an imaginary function FUN(Ti) for each alternative type Ti for which Ti = std::forward<T>(t) is well-formed for some invented variable x. The overload FUN(Tj) selected by overload resolution for the expression FUN(std::forward<T>(t)) defines the alternative Tj which is the type of the contained value after construction.

Constraints:
(15.1) sizeof...(Types) is nonzero,
(15.2) is_same_v<remove_cvref_t<T>, variant> is false,
(15.3) remove_cvref_t<T> is neither a specialization of in_place_type_t nor a specialization of in_place_index_t,
(15.4) is_constructible_v<Tj, T> is true, and
(15.5) the expression FUN(std::forward<T>(t)) (with FUN being the above-mentioned set of imaginary functions) is well-formed.

[Note 2: variant<string, string> v("abc"); is ill-formed, as both alternative types have an equally viable constructor for the argument. — end note]

Effects: Initializes *this to hold the alternative type Tj and direct-non-list-initializes the contained value with std::forward<T>(t).

Postconditions: holds_alternative<Tj>(*this) is true.

Throws: Any exception thrown by the initialization of the selected alternative Tj.

Remarks: The exception specification is equivalent to is_nothrow_constructible_v<Tj, T>. If Tj’s selected constructor is a constexpr constructor, this constructor is a constexpr constructor.

template<class T, class... Args> constexpr explicit variant(in_place_type_t<T>, Args&&... args);

Constraints:
(20.1) There is exactly one occurrence of T in Types... and
— `is_constructible_v<T, Args...>` is true.

**Effects:** Direct-non-list-initializes the contained value of type T with `std::forward<Args>(args)`.

**Postconditions:** `holds_alternative<T>(*this)` is true.

**Throws:** Any exception thrown by calling the selected constructor of T.

**Remarks:** If T's selected constructor is a constexpr constructor, this constructor is a constexpr constructor.

template<class T, class U, class... Args>
constexpr explicit variant(in_place_type_t<T>, initializer_list<U> il, Args&&... args);

**Constraints:**

— There is exactly one occurrence of T in Types... and

— `is_constructible_v<T, initializer_list<U>&, Args...>` is true.

**Effects:** Direct-non-list-initializes the contained value of type T with il, `std::forward<Args>(args)`.

**Postconditions:** `holds_alternative<T>(*this)` is true.

**Throws:** Any exception thrown by calling the selected constructor of T.

**Remarks:** If T's selected constructor is a constexpr constructor, this constructor is a constexpr constructor.

template<size_t I, class... Args>
constexpr explicit variant(in_place_index_t<I>, Args&&... args);

**Constraints:**

— I is less than `sizeof...(Types)` and

— `is_constructible_v<T_I, Args...>` is true.

**Effects:** Direct-non-list-initializes the contained value of type T_I with `std::forward<Args>(args)`.

**Postconditions:** `index()` is I.

**Throws:** Any exception thrown by calling the selected constructor of T_I.

**Remarks:** If T_I's selected constructor is a constexpr constructor, this constructor is a constexpr constructor.

template<size_t I, class U, class... Args>
constexpr explicit variant(in_place_index_t<I>, initializer_list<U> il, Args&&... args);

**Constraints:**

— I is less than `sizeof...(Types)` and

— `is_constructible_v<T_I, initializer_list<U>&, Args...>` is true.

**Effects:** Direct-non-list-initializes the contained value of type T_I with il, `std::forward<Args>(args)`.

**Postconditions:** `index()` is I.

**Remarks:** If T_I's selected constructor is a constexpr constructor, this constructor is a constexpr constructor.

### 22.6.3.3 Destructor

```cpp
constexpr ~variant();
```

**Effects:** If `valueless_by_exception()` is false, destroys the currently contained value.

**Remarks:** If `is_trivially_destructible_v<T_i>` is true for all T_i, then this destructor is trivial.

### 22.6.3.4 Assignment

```cpp
constexpr variant& operator=(const variant& rhs);
```

**Effects:**

— Let j be rhs.index().
If neither \*this nor rhs holds a value, there is no effect.

Otherwise, if \*this holds a value but rhs does not, destroys the value contained in \*this and sets \*this to not hold a value.

Otherwise, if \texttt{index()} == \texttt{j}, assigns the value contained in rhs to the value contained in \*this.

Otherwise, if either \texttt{is_nothrow_copy_constructible_v<T\texttt{j}}> is true or \texttt{is_nothrow_move_constructible_v<T\texttt{j}>} is false, equivalent to \texttt{emplace\langle j\rangle\langle GET\langle j\rangle\rangle(rhs)}.

Otherwise, equivalent to \texttt{operator=(variant(rhs))}.

Postconditions: \texttt{index()} == \texttt{rhs.index()}.

Returns: \*this.

Remarks: This operator is defined as deleted unless \texttt{is_copy_constructible_v<T\texttt{i}>} \&\& \texttt{is_copyAssignable_v<T\texttt{i}>} is true for all \texttt{i}. If \texttt{is_trivially_copy_constructible_v<T\texttt{i}>} \&\& \texttt{is_trivially_copyAssignable_v<T\texttt{i}>} \&\& \texttt{is_trivially_destructible_v<T\texttt{i}>} is true for all \texttt{i}, this assignment operator is trivial.

3 Postconditions: \texttt{index()} == \texttt{rhs.index()}.

4 Returns: \*this.

5 Remarks: If \texttt{is_trivially_move_constructible_v<T\texttt{i}>} \&\& \texttt{is_trivially_move_assignable_v<T\texttt{i}>} \&\& \texttt{is_trivially_destructible_v<T\texttt{i}>} is true for all \texttt{i}, this assignment operator is trivial. The exception specification is equivalent to \texttt{is_nothrow_move_constructible_v<T\texttt{i}>} \&\& \texttt{is_nothrow_move_assignable_v<T\texttt{i}>}} for all \texttt{i}.

6 Let \texttt{j} be \texttt{rhs.index()}.

7 Constraints: \texttt{is_move_constructible_v<T\texttt{j}>} \&\& \texttt{is_move_assignable_v<T\texttt{i}>} is true for all \texttt{i}.

8 Effects:

(8.1) If neither \*this nor rhs holds a value, there is no effect.

(8.2) Otherwise, if \*this holds a value but rhs does not, destroys the value contained in \*this and sets \*this to not hold a value.

(8.3) Otherwise, if \texttt{index()} == \texttt{j}, assigns \texttt{GET\langle j\rangle\langle std::move(rhs)\rangle} to the value contained in \*this.

(8.4) Otherwise, equivalent to \texttt{emplace\langle j\rangle\langle GET\langle j\rangle\langle std::move(rhs)\rangle\rangle}.

9 Returns: \*this.

10 Remarks: If \texttt{is_trivially_move_constructible_v<T\texttt{j}>} \&\& \texttt{is_trivially_move_assignable_v<T\texttt{j}>} \&\& \texttt{is_trivially_destructible_v<T\texttt{j}>} is true for all \texttt{i}, this assignment operator is trivial. The exception specification is equivalent to \texttt{is_nothrow_move_constructible_v<T\texttt{j}>} \&\& \texttt{is_nothrow_move_assignable_v<T\texttt{j}>}} for all \texttt{i}.

(10.1) If an exception is thrown during the call to \texttt{T\texttt{j}'}s move construction (with \texttt{j} being \texttt{rhs.index()}), the \texttt{variant} will hold no value.

(10.2) If an exception is thrown during the call to \texttt{T\texttt{j}'}s move assignment, the state of the contained value is as defined by the exception safety guarantee of \texttt{T\texttt{j}'}s move assignment; \texttt{index()} will be \texttt{j}.

template<class \texttt{T}> constexpr variant& operator=(\texttt{T&& t}) noexcept(see below);

Let \texttt{T\texttt{j}} be a type that is determined as follows: build an imaginary function \texttt{FUN(T\texttt{i})} for each alternative type \texttt{T\texttt{i}} for which \texttt{T\texttt{i} x[] = {std::forward<T\langle t\rangle\langle t\rangle};} is well-formed for some invented variable \texttt{x}. The overload \texttt{FUN(T\texttt{j})} selected by overload resolution for the expression \texttt{FUN(std::forward\langle T\rangle\langle t\rangle\langle t\rangle)} defines the alternative \texttt{T\texttt{j}} which is the type of the contained value after assignment.

12 Constraints:

(12.1) \texttt{is_same_v\langle remove_cvref_t\langle T\rangle, variant\rangle} is false,

(12.2) \texttt{is_assignable_v<T\texttt{j}&&, T\rangle} \&\& \texttt{is_constructible_v<T\texttt{j}, T\rangle} is true, and

(12.3) the expression \texttt{FUN(std::forward\langle T\rangle\langle t\rangle\langle t\rangle)} (with \texttt{FUN} being the above-mentioned set of imaginary functions) is well-formed.

[Note 1: \texttt{variant<string, string> v; v = "abc";} is ill-formed, as both alternative types have an equally viable constructor for the argument. — end note]

13 Effects:

(13.1) If \*this holds a \texttt{T\texttt{j}}, assigns \texttt{std::forward\langle T\rangle\langle t\rangle\langle t\rangle} to the value contained in \*this.
— Otherwise, if \texttt{is\_nothrow\_constructible\_v<T_j, T> || !is\_nothrow\_move\_constructible\_v<T_j, T>} is true, equivalent to \texttt{emplace<T_j>\(\text{std::forward<T}\(t\))\)}.

— Otherwise, equivalent to \texttt{emplace<T_j>(\text{std::forward<T}\(t\)))\}}.

\textit{Postconditions:} \texttt{holds\_alternative\_v<T_j>\(*\text{this}\)} is true, with \(T_j\) selected by the imaginary function overload resolution described above.

\textit{Returns:} \texttt{*\text{this}}.

\textit{Remarks:} The exception specification is equivalent to:

\texttt{is\_nothrow\_assignable\_v<T_j,T> \&\& is\_nothrow\_constructible\_v<T_j, T>}

— If an exception is thrown during the assignment of \texttt{std::forward<T}\(t\)} to the value contained in \texttt{*\text{this}}, the state of the contained value and \(t\) are as defined by the exception safety guarantee of the assignment expression; \texttt{valueless\_by\_exception()} will be \texttt{false}.

— If an exception is thrown during the initialization of the contained value, the \texttt{variant} object is permitted to not hold a value.

### 22.6.3.5 Modifiers

\texttt{template<class T, class... Args> constexpr T& emplace(Args&&... args);}  
\textit{Constraints:} \texttt{is\_constructible\_v<T, Args...>} is true, and \(T\) occurs exactly once in \texttt{Types}.

\textit{Effects:} Equivalent to:

\texttt{return emplace<\(I\)}(\texttt{std::forward<Args>(args)...});

where \(I\) is the zero-based index of \(T\) in \texttt{Types}.

\texttt{template<class T, class U, class... Args> constexpr T& emplace(initializer\_list<U> il, Args&&... args);}  
\textit{Constraints:} \texttt{is\_constructible\_v<T, initializer\_list<U>&, Args...>} is true, and \(T\) occurs exactly once in \texttt{Types}.

\textit{Effects:} Equivalent to:

\texttt{return emplace<\(I\)}(\texttt{il, std::forward<Args>(args)...});

where \(I\) is the zero-based index of \(T\) in \texttt{Types}.

\texttt{template<size_t I, class... Args> constexpr variant\_alternative\_t<I, variant<Types...>>& emplace(Args&&... args);}  
\textit{Mandates:} \(I < \text{sizeof...}(\text{Types})\).

\textit{Constraints:} \texttt{is\_constructible\_v<T_I, Args...>} is true.

\textit{Effects:} Destroys the currently contained value if \texttt{valueless\_by\_exception()} is \texttt{false}. Then direct-
non-list-initializes the contained value of type \(T_I\) with the arguments \texttt{std::forward<Args>(args)...}.

\textit{Postconditions:} \texttt{index()} is \(I\).

\textit{Returns:} A reference to the new contained value.

\textit{Throws:} Any exception thrown during the initialization of the contained value.

\textit{Remarks:} If an exception is thrown during the initialization of the contained value, the \texttt{variant} is permitted to not hold a value.

\texttt{template<size_t I, class U, class... Args> constexpr variant\_alternative\_t<I, variant<Types...>>& emplace(initializer\_list<U> il, Args&&... args);}  
\textit{Mandates:} \(I < \text{sizeof...}(\text{Types})\).

\textit{Constraints:} \texttt{is\_constructible\_v<T_I, initializer\_list<U>&, Args...>} is true.

\textit{Effects:} Destroys the currently contained value if \texttt{valueless\_by\_exception()} is \texttt{false}. Then direct-
non-list-initializes the contained value of type \(T_I\) with \texttt{il, std::forward<Args>(args)...}.

\textit{Postconditions:} \texttt{index()} is \(I\).

\textit{Returns:} A reference to the new contained value.
22.6.3.6 Value status

```cpp
constexpr bool valueless_by_exception() const noexcept;
```

**Effects:** Returns `false` if and only if the `variant` holds a value.

**Remarks:** If an exception is thrown during the initialization of the contained value, the `variant` is permitted to not hold a value.

22.6.3.7 Swap

```cpp
constexpr void swap(variant& rhs) noexcept(see below);
```

**Mandates:** `is_move_constructible_v<T_i>` is true for all `i`.

**Preconditions:** Each `T_i` meets the `Cpp17Swappable` requirements (16.4.4.3).

**Effects:**

1. If `valueless_by_exception() && rhs.valueless_by_exception()` no effect.
2. Otherwise, if `index() == rhs.index()`, calls `swap(GET<i>(*this), GET<i>(rhs))` where `i` is `index()`.
3. Otherwise, exchanges values of `rhs` and `*this`.

**Throws:** If `index() == rhs.index()`, any exception thrown by `swap(GET<i>(*this), GET<i>(rhs))` with `i` being `index()`. Otherwise, any exception thrown by the move constructor of `T_i` or `T_j` with `i` being `index()` and `j` being `rhs.index()`.

**Remarks:** If an exception is thrown during the call to function `swap(GET<i>(*this), GET<i>(rhs))`, the states of the contained values of `*this` and of `rhs` are determined by the exception safety guarantee of `swap` for `lvalues` of `T_i` with `i` being `index()`. If an exception is thrown during the exchange of the values of `*this` and `rhs`, the states of the values of `*this` and of `rhs` are determined by the exception safety guarantee of `variant`’s move constructor. The exception specification is equivalent to the logical `AND` of `is_nothrow_move_constructible_v<T_i> && is_nothrow_swappable_v<T_i>` for all `i`.

22.6.4 variant helper classes

```cpp
template<class T> struct variant_size;
```

All specializations of `variant_size` meet the `Cpp17UnaryTypeTrait` requirements (21.3.2) with a base characteristic of `integral_constant<size_t, N>` for some `N`.

```cpp
template<class T> struct variant_size<const T>;
```

Let `VS` denote `variant_size<T>` of the cv-unqualified type `T`. Then each specialization of the template meets the `Cpp17UnaryTypeTrait` requirements (21.3.2) with a base characteristic of `integral_constant<size_t, VS::value>`.

```cpp
template<class... Types>
struct variant_size<variant<Types...>> : integral_constant<size_t, sizeof...(Types)> { };
```
Let VA denote variant_alternative<I, T> of the cv-unqualified type T. Then each specialization of the template meets the Cpp17TransformationTrait requirements (21.3.2) with a member typedef type that names the type add_const_t<VA::type>.

variant_alternative<I, variant<Types...>>::type

Mandates: I < sizeof...(Types).

Type: The type T_I.

22.6.5 Value access

Mandates: The type T occurs exactly once in Types.

Returns: true if index() is equal to the zero-based index of T in Types.

Mandates: I < sizeof...(Types).

Preconditions: v.index() is I.

Returns: A reference to the object stored in the variant.

Mandates: I < sizeof...(Types).

Effects: If v.index() is I, returns a reference to the object stored in the variant. Otherwise, throws an exception of type bad_variant_access.

Mandates: The type T occurs exactly once in Types.

Effects: If v holds a value of type T, returns a reference to that value. Otherwise, throws an exception of type bad_variant_access.

Mandates: I < sizeof...(Types).
template<class T, class... Types>
constexpr add_pointer_t<const T>
get_if(const variant<Types...>* v) noexcept;

get_if(variant<Types...>* v) noexcept;

template<class T, class... Types>
constexpr add_pointer_t<T>
get_if(variant<Types...>* v) noexcept;

§ 22.6.6 Relational operators [variant.relops]

template<class... Types>
constexpr bool operator==(const variant<Types...>& v, const variant<Types...>& w);

Constraints: GET<i>(v) == GET<i>(w) is a valid expression that is convertible to bool, for all i.

Returns: If v.index() != w.index(), false; otherwise if v.valueless_by_exception(), true; otherwise GET<i>(v) == GET<i>(w) with i being v.index().

template<class... Types>
constexpr bool operator!=(const variant<Types...>& v, const variant<Types...>& w);

Constraints: GET<i>(v) != GET<i>(w) is a valid expression that is convertible to bool, for all i.

Returns: If v.index() != w.index(), true; otherwise if v.valueless_by_exception(), false; otherwise GET<i>(v) != GET<i>(w) with i being v.index().

template<class... Types>
constexpr bool operator<(const variant<Types...>& v, const variant<Types...>& w);

Constraints: GET<i>(v) < GET<i>(w) is a valid expression that is convertible to bool, for all i.

Returns: If w.valueless_by_exception(), false; otherwise if v.valueless_by_exception(), true; otherwise if v.index() < w.index(), true; otherwise if v.index() > w.index(), false; otherwise GET<i>(v) < GET<i>(w) with i being v.index().

template<class... Types>
constexpr bool operator>(const variant<Types...>& v, const variant<Types...>& w);

Constraints: GET<i>(v) > GET<i>(w) is a valid expression that is convertible to bool, for all i.

Returns: If v.valueless_by_exception(), false; otherwise if w.valueless_by_exception(), true; otherwise if v.index() > w.index(), true; otherwise if v.index() < w.index(), false; otherwise GET<i>(v) > GET<i>(w) with i being v.index().

template<class... Types>
constexpr bool operator<=(const variant<Types...>& v, const variant<Types...>& w);

Constraints: GET<i>(v) <= GET<i>(w) is a valid expression that is convertible to bool, for all i.

Returns: If v.valueless_by_exception(), true; otherwise if w.valueless_by_exception(), false; otherwise if v.index() < w.index(), true; otherwise if v.index() > w.index(), false; otherwise GET<i>(v) <= GET<i>(w) with i being v.index().

template<class... Types>
constexpr bool operator>=(const variant<Types...>& v, const variant<Types...>& w);

Returns: If w.valueless_by_exception(), true; otherwise if v.valueless_by_exception(), false; otherwise if v.index() > w.index(), true; otherwise if v.index() < w.index(), false; otherwise GET<i>(v) >= GET<i>(w) with i being v.index().
operator<(const variant<Types...>& v, const variant<Types...>& w);

Effects: Equivalent to:

```c++
if (v.valueless_by_exception() && w.valueless_by_exception())
    return strong_ordering::equal;
if (v.valueless_by_exception()) return strong_ordering::less;
if (w.valueless_by_exception()) return strong_ordering::greater;
if (auto c = v.index() <=> w.index(); c != 0) return c;
return GET<i>(v) <=> GET<i>(w);
```

with \( i \) being \( v.index() \).

### 22.6.7 Visitation

#### [variant.visit]

```c++
template<class Visitor, class... Variants>
constexpr
see below visit(Visitor&& vis, Variants&&... vars);
template<class R, class Visitor, class... Variants>
constexpr R visit(Visitor&& vis, Variants&&... vars);
```

Let \( \text{as-variant} \) denote the following exposition-only function templates:

```c++
template<class... Ts>
auto&& as-variant(variant<Ts...>&& var) { return var; }
template<class... Ts>
auto&& as-variant(const variant<Ts...>& var) { return var; }
template<class... Ts>
auto&& as-variant(variant<Ts...>& var) { return std::move(var); }
template<class... Ts>
auto&& as-variant(const variant<Ts...>& var) { return std::move(var); }
```

Let \( n \) be \( \text{sizeof}(\ldots) \). For each \( 0 \leq i < n \), let \( V_i \) denote the type \( \text{decltype(as-variant(std::forward<Variants,i>(vars)))} \).

Constraints: \( V_i \) is a valid type for all \( 0 \leq i < n \).

Let \( V \) denote the pack of types \( V_i \).

Let \( m \) be a pack of \( n \) values of type \( \text{size_t} \). Such a pack is valid if \( 0 \leq m_i < \text{variant_size_v<remove_reference_t<V_i>>} \) for all \( 0 \leq i < n \). For each valid pack \( m \), let \( e(m) \) denote the expression:

```c++
INVOLVE(std::forward<Visitor>(vis), GET<m>(std::forward<V>(vars))...) // see 22.10.4
```

for the first form and

```c++
INVOLVE<R>(std::forward<Visitor>(vis), GET<m>(std::forward<V>(vars))...) // see 22.10.4
```

for the second form.

Mandates: For each valid pack \( m \), \( e(m) \) is a valid expression. All such expressions are of the same type and value category.

Returns: \( e(m) \), where \( m \) is the pack for which \( m_i \) is \( \text{as-variant}(vars_i).index() \) for all \( 0 \leq i < n \). The return type is \( \text{decltype}(e(m)) \) for the first form.

Throws: \( \text{bad_variant_access} \) if \( \text{as-variant}(vars).valueless_by_exception() \) is true.

Complexity: For \( n \leq 1 \), the invocation of the callable object is implemented in constant time, i.e., for \( n = 1 \), it does not depend on the number of alternative types of \( V_0 \). For \( n > 1 \), the invocation of the callable object has no complexity requirements.

```c++
template<class Self, class Visitor>
constexpr decltype(auto) visit(this Self&& self, Visitor&& vis);
```

Let \( V \) be \( \text{OVERRIDE_REF}(\text{Self&&, COPY_CONST (remove_reference_t<Self>, variant})) (22.2.4) \).

Constraints: The call to \( \text{visit} \) does not use an explicit \( \text{template-argument-list} \) that begins with a type \( \text{template-argument} \).

Effects: Equivalent to:

```c++
return std::visit(std::forward<Visitor>(vis), (V)self);
```
template<class R, class Self, class Visitor>
constexpr R visit(this Self&& self, Visitor&& vis);

Let \( V \) be \texttt{OVERLOAD\_REF\!(Self\&\&, \texttt{COPY\_CONST}\!(\texttt{remove\_reference\_t\!\!(Self)})\!, \texttt{variant})} \texttt{(22.2.4)}.

**Effects**: Equivalent to: return std::\texttt{visit<R>}(std::\texttt{forward<Visitor>}(vis), (V)\texttt{self});

### 22.6.8 Class monostate

```cpp
struct monostate{};
```

The class \texttt{monostate} can serve as a first alternative type for a \texttt{variant} to make the \texttt{variant} type default constructible.

### 22.6.9 monostate relational operators

```cpp
constexpr bool operator==(monostate, monostate) noexcept { return true; }
castexpr strong_ordering operator<=>(monostate, monostate) noexcept
{ return strong_ordering::equal; }
```

[Note 1: \texttt{monostate} objects have only a single state; they thus always compare equal. — end note]

### 22.6.10 Specialized algorithms

```cpp
template<class... Types>
constexpr void swap(variant<Types...>& v, variant<Types...>& w) noexcept(see below);
```

**Constraints**: \( \text{is\_move\_constructible\_v<T> \&\& is\_swappable\_v<T> } \) is true for all \( i \).

**Effects**: Equivalent to \( v\cdot\text{swap}(w) \).

**Remarks**: The exception specification is equivalent to \( \text{noexcept}(v\cdot\text{swap}(w)) \).

### 22.6.11 Class bad_variant_access

```cpp
namespace std {
    class bad_variant_access : public exception {
public:
        // see 17.9.3 for the specification of the special member functions
        const char* what() const noexcept override;
    };
}
```

Objects of type \texttt{bad\_variant\_access} are thrown to report invalid accesses to the value of a \texttt{variant} object.

```cpp
const char* what() const noexcept override;
```

**Returns**: An implementation-defined \texttt{ntbs}.

### 22.6.12 Hash support

```cpp
template<class... Types> struct hash<variant<Types...>>;
```

The specialization \texttt{hash<variant<Types...>>> is enabled \texttt{(22.10.19)} if and only if every specialization in \texttt{hash<remove\_const\_t<Types>>>... is enabled. The member functions are not guaranteed to be \texttt{noexcept}.

```cpp
template<> struct hash<monostate>;
```

The specialization is enabled \texttt{(22.10.19)}.

### 22.7 Storage for any type

#### 22.7.1 General

Subclause 22.7 describes components that C++ programs may use to perform operations on objects of a discriminated type.

[Note 1: The discriminated type can contain values of different types but does not attempt conversion between them, i.e., \( 5 \) is held strictly as an \texttt{int} and is not implicitly convertible either to \"5\" or to \( 5.0 \). This indifference to interpretation but awareness of type effectively allows safe, generic containers of single values, with no scope for surprises from ambiguous conversions. — end note]
22.7.2 Header <any> synopsis

namespace std {
    // 22.7.3, class bad_any_cast
    class bad_any_cast;

    // 22.7.4, class any
    class any;

    // 22.7.5, non-member functions
    void swap(any& x, any& y) noexcept;
    template<class T, class... Args>
    any make_any(Args&&... args);
    template<class T, class U, class... Args>
    any make_any(initializer_list<U> il, Args&&... args);

    template<class T>
    T any_cast(const any& operand);
    template<class T>
    T any_cast(any& operand);
    template<class T>
    T any_cast(any&& operand);

    template<class T>
    const T* any_cast(const any* operand) noexcept;
    template<class T>
    T* any_cast(any* operand) noexcept;
}

22.7.3 Class bad_any_cast

namespace std {
    class bad_any_cast : public bad_cast {
        public:
            // see 17.9.3 for the specification of the special member functions
            const char* what() const noexcept override;
    }
};

1 Objects of type bad_any_cast are thrown by a failed any_cast (22.7.5).

    const char* what() const noexcept override;

2 Returns: An implementation-defined ntbs.

22.7.4 Class any

22.7.4.1 General

namespace std {
    class any {
        public:
            // 22.7.4.2, construction and destruction
            constexpr any() noexcept;
            any(const any& other);
            any(any&& other) noexcept;

            template<class T>
            any(T&& value);

            template<class T, class... Args>
            explicit any(in_place_type_t<T>, Args&&...);
            template<class T, class U, class... Args>
            explicit any(in_place_type_t<T>, initializer_list<U>, Args&&...);

            ~any();
        }
    }
An object of class any stores an instance of any type that meets the constructor requirements or it has no value, and this is referred to as the state of the class any object. The stored instance is called the contained value. Two states are equivalent if either they both have no value, or they both have a value and the contained values are equivalent.

The non-member any_cast functions provide type-safe access to the contained value.

Implementations should avoid the use of dynamically allocated memory for a small contained value. However, any such small-object optimization shall only be applied to types T for which is_nothrow_move_constructible_v<T> is true.

[Example 1: A contained value of type int could be stored in an internal buffer, not in separately-allocated memory. —end example]

### 22.7.4.2 Construction and destruction

**constexpr any() noexcept;**

**Postconditions:** has_value() is false.

any(const any& other);

**Effects:** If other.has_value() is false, constructs an object that has no value. Otherwise, equivalent to any(in_place_type<T>, any_cast<const T&>(other)) where T is the type of the contained value.

**Throws:** Any exceptions arising from calling the selected constructor for the contained value.

any(any&& other) noexcept;

**Effects:** If other.has_value() is false, constructs an object that has no value. Otherwise, constructs an object of type any that contains either the contained value of other, or contains an object of the same type constructed from the contained value of other considering that contained value as an rvalue.

**template<class T>**
any(T&& value);

**Let VT be decay_t<T>**.

**Constraints:** VT is not the same type as any, VT is not a specialization of in_place_type_t, and is_copy_constructible_v<VT> is true.

**Preconditions:** VT meets the Cpp17CopyConstructible requirements.

**Effects:** Constructs an object of type any that contains an object of type VT direct-initialized with std::forward<T>(value).

**Throws:** Any exception thrown by the selected constructor of VT.
template<class T, class... Args>
explicit any(in_place_type_t<T>, Args&&... args);

Let VT be decay_t<T>.

Constraints: is_copy_constructible_v<VT> is true and is_constructible_v<VT, Args...> is true.

Preconditions: VT meets the Cpp17CopyConstructible requirements.
Effects: Direct-non-list-initializes the contained value of type VT with std::forward<Args>(args)....
Postconditions: *this contains a value of type VT.
Throws: Any exception thrown by the selected constructor of VT.

template<class T, class U, class... Args>
explicit any(in_place_type_t<T>, initializer_list<U> il, Args&&... args);

Let VT be decay_t<T>.

Constraints: is_copy_constructible_v<VT> is true and is_constructible_v<VT, initializer_list<U>&, Args...> is true.

Preconditions: VT meets the Cpp17CopyConstructible requirements.
Effects: Direct-non-list-initializes the contained value of type VT with il, std::forward<Args>(args)....
Postconditions: *this contains a value.
Throws: Any exception thrown by the selected constructor of VT.

~any();

Effects: As if by reset().

22.7.4.3 Assignment [any.assign]

any& operator=(const any& rhs);

Effects: As if by any(rhs).swap(*this). No effects if an exception is thrown.
Returns: *this.
Throws: Any exceptions arising from the copy constructor for the contained value.

any& operator=(any&& rhs) noexcept;

Effects: As if by any(std::move(rhs)).swap(*this).
Postconditions: The state of *this is equivalent to the original state of rhs.
Returns: *this.

template<class T>
any& operator=(T&& rhs);

Let VT be decay_t<T>.

Constraints: VT is not the same type as any and is_copy_constructible_v<VT> is true.
Preconditions: VT meets the Cpp17CopyConstructible requirements.
Effects: Constructs an object tmp of type any that contains an object of type VT direct-initialized with std::forward<T>(rhs), and tmp.swap(*this). No effects if an exception is thrown.
Returns: *this.
Throws: Any exception thrown by the selected constructor of VT.

22.7.4.4 Modifiers [any.modifiers]

decay_t<T>& emplace(Args&&... args);

Let VT be decay_t<T>.

Constraints: VT is not the same type as any and is_copy_constructible_v<VT> is true.
Preconditions: VT meets the Cpp17CopyConstructible requirements.
Effects: Constructs an object tmp of type any that contains an object of type VT direct-initialized with std::forward<T>(args), and tmp.swap(*this). No effects if an exception is thrown.
Returns: *this.
Throws: Any exception thrown by the selected constructor of VT.
Constraints: \( \text{is\_copy\_constructible\_v<VT>} \) is true and \( \text{is\_constructible\_v<VT, Args...>} \) is true.

Preconditions: VT meets the Cpp17CopyConstructible requirements.

Effects: Calls \text{reset()}. Then direct-non-list-initializes the contained value of type VT with \text{std::forward<Args>(args)...}.

Postconditions: \(*\text{this}\) contains a value.

Returns: A reference to the new contained value.

Throws: Any exception thrown by the selected constructor of VT.

Remarks: If an exception is thrown during the call to VT's constructor, \(*\text{this}\) does not contain a value, and any previously contained value has been destroyed.

\[
\text{template<class T, class U, class... Args>}
\text{decay_t<T>& emplace(initializer_list<U> il, Args&&... args);} \\
\text{Let VT be decay_t<T>.

Constraints: \( \text{is\_copy\_constructible\_v<VT>} \) is true and \( \text{is\_constructible\_v<VT, initializer\_list<U>>& , Args...>} \) is true.

Preconditions: VT meets the Cpp17CopyConstructible requirements.

Effects: Calls \text{reset()}. Then direct-non-list-initializes the contained value of type VT with il, std::forward<Args>(args)....

Postconditions: \(*\text{this}\) contains a value.

Returns: A reference to the new contained value.

Throws: Any exception thrown by the selected constructor of VT.

Remarks: If an exception is thrown during the call to VT's constructor, \(*\text{this}\) does not contain a value, and any previously contained value has been destroyed.

\text{void reset() noexcept;}

Effects: If \text{has\_value()} is true, destroys the contained value.

Postconditions: \text{has\_value()} is false.

\text{void swap(any& rhs) noexcept;}

Effects: Exchanges the states of \(*\text{this}\) and rhs.

\text{22.7.4.5 Observers [any.observers]}

\text{bool has\_value() const noexcept;}

Returns: true if \(*\text{this}\) contains an object, otherwise false.

\text{const type\_info& type() const noexcept;}

Returns: typeid(T) if \(*\text{this}\) has a contained value of type T, otherwise typeid(void).

[Note 1: Useful for querying against types known either at compile time or only at runtime. — end note]

\text{22.7.5 Non-member functions [any.nonmembers]}

\text{void swap(any& x, any& y) noexcept;}

Effects: Equivalent to \text{x.swap(y)}.

\text{template<class T, class... Args>}
\text{any make\_any(Args&&... args);} \\
Effects: Equivalent to: return any(in_place_type<T>, std::forward<Args>(args)...);

\text{template<class T, class U, class... Args>}
\text{any make\_any(initializer\_list<U> il, Args&&... args);} \\
Effects: Equivalent to: return any(in_place_type<T>, il, std::forward<Args>(args)...);
### 22.8 Expected objects

#### 22.8.1 General

Subclause 22.8 describes the class template `expected` that represents expected objects. An `expected<T, E>` object holds an object of type `T` or an object of type `E` and manages the lifetime of the contained objects.

#### 22.8.2 Header `<expected>` synopsis
// mostly freestanding
namespace std {
    // 22.8.3, class template unexpected
    template<class E> class unexpected;

    // 22.8.4, class template bad_expected_access
    template<class E> class bad_expected_access;

    // 22.8.5, specialization for void
    template<> class bad_expected_access<void>;

    // in-place construction of unexpected values
    struct unexpect_t {
        explicit unexpect_t() = default;
    };
    inline constexpr unexpect_t unexpect{};

    // 22.8.6, class template expected
    template<class T, class E> class expected; // partially freestanding

    // 22.8.7, partial specialization of expected for void types
    template<class T, class E> requires is_void_v<T> class expected<T, E>; // partially freestanding
}

22.8.3 Class template unexpected

22.8.3.1 General

Subclause 22.8.3 describes the class template unexpected that represents unexpected objects stored in expected objects.

namespace std {
    template<class E>
    class unexpected {
    public:
        // 22.8.3.2, constructors
        constexpr unexpected(const unexpected&) = default;
        constexpr unexpected(unexpected&&) = default;
        template<class Err = E>
            constexpr explicit unexpected(Err&&);
        template<class... Args>
            constexpr explicit unexpected(in_place_t, Args&&...);
        template<class U, class... Args>
            constexpr explicit unexpected(in_place_t, initializer_list<U>, Args&&...);

        constexpr unexpected& operator=(const unexpected&) = default;
        constexpr unexpected& operator=(unexpected&&) = default;

        constexpr const E& error() const & noexcept;
        constexpr E& error() & noexcept;
        constexpr const E&& error() const && noexcept;
        constexpr E&& error() && noexcept;
        constexpr void swap(unexpected& other) noexcept(see below);

        template<class E2>
            friend constexpr bool operator==(const unexpected&, const unexpected<E2>&);

            friend constexpr void swap(unexpected& x, unexpected& y) noexcept(noexcept(x.swap(y)));

    private:
        E unex;  // exposition only
    };

    template<class E> unexpected(E) -> unexpected<E>;
}
A program that instantiates the definition of `unexpected` for a non-object type, an array type, a specialization of `unexpected`, or a cv-qualified type is ill-formed.

### 22.8.3.2 Constructors

```
template<class Err = E>
constexpr explicit unexpected(Err&& e);
```

**Constraints:**

1. `is_same_v<remove_cvref_t<Err>, unexpected> is false; and`
2. `is_same_v<remove_cvref_t<Err>, in_place_t> is false; and`
3. `is_constructible_v<E, Err> is true.`

**Effects:** Direct-non-list-initializes `unex` with `std::forward<Err>(e)`.

**Throws:** Any exception thrown by the initialization of `unex`.

```
template<class... Args>
constexpr explicit unexpected(in_place_t, Args&&... args);
```

**Constraints:**

1. `is_constructible_v<E, Args...> is true`.

**Effects:** Direct-non-list-initializes `unex` with `std::forward<Args>(args)....`

**Throws:** Any exception thrown by the initialization of `unex`.

```
template<class U, class... Args>
constexpr explicit unexpected(in_place_t, initializer_list<U> il, Args&&... args);
```

**Constraints:**

1. `is_constructible_v<E, initializer_list<U>&, Args...> is true`.

**Effects:** Direct-non-list-initializes `unex` with `il, std::forward<Args>(args)....`

**Throws:** Any exception thrown by the initialization of `unex`.

### 22.8.3.3 Observers

```
constexpr const E& error() const & noexcept;
```

**Returns:** `unex`.

```
constexpr E&& error() && noexcept;
```

**Returns:** `std::move(unex)`.

### 22.8.3.4 Swap

```
constexpr void swap(unexpected& other) noexcept(is_nothrow_swappable_v<E>);
```

**Mandates:** `is_swappable_v<E> is true`.

**Effects:** Equivalent to: `using std::swap; swap(unex, other.unex);`

```
friend constexpr void swap(unexpected& x, unexpected& y) noexcept(noexcept(x.swap(y)));
```

**Constraints:** `is_swappable_v<E> is true`.

**Effects:** Equivalent to `x.swap(y)`.

### 22.8.3.5 Equality operator

```
template<class E2>
friend constexpr bool operator==(const unexpected& x, const unexpected<E2>& y);
```

**Mandates:** The expression `x.error() == y.error()` is well-formed and its result is convertible to `bool`.

**Returns:** `x.error() == y.error()`.
22.8.4 Class template bad_expected_access

```cpp
namespace std {
    template<class E>
    class bad_expected_access : public bad_expected_access<void> {
        public:
            explicit bad_expected_access(E);
        const char* what() const noexcept override;
        E& error() & noexcept;
        const E& error() const & noexcept;
        E&& error() && noexcept;
        const E&& error() const && noexcept;
    }
}
```

1 The class template bad_expected_access defines the type of objects thrown as exceptions to report the situation where an attempt is made to access the value of an expected object for which has_value() is false.

2 *Effects*: Initializes `unex` with `std::move(e)`.

3 *Returns*: `unex`.

4 *Returns*: `std::move(unex)`.

5 *Returns*: An implementation-defined Ntbs.

22.8.5 Class template specialization bad_expected_access<void>

```cpp
namespace std {
    template<class E>
    class bad_expected_access<void> : public exception {
        protected:
            bad_expected_access() noexcept;
            bad_expected_access(const bad_expected_access&) noexcept;
            bad_expected_access(bad_expected_access&&) noexcept;
            bad_expected_access& operator=(const bad_expected_access& noexcept);
            bad_expected_access& operator=(bad_expected_access&&) noexcept;
            ~bad_expected_access();
        }
    }
}
```

1 *Returns*: An implementation-defined Ntbs.

22.8.6 Class template expected

22.8.6.1 General

```cpp
namespace std {
    template<class T, class E>
    class expected {
        public:
            using value_type = T;
    }
}
```
using error_type = E;
using unexpected_type = unexpected<E>;

template<class U>
using rebind = expected<U, error_type>;

// 22.8.6.2, constructors
constexpr expected();
constexpr expected(const expected&);
constexpr expected(expected&&) noexcept(see below);
template<class U, class G>
  constexpr explicit(see below) expected(const expected<U, G>&);
template<class U, class G>
  constexpr explicit(see below) expected(expected<U, G>&&);

template<class U = T>
  constexpr explicit(see below) expected(U&& v);

template<class G>
  constexpr explicit(see below) expected(const unexpected<G>&);
template<class G>
  constexpr explicit(see below) expected(unexpected<G>&&);

template<class... Args>
  constexpr explicit(in_place_t, Args&&...);

template<class U, class... Args>
  constexpr explicit(in_place_t, initializer_list<U>, Args&&...);

// 22.8.6.3, destructor
constexpr ~expected();

// 22.8.6.4, assignment
constexpr expected& operator=(const expected&);
constexpr expected& operator=(expected&&) noexcept(see below);
template<class U = T> constexpr expected& operator=(U&&);
template<class G>
  constexpr expected& operator=(const unexpected<G>&);
template<class G>
  constexpr expected& operator=(unexpected<G>&&);

template<class... Args>
  constexpr T& emplace(Args&&...) noexcept;

template<class U, class... Args>
  constexpr T& emplace(initializer_list<U>, Args&&...) noexcept;

// 22.8.6.5, swap
constexpr void swap(expected&) noexcept(see below);
friend constexpr void swap(expected& x, expected& y) noexcept(noexcept(x.swap(y)));

// 22.8.6.6, observers
constexpr const T* operator->() const noexcept;
constexpr T* operator->() noexcept;
constexpr const T& operator*() const & noexcept;
constexpr T& operator*() & noexcept;
constexpr const T&& operator*() const && noexcept;
constexpr T&& operator*() && noexcept;
constexpr explicit operator bool() const noexcept;
constexpr bool has_value() const noexcept;
constexpr T& value() &;  // freestanding-deleted
constexpr T& value() &&;  // freestanding-deleted
constexpr const T&& value() const &&;    // freestanding-deleted
constexpr T&& value() &&;    // freestanding-deleted
constexpr const E& error() const & noexcept;
constexpr E& error() & noexcept;
constexpr const E&& error() const && noexcept;
constexpr E&& error() && noexcept;
template<class U> constexpr T value_or(U&&) const &;
template<class U> constexpr T value_or(U&&) &&;
template<class G = E> constexpr E error_or(G&&) const &;
template<class G = E> constexpr E error_or(G&&) &&;

// 22.8.6.7, monadic operations
template<class F> constexpr auto and_then(F&& f) &;
template<class F> constexpr auto and_then(F&& f) &&;
template<class F> constexpr auto and_then(F&& f) const &;
template<class F> constexpr auto and_then(F&& f) const &&;
template<class F> constexpr auto or_else(F&& f) &;
template<class F> constexpr auto or_else(F&& f) &&;
template<class F> constexpr auto or_else(F&& f) const &;
template<class F> constexpr auto or_else(F&& f) const &&;
template<class F> constexpr auto transform(F&& f) &;
template<class F> constexpr auto transform(F&& f) &&;
template<class F> constexpr auto transform(F&& f) const &;
template<class F> constexpr auto transform(F&& f) const &&;
template<class F> constexpr auto transform_error(F&& f) &;
template<class F> constexpr auto transform_error(F&& f) &&;
template<class F> constexpr auto transform_error(F&& f) const &;
template<class F> constexpr auto transform_error(F&& f) const &&;

// 22.8.6.8, equality operators
template<class T2, class E2> requires (!is_void_v<T2>)
friend constexpr bool operator==(const expected& x, const expected<T2, E2>& y);
template<class T2>
friend constexpr bool operator==(const expected&, const T2&);  
template<class E2>
friend constexpr bool operator==(const expected&, const unexpected<E2>&);

private:
    bool has_val;         // exposition only
union {
    T val;                  // exposition only
    E unez;                 // exposition only
};
};

1 Any object of type expected<T, E> either contains a value of type T or a value of type E within its own storage. Implementations are not permitted to use additional storage, such as dynamic memory, to allocate the object of type T or the object of type E. Member has_val indicates whether the expected<T, E> object contains an object of type T.

2 A type T is a valid value type for expected, if remove_cv_t<T> is void or a complete non-array object type that is not in_place_t, unexpect_t, or a specialization of unexpected. A program which instantiates class template expected<T, E> with an argument T that is not a valid value type for expected is ill-formed. A program that instantiates the definition of the template expected<T, E> with a type for the E parameter that is not a valid template argument for unexpected is ill-formed.

3 When T is not cv void, it shall meet the Cpp17Destructible requirements (Table 35). E shall meet the Cpp17Destructible requirements.

22.8.6.2 Constructors

1 The exposition-only variable template converts-from-any-cvref defined in 22.5.3.2 is used by some constructors for expected.
constexpr expected();

Constraints: \( \text{is\_default\_constructible\_v<T> is true.} \)

Effects: Value-initializes \( \text{val} \).

Postconditions: \( \text{has\_value()} \) is true.

Throws: Any exception thrown by the initialization of \( \text{val} \).

call(caller) expected(const expected& rhs);

Effects: If \( \text{rhs.has\_value()} \) is true, direct-non-list-initializes \( \text{val} \) with \( \text{*rhs} \). Otherwise, direct-non-list-initializes \( \text{unex} \) with \( \text{rhs.error()} \).

Postconditions: \( \text{rhs.has\_value()} == \text{this->has\_value()} \).

Throws: Any exception thrown by the initialization of \( \text{val} \) or \( \text{unex} \).

Remarks: This constructor is defined as deleted unless

\( \text{— is\_copy\_constructible\_v<T> is true and} \)
\( \text{— is\_copy\_constructible\_v<E> is true.} \)

This constructor is trivial if

\( \text{— is\_trivially\_copy\_constructible\_v<T> is true and} \)
\( \text{— is\_trivially\_copy\_constructible\_v<E> is true.} \)

call(caller) expected(expected&& rhs) noexcept(see below);

Constraints:

\( \text{— is\_move\_constructible\_v<T> is true and} \)
\( \text{— is\_move\_constructible\_v<E> is true.} \)

Effects: If \( \text{rhs.has\_value()} \) is true, direct-non-list-initializes \( \text{val} \) with \( \text{std::move(\text{*rhs})} \). Otherwise, direct-non-list-initializes \( \text{unex} \) with \( \text{std::move(\text{rhs.error()})} \).

Postconditions: \( \text{rhs.has\_value()} \) is unchanged; \( \text{rhs.has\_value()} == \text{this->has\_value()} \) is true.

Throws: Any exception thrown by the initialization of \( \text{val} \) or \( \text{unex} \).

Remarks: The exception specification is equivalent to \( \text{is\_nothrow\_move\_constructible\_v<T>} \) \&\& \( \text{is\_nothrow\_move\_constructible\_v<E>} \).

This constructor is trivial if

\( \text{— is\_trivially\_move\_constructible\_v<T> is true and} \)
\( \text{— is\_trivially\_move\_constructible\_v<E> is true.} \)

template<class U, class G>
call(caller) constexpr explicit(see below) expected(const expected<U, G>& rhs);

template<class U, class G>
call(caller) constexpr explicit(see below) expected(expected<U, G>&& rhs);

Let:

\( \text{— UF be const U\& for the first overload and U for the second overload.} \)
\( \text{— GF be const G\& for the first overload and G for the second overload.} \)

Constraints:

\( \text{— is\_constructible\_v<T, UF> is true; and} \)
\( \text{— is\_constructible\_v<E, GF> is true; and} \)
\( \text{— if T is not cv bool, converts\_from\_any\_cvref\_v<T, expected\_v<G>, U>> is false; and} \)
\( \text{— is\_constructible\_v\_unexpected\_v\_expected\_v<U, G>, expected\_v<G, U>> is false; and} \)
\( \text{— is\_constructible\_v\_unexpected\_v\_expected\_v<U, G>> is false; and} \)
\( \text{— is\_constructible\_v\_unexpected\_v\_expected\_v<U, G>> is false; and} \)
\( \text{— is\_constructible\_v\_unexpected\_v\_expected\_v<U, G>> is false.} \)
Effects: If \( \text{rhs}.\text{has\_value}() \), direct-non-list-initializes \( \text{val} \) with \( \text{std}::\text{forward<UF>}(*\text{rhs}) \). Otherwise, direct-non-list-initializes \( \text{unex} \) with \( \text{std}::\text{forward<GF>}(\text{rhs}.\text{error})() \).

Postconditions: \( \text{rhs}.\text{has\_value}() \) is unchanged; \( \text{rhs}.\text{has\_value}() == \text{this->has\_value}() \) is true.

Throws: Any exception thrown by the initialization of \( \text{val} \) or \( \text{unex} \).

Remarks: The expression inside explicit is equivalent to \(!\text{is\_convertible\_v<UF, T> || !\text{is\_convertible\_v<GF, E>}}\).

\[
\text{template<class U = T>}
\]
\[
\text{constexpr explicit(!is\_convertible\_v<U, T>) expected(U&& v);}
\]

Constraints:

\[(23.1)\] is\_same\_v<remove\_cvref\_t<U>, in\_place\_t> is false; and

\[(23.2)\] is\_same\_v<expected, remove\_cvref\_t<U>> is false; and

\[(23.3)\] remove\_cvref\_t<U> is not a specialization of unexpected; and

\[(23.4)\] is\_constructible\_v<T, U> is true; and

\[(23.5)\] if \( T \) is cv bool, remove\_cvref\_t<U> is not a specialization of expected.

Effects: Direct-non-list-initializes \( \text{val} \) with \( \text{std}::\text{forward<U>}(v) \).

Postconditions: \( \text{has\_value}() \) is true.

| 24 | Throws: Any exception thrown by the initialization of \( \text{val} \). |

\[
\text{template<class G>}
\]
\[
\text{constexpr explicit(!is\_convertible\_v<const G&, E>) expected(const unexpected<G>& e);}
\]

\[
\text{template<class G>}
\]
\[
\text{constexpr explicit(!is\_convertible\_v<G, E>) expected(unexpected<G>&& e);} \]

Let GF be const G& for the first overload and G for the second overload.

Constraints: \( \text{is\_constructible\_v<E, GF> is true} \).

Effects: Direct-non-list-initializes \( \text{unex} \) with \( \text{std}::\text{forward<GF>}(e.\text{error})() \).

Postconditions: \( \text{has\_value}() \) is false.

| 31 | Throws: Any exception thrown by the initialization of \( \text{unex} \). |

\[
\text{template<class... Args>}
\]
\[
\text{constexpr expected(in\_place\_t, Args&&... args);} \]

Constraints: \( \text{is\_constructible\_v<T, Args...> is true} \).

Effects: Direct-non-list-initializes \( \text{val} \) with \( \text{std}::\text{forward<Args>}(args)... \).

Postconditions: \( \text{has\_value}() \) is true.

| 35 | Throws: Any exception thrown by the initialization of \( \text{val} \). |

\[
\text{template<class U, class... Args>}
\]
\[
\text{constexpr expected(in\_place\_t, initializer\_list<U> il, Args&&... args);} \]

Constraints: \( \text{is\_constructible\_v<T, initializer\_list<U>&, Args...> is true} \).

Effects: Direct-non-list-initializes \( \text{val} \) with \( \text{il}, \text{std}::\text{forward<Args>}(args)... \).

Postconditions: \( \text{has\_value}() \) is true.

| 39 | Throws: Any exception thrown by the initialization of \( \text{val} \). |

\[
\text{template<class... Args>}
\]
\[
\text{constexpr expected(unexpect\_t, Args&&... args);} \]

Constraints: \( \text{is\_constructible\_v<E, Args...> is true} \).

Effects: Direct-non-list-initializes \( \text{unex} \) with \( \text{std}::\text{forward<Args>}(args)... \).

Postconditions: \( \text{has\_value}() \) is false.

| 43 | Throws: Any exception thrown by the initialization of \( \text{unex} \). |
template<class U, class... Args>
constexpr explicit expected(unexpect_t, initializer_list<U> il, Args&&... args);

44 Constraints: \text{is\_constructible\_v}<E, initializer\_list<U>&, Args...> is true.
45 Effects: Direct-non-list-initializes \text{unex} with \text{il}, std::forward<Args>(args)....
46 Postconditions: has\_value() is false.
47 Throws: Any exception thrown by the initialization of \text{unex}.

22.8.6.3 Destructor

constexpr ~expected();

1 Effects: If has\_value() is true, destroys \text{val}, otherwise destroys \text{unex}.
2 Remarks: If \text{is\_trivially\_destructible\_v}<T> is true, and \text{is\_trivially\_destructible\_v}<E> is true, then this destructor is a trivial destructor.

22.8.6.4 Assignment

1 This subclause makes use of the following exposition-only function template:

```cpp
template<class T, class U, class... Args>
constexpr void reinit-expected(T& newval, U& oldval, Args&&... args) {
    // exposition only
    if constexpr (is_nothrow_constructible_v<T, Args...>) {
        destroy_at(addressof(oldval));
        construct_at(addressof(newval), std::forward<Args>(args)...);
    } else if constexpr (is_nothrow_move_constructible_v<T>) {
        T tmp(std::forward<Args>(args)...);
        destroy_at(addressof(oldval));
        construct_at(addressof(newval), std::move(tmp));
    } else {
        U tmp(std::move(oldval));
        destroy_at(addressof(oldval));
        try {
            construct_at(addressof(newval), std::forward<Args>(args)...);
        } catch (...) {
            construct_at(addressof(oldval), std::move(tmp));
            throw;
        }
    }
}
```

constexpr expected& operator=(const expected& rhs);

1 Effects:
(2.1) If this->has\_value() && rhs.has\_value() is true, equivalent to \text{val} = *rhs.
(2.2) Otherwise, if this->has\_value() is true, equivalent to:
\hspace{1cm} \text{reinit-expected}(\text{unex}, \text{val}, rhs.error())
(2.3) Otherwise, if rhs.has\_value() is true, equivalent to:
\hspace{1cm} \text{reinit-expected}((\text{val}, \text{unex}, *rhs)
(2.4) Otherwise, equivalent to \text{unex} = rhs.error().

Then, if no exception was thrown, equivalent to: has\_val = rhs.has\_value(); return *this;

Returns: *this.

2 Remarks: This operator is defined as deleted unless:
(4.1) \text{is\_copy\_assignable\_v}<T> is true and
(4.2) \text{is\_copy\_constructible\_v}<T> is true and
(4.3) \text{is\_copy\_assignable\_v}<E> is true and
(4.4) \text{is\_copy\_constructible\_v}<E> is true and
(4.5) \text{is\_nothrow\_move\_constructible\_v}<T> || \text{is\_nothrow\_move\_constructible\_v}<E> is true.
```cpp
constexpr expected& operator=(expected&& rhs) noexcept(see below);

Constraints:

(5.1) — is_move_constructible_v<T> is true and
(5.2) — is_move_assignable_v<T> is true and
(5.3) — is_move_constructible_v<E> is true and
(5.4) — is_move_assignable_v<E> is true and
(5.5) — is_nothrow_move_constructible_v<T> || is_nothrow_move_constructible_v<E> is true.

Effects:

(6.1) — If this->has_value() && rhs.has_value() is true, equivalent to val = std::move(*rhs).
(6.2) — Otherwise, if this->has_value() is true, equivalent to:
    
    ```cpp
    reinit-expected(unex, val, std::move(rhs.error()))
    ```

(6.3) — Otherwise, if rhs.has_value() is true, equivalent to:

(6.4) — Otherwise, equivalent to unex = std::move(rhs.error()).

Then, if no exception was thrown, equivalent to: has_val = rhs.has_value(); return *this;

Returns: *this.

Remarks: The exception specification is equivalent to:

```cpp
is_nothrow_move_constructorable_v<T> && is_nothrow_move_constructible_v<T> &&
is_nothrow_move_assignable_v<E> && is_nothrow_move_constructible_v<E>
```

```
template<class U = T>
constexpr expected& operator=(U&& v);
```

Constraints:

(9.1) — is_same_v<expected, remove_cvref_t<U>> is false; and
(9.2) — remove_cvref_t<U> is not a specialization of unexpected; and
(9.3) — is_constructible_v<T, U> is true; and
(9.4) — is_assignable_v<T&, U> is true; and
(9.5) — is_nothrow_constructible_v<T, U> || is_nothrow_move_constructible_v<T> ||
    is_nothrow_move_constructible_v<E> is true.

Effects:

(10.1) — If has_value() is true, equivalent to: val = std::forward<U>(v);
(10.2) — Otherwise, equivalent to:

```cpp
reinit-expected(val, unex, std::forward<U>(v));
has_val = true;
``` 

Returns: *this.

```
template<class G>
constexpr expected& operator=(const unexpected<G>& e);
```

```
template<class G>
constexpr expected& operator=(unexpected<G>&& e);
```

Let GF be const G& for the first overload and G for the second overload.

Constraints:

(13.1) — is_constructible_v<E, GF> is true; and
(13.2) — is_assignable_v<E&, GF> is true; and
(13.3) — is_nothrow_constructible_v<E, GF> || is_nothrow_move_constructible_v<T> ||
    is_nothrow_move_constructible_v<E> is true.

Effects:
```
(14.1) If \texttt{has\_value()} is \texttt{true}, equivalent to:
\begin{verbatim}
reinit-expected(unex, val, std::forward<GF>(e.error()));
has_val = false;
\end{verbatim}
(14.2) Otherwise, equivalent to: \texttt{unex = std::forward<GF>(e.error());}

Returns: \texttt{*this}.

template<class... Args>
constexpr T& emplace(Args&&... args) noexcept;

Constraints: \texttt{is\_nothrow\_constructible\_v<T, Args...> is true.}

Effects: Equivalent to:
\begin{verbatim}
if (has_value()) {
    destroy_at(addressof(val));
} else {
    destroy_at(addressof(unex));
    has_val = true;
}
return *construct_at(addressof(val), std::forward<Args>(args)...);
\end{verbatim}

template<class U, class... Args>
constexpr T& emplace(initializer_list<U> il, Args&&... args) noexcept;

Constraints: \texttt{is\_nothrow\_constructible\_v<T, initializer\_list<U>&, Args...> is true.}

Effects: Equivalent to:
\begin{verbatim}
if (has_value()) {
    destroy_at(addressof(val));
} else {
    destroy_at(addressof(unex));
    has_val = true;
}
return *construct_at(addressof(val), il, std::forward<Args>(args)...);
\end{verbatim}

22.8.6.5 Swap [expected.object.swap]

constexpr void swap(expected& rhs) noexcept(see below);

Constraints:
(1.1) \texttt{is\_swappable\_v<T> is true and}
(1.2) \texttt{is\_swappable\_v<E> is true and}
(1.3) \texttt{is\_move\_constructible\_v<T> && is\_move\_constructible\_v<E> is true, and}
(1.4) \texttt{is\_nothrow\_move\_constructible\_v<T> || is\_nothrow\_move\_constructible\_v<E> is true.}

Effects: See Table 67.

Table 67 — swap(expected&) effects [tab:expected.object.swap]

<table>
<thead>
<tr>
<th>\texttt{this-&gt;has_value()}</th>
<th>\texttt{!this-&gt;has_value()}</th>
</tr>
</thead>
</table>
| \texttt{rhs.has\_value()}   | equivalent to: using std::swap;
|                            | swap(val, rhs.val);         |
| \texttt{!rhs.has\_value()}  | equivalent to: using std::swap;
|                            | swap(unex, rhs.unex);       |

For the case where \texttt{rhs.has\_value()} is \texttt{false} and \texttt{this->has\_value()} is \texttt{true}, equivalent to:
\begin{verbatim}
if constexpr (is_nothrow_move_constructible_v<E>) {
    E tmp(std::move(rhs.unex));
    destroy_at(addressof(rhs.unex));
    try {
        construct_at(addressof(rhs.val), std::move(val));
    } catch (std::bad_alloc&) {
        // handle exception
    }
    destroy_at(addressof(val));
}\end{verbatim}
```cpp
construct_at(addressof(unex), std::move(tmp));
} catch(...) {
    construct_at(addressof(rhs.unex), std::move(tmp));
    throw;
} } else {
    T tmp(std::move(val));
    destroy_at(addressof(val));
    try {
        construct_at(addressof(unex), std::move(rhs.unex));
        destroy_at(addressof(rhs.unex));
        construct_at(addressof(rhs.val), std::move(tmp));
    } catch (...) {
        construct_at(addressof(val), std::move(tmp));
        throw;
    } } has_val = false;
    rhs.has_val = true;

Throws: Any exception thrown by the expressions in the Effects.

Remarks: The exception specification is equivalent to:

```cpp
is_nothrow_move_constructible_v<T> && is_nothrow_swappable_v<T>
&& is_nothrow_move_constructible_v<E> && is_nothrow_swappable_v<E>
```

friend constexpr void swap(expected& x, expected& y) noexcept(noexcept(x.swap(y)));

Effects: Equivalent to `x.swap(y)`.

### 22.8.6.6 Observers

```cpp
constexpr const T* operator->() const noexcept;  
constexpr T* operator->() noexcept;  
 Preconditions: has_value() is true.
 Returns: addressof(val).

constexpr const T* operator*() const & noexcept;  
constexpr T* operator*() & noexcept;  
 Preconditions: has_value() is true.
 Returns: val.

constexpr T& operator*() const & noexcept;  
constexpr T& operator*() & noexcept;  
 Preconditions: has_value() is true.
 Returns: val.

constexpr explicit operator bool() const noexcept;  
constexpr bool has_value() const noexcept;  
 Returns: has_val.

constexpr const T value() const &;  
constexpr T value() &;  
 Mandates: is_copy_constructible_v<E> is true.
 Returns: val, if has_value() is true.
 Throws: bad_expected_access(as_const(error())) if has_value() is false.

constexpr T& value() &;  
constexpr T& value() const &;  
 Mandates: is_copy_constructible_v<E> is true and is_constructible_v<E, decltype(std::move(error()))> is true.

```
Returns: std::move(val), if has_value() is true.

Throws: bad_expected_access(std::move(error())) if has_value() is false.

constexpr const E& error() const & noexcept;
constexpr E& error() & noexcept;

Preconditions: has_value() is false.

Returns: unex.

template<class U> constexpr T value_or(U&& v) const &;
Mandates: is_copy_constructible_v<T> is true and is_convertible_v<U, T> is true.

Returns: has_value() ? **this : static_cast<T>(std::forward<U>(v)).

template<class G = E> constexpr E error_or(G&& e) const &;
Mandates: is_copy_constructible_v<E> is true and is_convertible_v<G, E> is true.

Returns: std::forward<G>(e) if has_value() is true, error() otherwise.

22.8.6.7 Monadic operations

template<class F> constexpr auto and_then(F&& f) &;
template<class F> constexpr auto and_then(F&& f) const &;
Let U be remove_cvref_t<invoke_result_t<F, decltype((val))>>.

Constraints: is_constructible_v<E, decltype(error())> is true.

Mandates: U is a specialization of expected and is_same_v<U::error_type, E> is true.

Effects: Equivalent to:
if (has_value())
    return invoke(std::forward<F>(f), val);
else
    return U(unexpect, error());

template<class F> constexpr auto and_then(F&& f) &&;
template<class F> constexpr auto and_then(F&& f) const &&;
Let U be remove_cvref_t<invoke_result_t<F, decltype(std::move(val))>>.

Constraints: is_constructible_v<E, decltype(std::move(error()))> is true.

Mandates: U is a specialization of expected and is_same_v<U::error_type, E> is true.

Effects: Equivalent to:
if (has_value())
    return invoke(std::forward<F>(f), std::move(val));
else
    return U(unexpect, std::move(error()));

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Let G be \text{remove_cvref_t}\langle \text{invoke\_result\_t}\langle F, \text{decltype(error())}\rangle\rangle.

Constraints: is\_constructible\_v\langle T, \text{decltype(\langle val\rangle)}\rangle is true.

Mandates: G is a specialization of expected and is\_same\_v\langle G::\text{value\_type}, T\rangle is true.

Effects: Equivalent to:
if (has\_value())
  return G(in\_place, val);
else
  return invoke(std::forward<F>(f), error());

Let G be \text{remove_cvref_t}\langle \text{invoke\_result\_t}\langle F, \text{decltype(std::move(error()))}\rangle\rangle.

Constraints: is\_constructible\_v\langle T, \text{decltype(std::move(val))}\rangle is true.

Mandates: G is a specialization of expected and is\_same\_v\langle G::\text{value\_type}, T\rangle is true.

Effects: Equivalent to:
if (has\_value())
  return G(in\_place, std::move(val));
else
  return invoke(std::forward<F>(f), std::move(error()));

Let U be \text{remove\_cv\_t}\langle \text{invoke\_result\_t}\langle F, \text{decltype(\langle val\rangle)}\rangle\rangle.

Constraints: is\_constructible\_v\langle E, \text{decltype(error())}\rangle is true.

Mandates: U is a valid value type for expected. If is\_void\_v\langle U\rangle is false, the declaration
U u(invoke(std::forward<F>(f), val));
is well-formed.

Effects:
\begin{enumerate}
\item If has\_value() is false, returns expected\langle U, E\rangle(unexpect, error()).
\item Otherwise, if is\_void\_v\langle U\rangle is false, returns an expected\langle U, E\rangle object whose has\_val member is true and val member is direct-non-list-initialized with invoke(std::forward<F>(f), val).
\item Otherwise, evaluates invoke(std::forward<F>(f), val) and then returns expected\langle U, E\rangle().
\end{enumerate}

Let U be \text{remove\_cv\_t}\langle \text{invoke\_result\_t}\langle F, \text{decltype(std::move(val))}\rangle\rangle.

Constraints: is\_constructible\_v\langle E, \text{decltype(std::move(error()))}\rangle is true.

Mandates: U is a valid value type for expected. If is\_void\_v\langle U\rangle is false, the declaration
U u(invoke(std::forward<F>(f), std::move(val)));
is well-formed.

Effects:
\begin{enumerate}
\item If has\_value() is false, returns expected\langle U, E\rangle(unexpect, std::move(error())).
\item Otherwise, if is\_void\_v\langle U\rangle is false, returns an expected\langle U, E\rangle object whose has\_val member is true and val member is direct-non-list-initialized with invoke(std::forward<F>(f), std::move(val)).
\item Otherwise, evaluates invoke(std::forward<F>(f), std::move(val)) and then returns expected\langle U, E\rangle().
\end{enumerate}
Let \( G \) be \( \text{remove_cv_t<invoke_result_t<F, decltype(error())>>} \).

Constraints: \( \text{is_constructible_v<T, decltype((val))}> \) is true.

Mandates: \( G \) is a valid template argument for \text{unexpected} (22.8.3.1) and the declaration
\[
G \ g(\text{invoke}(\text{std::forward<F>(f)}, \text{error}()));
\]
is well-formed.

Returns: If \( \text{has_value()} \) is true, \text{expected}<T, G>(\text{in_place}, \text{val}); otherwise, an \text{expected}<T, G> object whose \text{has_val} member is false and \text{unex} member is direct-non-list-initialized with \text{invoke}(\text{std::forward<F>(f)}, \text{error}()).

Let \( G \) be \( \text{remove_cv_t<invoke_result_t<F, decltype(std::move(error()))>>} \).

Constraints: \( \text{is_constructible_v<T, decltype(std::move(val))}> \) is true.

Mandates: \( G \) is a valid template argument for \text{unexpected} (22.8.3.1) and the declaration
\[
G \ g(\text{invoke}(\text{std::forward<F>(f)}, \text{std::move(error())}));
\]
is well-formed.

Returns: If \( \text{has_value()} \) is true, \text{expected}<T, G>(\text{in_place, std::move(val)}); otherwise, an \text{expected}<T, G> object whose \text{has_val} member is false and \text{unex} member is direct-non-list-initialized with \text{invoke}(\text{std::forward<F>(f)}, \text{std::move(error())}).

22.8.6.8 Equality operators

```
template<class T2, class E2> requires (!\text{is_void_v<T2>>}
friend constexpr bool operator==(const \text{expected}& x, const \text{expected}<T2, E2>& y);

Mandates: The expressions \( *x == *y \) and \( x.\text{error}() == y.\text{error}() \) are well-formed and their results are convertible to \text{bool}.

Returns: If \( x.\text{has_value()} \) does not equal \( y.\text{has_value()}, \text{false} \); otherwise if \( x.\text{has_value()} \) is true, \( *x == *y \); otherwise \( x.\text{error}() == y.\text{error}() \).
```

```template<class T2> friend constexpr bool operator==(const \text{expected}& x, const T2& v);

Mandates: The expression \( *x == v \) is well-formed and its result is convertible to \text{bool}.

[Note 1: \( T \) need not be \text{Cpp17EqualityComparable}. — end note]

Returns: \( x.\text{has_value()} && \text{static_cast<\text{bool}}>(*x == v) \).
```

```template<class E2> friend constexpr bool operator==(const \text{expected}& x, const \text{unexpected}<E2>& e);

Mandates: The expression \( x.\text{error}() == e.\text{error}() \) is well-formed and its result is convertible to \text{bool}.

Returns: \( !x.\text{has_value()} && \text{static_cast<\text{bool}}>(x.\text{error}() == e.\text{error}()) \).
```

22.8.7 Partial specialization of \text{expected} for \text{void} types

```
22.8.7.1 General

```
```template<T, class E> requires \text{is_void_v<T>}
class \text{expected}<T, E> {
public:
   using value_type = T;
   using error_type = E;
   using unexpected_type = \text{unexpected}<E>;

   template<class U>
   using rebind = \text{expected}<U, error_type>;
```
// 22.8.7.2, constructors
constexpr expected() noexcept;
constexpr expected(const expected&);
constexpr expected(expected&&) noexcept;

template<class U, class G>
constexpr explicit(U, G&&) expected(U, G&&);

template<class G>
constexpr explicit(in_place_t) noexcept;

template<class... Args>
constexpr expected(unexpect_t, Args&&...);

// 22.8.7.3, destructor
constexpr ~expected();

// 22.8.7.4, assignment
constexpr expected& operator=(const expected&);
constexpr expected& operator=(expected&&) noexcept;

template<class G>
constexpr expected& operator=(const unexpected<G>&);

template<class G>
constexpr expected& operator=(unexpected<G>&&);

constexpr void emplace() noexcept;

// 22.8.7.5, swap
constexpr void swap(expected&) noexcept;
friend constexpr void swap(expected& x, expected& y) noexcept(noexcept(x.swap(y)));

// 22.8.7.6, observers
constexpr explicit operator bool() const noexcept;
constexpr bool has_value() const noexcept;
constexpr void operator*() const noexcept;
constexpr void value() const &;
constexpr void value() &&;

constexpr const E& error() const & noexcept;
constexpr E& error() & noexcept;
constexpr const E&& error() const && noexcept;
constexpr E&& error() && noexcept;

template<class G = E> constexpr E error_or(G&&) const &;

// 22.8.7.7, monadic operations
template<class F> constexpr auto and_then(F&& f) &;

template<class F> constexpr auto and_then(F&& f) &&;

template<class F> constexpr auto or_else(F&& f) &;

template<class F> constexpr auto or_else(F&& f) &&;

template<class F> constexpr auto transform(F&& f) &;

template<class F> constexpr auto transform(F&& f) &&;

template<class F> constexpr auto transform_error(F&& f) &;
template<class F> constexpr auto transform_error(F&& f) &&;

// 22.8.7.8, equality operators
template<class T2, class E2> requires is_void_v<T2>
friend constexpr bool operator==(const expected& x, const expected<T2, E2>& y);

private:
    bool has_val;       // exposition only
    union {
        E unex;      // exposition only
    };

1 Any object of type expected<T, E> either represents a value of type T, or contains a value of type E within its own storage. Implementations are not permitted to use additional storage, such as dynamic memory, to allocate the object of type E. Member has_val indicates whether the expected<T, E> object represents a value of type T.

2 A program that instantiates the definition of the template expected<T, E> with a type for the E parameter that is not a valid template argument for unexpected is ill-formed.

3 E shall meet the requirements of Cpp17Destructible (Table 35).

22.8.7.2 Constructors

constexpr expected() noexcept;

Postconditions: has_value() is true.

constexpr expected(const expected& rhs);

Effects: If rhs.has_value() is false, direct-non-list-initializes unex with rhs.error().

Postconditions: rhs.has_value() == this->has_value().

Throws: Any exception thrown by the initialization of unex.

Remarks: This constructor is defined as deleted unless is_copy_constructible_v<E> is true.

This constructor is trivial if is_trivially_copy_constructible_v<E> is true.

constexpr expected(expected&& rhs) noexcept(is_nothrow_move_constructible_v<E>);

Constraints: is_move_constructible_v<E> is true.

Effects: If rhs.has_value() is false, direct-non-list-initializes unex with std::move(rhs.error()).

Postconditions: rhs.has_value() is unchanged; rhs.has_value() == this->has_value() is true.

Throws: Any exception thrown by the initialization of unex.

Remarks: This constructor is trivial if is_trivially_move_constructible_v<E> is true.

template<class U, class G>
constexpr explicit(!is_convertible_v<const G&, E>) expected(const expected<U, G>&& rhs);

template<class U, class G>
constexpr explicit(!is_convertible_v<G, E>) expected(U&& u, E&& e);
— is_constructible_v<unexpected<E>, const expected<U, G>> is false.

Effects: If rhs.has_value() is false, direct-non-list-initializes unez with std::forward<GF>(rhs.error()).
Postconditions: rhs.has_value() is unchanged; rhs.has_value() == this->has_value() is true.
Throws: Any exception thrown by the initialization of unez.

template<class G>
constexpr explicit(!is_convertible_v<const G&, E>) expected(const unexpected<G>& e);
template<class G>
constexpr explicit(!is_convertible_v<G, E>) expected(unexpected<G>&& e);

Let GF be const G& for the first overload and G for the second overload.
Constraints: is_constructible_v<E, GF> is true.
Effects: Direct-non-list-initializes unez with std::forward<GF>(e.error()).
Postconditions: has_value() is false.
Throws: Any exception thrown by the initialization of unez.

constexpr explicit expected(in_place_t) noexcept;

Postconditions: has_value() is false.

constexpr ~expected();

Effects: If has_value() is false, destroys unez.
Remarks: If is_trivially_destructible_v<E> is true, then this destructor is a trivial destructor.

22.8.7.4 Assignment [expected.void.assign]

constexpr expected& operator=(const expected& rhs);

Effects:
(1.1) — If this->has_value() & rhs.has_value() is true, no effects.
(1.2) — Otherwise, if this->has_value() is true, equivalent to: construct_at(addressof(unez), rhs.unez); has_val = false;
(1.3) — Otherwise, if rhs.has_value() is true, destroys unez and sets has_val to true.
(1.4) — Otherwise, equivalent to unez = rhs.error().

Returns: *this.
Remarks: This operator is defined as deleted unless is_copyAssignable_v<E> is true and is_copy_constructible_v<E> is true.
constexpr expected& operator=(expected&& rhs) noexcept(see below);

Constraints: is_move_constructible_v<E> is true and is_move_assignable_v<E> is true.

Effects:

(5.1) — If this->has_value() && rhs.has_value() is true, no effects.
(5.2) — Otherwise, if this->has_value() is true, equivalent to:
      construct_at(addressof(unex), std::move(rhs.unex));
      has_val = false;
(5.3) — Otherwise, if rhs.has_value() is true, destroys unex and sets has_val to true.
(5.4) — Otherwise, equivalent to unex = std::move(rhs.error()).

Returns: *this.

Remarks: The exception specification is equivalent to is_nothrow_move_constructible_v<E> &&
          is_nothrow_move_assignable_v<E>.

template<class G>
constexpr expected& operator=(const unexpected<G>& e);

template<class G>
constexpr expected& operator=(unexpected<G>&& e);

Let GF be const G& for the first overload and G for the second overload.

Constraints: is_constructible_v<E, GF> is true and is_assignable_v<E&, GF> is true.

Effects:

(10.1) — If has_value() is true, equivalent to:
       construct_at(addressof(unex), std::forward<GF>(e.error()));
       has_val = false;
(10.2) — Otherwise, equivalent to: unex = std::forward<GF>(e.error());

Returns: *this.

cstexpr void emplace() noexcept;

Effects: If has_value() is false, destroys unex and sets has_val to true.

22.8.7.5 Swap [expected::void.swap]

constexpr void swap(expected& rhs) noexcept(see below);

Constraints: is_swappable_v<E> is true and is_move_constructible_v<E> is true.

Effects: See Table 68.

Table 68 — swap(expected&) effects [tab:expected::void.swap]

<table>
<thead>
<tr>
<th>this-&gt;has_value()</th>
<th>!this-&gt;has_value()</th>
</tr>
</thead>
<tbody>
<tr>
<td>rhs.has_value()</td>
<td>no effects</td>
</tr>
<tr>
<td>!rhs.has_value()</td>
<td>see below</td>
</tr>
<tr>
<td></td>
<td>calls rhs.swap(*this)</td>
</tr>
<tr>
<td></td>
<td>equivalent to: using std::swap;</td>
</tr>
<tr>
<td></td>
<td>swap(unex, rhs.unex);</td>
</tr>
</tbody>
</table>

For the case where rhs.has_value() is false and this->has_value() is true, equivalent to:

construct_at(addressof(unex), std::move(rhs.unex));
destroy_at(addressof(rhs.unex));
has_val = false;
 rhs.has_val = true;

Throws: Any exception thrown by the expressions in the Effects.

Remarks: The exception specification is equivalent to is_nothrow_move_constructible_v<E> &&
          is_nothrow_swappable_v<E>.  

§ 22.8.7.5 © ISO/IEC 774
friend constexpr void swap(expected& x, expected& y) noexcept(noexcept(x.swap(y)));  

**Effects:** Equivalent to x.swap(y).

### 22.8.7.6 Observers

```cpp
constexpr explicit operator bool() const noexcept;
constexpr bool has_value() const noexcept;
```

**Returns:** has_val.

```cpp
constexpr void operator*() const noexcept;
```

**Preconditions:** has_value() is true.

```cpp
constexpr void value() const &;
```

**Mandates:** is_copy_constructible_v<E> is true.

**Throws:** bad_expected_access(error()) if has_value() is false.

```cpp
constexpr void value() &&;
```

**Mandates:** is_copy_constructible_v<E> is true and is_move_constructible_v<E> is true.

**Throws:** bad_expected_access(std::move(error())) if has_value() is false.

```cpp
constexpr const E& error() const & noexcept;
constexpr E& error() & noexcept;
```

**Preconditions:** has_value() is false.

```cpp
constexpr E&& error() && noexcept;
```

**Preconditions:** has_value() is false.

```cpp
template<class G = E> constexpr E error_or(G&& e) const &;
```

**Mandates:** is_copy_constructible_v<E> is true and is_convertible_v<G, E> is true.

**Returns:** std::forward<G>(e) if has_value() is true, error() otherwise.

```cpp
template<class G = E> constexpr E error_or(G&& e) &&;
```

**Mandates:** is_move_constructible_v<E> is true and is_convertible_v<G, E> is true.

**Returns:** std::move(error()) if has_value() is false, std::move(error()) otherwise.

### 22.8.7.7 Monadic operations

```cpp
template<class F> constexpr auto and_then(F&& f) &;
template<class F> constexpr auto and_then(F&& f) const &;
```

**Let U be remove_cvref_t<invoke_result_t<F>>.**

**Constraints:** is_constructible_v<E, decltype(error())> is true.

**Mandates:** U is a specialization of expected and is_same_v<u::error_type, E> is true.

**Effects:** Equivalent to:

```cpp
if (has_value())
   return invoke(std::forward<F>(f));
else
   return U(unexpect, error());
```

```cpp
template<class F> constexpr auto and_then(F&& f) &&;
template<class F> constexpr auto and_then(F&& f) const &&;
```

**Let U be remove_cvref_t<invoke_result_t<F>>.**

**Constraints:** is_constructible_v<E, decltype(std::move(error()))> is true.
Mandates: U is a specialization of `expected` and `is_same_v<U::error_type, E>` is true.

Effects: Equivalent to:

```cpp
doxygen
if (has_value())
    return invoke(std::forward<F>(f));
else
    return U(unexpect, std::move(error()));
```

template<class F> constexpr auto or_else(F&& f) &;  
template<class F> constexpr auto or_else(F&& f) const &;

Let G be `remove_cvref_t<invoke_result_t<F, decltype(error())>>`.

Mandates: G is a specialization of `expected` and `is_same_v<G::value_type, T>` is true.

Effects: Equivalent to:

```cpp
doxygen
if (has_value())
    return G();
else
    return invoke(std::forward<F>(f), error());
```

template<class F> constexpr auto or_else(F&& f) &&;  
template<class F> constexpr auto or_else(F&& f) const &&;

Let U be `remove_cv_t<invoke_result_t<F, decltype(error())>>`.

Mandates: U is a valid value type for `expected`. If `is_void_v<U>` is false, the declaration

```cpp
doxygen
U u(invoke(std::forward<F>(f)));  
```

is well-formed.

Effects:

(22.1) — If has_value() is false, returns expected<U, E>(unexpected, error()).

(22.2) — Otherwise, if is_void_v<U is false, returns an expected<U, E> object whose has_val member is true and val member is direct-non-list-initialized with invoke(std::forward<F>(f)).

(22.3) — Otherwise, evaluates invoke(std::forward<F>(f)) and then returns expected<U, E>().

§ 22.8.7.7 © ISO/IEC 776
template<class F> constexpr auto transform_error(F&& f) &;
    template<class F> constexpr auto transform_error(F&& f) const &;
Let G be remove_cv_t<invoke_result_t<F, decltype(error())>>.
Mandates: G is a valid template argument for unexpected (22.8.3.1) and the declaration
          G g(invoke(std::forward<F>(f), error()));
          is well-formed.
Returns: If has_value() is true, expected<T, G>(); otherwise, an expected<T, G> object whose
          has_val member is false and unex member is direct-non-list-initialized with invoke(std::for-
          ward<F>(f), error()).

template<class F> constexpr auto transform_error(F&& f) &&;
    template<class F> constexpr auto transform_error(F&& f) const &&;
Let G be remove_cv_t<invoke_result_t<F, decltype(std::move(error()))>>.
Mandates: G is a valid template argument for unexpected (22.8.3.1) and the declaration
          G g(invoke(std::forward<F>(f), std::move(error())));
          is well-formed.
Returns: If has_value() is true, expected<T, G>(); otherwise, an expected<T, G> object whose
          has_val member is false and unex member is direct-non-list-initialized with invoke(std::for-
          ward<F>(f), std::move(error())).

22.8.7.8 Equality operators [expected.void.eq]

    template<class T2, class E2> requires is_void_v<T2>
    friend constexpr bool operator==(const expected& x, const expected<T2, E2>& y);
    Mandates: The expression x.error() == y.error() is well-formed and its result is convertible to
              bool.
    Returns: If x.has_value() does not equal y.has_value(), false; otherwise x.has_value() ||
              static_cast<bool>(x.error() == y.error()).

    template<class E2>
    friend constexpr bool operator==(const expected& x, const unexpected<E2>& e);
    Mandates: The expression x.error() == e.error() is well-formed and its result is convertible to
              bool.
    Returns: !x.has_value() && static_cast<bool>(x.error() == e.error()).

22.9 Bitsets [bitset]
22.9.1 Header <bitset> synopsis [bitset.syn]
The header <bitset> defines a class template and several related functions for representing and manipulating
fixed-size sequences of bits.

#include <string>  // see 23.4.2
#include <iosfwd>  // for istream (31.7.1), ostream (31.7.2), see 31.3.1

namespace std {
    template<size_t N> class bitset;

    // 22.9.4, bitset operators
    template<size_t N>
    constexpr bitset<N> operator&(const bitset<N>&, const bitset<N>&) noexcept;
    template<size_t N>
    constexpr bitset<N> operator|(const bitset<N>&, const bitset<N>&) noexcept;
    template<size_t N>
    constexpr bitset<N> operator^(const bitset<N>&, const bitset<N>&) noexcept;

} // namespace std

§ 22.9.1
22.9.2 Class template bitset

22.9.2.1 General

namespace std {
    template<size_t N> class bitset {
        public:
            // bit reference
            class reference {
                friend class bitset;
                constexpr reference() noexcept;
                constexpr reference(const reference&) = default;
                constexpr ~reference();
                constexpr reference& operator=(bool x) noexcept;
                constexpr reference& operator=(const reference&) noexcept;
                constexpr bool operator~() const noexcept;
                constexpr operator bool() const noexcept;
                constexpr reference& flip() noexcept;
            };

        // 22.9.2.2, constructors
        constexpr bitset() noexcept;
        constexpr bitset(unsigned long long val) noexcept;
        template<class charT, class traits, class Allocator>
        constexpr explicit bitset(
            const basic_string<charT, traits, Allocator>& str,
            typename basic_string<charT, traits, Allocator>::size_type pos = 0,
            typename basic_string<charT, traits, Allocator>::size_type n = basic_string<charT, traits, Allocator>::npos,
            charT zero = charT('0'),
            charT one = charT('1'));
        template<class charT, class traits>
        constexpr explicit bitset(
            const charT* str,
            typename basic_string_view<charT>::size_type n = basic_string_view<charT>::npos,
            charT zero = charT('0'),
            charT one = charT('1'));

        // 22.9.2.3, bitset operations
        constexpr bitset& operator&=(const bitset& rhs) noexcept;
        constexpr bitset& operator|=(const bitset& rhs) noexcept;
        constexpr bitset& operator^=(const bitset& rhs) noexcept;
        constexpr bitset& operator<<=(size_t pos) noexcept;
        constexpr bitset& operator>>=(size_t pos) noexcept;
        constexpr bitset operator<<(size_t pos) const noexcept;
        constexpr bitset operator>>(size_t pos) const noexcept;
        constexpr bitset& set() noexcept;
    };
}
consts

```cpp
constexpr bitset& set(size_t pos, bool val = true);
constexpr bitset& reset() noexcept;
constexpr bitset& reset(size_t pos);
constexpr bitset& flip() noexcept;
constexpr bitset& flip(size_t pos);
```

// element access
```cpp
constexpr bool operator[](size_t pos) const;
constexpr reference operator[](size_t pos);
```

```cpp
constexpr unsigned long to_ulong() const;
constexpr unsigned long long to_ullong() const;
```

```cpp
template<class charT = char,
    class traits = char_traits<charT>,
    class Allocator = allocator<charT>>
constexpr basic_string<charT, traits, Allocator>
to_string(charT zero = charT('0'), charT one = charT('1')) const;
```

// observers
```cpp
constexpr size_t count() const noexcept;
constexpr size_t size() const noexcept;
constexpr bool operator==(const bitset& rhs) const noexcept;
constexpr bool test(size_t pos) const;
constexpr bool all() const noexcept;
constexpr bool any() const noexcept;
constexpr bool none() const noexcept;
```

1. The class template `bitset<N>` describes an object that can store a sequence consisting of a fixed number of bits, N.
2. Each bit represents either the value zero (reset) or one (set). To toggle a bit is to change the value zero to one, or the value one to zero. Each bit has a non-negative position pos. When converting between an object of class `bitset<N>` and a value of some integral type, bit position pos corresponds to the bit value `1 << pos`. The integral value corresponding to two or more bits is the sum of their bit values.
3. The functions described in §22.9.2 can report three kinds of errors, each associated with a distinct exception:
   - an invalid-argument error is associated with exceptions of type `invalid_argument` (19.2.5);
   - an out-of-range error is associated with exceptions of type `out_of_range` (19.2.7);
   - an overflow error is associated with exceptions of type `overflow_error` (19.2.10).

22.9.2.2 Constructors

```cpp
constexpr bitset() noexcept;
```

1. Effects: Initializes all bits in *this to zero.

```cpp
constexpr bitset(unsigned long long val) noexcept;
```

2. Effects: Initializes the first M bit positions to the corresponding bit values in val. M is the smaller of N and the number of bits in the value representation (6.8.1) of `unsigned long long`. If M < N, the remaining bit positions are initialized to zero.

```cpp
template<class charT, class traits, class Allocator>
constexpr explicit bitset(
    const basic_string<charT, traits, Allocator>& str,
    typename basic_string<charT, traits, Allocator>::size_type pos = 0,
    typename basic_string<charT, traits, Allocator>::size_type n = basic_string<charT, traits, Allocator>::npos,
);```

§ 22.9.2.2 ©ISO/IEC 779
charT zero = charT('0'),
charT one = charT('1'));

template<class charT, class traits>
constexpr explicit bitset(
    basic_string_view<charT, traits> str,
    typename basic_string_view<charT, traits>::size_type pos = 0,
    typename basic_string_view<charT, traits>::size_type n
    = basic_string_view<charT, traits>::npos,
    charT zero = charT('0'),
    charT one = charT('1'));

Effects: Determines the effective length rlen of the initializing string as the smaller of n and str.size() - pos. Initializes the first M bit positions to values determined from the corresponding characters in the string str. M is the smaller of N and rlen.

An element of the constructed object has value zero if the corresponding character in str, beginning at position pos, is zero. Otherwise, the element has the value one. Character position pos + M - 1 corresponds to bit position zero. Subsequent decreasing character positions correspond to increasing bit positions.

If M < N, remaining bit positions are initialized to zero.

The function uses traits::eq to compare the character values.

Throws: out_of_range if pos > str.size() or invalid_argument if any of the rlen characters in str beginning at position pos is other than zero or one.

Effects: As if by:
bitset(n == basic_string_view<charT>::npos
 ? basic_string_view<charT>(str)
 : basic_string_view<charT>(str, n),
 0, n, zero, one)

22.9.2.3 Members

constexpr bitset& operator&=(const bitset& rhs) noexcept;
Effects: Clears each bit in *this for which the corresponding bit in rhs is clear, and leaves all other bits unchanged.
Returns: *this.

constexpr bitset& operator|=(const bitset& rhs) noexcept;
Effects: Sets each bit in *this for which the corresponding bit in rhs is set, and leaves all other bits unchanged.
Returns: *this.

constexpr bitset& operator^=(const bitset& rhs) noexcept;
Effects: Toggles each bit in *this for which the corresponding bit in rhs is set, and leaves all other bits unchanged.
Returns: *this.

constexpr bitset& operator<<=(size_t pos) noexcept;
Effects: Replaces each bit at position I in *this with a value determined as follows:

(7.1) — If I < pos, the new value is zero;

(7.2) — If I >= pos, the new value is the previous value of the bit at position I - pos.

Returns: *this.
constexpr bitset& operator>>(size_t pos) noexcept;

Effects: Replaces each bit at position I in *this with a value determined as follows:
(9.1) If pos >= N - I, the new value is zero;
(9.2) If pos < N - I, the new value is the previous value of the bit at position I + pos.

Returns: *this.

constexpr bitset operator<<(size_t pos) const noexcept;

Returns: bitset(*this) <<= pos.

constexpr bitset operator>>(size_t pos) const noexcept;

Returns: bitset(*this) >>= pos.

constexpr bitset& set() noexcept;

Effects: Sets all bits in *this.

Returns: *this.

constexpr bitset& set(size_t pos, bool val = true);

Effects: Stores a new value in the bit at position pos in *this. If val is true, the stored value is one, otherwise it is zero.

Returns: *this.

Throws: out_of_range if pos does not correspond to a valid bit position.

constexpr bitset& reset() noexcept;

Effects: Resets all bits in *this.

Returns: *this.

constexpr bitset& reset(size_t pos);

Effects: Resets the bit at position pos in *this.

Returns: *this.

Throws: out_of_range if pos does not correspond to a valid bit position.

constexpr bitset operator~() const noexcept;

Effects: Constructs an object x of class bitset and initializes it with *this.

Returns: x.flip().

constexpr bitset& flip() noexcept;

Effects: Toggles all bits in *this.

Returns: *this.

constexpr bitset& flip(size_t pos);

Effects: Toggles the bit at position pos in *this.

Returns: *this.

Throws: out_of_range if pos does not correspond to a valid bit position.

constexpr bool operator[](size_t pos) const;

Preconditions: pos is valid.

Returns: true if the bit at position pos in *this has the value one, otherwise false.

Throws: Nothing.

constexpr bitset::reference operator[](size_t pos);

Preconditions: pos is valid.
Returns: An object of type `bitset::reference` such that `(*this)[pos] == this->test(pos)`, and such that `(*this)[pos] = val` is equivalent to `this->set(pos, val)`.

Throws: Nothing.

Remarks: For the purpose of determining the presence of a data race (6.9.2), any access or update through the resulting reference potentially accesses or modifies, respectively, the entire underlying bitset.

```cpp
constexpr unsigned long to_ulong() const;
```

Returns: `x`.

Throws: `overflow_error` if the integral value `x` corresponding to the bits in `*this` cannot be represented as type `unsigned long`.

```cpp
constexpr unsigned long long to_ullong() const;
```

Returns: `x`.

Throws: `overflow_error` if the integral value `x` corresponding to the bits in `*this` cannot be represented as type `unsigned long long`.

```cpp
template<class charT = char,
         class traits = char_traits<charT>,
         class Allocator = allocator<charT>>
constexpr basic_string<charT, traits, Allocator>
to_string(charT zero = charT('0'), charT one = charT('1')) const;
```

Effects: Constructs a string object of the appropriate type and initializes it to a string of length `N` characters. Each character is determined by the value of its corresponding bit position in `*this`. Character position `N - 1` corresponds to bit position zero. Subsequent decreasing character positions correspond to increasing bit positions. Bit value zero becomes the character `zero`, bit value one becomes the character `one`.

Returns: The created object.

```cpp
constexpr size_t count() const noexcept;
```

Returns: A count of the number of bits set in `*this`.

```cpp
constexpr size_t size() const noexcept;
```

Returns: `N`.

```cpp
constexpr bool operator==(const bitset& rhs) const noexcept;
```

Returns: `true` if the value of each bit in `*this` equals the value of the corresponding bit in `rhs`.

```cpp
constexpr bool test(size_t pos) const;
```

Returns: `true` if the bit at position `pos` in `*this` has the value one.

Throws: `out_of_range` if `pos` does not correspond to a valid bit position.

```cpp
constexpr bool all() const noexcept;
```

Returns: `count() == size()`.

```cpp
constexpr bool any() const noexcept;
```

Returns: `count() != 0`.

```cpp
constexpr bool none() const noexcept;
```

Returns: `count() == 0`.

### 22.9.3 bitset hash support

```cpp
template<Size_t N> struct hash<bitset<N>>;
```

The specialization is enabled (22.10.19).
22.9.4 bitset operators

```cpp
template<size_t N>
constexpr bitset<N> operator&(const bitset<N>& lhs, const bitset<N>& rhs) noexcept;

template<size_t N>
constexpr bitset<N> operator|(const bitset<N>& lhs, const bitset<N>& rhs) noexcept;

template<size_t N>
constexpr bitset<N> operator^(const bitset<N>& lhs, const bitset<N>& rhs) noexcept;
```

22.10 Function objects

22.10.1 General

A function object type is an object type (6.8.1) that can be the type of the postfix-expression in a function call (7.6.1.3, 12.2.2.2). A function object is an object of a function object type. In the places where one would expect to pass a pointer to a function to an algorithmic template (Clause 27), the interface is specified to accept a function object. This not only makes algorithmic templates work with pointers to functions, but also enables them to work with arbitrary function objects.

22.10.2 Header <functional> synopsis

```cpp
namespace std {
  // 22.10.5, invoke
  template<class F, class... Args>
  constexpr invoke_result_t<F, Args...> invoke(F&& f, Args&&... args) noexcept
    (is_nothrow_invocable_v<F, Args...>);  // freestanding
```

198) Such a type is a function pointer or a class type which has a member operator() or a class type which has a conversion to a pointer to function.
template<class R, class F, class... Args>
constexpr R invoke_r(F&& f, Args&&... args) noexcept(is_nothrow_invocable_r_v<R, F, Args...>);

// 22.10.6, reference_wrapper
template<class T> class reference_wrapper; // freestanding

template<class T> constexpr reference_wrapper<T> ref(T&) noexcept; // freestanding
template<class T> constexpr reference_wrapper<const T> cref(const T&) noexcept; // freestanding
template<class T> void ref(const T&) = delete; // freestanding
template<class T> void cref(const T&) = delete; // freestanding

template<class T>
constexpr reference_wrapper<T> ref(reference_wrapper<T>) noexcept; // freestanding
template<class T>
constexpr reference_wrapper<const T> cref(reference_wrapper<T>) noexcept; // freestanding

// 22.10.6.8, common_reference related specializations
template<class R, class T, template<class> class RQual, template<class> class TQual>
requires see below
struct basic_common_reference<R, T, RQual, TQual>;

template<class T, class R, template<class> class TQual, template<class> class RQual>
requires see below
struct basic_common_reference<T, R, TQual, RQual>;

// 22.10.7, arithmetic operations
template<class T = void> struct plus; // freestanding
template<class T = void> struct minus; // freestanding
template<class T = void> struct multiplies; // freestanding
template<class T = void> struct divides; // freestanding
template<class T = void> struct modulus; // freestanding
template<class T = void> struct negate; // freestanding

template<> struct plus<void>; // freestanding
template<> struct minus<void>; // freestanding
template<> struct multiplies<void>; // freestanding
template<> struct divides<void>; // freestanding
template<> struct modulus<void>; // freestanding
template<> struct negate<void>; // freestanding

// 22.10.8, comparisons
template<class T = void> struct equal_to; // freestanding
template<class T = void> struct not_equal_to; // freestanding
template<class T = void> struct greater; // freestanding
template<class T = void> struct less; // freestanding
template<class T = void> struct greater_equal; // freestanding
template<class T = void> struct less_equal; // freestanding

template<> struct equal_to<void>; // freestanding
template<> struct not_equal_to<void>; // freestanding
template<> struct greater<void>; // freestanding
template<> struct less<void>; // freestanding
template<> struct greater_equal<void>; // freestanding
template<> struct less_equal<void>; // freestanding

// 22.10.8.8, class compare_three_way
struct compare_three_way; // freestanding

// 22.10.10, logical operations
template<class T = void> struct logical_and; // freestanding
template<class T = void> struct logical_or; // freestanding
template<class T = void> struct logical_not; // freestanding

template<> struct logical_and<void>; // freestanding
template<> struct logical_or<void>; // freestanding
template<> struct logical_not<void>; // freestanding

§ 22.10.2
// 22.10.11, bitwise operations
template<class T = void> struct bit_and; // freestanding
template<class T = void> struct bit_or; // freestanding
template<class T = void> struct bit_xor; // freestanding
template<class T = void> struct bit_not; // freestanding
template<> struct bit_and<void>; // freestanding
template<> struct bit_or<void>; // freestanding
template<> struct bit_xor<void>; // freestanding
template<> struct bit_not<void>; // freestanding

// 22.10.12, identity
struct identity; // freestanding

// 22.10.13, function template not_fn
template<class F> constexpr unspecified not_fn(F&& f); // freestanding
template<class F> constexpr unspecified not_fn() noexcept; // freestanding

// 22.10.14, function templates bind_front and bind_back
template<class F, class... Args> constexpr unspecified bind_front(F&&, Args&&...); // freestanding
template<class F, class... Args> constexpr unspecified bind_front(Args&&...); // freestanding
template<class F, class... Args> constexpr unspecified bind_back(F&&, Args&&...); // freestanding
template<class F, class... Args> constexpr unspecified bind_back(Args&&...); // freestanding

// 22.10.15, bind
template<class T> struct is_bind_expression; // freestanding
template<class T> constexpr bool is_bind_expression_v = is_bind_expression<T>::value; // freestanding

namespace placeholders {
    // M is the implementation-defined number of placeholders
    see below _1; // freestanding
    see below _2; // freestanding
    .
    .
    see below _M; // freestanding
}

// 22.10.16, member function adaptors
template<class R, class T> constexpr unspecified mem_fn(R T::*); // freestanding

// 22.10.17, polymorphic function wrappers
// 22.10.17.2, class bad_function_call
class bad_function_call;

// 22.10.17.3, class template function
template<class> class function; // not defined
template<class R, class... ArgTypes> class function<R(ArgTypes...)>;
function specialized algorithms

Template:
\[\text{template\langle class R, class\ldots ArgTypes\rangle}\]
void swap(function\langle R(ArgTypes\ldots)\rangle&, function\langle R(ArgTypes\ldots)\rangle&) noexcept;

function null pointer comparison operator functions

Template:
\[\text{template\langle class R, class\ldots ArgTypes\rangle}\]
bool operator==(const function\langle R(ArgTypes\ldots)\rangle&, nullptr_t) noexcept;

move-only wrapper

Template:
\[\text{template\langle class\ldots S\rangle class move_only_function; \text{ // not defined}\}
\text{template\langle class R, class\ldots ArgTypes\rangle class move_only_function\langle R(ArgTypes\ldots)\rangle cv ref noexcept(noex)\rangle; \text{ // see below}\]

copyable wrapper

Template:
\[\text{template\langle class\ldots S\rangle class copyable_function; \text{ // not defined}\}
\text{template\langle class R, class\ldots ArgTypes\rangle class copyable_function\langle R(ArgTypes\ldots)\rangle cv ref noexcept(noex)\rangle; \text{ // see below}\]

non-owning wrapper

Template:
\[\text{template\langle class\ldots S\rangle class function_ref; \text{ // freestanding, not defined}\}
\text{template\langle class R, class\ldots ArgTypes\rangle class function_ref\langle R(ArgTypes\ldots)\rangle cv noexcept(noex)\rangle; \text{ // freestanding, see below}\]

searchers

Template:
\[\text{template\langle class ForwardIterator1, class BinaryPredicate = equal_to\rangle class default_searcher; \text{ // freestanding}\}
\text{template\langle class RandomAccessIterator, class Hash = hash<typename iterator_traits\langle RandomAccessIterator\rangle::value_type>, class BinaryPredicate = equal_to\rangle class boyer_moore_searcher;}
\text{template\langle class RandomAccessIterator, class Hash = hash<typename iterator_traits\langle RandomAccessIterator\rangle::value_type>, class BinaryPredicate = equal_to\rangle class boyer_moore_horspool_searcher;}

hash

Template:
\[\text{template\langle class T\rangle struct hash; \text{ // freestanding}\}
\text{namespace ranges { \text{ // 22.10.9, concept-constrained comparisons}\}
struct equal_to; \text{ // freestanding}\}
struct not_equal_to; \text{ // freestanding}\}
struct greater; \text{ // freestanding}\}
struct less; \text{ // freestanding}\}
struct greater_equal; \text{ // freestanding}\}
struct less_equal; \text{ // freestanding}\}
}\]

Example 1: If a C++ program wants to have a by-element addition of two vectors a and b containing double and put the result into a, it can do:
\[\text{transform(a.begin(), a.end(), b.begin(), a.begin(), plus\langle double\rangle()); \text{ -- end example}\]

Example 2: To negate every element of a:
\[\text{transform(a.begin(), a.end(), a.begin(), negate\langle double\rangle()); \text{ -- end example}\]

22.10.3 Definitions

The following definitions apply to this Clause:
2. A call signature is the name of a return type followed by a parenthesized comma-separated list of zero or more argument types.

3. A callable type is a function object type (22.10) or a pointer to member.

4. A callable object is an object of a callable type.

5. A call wrapper type is a type that holds a callable object and supports a call operation that forwards to that object.

6. A call wrapper is an object of a call wrapper type.

7. A target object is the callable object held by a call wrapper.

8. A call wrapper type may additionally hold a sequence of objects and references that may be passed as arguments to the target object. These entities are collectively referred to as bound argument entities.

9. The target object and bound argument entities of the call wrapper are collectively referred to as state entities.

### 22.10.4 Requirements

Define `INVOKE(f, t₁, t₂, ..., tₙ)` as follows:

1.1. 

```
| (t₁.*f)(t₂, ..., tₙ) when f is a pointer to a member function of a class T and is_same_v<T, remove_cvref_t<decltype(t₁)>> || is_base_of_v<T, remove_cvref_t<decltype(t₁)>> is true;
```

1.2. 

```
| (t₁.get().*f)(t₂, ..., tₙ) when f is a pointer to a member function of a class T and remove_cvref_t<decltype(t₁)> is a specialization of reference_wrapper;
```

1.3. 

```
| ((t₁).[f](t₂, ..., tₙ) when f is a pointer to a member function of a class T and t₁ does not satisfy the previous two items;
```

1.4. 

```
| t₁.*f when N = 1 and f is a pointer to data member of a class T and is_same_v<T, remove_cvref_t<decltype(t₁)>> || is_base_of_v<T, remove_cvref_t<decltype(t₁)>> is true;
```

1.5. 

```
| t₁.get().*f when N = 1 and f is a pointer to data member of a class T and remove_cvref_t<decltype(t₁)> is a specialization of reference_wrapper;
```

1.6. 

```
| (*t₁).*f when N = 1 and f is a pointer to data member of a class T and t₁ does not satisfy the previous two items;
```

1.7. 

```
| f(t₁, t₂, ..., tₙ) in all other cases.
```

Define `INVOKE<R>(f, t₁, t₂, ..., tₙ)` as `static_cast<void>(INVOKE(f, t₁, t₂, ..., tₙ))` if `R` is `cv` `void`, otherwise `INVOKE(f, t₁, t₂, ..., tₙ)` implicitly converted to `R`. If `reference_converter_from_-temporary_v<R, decltype(INVOKE(f, t₁, t₂, ..., tₙ))>` is `true`, `INVOKE<R>(f, t₁, t₂, ..., tₙ)` is ill-formed.

3. Every call wrapper (22.10.3) meets the Cpp17MoveConstructible and Cpp17Destructible requirements. An argument forwarding call wrapper is a call wrapper that can be called with an arbitrary argument list and delivers the target object to the target object as references. This forwarding step delivers rvalue arguments as rvalue references and lvalue arguments as lvalue references.

[Note 1: In a typical implementation, argument forwarding call wrappers have an overloaded function call operator of the form]

```
template<class... UnBoundArgs>
constexpr R operator()(UnBoundArgs&&... unbound_args) cv-qual;
```

4. A perfect forwarding call wrapper is an argument forwarding call wrapper that forwards its state entities to the underlying call expression. This forwarding step delivers a state entity of type `T` as `cv T&` when the call is performed on an lvalue of the call wrapper type and as `cv T&&` otherwise, where `cv` represents the cv-qualifiers of the call wrapper and where `cv` shall be neither `volatile` nor `const volatile`.

5. A call pattern defines the semantics of invoking a perfect forwarding call wrapper. A postfix call performed on a perfect forwarding call wrapper is expression-equivalent (3.21) to an expression `e` determined from its call pattern `cp` by replacing all occurrences of the arguments of the call wrapper and its state entities with references as described in the corresponding forwarding steps.

6. A simple call wrapper is a perfect forwarding call wrapper that meets the Cpp17CopyConstructible and Cpp17CopyAssignable requirements and whose copy constructor, move constructor, and assignment operators are constexpr functions that do not throw exceptions.
The copy/move constructor of an argument forwarding call wrapper has the same apparent semantics as if memberwise copy/move of its state entities were performed (11.4.5.3).

[Note 2: This implies that each of the copy/move constructors has the same exception-specification as the corresponding implicit definition and is declared as constexpr if the corresponding implicit definition would be considered to be constexpr. — end note]

Argument forwarding call wrappers returned by a given standard library function template have the same type if the types of their corresponding state entities are the same.

22.10.5 invoke functions

```cpp
template<class F, class... Args>
constexpr invoke_result_t<F, Args...> invoke(F&& f, Args&&... args)
    noexcept(is_nothrow_invocable_v<F, Args...>);
```

1 Constraints: is_invocable_v<F, Args...> is true.

2 Returns: INVOKE(std::forward<F>(f), std::forward<Args>(args)...) (22.10.4).

```cpp
template<class R, class F, class... Args>
constexpr R invoke_r(F&& f, Args&&... args)
    noexcept(is_nothrow_invocable_r_v<R, F, Args...>);
```

3 Constraints: is_invocable_r_v<R, F, Args...> is true.

4 Returns: INVOKE<R>(std::forward<F>(f), std::forward<Args>(args)...) (22.10.4).

22.10.6 Class template reference_wrapper

22.10.6.1 General

```cpp
namespace std {
    template<class T> class reference_wrapper {
    public:
        // types
        using type = T;

        // 22.10.6.2, constructors
        template<class U>
            constexpr reference_wrapper(U&&) noexcept(see below);
        constexpr reference_wrapper(const reference_wrapper& x) noexcept;

        // 22.10.6.3, assignment
        constexpr reference_wrapper& operator=(const reference_wrapper& x) noexcept;

        // 22.10.6.4, access
        constexpr operator T& () const noexcept;
        constexpr T& get() const noexcept;

        // 22.10.6.5, invocation
        template<class... ArgTypes>
            constexpr invoke_result_t<T&, ArgTypes...> operator()(ArgTypes&&...) const
                noexcept(is_nothrow_invocable_v<T&, ArgTypes...>);

        // 22.10.6.6, comparisons
        friend constexpr bool operator==(reference_wrapper, reference_wrapper);
        friend constexpr bool operator==(reference_wrapper, const T&);
        friend constexpr bool operator==(reference_wrapper, reference_wrapper<const T&>);

        friend constexpr auto operator<=>(reference_wrapper, reference_wrapper);
        friend constexpr auto operator<=>(reference_wrapper, const T&);
        friend constexpr auto operator<=>(reference_wrapper, reference_wrapper<const T&>);
    };

    template<class T>
        reference_wrapper(T&) -> reference_wrapper<T>;
}
```
reference_wrapper<T> is a Cpp17CopyConstructible and Cpp17CopyAssignable wrapper around a reference to an object or function of type T.

reference_wrapper<T> is a trivially copyable type (6.8.1).

The template parameter T of reference_wrapper may be an incomplete type.

[Note 1: Using the comparison operators described in 22.10.6.6 with T being an incomplete type can lead to an ill-formed program with no diagnostic required (13.8.4.1, 13.5.2.3). — end note]

### 22.10.6.2 Constructors

```cpp
// refwrap.const

template<class U>
constexpr reference_wrapper(U&& u) noexcept(see below);
```

Let FUN denote the exposition-only functions

```cpp
void FUN(T&) noexcept;
void FUN(T&&) = delete;
```

**Constraints:** The expression FUN(declval<U>()) is well-formed and is_same_v<remove_cvref_t<U>, reference_wrapper> is false.

**Effects:** Creates a variable r as if by T& r = std::forward<U>(u), then constructs a reference_wrapper object that stores a reference to r.

**Remarks:** The exception specification is equivalent to noexcept(FUN(declval<U>())).

```cpp
constexpr reference_wrapper(const reference_wrapper& x) noexcept;
```

**Effects:** Constructs a reference_wrapper object that stores a reference to x.get().

### 22.10.6.3 Assignment

```cpp
// refwrap.assign

constexpr reference_wrapper& operator=(const reference_wrapper& x) noexcept;
```

**Postconditions:** *this stores a reference to x.get().

### 22.10.6.4 Access

```cpp
// refwrap.access

constexpr operator T& () const noexcept;
```

**Returns:** The stored reference.

```cpp
constexpr T& get() const noexcept;
```

**Returns:** The stored reference.

### 22.10.6.5 Invocation

```cpp
// refwrap.invoke

template<class... ArgTypes>
constexpr invoke_result_t<T&, ArgTypes...> operator()(ArgTypes&&... args) const noexcept(is_nothrow_invocable_v<T&, ArgTypes...>);
```

**Mandates:** T is a complete type.

**Returns:** INVOKE(get(), std::forward<ArgTypes>(args)...) (22.10.4)

### 22.10.6.6 Comparisons

```cpp
// refwrap.comparisons

friend constexpr bool operator==(reference_wrapper x, reference_wrapper y);
```

**Constraints:** The expression x.get() == y.get() is well-formed and its result is convertible to bool.

**Returns:** x.get() == y.get().

```cpp
friend constexpr bool operator==(reference_wrapper x, const T& y);
```

**Constraints:** The expression x.get() == y is well-formed and its result is convertible to bool.

**Returns:** x.get() == y.
friend constexpr bool operator== (reference_wrapper x, reference_wrapper<const T> y);

Constraints: is_const_v<T> is false and the expression x.get() == y.get() is well-formed and its result is convertible to bool.

Returns: x.get() == y.get().

friend constexpr auto operator<=>(reference_wrapper x, reference_wrapper y);

Constraints: The expression synth-three-way(x.get(), y.get()) is well-formed.

Returns: synth-three-way(x.get(), y.get()).

friend constexpr auto operator<=>(reference_wrapper x, const T& y);

Constraints: The expression synth-three-way(x.get(), y) is well-formed.

Returns: synth-three-way(x.get(), y).

friend constexpr auto operator<=>(reference_wrapper x, reference_wrapper<const T> y);

Constraints: is_const_v<T> is false. The expression synth-three-way(x.get(), y.get()) is well-formed.

Returns: synth-three-way(x.get(), y.get()).

22.10.6.7 Helper functions

The template parameter T of the following ref and cref function templates may be an incomplete type.

template<class T> constexpr reference_wrapper<T> ref(T& t) noexcept;

Returns: reference_wrapper<T>(t).

template<class T> constexpr reference_wrapper<T> ref(reference_wrapper<T> t) noexcept;

Returns: t.

template<class T> constexpr reference_wrapper<const T> cref(const T& t) noexcept;

Returns: reference_wrapper<const T>(t).

template<class T> constexpr reference_wrapper<const T> cref(reference_wrapper<T> t) noexcept;

Returns: t.

22.10.6.8 common_reference related specializations

namespace std {

template<class T>
constexpr bool is-ref-wrapper = false;

// exposition only

template<class T>
constexpr bool is-ref-wrapper<reference_wrapper<T>> = true;

concept ref-wrap-common-reference-exists-with =
  is-ref-wrapper<R> &&
  requires ( typename common_reference_t<typename R::type&, TQ>; } &&
  convertible_to<RQ, common_reference_t<typename R::type&, TQ>>;

template<class R, class T, class RQual, class TQual>
requires (ref-wrap-common-reference-exists-with<R, T, RQual<R>, TQual<T>> &&
  !ref-wrap-common-reference-exists-with<T, R, TQual<T>, RQual<R>>)
struct basic_common_reference<R, T, RQual, TQual> {
  using type = common_reference_t<typename R::type&, TQual<T>>;
};

template<class T, class R, class TQual, class RQual>
requires (ref-wrap-common-reference-exists-with<R, T, RQual<R>, TQual<T>> &&
  !ref-wrap-common-reference-exists-with<T, R, TQual<T>, RQual<R>>)
struct basic_common_reference<T, R, TQual, RQual> {
  using type = common_reference_t<typename R::type&, TQual<T>>;
};
The library provides basic function object classes for all of the arithmetic operators in the language (7.6.5, 7.6.6).

22.10.7.2 Class template plus

\begin{verbatim}
template<class T = void> struct plus {
    constexpr T operator()(const T& x, const T& y) const;
};
constexpr T operator()(const T& x, const T& y) const;
\end{verbatim}

\textit{Returns:} $x + y$.

\begin{verbatim}
template<> struct plus<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    \rightarrow decltype(std::forward<T>(t) + std::forward<U>(u));
};
\end{verbatim}

\textit{Returns:} $\text{std::forward<T>(t)} + \text{std::forward<U>(u)}$.

22.10.7.3 Class template minus

\begin{verbatim}
template<class T = void> struct minus {
    constexpr T operator()(const T& x, const T& y) const;
};
constexpr T operator()(const T& x, const T& y) const;
\end{verbatim}

\textit{Returns:} $x - y$.

\begin{verbatim}
template<> struct minus<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    \rightarrow decltype(std::forward<T>(t) - std::forward<U>(u));
};
\end{verbatim}

\textit{Returns:} $\text{std::forward<T>(t)} - \text{std::forward<U>(u)}$.

22.10.7.4 Class template multiplies

\begin{verbatim}
template<class T = void> struct multiplies {
    constexpr T operator()(const T& x, const T& y) const;
};
constexpr T operator()(const T& x, const T& y) const;
\end{verbatim}

\textit{Returns:} $x \times y$.
using is_transparent = unspecified;

};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
-> decltype(std::forward<T>(t) * std::forward<U>(u));

Returns: std::forward<T>(t) * std::forward<U>(u).

22.10.7.5 Class template divides

template<class T = void> struct divides {
  constexpr T operator()(const T& x, const T& y) const;
};

constexpr T operator()(const T& x, const T& y) const;

1 Returns: x / y.

template<> struct divides<void> {
  template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
-> decltype(std::forward<T>(t) / std::forward<U>(u));

  using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
-> decltype(std::forward<T>(t) / std::forward<U>(u));

2 Returns: std::forward<T>(t) / std::forward<U>(u).

22.10.7.6 Class template modulus

template<class T = void> struct modulus {
  constexpr T operator()(const T& x, const T& y) const;
};

constexpr T operator()(const T& x, const T& y) const;

1 Returns: x % y.

template<> struct modulus<void> {
  template<class T> constexpr auto operator()(T&& t) const
-> decltype(-std::forward<T>(t));

  using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
-> decltype(std::forward<T>(t) % std::forward<U>(u));

2 Returns: std::forward<T>(t) % std::forward<U>(u).

22.10.7.7 Class template negate

template<class T = void> struct negate {
  constexpr T operator()(const T& x) const;
};

constexpr T operator()(const T& x) const;

1 Returns: -x.

template<> struct negate<void> {
  template<class T> constexpr auto operator()(T&& t) const
-> decltype(-std::forward<T>(t));

  using is_transparent = unspecified;
};

§ 22.10.7.7 © ISO/IEC 792
template<class T> constexpr auto operator()(T&& t) const
    -> decltype(-std::forward<T>(t));

Returns: -std::forward<T>(t).

22.10.8 Comparisons
    [comparisons]
22.10.8.1 General
    [comparisons.general]
The library provides basic function object classes for all of the comparison operators in the language (7.6.9, 7.6.10).

For templates less, greater, less_equal, and greater_equal, the specializations for any pointer type yield a result consistent with the implementation-defined strict total order over pointers (3.27).

[Note 1: If a < b is well-defined for pointers a and b of type P, then (a < b) == less<P>()(a, b), (a > b) == greater<P>()(a, b), and so forth. — end note]

For template specializations less<void>, greater<void>, less_equal<void>, and greater_equal<void>, if the call operator calls a built-in operator comparing pointers, the call operator yields a result consistent with the implementation-defined strict total order over pointers.

22.10.8.2 Class template equal_to
    [comparisons.equal.to]
template<class T = void> struct equal_to {
    constexpr bool operator()(const T& x, const T& y) const;
};

constexpr bool operator()(const T& x, const T& y) const;

1 Returns: x == y.

template<> struct equal_to<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) == std::forward<U>(u));

    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) == std::forward<U>(u));

2 Returns: std::forward<T>(t) == std::forward<U>(u).

22.10.8.3 Class template not_equal_to
    [comparisons.not.equal.to]
template<class T = void> struct not_equal_to {
    constexpr bool operator()(const T& x, const T& y) const;
};

constexpr bool operator()(const T& x, const T& y) const;

1 Returns: x != y.

template<> struct not_equal_to<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) != std::forward<U>(u));

    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) != std::forward<U>(u));

2 Returns: std::forward<T>(t) != std::forward<U>(u).

22.10.8.4 Class template greater
    [comparisons.greater]
template<class T = void> struct greater {
    constexpr bool operator()(const T& x, const T& y) const;
};
constexpr bool operator()(const T& x, const T& y) const;

Returns: x > y.

template<> struct greater<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) > std::forward<U>(u));

    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) > std::forward<U>(u));

Returns: std::forward<T>(t) > std::forward<U>(u).

22.10.8.5 Class template less

template<class T = void> struct less {
    constexpr bool operator()(const T& x, const T& y) const;
};

constexpr bool operator()(const T& x, const T& y) const;

Returns: x < y.

template<> struct less<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) < std::forward<U>(u));

    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) < std::forward<U>(u));

Returns: std::forward<T>(t) < std::forward<U>(u).

22.10.8.6 Class template greater_equal

template<class T = void> struct greater_equal {
    constexpr bool operator()(const T& x, const T& y) const;
};

constexpr bool operator()(const T& x, const T& y) const;

Returns: x >= y.

template<> struct greater_equal<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) >= std::forward<U>(u));

    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) >= std::forward<U>(u));

Returns: std::forward<T>(t) >= std::forward<U>(u).

22.10.8.7 Class template less_equal

template<class T = void> struct less_equal {
    constexpr bool operator()(const T& x, const T& y) const;
};

constexpr bool operator()(const T& x, const T& y) const;

Returns: x <= y.
template<> struct less_equal<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) <= std::forward<U>(u));
    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) <= std::forward<U>(u));

22.10.8.8 Class compare_three_way

namespace std {
    struct compare_three_way {
        template<class T, class U>
            constexpr auto operator()(T&& t, U&& u) const;
        using is_transparent = unspecified;
    }
}

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const;

1 Constraints: T and U satisfy three_way_comparable_with.

2 Preconditions: If the expression std::forward<T>(t) <=> std::forward<U>(u) results in a call to a built-in operator <=> comparing pointers of type P, the conversion sequences from both T and U to P are equality-preserving (18.2); otherwise, T and U model three_way_comparable_with.

3 Effects:
(3.1) — If the expression std::forward<T>(t) <=> std::forward<U>(u) results in a call to a built-in operator <=> comparing pointers of type P, returns strong_ordering::less if (the converted value of) t precedes u in the implementation-defined strict total order over pointers (3.27), strong_ordering::greater if u precedes t, and otherwise strong_ordering::equal.
(3.2) — Otherwise, equivalent to: return std::forward<T>(t) <=> std::forward<U>(u);

22.10.9 Concept-constrained comparisons

struct ranges::equal_to {
    template<class T, class U>
        constexpr bool operator()(T&& t, U&& u) const;
    using is_transparent = unspecified;
};

template<class T, class U> constexpr bool operator()(T&& t, U&& u) const;

1 Constraints: T and U satisfy equality_comparable_with.

2 Preconditions: If the expression std::forward<T>(t) == std::forward<U>(u) results in a call to a built-in operator == comparing pointers of type P, the conversion sequences from both T and U to P are equality-preserving (18.2); otherwise, T and U model equality_comparable_with.

3 Effects:
(3.1) — If the expression std::forward<T>(t) == std::forward<U>(u) results in a call to a built-in operator == comparing pointers: returns false if either (the converted value of) t precedes u or u precedes t in the implementation-defined strict total order over pointers (3.27) and otherwise true.
(3.2) — Otherwise, equivalent to: return std::forward<T>(t) == std::forward<U>(u);

struct ranges::not_equal_to {
    template<class T, class U>
        constexpr bool operator()(T&& t, U&& u) const;
};
using is_transparent = unspecified;
};

template<class T, class U>
constexpr bool operator()(T&& t, U&& u) const;

Constraints: T and U satisfy equality_comparable_with.

Effects: Equivalent to:
return !ranges::equal_to{}(std::forward<T>(t), std::forward<U>(u));

struct ranges::greater {
    template<class T, class U>
    constexpr bool operator()(T&& t, U&& u) const;
    using is_transparent = unspecified;
};

template<class T, class U>
constexpr bool operator()(T&& t, U&& u) const;

Constraints: T and U satisfy totally_ordered_with.

Effects: Equivalent to:
return ranges::less{}(std::forward<U>(u), std::forward<T>(t));

struct ranges::less {
    template<class T, class U>
    constexpr bool operator()(T&& t, U&& u) const;
    using is_transparent = unspecified;
};

template<class T, class U>
constexpr bool operator()(T&& t, U&& u) const;

Constraints: T and U satisfy totally_ordered_with.

Preconditions: If the expression std::forward<T>(t) < std::forward<U>(u) results in a call to a built-in operator < comparing pointers of type P, the conversion sequences from both T and U to P are equality-preserving (18.2); otherwise, T and U model totally_ordered_with. For any expressions ET and EU such that declyte((ET)) is T and declyte((EU)) is U, exactly one of ranges::less{}(ET, EU), ranges::less{}(EU, ET), or ranges::equal_to{}(ET, EU) is true.

Effects:
(10.1) — If the expression std::forward<T>(t) < std::forward<U>(u) results in a call to a built-in operator < comparing pointers: returns true if (the converted value of) t precedes u in the implementation-defined strict total order over pointers (3.27) and otherwise false.
(10.2) — Otherwise, equivalent to: return std::forward<T>(t) < std::forward<U>(u);

struct ranges::greater_equal {
    template<class T, class U>
    constexpr bool operator()(T&& t, U&& u) const;
    using is_transparent = unspecified;
};

template<class T, class U>
constexpr bool operator()(T&& t, U&& u) const;

Constraints: T and U satisfy totally_ordered_with.

Effects: Equivalent to:
return !ranges::less{}(std::forward<T>(t), std::forward<U>(u));

struct ranges::less_equal {
    template<class T, class U>
    constexpr bool operator()(T&& t, U&& u) const;
};
using is_transparent = unspecified;
};

template<class T, class U>
constexpr bool operator()(T&& t, U&& u) const;

Constraints: T and U satisfy totally_ordered_with.

Effects: Equivalent to:

```
return !ranges::less{}(std::forward<U>(u), std::forward<T>(t));
```

## 22.10.10 Logical operations

### 22.10.10.1 General

The library provides basic function object classes for all of the logical operators in the language (7.6.14, 7.6.15, 7.6.2.2).

### 22.10.10.2 Class template logical_and

```
template<class T = void> struct logical_and {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

```
constexpr bool operator()(const T& x, const T& y) const;
```

1 Returns: \(x \&\& y\).

```
template<> struct logical_and<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) \&\& std::forward<U>(u));
    using is_transparent = unspecified;
};
```

2 Returns: \(\text{std::forward}(t) \&\& \text{std::forward}(u)\).

### 22.10.10.3 Class template logical_or

```
template<class T = void> struct logical_or {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

```
constexpr bool operator()(const T& x, const T& y) const;
```

1 Returns: \(x || y\).

```
template<> struct logical_or<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) || std::forward<U>(u));
    using is_transparent = unspecified;
};
```

2 Returns: \(\text{std::forward}(t) || \text{std::forward}(u)\).

### 22.10.10.4 Class template logical_not

```
template<class T = void> struct logical_not {
    constexpr bool operator()(const T& x) const;
};
```

```
constexpr bool operator()(const T& x) const;
```

1 Returns: \(!x\).
template<> struct logical_not<void> {
    template<class T> constexpr auto operator()(T&& t) const
    -> decltype(!std::forward<T>(t));

    using is_transparent = unspecified;
};

template<class T> constexpr auto operator()(T&& t) const
-> decltype(!std::forward<T>(t));

Returns: !std::forward<T>(t).

### 22.10.11 Bitwise operations

#### 22.10.11.1 General

The library provides basic function object classes for all of the bitwise operators in the language (7.6.11, 7.6.13, 7.6.12, 7.6.2.2).

#### 22.10.11.2 Class template bit_and

```cpp
template<class T = void> struct bit_and {
    constexpr T operator()(const T& x, const T& y) const;
};

constexpr T operator()(const T& x, const T& y) const;

Returns: x & y.
```

```cpp
template<> struct bit_and<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) & std::forward<U>(u));

    using is_transparent = unspecified;
};
```

```cpp
template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
-> decltype(std::forward<T>(t) & std::forward<U>(u));

Returns: std::forward<T>(t) & std::forward<U>(u).
```

#### 22.10.11.3 Class template bit_or

```cpp
template<class T = void> struct bit_or {
    constexpr T operator()(const T& x, const T& y) const;
};

constexpr T operator()(const T& x, const T& y) const;

Returns: x | y.
```

```cpp
template<> struct bit_or<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) | std::forward<U>(u));

    using is_transparent = unspecified;
};
```

```cpp
template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
-> decltype(std::forward<T>(t) | std::forward<U>(u));

Returns: std::forward<T>(t) | std::forward<U>(u).
```

#### 22.10.11.4 Class template bit_xor

```cpp
template<class T = void> struct bit_xor {
    constexpr T operator()(const T& x, const T& y) const;
};
```
constexpr T operator()(const T& x, const T& y) const;

Returns: x ^ y.

template<> struct bit_xor<void> {
    template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
        -> decltype(std::forward<T>(t) ^ std::forward<U>(u));

    using is_transparent = unspecified;
};

template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) ^ std::forward<U>(u));

22.10.11.5 Class template bit_not

template<class T = void> struct bit_not {
    constexpr T operator()(const T& x) const;
};

constexpr T operator()(const T& x) const;

Returns: ~x.

template<> struct bit_not<void> {
    template<class T> constexpr auto operator()(T&& t) const
        -> decltype(~std::forward<T>(t));

    using is_transparent = unspecified;
};

template<class T> constexpr auto operator()(T&& t) const
    -> decltype(~std::forward<T>(t));

22.10.12 Class identity

struct identity {
    template<class T>
        constexpr T&& operator()(T&& t) const noexcept;

    using is_transparent = unspecified;
};

template<class T>
    constexpr T&& operator()(T&& t) const noexcept;

Effects: Equivalent to: return std::forward<T>(t);

22.10.13 Function template not_fn

template<class F> constexpr unspecified not_fn(F&& f);

In the text that follows:

(1.1) — g is a value of the result of a not_fn invocation,
(1.2) — FD is the type decay_t<F>,
(1.3) — fd is the target object of g (22.10.3) of type FD, direct-non-list-initialized with std::forward<F>
    >(f),
(1.4) — call_args is an argument pack used in a function call expression (7.6.1.3) of g.

Mandates: is_constructible_v<FD, F> && is_move_constructible_v<FD> is true.

Preconditions: FD meets the Cpp17MoveConstructible requirements.

Returns: A perfect forwarding call wrapper (22.10.4) g with call pattern !invoke(fd, call_args...).
Throws: Any exception thrown by the initialization of \textit{fd}.

\begin{verbatim}
template<auto f> constexpr unspecified not_fn() noexcept;
\end{verbatim}

In the text that follows:

(6.1) \textit{F} is the type of \textit{f},
(6.2) \textit{g} is a value of the result of a \textit{not_fn} invocation,
(6.3) \textit{call_args} is an argument pack used in a function call expression (7.6.1.3) of \textit{g}.

Mandates: If \textit{is_pointer_v\textless F\textgreater} || \textit{is_member_pointer_v\textless F\textgreater} is true, then \textit{f} \(!=\) \textit{nullptr} is true.

Returns: A perfect forwarding call wrapper (22.10.4) \textit{g} that does not have state entities, and has the call pattern \texttt{!invoke(f, call_args...)}.

\subsection*{22.10.14 Function templates \texttt{bind_front} and \texttt{bind_back} \hfill \textbf{[func.bind.partial]}}

\begin{verbatim}
template<class F, class... Args>
constexpr unspecified bind_front(F&& f, Args&&... args);
template<class F, class... Args>
constexpr unspecified bind_back(F&& f, Args&&... args);
\end{verbatim}

Within this subclause:

(1.1) \textit{g} is a value of the result of a \texttt{bind_front} or \texttt{bind_back} invocation,
(1.2) \textit{FD} is the type \texttt{decay\_t\textless F\textgreater},
(1.3) \textit{fd} is the target object of \textit{g} (22.10.3) of type \textit{FD}, direct-non-list-initialized with \texttt{std::forward\textless F \textgreater}(f),
(1.4) \textit{BoundArgs} is a pack that denotes \texttt{decay\_t\textless Args\textgreater...},
(1.5) \textit{bound_args} is a pack of bound argument entities of \textit{g} (22.10.3) of types \texttt{BoundArgs...}, direct-non-list-initialized with \texttt{std::forward\textless Args\textgreater}(args)..., respectively, and
(1.6) \textit{call_args} is an argument pack used in a function call expression (7.6.1.3) of \textit{g}.

Mandates:

\begin{verbatim}
is_constructible_v\textless FD, F\textgreater &&
is_move_constructible_v\textless FD\textgreater &&
(is_constructible_v\textless BoundArgs, Args\textgreater && ... &&)
(is_move_constructible_v\textless BoundArgs\textgreater && ... &&)
\end{verbatim}

is true.

Preconditions: \textit{FD} meets the \texttt{Cpp17MoveConstructible} requirements. For each \textit{T_i} in \textit{BoundArgs}, if \textit{T_i} is an object type, \textit{T_i} meets the \texttt{Cpp17MoveConstructible} requirements.

Returns: A perfect forwarding call wrapper (22.10.4) \textit{g} with call pattern:

(4.1) \texttt{invoke(fd, bound_args..., call_args...) for a \texttt{bind_front} invocation, or}
(4.2) \texttt{invoke(fd, call_args..., bound_args...) for a \texttt{bind_back} invocation.}

Throws: Any exception thrown by the initialization of the state entities of \textit{g} (22.10.3).

\begin{verbatim}
template<auto f, class... Args>
constexpr unspecified bind_front(Args&&... args);
template<auto f, class... Args>
constexpr unspecified bind_back(Args&&... args);
\end{verbatim}

Within this subclause:

(6.1) \textit{F} is the type of \textit{f},
(6.2) \textit{g} is a value of the result of a \texttt{bind_front} or \texttt{bind_back} invocation,
(6.3) \textit{BoundArgs} is a pack that denotes \texttt{decay\_t\textless Args\textgreater...},
(6.4) \textit{bound_args} is a pack of bound argument entities of \textit{g} (22.10.3) of types \texttt{BoundArgs...}, direct-non-list-initialized with \texttt{std::forward\textless Args\textgreater}(args)..., respectively, and
(6.5) \textit{call_args} is an argument pack used in a function call expression (7.6.1.3) of \textit{g}.
Mandates:
— (is_constructible_v<BoundArgs, Args> && ...) is true, and
— (is_move_constructible_v<BoundArgs> && ...) is true, and
— if is_pointer_v<F> || is_member_pointer_v<F> is true, then f != nullptr is true.

Preconditions: For each Ti in BoundArgs, Ti meets the Cpp17MoveConstructible requirements.

Returns: A perfect forwarding call wrapper (22.10.4) g that does not have a target object, and has the call pattern:
— invoke(f, bound_args..., call_args...) for a bind_front invocation, or
— invoke(f, call_args..., bound_args...) for a bind_back invocation.

22.10.15 Function object binders

22.10.15.1 General

22.10.15.2 Class template is_bind_expression

namespace std {
  template<class T> struct is_bind_expression; // see below
}

1 The class template is_bind_expression can be used to detect function objects generated by bind. The function template bind uses is_bind_expression to detect subexpressions.

2 Specializations of the is_bind_expression template shall meet the Cpp17UnaryTypeTrait requirements (21.3.2). The implementation provides a definition that has a base characteristic of true_type if T is a type returned from bind, otherwise it has a base characteristic of false_type. A program may specialize this template for a program-defined type T to have a base characteristic of true_type to indicate that T should be treated as a subexpression in a bind call.

22.10.15.3 Class template is_placeholder

namespace std {
  template<class T> struct is_placeholder; // see below
}

1 The class template is_placeholder can be used to detect the standard placeholders _1, _2, and so on (22.10.15.5). The function template bind uses is_placeholder to detect placeholders.

2 Specializations of the is_placeholder template shall meet the Cpp17UnaryTypeTrait requirements (21.3.2). The implementation provides a definition that has the base characteristic of integral_constant<int, J> if T is the type of std::placeholders::_J, otherwise it has a base characteristic of integral_constant<int, 0>. A program may specialize this template for a program-defined type T to have a base characteristic of integral_constant<int, N> with N > 0 to indicate that T should be treated as a placeholder type.

22.10.15.4 Function template bind

In the text that follows:
— g is a value of the result of a bind invocation,
— FD is the type decay_t<F>,
— fd is an lvalue that is a target object of g (22.10.3) of type FD direct-non-list-initialized with std::forward<F>(f),
— Ti is the i_th type in the template parameter pack BoundArgs,
— TDi is the type decay_t<Ti>,
— ti is the i_th argument in the function parameter pack bound_args,
— td is a bound argument entity of g (22.10.3) of type TDi direct-non-list-initialized with std::forward<Ti>(ti),
— Uj is the j_th deduced type of the UnBoundArgs&&... parameter of the argument forwarding call wrapper, and
— \( u_j \) is the \( j \)'th argument associated with \( U_j \).

```cpp
template<class F, class... BoundArgs>
constexpr unspecified bind(F&& f, BoundArgs&&... bound_args);
```

2. **Mandates:** \( \text{is\_constructible}_v<\text{FD}, F> \) is true. For each \( T_j \) in \( \text{BoundArgs} \), \( \text{is\_constructible}_v<T_j> \) is true.

3. **Preconditions:** \( \text{FD} \) and each \( \text{TD}_i \) meet the `Cpp17MoveConstructible` and `Cpp17Destructible` requirements.

4. **Returns:** An argument forwarding call wrapper \( g \) (22.10.4). A program that attempts to invoke a volatile-qualified \( g \) is ill-formed. When \( g \) is not volatile-qualified, invocation of \( g(u_1, u_2, \ldots, u_M) \) is expression-equivalent (3.21) to

\[
\text{INVOKExR}(\text{static\_cast}<\text{V}_1>(v_1), \text{static\_cast}<\text{V}_2>(v_2), \ldots, \text{static\_cast}<\text{V}_N>(v_N))
\]

for the first overload, and

\[
\text{INVOKExR}(\text{static\_cast}<\text{V}_1>(v_1), \text{static\_cast}<\text{V}_2>(v_2), \ldots, \text{static\_cast}<\text{V}_N>(v_N))
\]

for the second overload, where the values and types of the target argument \( v_{td} \) and of the bound arguments \( v_1, v_2, \ldots, v_N \) are determined as specified below.

5. **Throws:** Any exception thrown by the initialization of the state entities of \( g \).

6. **Note 1:** If all of \( \text{FD} \) and \( \text{TD}_i \) meet the requirements of `Cpp17CopyConstructible`, then the return type meets the requirements of `Cpp17CopyConstructible`. — end note

7. The values of the \textit{bound arguments} \( v_1, v_2, \ldots, v_N \) and their corresponding types \( V_1, V_2, \ldots, V_N \) depend on the types \( \text{TD}_i \) derived from the call to \texttt{bind} and the cv-qualifiers \( \texttt{cv} \) of the call wrapper \( g \) as follows:

7.1. — if \( \text{TD}_i \) is `reference\_wrapper<\texttt{T}>&>`, the argument is \( \texttt{td}_i\texttt{.get()} \) and its type \( V_i \) is \( \texttt{T}\&\);

7.2. — if the value of \( \text{is\_bind\_expression}_v<\text{TD}_i> \) is true, the argument is

\[
\text{static\_cast}<\texttt{cv} \text{ TD}_i\&>(\texttt{td}_i)(\texttt{std::forward}<\texttt{U}_j>(u_j)\ldots)
\]

and its type \( V_i \) is \( \text{std::invoke\_result}\_t<\texttt{cv} \text{ TD}_i\&, \texttt{U}_j\ldots>&\);

7.3. — if the value \( j \) of \( \text{is\_placeholder}_v<\text{TD}_i> \) is not zero, the argument is \( \texttt{std::forward}<\texttt{U}_j>(u_j) \) and its type \( V_i \) is \( \texttt{U}_j\&\&\);

7.4. — otherwise, the value is \( \texttt{td}_i \), and its type \( V_i \) is \( \texttt{cv} \text{ TD}_i\&\).

8. The value of the target argument \( v_{td} \) is \( \texttt{fd} \) and its corresponding type \( V_{td} \) is \( \texttt{cv} \texttt{ FD}_k \).

### 22.10.15.5 Placeholders

```cpp
namespace std::placeholders {
    // M is the number of placeholders
    see below _1;
    see below _2;
    
    see below _M;
}
```

1. The number \( M \) of placeholders is implementation-defined.

2. All placeholder types meet the `Cpp17DefaultConstructible` and `Cpp17CopyConstructible` requirements, and their default constructors and copy/move constructors are constexpr functions that do not throw exceptions. It is implementation-defined whether placeholder types meet the `Cpp17CopyAssignable` requirements, but if so, their copy assignment operators are constexpr functions that do not throw exceptions.

3. Placeholders should be defined as:

```cpp
inline constexpr unspecified _1{};
```
If they are not, they are declared as:

```cpp
extern unspecified _1;
```

Placeholders are freestanding items (16.3.3.6).

### 22.10.16 Function template \texttt{mem\_fn}

**Returns**: A simple call wrapper (22.10.4) \texttt{fn} with call pattern \texttt{invoke(pmd, call\_args...), where pmd is the target object of \texttt{fn} of type R \texttt{T::* direct-non-list-initialized with \texttt{pm}, and call\_args is an argument pack used in a function call expression (7.6.1.3) of \texttt{fn}.}**

### 22.10.17 Polymorphic function wrappers

**Subclause 22.10.17 describes polymorphic wrapper classes that encapsulate arbitrary callable objects.**

1. Let \(t\) be an object of a type that is a specialization of \texttt{function}, \texttt{copyable\_function}, or \texttt{move\_only\_function}, such that the target object \(x\) of \(t\) has a type that is a specialization of \texttt{function}, \texttt{copyable\_function}, or \texttt{move\_only\_function}. Each argument of the invocation of \(x\) evaluated as part of the invocation of \(t\) may alias an argument in the same position in the invocation of \(t\) that has the same type, even if the corresponding parameter is not of reference type.

2. **Recommended practice**: Implementations should avoid double wrapping when constructing polymorphic wrappers from one another.

### 22.10.17.2 Class \texttt{bad\_function\_call}

**Returns**: An implementation-defined \texttt{ntbs}.

### 22.10.17.3 Class template \texttt{function}

**General**

1. An exception of type \texttt{bad\_function\_call} is thrown by \texttt{function::operator()} (22.10.17.3.5) when the function wrapper object has no target.

```cpp
namespace std {
    class bad_function_call : public exception {
    public:
        // see 17.9.3 for the specification of the special member functions
        const char* what() const noexcept override;
    }
}
```

2. **Returns**: An implementation-defined \texttt{ntbs}.

### 22.10.17.3.1 General

```cpp
namespace std {
    template<class R, class... ArgTypes>
    class function<R(ArgTypes...)> {
    public:
        using result_type = R;

        // 22.10.17.3.2, construct/copy/destroy
        function() noexcept;
        function(nullptr_t) noexcept;
        function(const function&);
        function(function&&) noexcept;
        template<class F> function(F&&);
    }
}
```
function& operator=(const function&);
function& operator=(function&&);
function& operator=(nullptr_t) noexcept;
template<class F> function& operator=(F&&);
template<class F> function& operator=(reference_wrapper<F>) noexcept;
~function();

// 22.10.17.3.3, function modifiers
void swap(function&) noexcept;

// 22.10.17.3.4, function capacity
explicit operator bool() const noexcept;

// 22.10.17.3.5, function invocation
R operator()(ArgTypes...) const;

// 22.10.17.3.6, function target access
const type_info& target_type() const noexcept;
template<class T> T* target() noexcept;
template<class T> const T* target() const noexcept;
};
template<class R, class... ArgTypes>
function(R(*)(ArgTypes...)) -> function<R(ArgTypes...)>;
template<class F> function(F) -> function<see below>;

1 The function class template provides polymorphic wrappers that generalize the notion of a function pointer. Wrappers can store, copy, and call arbitrary callable objects (22.10.3), given a call signature (22.10.3).

2 A callable type (22.10.3) F is Lvalue-Callable for argument types ArgTypes and return type R if the expression

\[ \text{INVOKER}_R\left((\text{declval}\langle F\&\rangle()), \text{declval}\langle\text{ArgTypes}\rangle()\ldots) \right] \]

considered as an unevaluated operand (7.2.3), is well-formed (22.10.4).

3 The function class template is a call wrapper (22.10.3) whose call signature (22.10.3) is R(ArgTypes...).

4 [Note 1: The types deduced by the deduction guides for function might change in future revisions of C++. — end note]

22.10.17.3.2 Constructors and destructor [func.wrap.func.con]

function() noexcept;

1 Postconditions: !*this.

function(nullptr_t) noexcept;

2 Postconditions: !*this.

function(const function& f);

3 Postconditions: !*this if !f; otherwise, the target object of *this is a copy of f.target().

4 Throws: Nothing if f’s target is a specialization of reference_wrapper or a function pointer. Otherwise, may throw bad_alloc or any exception thrown by the copy constructor of the stored callable object.

5 Recommended practice: Implementations should avoid the use of dynamically allocated memory for small callable objects, for example, where f’s target is an object holding only a pointer or reference to an object and a member function pointer.

function(function&& f) noexcept;

6 Postconditions: If f, *this has no target; otherwise, the target of *this is equivalent to the target of f before the construction, and f is in a valid state with an unspecified value.

7 Recommended practice: Implementations should avoid the use of dynamically allocated memory for small callable objects, for example, where f’s target is an object holding only a pointer or reference to an object and a member function pointer.
template<class F> function(F&& f);

Let FD be decay_t<F>.

Constraints:

(9.1) is_same_v<remove_cvref_t<F>, function> is false, and
(9.2) FD is L-value-Callable (22.10.17.3) for argument types ArgTypes... and return type R.

Mandates:

(10.1) is_copy_constructible_v<FD> is true, and
(10.2) is_constructible_v<FD, F> is true.

Preconditions: FD meets the Cpp17CopyConstructible requirements.

Postconditions: !this is true if any of the following hold:

(12.1) f is a null function pointer value.
(12.2) f is a null member pointer value.
(12.3) remove_cvref_t<F> is a specialization of the function class template, and !f is true.

Otherwise, *this has a target object of type FD direct-non-list-initialized with std::forward<F>(f).

Throws: Nothing if FD is a specialization of reference_wrapper or a function pointer type. Otherwise, may throw bad_alloc or any exception thrown by the initialization of the target object.

Recommended practice: Implementations should avoid the use of dynamically allocated memory for small callable objects, for example, where f refers to an object holding only a pointer or reference to an object and a member function pointer.

template<class F> function(F) -> function<see below>;

Constraints: &F::operator() is well-formed when treated as an unevaluated operand and either

(16.1) F::operator() is a non-static member function and decltype(&F::operator()) is either of the form R(G::*)(A...) cv k_opt noexcept opt or of the form R(*)(G, A...) noexcept opt for a type G, or
(16.2) F::operator() is a static member function and decltype(&F::operator()) is of the form R(*)(A...) noexcept opt.

Remarks: The deduced type is function<R(A...)>

[Example 1:

void f() {
    int i{5};
    function g = [&](double) { return i; }; // deduces function<int(double>)
}

— end example]

function& operator=(const function& f);

Effects: As if by function(f).swap(*this);

Returns: *this.

function& operator=(function&& f);

Effects: Replaces the target of *this with the target of f.

Returns: *this.

function& operator=(nullptr_t) noexcept;

Effects: If *this != nullptr, destroys the target of this.

Postconditions: !(this).

Returns: *this.
template<class F> function& operator=(F&& f);

Constraints: decay_t<F> is Lvalue-Callable (22.10.17.3) for argument types ArgTypes... and return type R.

Effects: As if by: function(std::forward<F>(f)).swap(*this);

Returns: *this.

template<class F> function& operator=(reference_wrapper<F> f) noexcept;

Effects: As if by: function(f).swap(*this);

Returns: *this.

~function();

Effects: If *this != nullptr, destroys the target of this.

22.10.17.3.3 Modifiers

void swap(function& other) noexcept;

Effects: Interchanges the target objects of *this and other.

22.10.17.3.4 Capacity

explicit operator bool() const noexcept;

Returns: true if *this has a target, otherwise false.

22.10.17.3.5 Invocation

R operator()(ArgTypes... args) const;

Returns: INVOKE<R>(f, std::forward<ArgTypes>(args))... (22.10.4), where f is the target object (22.10.3) of *this.

Throws: bad_function_call if !*this; otherwise, any exception thrown by the target object.

22.10.17.3.6 Target access

const type_info& target_type() const noexcept;

Returns: If *this has a target of type T, typeid(T); otherwise, typeid(void).

template<class T> T* target() noexcept;
template<class T> const T* target() const noexcept;

Returns: If target_type() == typeid(T) a pointer to the stored function target; otherwise a null pointer.

22.10.17.3.7 Null pointer comparison operator functions

template<class R, class... ArgTypes>
bool operator==(const function<R(ArgTypes...)>& f, nullptr_t) noexcept;

Returns: !f.

22.10.17.3.8 Specialized algorithms

template<class R, class... ArgTypes>
void swap(function<R(ArgTypes...)>& f1, function<R(ArgTypes...)>& f2) noexcept;

Effects: As if by: f1.swap(f2);

22.10.17.4 Move-only wrapper

22.10.17.4.1 General

The header provides partial specializations of move_only_function for each combination of the possible replacements of the placeholders cv, ref, and noex where

(1.1) — cv is either const or empty,

(1.2) — ref is either & or &&, or empty, and
— noex is either true or false.

For each of the possible combinations of the placeholders mentioned above, there is a placeholder inv-quals defined as follows:

— If ref is empty, let inv-quals be cv&;
— otherwise, let inv-quals be cv ref.

22.10.17.4.2 Class template move_only_function

```
namespace std {
    template<class R, class... ArgTypes>
    class move_only_function<R(ArgTypes...) cv ref noexcept(noex)> {
public:
    using result_type = R;

    move_only_function() noexcept;
    move_only_function(nullptr_t) noexcept;
    move_only_function(move_only_function&&) noexcept;
    template<class F> move_only_function(F&&);
    template<class T, class... Args>
        explicit move_only_function(in_place_type_t<T>, Args&&...);
    template<class T, class U, class... Args>
        explicit move_only_function(in_place_type_t<T>, initializer_list<U>, Args&&...);

    move_only_function& operator=(move_only_function&&);
    move_only_function& operator=(nullptr_t) noexcept;
    template<class F> move_only_function& operator=(F&&);
    ~move_only_function();

    // 22.10.17.4.3, constructors, assignment, and destructor
    move_only_function() noexcept;
    move_only_function(nullptr_t) noexcept;
    move_only_function(move_only_function&&) noexcept;
    template<class F> move_only_function(F&&);
    template<class T, class... Args>
        explicit move_only_function(in_place_type_t<T>, Args&&...);
    template<class T, class U, class... Args>
        explicit move_only_function(in_place_type_t<T>, initializer_list<U>, Args&&...);

    move_only_function& operator=(move_only_function&&);
    move_only_function& operator=(nullptr_t) noexcept;
    template<class F> move_only_function& operator=(F&&);
    ~move_only_function();

    // 22.10.17.4.4, invocation
    explicit operator bool() const noexcept;
    R operator()(ArgTypes...) cv ref noexcept(noex);

    // 22.10.17.4.5, utility
    void swap(move_only_function&) noexcept;
    friend void swap(move_only_function&, move_only_function&) noexcept;
    friend bool operator==(const move_only_function&, nullptr_t) noexcept;

private:
    template<class VT>
        static constexpr bool is-callable-from = see below; // exposition only
};
```

1 The move_only_function class template provides polymorphic wrappers that generalize the notion of a callable object (22.10.3). These wrappers can store, move, and call arbitrary callable objects, given a call signature.

2 Recommended practice: Implementations should avoid the use of dynamically allocated memory for a small contained value.

[Note 1: Such small-object optimization can only be applied to a type T for which is_nothrow_move_constructible_v<T> is true. — end note]

22.10.17.4.3 Constructors, assignment, and destructor

```
template<class VT>
    static constexpr bool is-callable-from = see below;

    If noex is true, is-callable-from<VT> is equal to:
        is_nothrow_invocable_r_v<R, VT cv ref, ArgTypes...> &&
        is_nothrow_invocable_r_v<R, VT inv-quals, ArgTypes...>
    Otherwise, is-callable-from<VT> is equal to:
```
is_invocable_r_v<R, VT cv ref, ArgTypes...> &&
is_invocable_r_v<R, VT inv-quals, ArgTypes...>

move_only_function() noexcept;
move_only_function(nullptr_t) noexcept;

Postconditions: *this has no target object.

move_only_function(move_only_function&& f) noexcept;

Postconditions: The target object of *this is the target object f had before construction, and f is in a valid state with an unspecified value.

template<class F> move_only_function(F&& f);

Let VT be decay_t<F>.

Constraints:

(5.1) remove_cvref_t<F> is not the same type as move_only_function, and
(5.2) remove_cvref_t<F> is not a specialization of in_place_type_t, and
(5.3) is-callable-from<VT> is true.

Mandates: is_constructible_v<VT, F> is true.

Preconditions: VT meets the Cpp17Destructible requirements, and if is_move_constructible_v<VT> is true, VT meets the Cpp17MoveConstructible requirements.

Postconditions: *this has no target object if any of the following hold:

(8.1) f is a null function pointer value, or
(8.2) f is a null member pointer value, or
(8.3) remove_cvref_t<F> is a specialization of the move_only_function class template, and f has no target object.

Otherwise, *this has a target object of type VT direct-non-list-initialized with std::forward<F>(f).

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless VT is a function pointer or a specialization of reference_wrapper.

template<class T, class... Args>
explicit move_only_function(in_place_type_t<T>, Args&&... args);

Let VT be decay_t<T>.

Constraints:

(11.1) is_constructible_v<VT, Args...> is true, and
(11.2) is-callable-from<VT> is true.

Mandates: VT is the same type as T.

Preconditions: VT meets the Cpp17Destructible requirements, and if is_move_constructible_v<VT> is true, VT meets the Cpp17MoveConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with std::forward<Args>(args)... .

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless VT is a function pointer or a specialization of reference_wrapper.

template<class T, class U, class... Args>
explicit move_only_function(in_place_type_t<T>, initializer_list<U> ilist, Args&&... args);

Let VT be decay_t<T>.

Constraints:

(17.1) is_constructible_v<VT, initializer_list<U>&, Args...> is true, and
(17.2) is-callable-from<VT> is true.
Mandates: VT is the same type as T.

Preconditions: VT meets the Cpp17Destructible requirements, and if is_move_constructible_v<VT> is true, VT meets the Cpp17MoveConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with ilist, std::forward<Args>(args)....

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless VT is a function pointer or a specialization of reference_wrapper.

move_only_function& operator=(move_only_function&& f);

Effects: Equivalent to: move_only_function(std::move(f)).swap(*this);

Returns: *this.

move_only_function& operator=(nullptr_t) noexcept;

Effects: Destroys the target object of *this, if any.

Returns: *this.

template<class F> move_only_function& operator=(F&& f);

Effects: Equivalent to: move_only_function(std::forward<F>(f)).swap(*this);

Returns: *this.

~move_only_function();

Effects: Destroys the target object of *this, if any.

22.10.17.4.4 Invocation

explicit operator bool() const noexcept;

1 Returns: true if *this has a target object, otherwise false.

R operator()(ArgTypes... args) cv ref noexcept(noex);

2 Preconditions: *this has a target object.

3 Effects: Equivalent to:

return INVOKE<R>(static_cast<F inv-quals>(f), std::forward<ArgTypes>(args)...);

where f is an lvalue designating the target object of *this and F is the type of f.

22.10.17.4.5 Utility

void swap(move_only_function& other) noexcept;

1 Effects: Exchanges the target objects of *this and other.

friend void swap(move_only_function& f1, move_only_function& f2) noexcept;

2 Effects: Equivalent to f1.swap(f2).

friend bool operator==(const move_only_function& f, nullptr_t) noexcept;

3 Returns: true if f has no target object, otherwise false.

22.10.17.5 Copyable wrapper

22.10.17.5.1 General

The header provides partial specializations of copyable_function for each combination of the possible replacements of the placeholders cv, ref, and noex where

(1.1) — cv is either const or empty,

(1.2) — ref is either &, &&, or empty, and

(1.3) — noex is either true or false.

For each of the possible combinations of the placeholders mentioned above, there is a placeholder inv-quals defined as follows:
If \textit{ref} is empty, let \textit{inv-quals} be \texttt{cv\&},

otherwise, let \textit{inv-quals} be \texttt{cv\ ref}.

### 22.10.17.5.2 Class template \texttt{copyable\_function}

```cpp
namespace std {
  template<class R, class... ArgTypes>
  class copyable\_function<R(ArgTypes...) cv ref noexcept(noex)> {
    public:
      using result\_type = R;
      // 22.10.17.5.3, constructors, assignments, and destructors
      copyable\_function() noexcept;
      copyable\_function(nullptr_t) noexcept;
      copyable\_function(const copyable\_function&);
      copyable\_function(copyable\_function&&) noexcept;
      template<class F> copyable\_function(F&&);
      template<class T, class... Args>
        explicit copyable\_function(in\_place\_type_t<T>, Args&&...);
      template<class T, class U, class... Args>
        explicit copyable\_function(in\_place\_type_t<T>, initializer\_list<U>, Args&&...);
      copyable\_function& operator=(const copyable\_function&);
      copyable\_function& operator=(copyable\_function&&);
      copyable\_function& operator=(nullptr_t) noexcept;
      template<class F> copyable\_function& operator=(F&&);
      ~copyable\_function();
      // 22.10.17.5.4, invocation
      explicit operator bool() const noexcept;
      R operator()(ArgTypes...) cv ref noexcept(noex);
      // 22.10.17.5.5, utility
      void swap(copyable\_function&) noexcept;
      friend void swap(copyable\_function&, copyable\_function&) noexcept;
      friend bool operator==(const copyable\_function&, nullptr_t) noexcept;
  private:
    template<class VT>
      static constexpr bool is\_callable\_from = see below; // exposition only
  };
}
```

1. The \texttt{copyable\_function} class template provides polymorphic wrappers that generalize the notion of a callable object (22.10.3). These wrappers can store, copy, move, and call arbitrary callable objects, given a call signature.

2. \textit{Recommended practice}: Implementations should avoid the use of dynamically allocated memory for a small contained value.

[Note 1: Such small-object optimization can only be applied to a type \texttt{T} for which \texttt{is\_nothrow\_move\_constructible\_v\<\texttt{T}\> is true. —end note}]

### 22.10.17.5.3 Constructors, assignments, and destructors

```cpp
template<class VT>
  static constexpr bool is\_callable\_from = see below;
```

1. If \textit{noex} is true, \texttt{is\_callable\_from\<VT\>} is equal to:

\[
\texttt{is\_nothrow\_invocable\_v\<R, VT cv ref, ArgTypes...\> \&\&}
\texttt{is\_nothrow\_invocable\_v\<R, VT inv-quals, ArgTypes...\>}
\]

Otherwise, \texttt{is\_callable\_from\<VT\>} is equal to:

\[
\texttt{is\_invocable\_v\<R, VT cv ref, ArgTypes...\> \&\&}
\texttt{is\_invocable\_v\<R, VT inv-quals, ArgTypes...\>}
\]
copyable_function() noexcept;
copyable_function(nullptr_t) noexcept;

Postconditions: *this has no target object.

Postconditions: *this has no target object if f had no target object. Otherwise, the target object of
*this is a copy of the target object of f.

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc.

Postconditions: The target object of *this is the target object f had before construction, and f is in a
valid state with an unspecified value.

Postconditions: *this has no target object if any of the following hold:
— f is a null function pointer value, or
— f is a null member pointer value, or
— remove_cvref_t<T> is a specialization of the copyable_function class template, and f has no
target object.

Otherwise, *this has a target object of type VT direct-non-list-initialized with std::forward<T>(f).

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless
VT is a function pointer or a specialization of reference_wrapper.

Let VT be decay_t<T

Postconditions: VT meets the Cpp17Destructible and Cpp17CopyConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with std::forward<T>(f).

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless
VT is a pointer or a specialization of reference_wrapper.

Let VT be decay_t<T

Preconditions: VT meets the Cpp17Destructible and Cpp17CopyConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with std::forward<T>(args)....

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless
VT is a pointer or a specialization of reference_wrapper.
Constraints:

— is_constructible_v<VT, initializer_list<U>&, Args...> is true, and
— is_callable_from<VT> is true.

Mandates:

— VT is the same type as T, and
— is_copy_constructible_v<VT> is true.

Preconditions: VT meets the Cpp17Destructible and Cpp17CopyConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with ilist, std::forward<Args>(args)....

Throws: Any exception thrown by the initialization of the target object. May throw bad_alloc unless VT is a pointer or a specialization of reference_wrapper.

copyable_function& operator=(const copyable_function& f);  
Effects: Equivalent to: copyable_function(f).swap(*this);
Returns: *this.

copyable_function& operator=(copyable_function&& f);  
Effects: Equivalent to: copyable_function(std::move(f)).swap(*this);
Returns: *this.

copyable_function& operator=(nullptr_t) noexcept;  
Effects: Destroys the target object of *this, if any.
Returns: *this.

template<class F> copyable_function& operator=(F&& f);  
Effects: Equivalent to: copyable_function(std::forward<F>(f)).swap(*this);
Returns: *this.

~copyable_function();  
Effects: Destroys the target object of *this, if any.

22.10.17.5.4 Invocation [func.wrap.copy.inv]

explicit operator bool() const noexcept;
Returns: true if *this has a target object, otherwise false.

R operator()(ArgTypes... args) cv ref noexcept(noex);
Preconditions: *this has a target object.
Effects: Equivalent to:
return INVOKE<R>(static_cast<F inv-quals>(f), std::forward<ArgTypes>(args)...);
where f is an lvalue designating the target object of *this and F is the type of f.

22.10.17.5.5 Utility [func.wrap.copy.util]

void swap(copyable_function& other) noexcept;
Effects: Exchanges the target objects of *this and other.

friend void swap(copyable_function& f1, copyable_function& f2) noexcept;
Effects: Equivalent to f1.swap(f2).

friend bool operator==(const copyable_function& f, nullptr_t) noexcept;
Returns: true if f has no target object, otherwise false.
22.10.17.6 Non-owning wrapper

22.10.17.6.1 General

The header provides partial specializations of function_ref for each combination of the possible replacements of the placeholders cv and noex where:

1. cv is either const or empty, and
2. noex is either true or false.

22.10.17.6.2 Class template function_ref

namespace std {
    template<class R, class... ArgTypes>
    class function_ref<R(ArgTypes...) cv noexcept(noex)>
        { public:
            // 22.10.17.6.3, constructors and assignment operators
            template<class F> function_ref(F*) noexcept;
            template<class F> constexpr function_ref(F&&) noexcept;
            template<auto f> constexpr function_ref(nontype_t<f>) noexcept;
            template<auto f, class U> constexpr function_ref(nontype_t<f>, U&&) noexcept;
            template<auto f, class T> constexpr function_ref(nontype_t<f>, cv T*) noexcept;
            constexpr function_ref(const function_ref&) noexcept = default;
            constexpr function_ref& operator=(const function_ref&) noexcept = default;
            template<class T> function_ref& operator=(T) = delete;
            // 22.10.17.6.4, invocation
            R operator()(ArgTypes...) const noexcept(noex);
        private:
            template<class... T>
                static constexpr bool is-invocable-using = see below; // exposition only
            R (*thunk-ptr)(BoundEntityType, Args&&...) noexcept(noex);
            BoundEntityType bound-entity; // exposition only
        };

    // 22.10.17.6.5, deduction guides
    template<class F>
        function_ref(F*) -> function_ref<F>;
    template<class F, class T>
        function_ref(nontype_t<f>, T&&) -> function_ref<see below>;
}

1 An object of class function_ref<R(ArgTypes...) cv noexcept(noex)> stores a pointer to function thunk-ptr and an object bound-entity. bound-entity has an unspecified trivially copyable type BoundEntityType, that models copyable and is capable of storing a pointer to object value or a pointer to function value. The type of thunk-ptr is R(*) (BoundEntityType, Args&&...) noexcept(noex).

2 Each specialization of function_ref is a trivially copyable type (6.8.1) that models copyable.

3 Within 22.10.17.6, call-args is an argument pack with elements such that decltype((call-args))... denote Args&&... respectively.

22.10.17.6.3 Constructors and assignment operators

template<class... T>
    static constexpr bool is-invocable-using = see below;

    If noex is true, is-invocable-using<T...> is equal to:
    is_nothrow_invocable_r_v<R, T..., ArgTypes...>

    Otherwise, is-invocable-using<T...> is equal to:
    is_invocable_r_v<R, T..., ArgTypes...>
template<class F> function_ref(F* f) noexcept;

Constraints:
(2.1) is_function_v<F> is true, and
(2.2) is_invocable_using<F> is true.

Preconditions: f is not a null pointer.

Effects: Initializes bound-entity with f, and thunk-ptr with the address of a function thunk such that thunk(bound-entity, call-args...) is expression-equivalent (3.21) to invoke_r<R>(f, call-args...).

template<class F> constexpr function_ref(F&& f) noexcept;

Let T be remove_reference_t<F>.

Constraints:
(6.1) remove_cvref_t<F> is not the same type as function_ref,
(6.2) is_member_pointer_v<T> is false, and
(6.3) is_invocable_using<cv T&> is true.

Effects: Initializes bound-entity with addressof(f), and thunk-ptr with the address of a function thunk such that thunk(bound-entity, call-args...) is expression-equivalent (3.21) to invoke_r<R>(static_cast<cv T&>(f), call-args...).

template<auto f> constexpr function_ref(nontype_t<f>) noexcept;

Let F be decltype(f).

Constraints: is_invocable_using<F> is true.

Mandates: If is_pointer_v<F> || is_member_pointer_v<F> is true, then f != nullptr is true.

Effects: Initializes bound-entity with a pointer to an unspecified object or null pointer value, and thunk-ptr with the address of a function thunk such that thunk(bound-entity, call-args...) is expression-equivalent (3.21) to invoke_r<R>(static_cast<cv T&>(f), call-args...).

template<auto f, class U> constexpr function_ref(nontype_t<f>, U&& obj) noexcept;

Let T be remove_reference_t<U> and F be decltype(f).

Constraints:
(13.1) is_rvalue_reference_v<U&&> is false, and
(13.2) is_invocable_using<F, cv T&> is true.

Mandates: If is_pointer_v<F> || is_member_pointer_v<F> is true, then f != nullptr is true.

Effects: Initializes bound-entity with addressof(obj), and thunk-ptr with the address of a function thunk such that thunk(bound-entity, call-args...) is expression-equivalent (3.21) to invoke_r<R>(f, static_cast<cv T&>(obj), call-args...).

template<auto f, class T> constexpr function_ref(nontype_t<f>, cv T* obj) noexcept;

Let F be decltype(f).

Constraints: is_invocable_using<F, cv T*> is true.

Mandates: If is_pointer_v<F> || is_member_pointer_v<F> is true, then f != nullptr is true.

Preconditions: If is_member_pointer_v<F> is true, obj is not a null pointer.

Effects: Initializes bound-entity with obj, and thunk-ptr with the address of a function thunk such that thunk(bound-entity, call-args...) is expression-equivalent (3.21) to invoke_r<R>(f, obj, call-args...).

template<class T> function_ref& operator=(T) = delete;

Constraints:
— T is not the same type as function_ref,
— is_pointer_v<T> is false, and
— T is not a specialization of nonetype_t.

22.10.17.6.5 Deduction guides

template<class F>
function_ref(F*) -> function_ref<F>;

Constraints: is_function_v<F> is true.

template<auto f>
function_ref(nontype_t<f>) -> function_ref<see below>;

Let F be remove_pointer_t<decltype(f)>.

Constraints: is_function_v<F> is true.

Remarks: The deduced type is function_ref<F>.

template<auto f, class T>
function_ref(nontype_t<f>, T&...) -> function_ref<see below>;

Let F be decltype(f).

Constraints:

1. F is of the form R(G::*)(A...) cv &opt noexcept(E) for a type G, or
2. F is of the form M G::* for a type G and an object type M, in which case let R be invoke_result_t<F, T&>, A... be an empty pack, and E be false, or
3. F is of the form R(*)(G, A...) noexcept(E) for a type G.

Remarks: The deduced type is function_ref<R(A...) noexcept(E)>.  

22.10.18 Searchers

22.10.18.1 General

Subclause 22.10.18 provides function object types (22.10) for operations that search for a sequence [pat_first, pat_last) in another sequence [first, last) that is provided to the object’s function call operator. The first sequence (the pattern to be searched for) is provided to the object’s constructor, and the second (the sequence to be searched) is provided to the function call operator.

Each specialization of a class template specified in 22.10.18 shall meet the Cpp17CopyConstructible and Cpp17CopyAssignable requirements. Template parameters named

1. ForwardIterator,
2. ForwardIterator1,
3. ForwardIterator2,
4. RandomAccessIterator,
5. RandomAccessIterator1,
6. RandomAccessIterator2, and
7. BinaryPredicate

of templates specified in 22.10.18 shall meet the same requirements and semantics as specified in 27.1. Template parameters named Hash shall meet the Cpp17Hash requirements (Table 37).

The Boyer-Moore searcher implements the Boyer-Moore search algorithm. The Boyer-Moore-Horspool searcher implements the Boyer-Moore-Horspool search algorithm. In general, the Boyer-Moore searcher will use more memory and give better runtime performance than Boyer-Moore-Horspool.
22.10.18.2 Class template default_searcher

namespace std {
    template<class ForwardIterator1, class BinaryPredicate = equal_to<>>
    class default_searcher {
    public:
        constexpr default_searcher(ForwardIterator1 pat_first, ForwardIterator1 pat_last,
                                  BinaryPredicate pred = BinaryPredicate());

    template<class ForwardIterator2>
    constexpr pair<ForwardIterator2, ForwardIterator2>
    operator()(ForwardIterator2 first, ForwardIterator2 last) const;

    private:
        ForwardIterator1 pat_first_;  // exposition only
        ForwardIterator1 pat_last_;  // exposition only
        BinaryPredicate pred_;  // exposition only
    };
}

constexpr default_searcher(ForwardIterator1 pat_first, ForwardIterator1 pat_last,
                            BinaryPredicate pred = BinaryPredicate());

Effects: Constructs a default_searcher object, initializing pat_first_ with pat_first, pat_last_ with pat_last, and pred_ with pred.

Throws: Any exception thrown by the copy constructor of BinaryPredicate or ForwardIterator1.

22.10.18.3 Class template boyer_moore_searcher

namespace std {
    template<class RandomAccessIterator1, 
             class Hash = hash<typename iterator_traits<RandomAccessIterator1>::value_type>,
             class BinaryPredicate = equal_to<>>
    class boyer_moore_searcher {
    public:
        boyer_moore_searcher(RandomAccessIterator1 pat_first,
                              RandomAccessIterator1 pat_last,
                              Hash hf = Hash(),
                              BinaryPredicate pred = BinaryPredicate());

    template<class RandomAccessIterator2>
    pair<RandomAccessIterator2, RandomAccessIterator2>
    operator()(RandomAccessIterator2 first, RandomAccessIterator2 last) const;

    private:
        RandomAccessIterator1 pat_first_;  // exposition only
        RandomAccessIterator1 pat_last_;  // exposition only
        Hash hash_;  // exposition only
        BinaryPredicate pred_;  // exposition only
    };
}

boyer_moore_searcher(RandomAccessIterator1 pat_first,
                      RandomAccessIterator1 pat_last,
                      Hash hf = Hash(),
                      BinaryPredicate pred = BinaryPredicate());
template<class RandomAccessIterator2>
pair<RandomAccessIterator2, RandomAccessIterator2>
operator()(RandomAccessIterator2 first, RandomAccessIterator2 last) const;

Mandates: RandomAccessIterator1 and RandomAccessIterator2 have the same value type.

Effects: Finds a subsequence of equal values in a sequence.

Returns: A pair of iterators $i$ and $j$ such that

- $i$ is the first iterator in the range $[first, last - (pat_last_ - pat_first_))$ such that for every non-negative integer $n$ less than $pat_last_ - pat_first_$, the following condition holds:
  \[ \text{pred}(*(i + n), *(pat_first_ + n)) \neq false, \]
- $j == \text{next}(i, \text{distance}(pat_first_, pat_last_))$.

Returns $\text{make_pair}(\text{first}, \text{first})$ if $[\text{pat_first}_, \text{pat_last}_]$ is empty, otherwise returns $\text{make_pair}(\text{last}, \text{last})$ if no such iterator is found.

Complexity: At most $(last - first) * (\text{pat_last}_ - \text{pat_first}_)$ applications of the predicate.
Let \( V \) be \texttt{iterator_traits}<\texttt{RandomAccessIterator1}>::\texttt{value_type}. For any two values \( A \) and \( B \) of type \( V \), if \( \text{pred}(A, B) \equiv \text{true} \), then \( \text{hf}(A) \equiv \text{hf}(B) \) is \text{true}.

\[ \text{Effects:} \text{ initializes pat_first_ with } \text{pat_first}, \text{ pat_last_ with } \text{pat_last}, \text{ hash_ with } \text{hf}, \text{ and pred_ with } \text{pred}. \]

\[ \text{Throws:} \text{ Any exception thrown by the copy constructor of } \texttt{RandomAccessIterator1}, \text{ or by the default constructor, copy constructor, or the copy assignment operator of the value type of } \texttt{RandomAccessIterator1}, \text{ or the copy constructor or } \text{operator\(\) of } \texttt{BinaryPredicate} \text{ or } \texttt{Hash}. \text{ May throw } \texttt{bad_alloc} \text{ if additional memory needed for internal data structures cannot be allocated.} \]

\[
\begin{align*}
\text{template<class RandomAccessIterator2> } &
\text{pair<RandomAccessIterator2, RandomAccessIterator2> } \\
&\text{operator()}(\text{RandomAccessIterator2 first, RandomAccessIterator2 last}) \text{ const;}
\end{align*}
\]

\[ \text{Mandates:} \text{ RandomAccessIterator1 and RandomAccessIterator2 have the same value type.} \]

\[ \text{Effects:} \text{ Finds a subsequence of equal values in a sequence.} \]

\[ \text{Returns:} \text{ A pair of iterators } i \text{ and } j \text{ such that} \]

\[
\begin{align*}
(7.1) & \text{ — } i \text{ is the first iterator in the range } [\text{first}, \text{last} - (\text{pat_last} - \text{pat_first})] \text{ such that for every non-negative integer } n \text{ less than } \text{pat_last} - \text{pat_first} \text{ the following condition holds:} \\
& \text{pred}(\ast(i + n), \ast(\text{pat_first} + n)) \equiv \text{false}, \text{ and} \\
(7.2) & \text{ — } j \equiv \text{next}(i, \text{distance}(\text{pat_first}, \text{pat_last})).
\end{align*}
\]

\[ \text{Returns } \text{make_pair}\(\)\(\text{first, first})\text{ if } [\text{pat_first, pat_last})\text{ is empty, otherwise returns } \text{make_pair}\(\text{last, last})\text{ if no such iterator is found.} \]

\[ \text{Complexity:} \text{ At most } (\text{last} - \text{first}) \ast (\text{pat_last} - \text{pat_first}) \text{ applications of the predicate.} \]

\subsection{22.10.19 Class template \texttt{hash} [unord.hash]}

The unordered associative containers defined in 24.5 use specializations of the class template \texttt{hash} (22.10.2) as the default hash function.

Each specialization of \texttt{hash} is either enabled or disabled, as described below.

\[ \text{[Note 1:} \text{ Enabled specializations meet the } \text{Cpp17Hash} \text{ requirements, and disabled specializations do not.} \text{ — end note]} \]

Each header that declares the template \texttt{hash} provides enabled specializations of \texttt{hash} for \texttt{nullptr_t} and all cv-unqualified arithmetic, enumeration, and pointer types. For any type \texttt{Key} for which neither the library nor the user provides an explicit or partial specialization of the class template \texttt{hash}, \texttt{hash}\(\text{Key}) is disabled.

If the library provides an explicit or partial specialization of \texttt{hash}\(\text{Key}), that specialization is enabled except as noted otherwise, and its member functions are \texttt{noexcept} except as noted otherwise.

If \texttt{H} is a disabled specialization of \texttt{hash}, these values are \texttt{false}: \texttt{is_default_constructible_v\<\texttt{H}\>}, \texttt{is_copy_constructible_v\<\texttt{H}\>}, \texttt{is_move_constructible_v\<\texttt{H}\>}, \texttt{is_copy_assignable_v\<\texttt{H}\>}, and \texttt{is_move_assignable_v\<\texttt{H}\>.} Disabled specializations of \texttt{hash} are not function object types (22.10).

\[ \text{[Note 2:} \text{ This means that the specialization of } \texttt{hash}\text{ exists, but any attempts to use it as a } \text{Cpp17Hash} \text{ will be ill-formed.} \text{ — end note]} \]

An enabled specialization \texttt{hash}\(\text{Key}) will:

\[
\begin{align*}
(5.1) & \text{ — meet the } \text{Cpp17Hash} \text{ requirements (Table 37), with } \texttt{Key} \text{ as the function call argument type, the } \\
& \text{Cpp17DefaultConstructible requirements (Table 30), the } \text{Cpp17CopyAssignable requirements (Table 34),} \\
(5.2) & \text{ — meet the requirement that if } k1 \equiv k2 \text{ is } \text{true}, \texttt{h(k1)} \equiv \texttt{h(k2)} \text{ is also } \text{true}, \text{ where } \texttt{h} \text{ is an object of type } \texttt{hash}\<\texttt{Key}> \text{ and } k1 \text{ and } k2 \text{ are objects of type } \texttt{Key}; \\
(5.3) & \text{ — meet the requirement that the expression } \texttt{h(k)}, \text{ where } \texttt{h} \text{ is an object of type } \texttt{hash}\<\texttt{Key}> \text{ and } k \text{ is an} \text{ object of type } \texttt{Key}, \text{ shall not throw an exception unless } \texttt{hash}\<\texttt{Key}> \text{ is a program-defined specialization.} \]

\section{22.11 Class \texttt{type_index} [type.index]}

\subsection{22.11.1 Header \texttt{<typeindex>} synopsis [type.index.synopsis]}

\[
\text{#include } <\text{compare}> \\
\text{// see 17.11.1}
\]
22.11.2 type_index overview

The class `type_index` provides a simple wrapper for `type_info` which can be used as an index type in associative containers (24.4) and in unordered associative containers (24.5).

22.11.3 type_index members

```cpp
namespace std {
    class type_index {
        public:
            type_index(const type_info& rhs) noexcept;
            bool operator==(const type_index& rhs) const noexcept;
            bool operator<(const type_info& rhs) const noexcept;
            bool operator>(const type_info& rhs) const noexcept;
            bool operator<=(const type_info& rhs) const noexcept;
            bool operator>=(const type_info& rhs) const noexcept;
            strong_ordering operator<=>(const type_index& rhs) const noexcept;
            size_t hash_code() const noexcept;
            const char* name() const noexcept;
        private:
            const type_info* target;  // exposition only
            // Note that the use of a pointer here, rather than a reference,
            // means that the default copy/move constructor and assignment
            // operators will be provided and work as expected.
    };  // type_index
}
```

1. The class `type_index` provides a simple wrapper for `type_info` which can be used as an index type in associative containers (24.4) and in unordered associative containers (24.5).

```cpp
1. type_index(const type_info& rhs) noexcept;
   Effects: Constructs a `type_index` object, the equivalent of `target = &rhs`.

2. bool operator==(const type_info& rhs) const noexcept;
   Returns: `*target == *rhs.target`.

3. bool operator<(const type_info& rhs) const noexcept;
   Returns: `target->before(*rhs.target)`.

4. bool operator>(const type_info& rhs) const noexcept;
   Returns: `rhs.target->before(*target)`.

5. bool operator<=(const type_info& rhs) const noexcept;
   Returns: `!rhs.target->before(*target)`.

6. bool operator>=(const type_info& rhs) const noexcept;
   Returns: `!target->before(*rhs.target)`.

7. strong_ordering operator<=>(const type_info& rhs) const noexcept;
   Effects: Equivalent to:
   ```cpp
   if (*target == *rhs.target) return strong_ordering::equal;
   if (target->before(*rhs.target)) return strong_ordering::less;
   return strong_ordering::greater;
   ```
   Returns: `target->hash_code()`.

8. size_t hash_code() const noexcept;
```

§ 22.11.3 © ISO/IEC 819
const char* name() const noexcept;

Returns: target->name().

22.11.4 Hash support

template<>
struct hash<type_index>;

For an object index of type type_index, hash<type_index>()(index) shall evaluate to the same result as index.hash_code().

22.12 Execution policies

22.12.1 General

Subclause 22.12 describes classes that are execution policy types. An object of an execution policy type indicates the kinds of parallelism allowed in the execution of an algorithm and expresses the consequent requirements on the element access functions.

[Example 1:
using namespace std;
vector<int> v = /* ... */;

    // standard sequential sort
    sort(v.begin(), v.end());

    // explicitly sequential sort
    sort(execution::seq, v.begin(), v.end());

    // permitting parallel execution
    sort(execution::par, v.begin(), v.end());

    // permitting vectorization as well
    sort(execution::par_unseq, v.begin(), v.end());

—end example]

[Note 1: Implementations can provide additional execution policies to those described in this document as extensions to address parallel architectures that require idiosyncratic parameters for efficient execution. — end note]

22.12.2 Header <execution> synopsis

namespace std {
    // 22.12.3, execution policy type trait
template<class T> struct is_execution_policy;
template<class T> constexpr bool is_execution_policy_v = is_execution_policy<T>::value;
}
namespace std::execution {
    // 22.12.4, sequenced execution policy
class sequenced_policy;

    // 22.12.5, parallel execution policy
class parallel_policy;

    // 22.12.6, parallel and unsequenced execution policy
class parallel_unsequenced_policy;

    // 22.12.7, unsequenced execution policy
class unsequenced_policy;

    // 22.12.8, execution policy objects
    inline constexpr sequenced_policy seq{ unspecified }; 
    inline constexpr parallel_policy par{ unspecified }; 
    inline constexpr parallel_unsequenced_policy par_unseq{ unspecified }; 
    inline constexpr unsequenced_policy unseq{ unspecified }; 
}

§ 22.12.2
22.12.3 Execution policy type trait

\[\text{execpol.type}\]

\[
\text{template<class } T \text{> struct is_execution_policy \{ see below \};}
\]

1. \(\text{is_execution_policy}\) can be used to detect execution policies for the purpose of excluding function signatures from otherwise ambiguous overload resolution participation.
2. \(\text{is_execution_policy}\) is a \textit{Cpp17UnaryTypeTrait} with a base characteristic of \texttt{true_type} if \(T\) is the type of a standard or implementation-defined execution policy, otherwise \texttt{false_type}.

\[\text{[Note 1: This provision reserves the privilege of creating non-standard execution policies to the library implementation. — end note]}\]

3. The behavior of a program that adds specializations for \(\text{is_execution_policy}\) is undefined.

22.12.4 Sequenced execution policy

\[\text{execpol.seq}\]

\[
\text{class execution::sequenced_policy \{ unspecified \};}
\]

1. The class \textit{execution::sequenced_policy} is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and require that a parallel algorithm’s execution may not be parallelized.
2. During the execution of a parallel algorithm with the \textit{execution::sequenced_policy} policy, if the invocation of an element access function exits via an exception, \texttt{terminate} is invoked (14.6.2).

22.12.5 Parallel execution policy

\[\text{execpol.par}\]

\[
\text{class execution::parallel_policy \{ unspecified \};}
\]

1. The class \textit{execution::parallel_policy} is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and indicate that a parallel algorithm’s execution may be parallelized.
2. During the execution of a parallel algorithm with the \textit{execution::parallel_policy} policy, if the invocation of an element access function exits via an exception, \texttt{terminate} is invoked (14.6.2).

22.12.6 Parallel and unsequenced execution policy

\[\text{execpol.parunseq}\]

\[
\text{class execution::parallel_unsequenced_policy \{ unspecified \};}
\]

1. The class \textit{execution::parallel_unsequenced_policy} is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and indicate that a parallel algorithm’s execution may be parallelized and vectorized.
2. During the execution of a parallel algorithm with the \textit{execution::parallel_unsequenced_policy} policy, if the invocation of an element access function exits via an exception, \texttt{terminate} is invoked (14.6.2).

22.12.7 Unsequenced execution policy

\[\text{execpol.unseq}\]

\[
\text{class execution::unsequenced_policy \{ unspecified \};}
\]

1. The class \textit{unsequenced_policy} is an execution policy type used as a unique type to disambiguate parallel algorithm overloading and indicate that a parallel algorithm’s execution may be vectorized, e.g., executed on a single thread using instructions that operate on multiple data items.
2. During the execution of a parallel algorithm with the \textit{execution::unsequenced_policy} policy, if the invocation of an element access function exits via an exception, \texttt{terminate} is invoked (14.6.2).

22.12.8 Execution policy objects

\[\text{execpol.objects}\]

\[
\text{inline constexpr execution::sequenced_policy execution::seq\{ unspecified \};}
\]
\[
\text{inline constexpr execution::parallel_policy execution::par\{ unspecified \};}
\]
\[
\text{inline constexpr execution::parallel_unsequenced_policy execution::par_unseq\{ unspecified \};}
\]
\[
\text{inline constexpr execution::unsequenced_policy execution::unseq\{ unspecified \};}
\]

1. The header \texttt{<execution>} declares global objects associated with each type of execution policy.
22.13 Primitive numeric conversions

22.13.1 Header <charconv> synopsis

When a function is specified with a type placeholder of **integer-type**, the implementation provides overloads for **char** and all cv-unqualified signed and unsigned integer types in lieu of **integer-type**. When a function is specified with a type placeholder of **floating-point-type**, the implementation provides overloads for all cv-unqualified floating-point types (6.8.2) in lieu of **floating-point-type**.

```cpp
namespace std {
    // floating-point format for primitive numerical conversion
    enum class chars_format {
        scientific = unspecified,
        fixed = unspecified,
        hex = unspecified,
        general = fixed | scientific
    };

    // 22.13.2, primitive numerical output conversion
    struct to_chars_result {
        // freestanding
        char* ptr;
        errc ec;
        friend bool operator==(const to_chars_result&, const to_chars_result&) = default;
        constexpr explicit operator bool() const noexcept { return ec == errc{}; }
    };

    constexpr to_chars_result to_chars_result to_chars(char* first, char* last,  // freestanding
        integer-type value, int base = 10);
    to_chars_result to_chars(char* first, char* last,  // freestanding
        bool value, int base = 10) = delete;
    to_chars_result to_chars(char* first, char* last,  // freestanding-deleted
        floating-point-type value);
    to_chars_result to_chars(char* first, char* last,  // freestanding-deleted
        floating-point-type value, chars_format fmt);
    to_chars_result to_chars(char* first, char* last,  // freestanding-deleted
        floating-point-type value, chars_format fmt, int precision);

    // 22.13.3, primitive numerical input conversion
    struct from_chars_result {
        // freestanding
        const char* ptr;
        errc ec;
        friend bool operator==(const from_chars_result&, const from_chars_result&) = default;
        constexpr explicit operator bool() const noexcept { return ec == errc{}; }
    };

    constexpr from_chars_result from_chars_result from_chars(const char* first, const char* last,  // freestanding
        integer-type& value, int base = 10);
    from_chars_result from_chars(const char* first, const char* last,  // freestanding-deleted
        floating-point-type& value,
        chars_format fmt = chars_format::general);
}
```

2 The type **chars_format** is a bitmask type (16.3.3.3.3) with elements **scientific**, **fixed**, and **hex**.

3 The types **to_chars_result** and **from_chars_result** have the data members and special members specified above. They have no base classes or members other than those specified.

22.13.2 Primitive numeric output conversion

All functions named **to_chars** convert **value** into a character string by successively filling the range [**first**, **last**), where [**first**, **last**) is required to be a valid range. If the member **ec** of the return value is such that the value is equal to the value of a value-initialized **errc**, the conversion was successful and the member **ptr** is the one-past-the-end pointer of the characters written. Otherwise, the member **ec** has
the value `errc::value_too_large`, the member `ptr` has the value `last`, and the contents of the range `[first, last)` are unspecified.

2 The functions that take a floating-point value but not a precision parameter ensure that the string representation consists of the smallest number of characters such that there is at least one digit before the radix point (if present) and parsing the representation using the corresponding `from_chars` function recovers value exactly.

[Note 1: This guarantee applies only if `to_chars` and `from_chars` are executed on the same implementation. — end note]

If there are several such representations, the representation with the smallest difference from the floating-point argument value is chosen, resolving any remaining ties using rounding according to `round_to_nearest` (17.3.4).

3 The functions taking a `chars_format` parameter determine the conversion specifier for `printf` as follows:

The conversion specifier is `f` if `fmt` is `chars_format::fixed`, `e` if `fmt` is `chars_format::scientific`, a (without leading "0x" in the result) if `fmt` is `chars_format::hex`, and `g` if `fmt` is `chars_format::general`.

```cpp
cconstexpr to_chars_result to_chars(char* first, char* last, integer-type value, int base = 10);
```

**Preconditions:** `base` has a value between 2 and 36 (inclusive).

**Effects:** The value of `value` is converted to a string of digits in the given base (with no redundant leading zeroes). Digits in the range 10..35 (inclusive) are represented as lowercase characters `a..z`. If `value` is less than zero, the representation starts with `'-`.

**Throws:** Nothing.

```cpp
to_chars_result to_chars(char* first, char* last, floating-point-type value);
```

**Effects:** `value` is converted to a string in the style of `printf` in the "C" locale. The conversion specifier is `f` or `e`, chosen according to the requirement for a shortest representation (see above); a tie is resolved in favor of `f`.

**Throws:** Nothing.

```cpp
to_chars_result to_chars(char* first, char* last, floating-point-type value, chars_format fmt);
```

**Preconditions:** `fmt` has the value of one of the enumerators of `chars_format`.

**Effects:** `value` is converted to a string in the style of `printf` in the "C" locale.

**Throws:** Nothing.

```cpp
to_chars_result to_chars(char* first, char* last, floating-point-type value, chars_format fmt, int precision);
```

**Preconditions:** `fmt` has the value of one of the enumerators of `chars_format`.

**Effects:** `value` is converted to a string in the style of `printf` in the "C" locale with the given precision.

**Throws:** Nothing.

**See also:** ISO/IEC 9899:2018, 7.21.6.1

### 22.13.3 Primitive numeric input conversion [charconv.from.chars]

All functions named `from_chars` analyze the string `[first, last)` for a pattern, where `[first, last)` is required to be a valid range. If no characters match the pattern, `value` is unmodified, the member `ptr` of the return value is `first` and the member `ec` is equal to `errc::invalid_argument`.

[Note 1: If the pattern allows for an optional sign, but the string has no digit characters following the sign, no characters match the pattern. — end note]

Otherwise, the characters matching the pattern are interpreted as a representation of a value of the type of `value`. The member `ptr` of the return value points to the first character not matching the pattern, or has the value `last` if all characters match. If the parsed value is not in the range representable by the type of `value`, `value` is unmodified and the member `ec` of the return value is equal to `errc::result_out_of_range`. Otherwise, `value` is set to the parsed value, after rounding according to `round_to_nearest` (17.3.4), and the member `ec` is value-initialized.

§ 22.13.3 ©ISO/IEC 823
constexpr from_chars_result from_chars(const char* first, const char* last, integer-type & value, int base = 10);

Preconditions: base has a value between 2 and 36 (inclusive).

Effects: The pattern is the expected form of the subject sequence in the "C" locale for the given nonzero base, as described for strtol, except that no "0x" or "0X" prefix shall appear if the value of base is 16, and except that '-' is the only sign that may appear, and only if value has a signed type.

Throws: Nothing.

from_chars_result from_chars(const char* first, const char* last, floating-point-type & value, chars_format fmt = chars_format::general);

Preconditions: fmt has the value of one of the enumerators of chars_format.

Effects: The pattern is the expected form of the subject sequence in the "C" locale, as described for strtod, except that

- the sign '+' may only appear in the exponent part;
- if fmt has chars_format::scientific set but not chars_format::fixed, the otherwise optional exponent part shall appear;
- if fmt has chars_format::fixed set but not chars_format::scientific, the optional exponent part shall not appear; and
- if fmt is chars_format::hex, the prefix "0x" or "0X" is assumed.

Example 1: The string 0x123 is parsed to have the value 0 with remaining characters x123. — end example

In any case, the resulting value is one of at most two floating-point values closest to the value of the string matching the pattern.

Throws: Nothing.

See also: ISO/IEC 9899:2018, 7.22.1.3, 7.22.1.4

22.14 Formatting [format]

22.14.1 Header <format> synopsis [format.syn]

namespace std {
    // 22.14.6.7, class template basic_format_context
    template<class Out, class charT> class basic_format_context;
    using format_context = basic_format_context<unspecified, char>;
    using wformat_context = basic_format_context<unspecified, wchar_t>;

    // 22.14.8.3, class template basic_format_args
    template<class Context> class basic_format_args;
    using format_args = basic_format_args<format_context>;
    using wformat_args = basic_format_args<wformat_context>;

    // 22.14.4, class template basic_format_string
    template<class charT, class... Args>
    struct basic_format_string;

    template<class charT> struct runtime-format-string {
        // exposition only
        private:
            basic_string_view<charT> str;
        // exposition only
        public:
            runtime-format-string(basic_string_view<charT> s) noexcept : str(s) {}  
            runtime-format-string(const runtime-format-string&) = delete;
            runtime-format-string& operator=(const runtime-format-string&) = delete;
        }
        runtime-format-string<char> runtime_format(string_view fmt) noexcept { return fmt; }
        runtime-format-string<wstring_view fmt> noexcept { return fmt; }

        template<class... Args>
        using format_string = basic_format_string<char, type_identity_t<Args>...>;

§ 22.14.1 ©ISO/IEC 824
template<class... Args>
using wformat_string = basic_format_string<wchar_t, type_identity_t<Args>...>;

// 22.14.5, formatting functions
template<class... Args>
string format(format_string<Args...> fmt, Args&&... args);
template<class... Args>
wstring format(wformat_string<Args...> fmt, Args&&... args);
template<class... Args>
string format(const locale& loc, format_string<Args...> fmt, Args&&... args);
template<class... Args>
wstring format(const locale& loc, wformat_string<Args...> fmt, Args&&... args);

string vformat(string_view fmt, format_args args);
wstring vformat(wstring_view fmt, wformat_args args);
string vformat(const locale& loc, string_view fmt, format_args args);
wstring vformat(const locale& loc, wstring_view fmt, wformat_args args);

template<class Out, class... Args>
Out format_to(Out out, format_string<Args...> fmt, Args&&... args);
template<class Out, class... Args>
Out format_to(Out out, wformat_string<Args...> fmt, Args&&... args);
template<class Out, class... Args>
Out format_to(Out out, const locale& loc, format_string<Args...> fmt, Args&&... args);
template<class Out, class... Args>
Out format_to(Out out, const locale& loc, wformat_string<Args...> fmt, Args&&... args);

template<class Out>
Out vformat_to(Out out, string_view fmt, format_args args);
template<class Out>
Out vformat_to(Out out, string_view fmt, wformat_args args);
template<class Out>
Out vformat_to(Out out, const locale& loc, string_view fmt, format_args args);
template<class Out>
Out vformat_to(Out out, const locale& loc, wstring_view fmt, wformat_args args);

template<class Out> struct format_to_n_result {
  Out out;
  iter_difference_t<Out> size;
};
template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n, format_string<Args...> fmt, Args&&... args);
template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n, wformat_string<Args...> fmt, Args&&... args);
template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n, const locale& loc, format_string<Args...> fmt, Args&&... args);
template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n, const locale& loc, wformat_string<Args...> fmt, Args&&... args);

template<class... Args>
size_t formatted_size(format_string<Args...> fmt, Args&&... args);
template<class... Args>
size_t formatted_size(wformat_string<Args...> fmt, Args&&... args);
template<class... Args>
size_t formatted_size(const locale& loc, format_string<Args...> fmt, Args&&... args);
template<class... Args>
size_t formatted_size(const locale& loc, wformat_string<Args...> fmt, Args&&... args);
// 22.14.6, formatter
template<class T, class charT = char> struct formatter;

// 22.14.6.2, formatter locking
template<class T>
constexpr bool enable_nonlocking_formatter_optimization = false;

// 22.14.6.3, concept formattable
template<class T, class charT>
concept formattable = see below;

template<class R, class charT>
concept const-formattable-range = // exposition only
ranges::input_range<const R> &&
formattable<ranges::range_reference_t<const R>, charT>;

template<class R, class charT>
using fmt-maybe-const = // exposition only
conditional_t<
const-formattable-range<R, charT>, 
const R, R>;

// 22.14.6.6, class template basic_format_parse_context
template<class charT> class basic_format_parse_context;
using format_parse_context = basic_format_parse_context<char>;
using wformat_parse_context = basic_format_parse_context<wchar_t>;

// 22.14.7, formatting of ranges
// 22.14.7.1, variable template format_kind
enum class range_format {
    disabled,
    map,
    set,
    sequence,
    string,
    debug_string
};

template<class R>
constexpr unspecified format_kind = unspecified;

template<ranges::input_range R>
requires same_as<R, remove_cvref_t<R>>
constexpr range_format format_kind<R> = see below;

// 22.14.7.2, class template range_formatter
template<class T, class charT = char>
requires same_as<remove_cvref_t<T>, T> && formattable<T, charT>
class range_formatter;

// 22.14.7.3, class template range-default-formatter
template<range_format K, ranges::input_range R, class charT>
struct range-default-formatter; // exposition only

// 22.14.7.4, 22.14.7.5, 22.14.7.6, specializations for maps, sets, and strings
template<ranges::input_range R, class charT>
requires (format_kind<R> != range_format::disabled) &&
formattable<ranges::range_reference_t<R>, charT>
struct formatter<R, charT> : range-default-formatter<format_kind<R>>, 
R, charT> { }

template<ranges::input_range R>
requires (format_kind<R> != range_format::disabled)
inline constexpr bool enable_nonlocking_formatter_optimization<R> = false;
// 22.14.8, arguments
// 22.14.8.1, class template basic_format_arg
template<class Context> class basic_format_arg;

// 22.14.8.2, class template format-arg-store
template<class Context, class... Args> class format-arg-store;
    // exposition only

template<class Context = format_context, class... Args>
    format-arg-store<Context, Args...>
        make_format_args(Args&... fmt_args);

template<class... Args>
    format-arg-store<wformat_context, Args...>
        make_wformat_args(Args&... args);

// 22.14.10, class format_error
class format_error;

The class template format_to_n_result has the template parameters, data members, and special members specified above. It has no base classes or members other than those specified.

22.14.2 Format string

22.14.2.1 General

A format string for arguments args is a (possibly empty) sequence of replacement fields, escape sequences, and characters other than { and }. Let charT be the character type of the format string. Each character that is not part of a replacement field or an escape sequence is copied unchanged to the output. An escape sequence is one of {{ or }}. It is replaced with { or }, respectively, in the output. The syntax of replacement fields is as follows:

replacement-field:
    { arg-id,opt format-specifier, opt }
arg-id:
    0 positive-integer
positive-integer:
    nonzero-digit
    positive-integer digit
nonnegative-integer:
    digit
    nonnegative-integer digit
nonzero-digit: one of
    1 2 3 4 5 6 7 8 9
digit: one of
    0 1 2 3 4 5 6 7 8 9
format-specifier:
    : format-spec

format-spec:
    as specified by the formatter specialization for the argument type; cannot start with }

The arg-id field specifies the index of the argument in args whose value is to be formatted and inserted into the output instead of the replacement field. If there is no argument with the index arg-id in args, the string is not a format string for args. The optional format-specifier field explicitly specifies a format for the replacement value.

[Example 1:

    string s = format("\{0\}-\{{*, \8");  // value of s is \"8-{*\"
   — end example]

If all arg-ids in a format string are omitted (including those in the format-spec, as interpreted by the corresponding formatter specialization), argument indices 0, 1, 2, ... will automatically be used in that order. If some arg-ids are omitted and some are present, the string is not a format string.

§ 22.14.2.1 ©ISO/IEC
[Note 1: A format string cannot contain a mixture of automatic and manual indexing. — end note]

[Example 2:

```c
string s0 = format("{0} to {1}"); // OK, automatic indexing
string s1 = format("{1} to {0}"); // OK, manual indexing
string s2 = format("{0} to {1}"); // not a format string (mixing automatic and manual indexing), // ill-formed
string s3 = format("{1} to {0}"); // not a format string (mixing automatic and manual indexing), // ill-formed
```
— end example]

The `format-spec` field contains format specifications that define how the value should be presented. Each type can define its own interpretation of the `format-spec` field. If `format-spec` does not conform to the format specifications for the argument type referred to by `arg-id`, the string is not a format string for `args`.

[Example 3:

(5.1) — For arithmetic, pointer, and string types the `format-spec` is interpreted as a `std-format-spec` as described in (22.14.2.2).

(5.2) — For chrono types the `format-spec` is interpreted as a `chrono-format-spec` as described in (29.12).

(5.3) — For user-defined formatter specializations, the behavior of the `parse` member function determines how the `format-spec` is interpreted.
— end example]

### 22.14.2.2 Standard format specifiers

[format.string.std]

Each `formatter` specialization described in 22.14.6.4 for fundamental and string types interprets `format-spec` as a `std-format-spec`.

[Note 1: The format specification can be used to specify such details as minimum field width, alignment, padding, and decimal precision. Some of the formatting options are only supported for arithmetic types. — end note]

The syntax of format specifications is as follows:

```
std-format-spec:
  fill-and-align_opt sign_opt #opt 0opt width_opt precision_opt Lopt type_opt

fill-and-align:
  fill_opt align

fill:
  any character other than { or }

align: one of
  < > ^

sign: one of
  + - space

width:
  positive-integer
  { arg-id_opt }

precision:
  . nonnegative-integer
  . { arg-id_opt }

type: one of
  a A b B c d e E f F g G o p P s x X ?
```

Field widths are specified in field width units; the number of column positions required to display a sequence of characters in a terminal. The minimum field width is the number of field width units a replacement field minimally requires of the formatted sequence of characters produced for a format argument. The estimated field width is the number of field width units that are required for the formatted sequence of characters produced for a format argument independent of the effects of the `width` option. The padding width is the greater of 0 and the difference of the minimum field width and the estimated field width.

[Note 2: The POSIX `wcswidth` function is an example of a function that, given a string, returns the number of column positions required by a terminal to display the string. — end note]
The **fill character** is the character denoted by the **fill** option or, if the **fill** option is absent, the space character. For a format specification in UTF-8, UTF-16, or UTF-32, the fill character corresponds to a single Unicode scalar value.

**Note 3:** The presence of a **fill** option is signaled by the character following it, which must be one of the alignment options. If the second character of **std-format-spec** is not a valid alignment option, then it is assumed that the **fill** and **align** options are both absent. — *end note*

The **align** option applies to all argument types. The meaning of the various alignment options is as specified in Table 69.

**Example 1:**

```cpp
class format {  
public:  
  static string format(const string& spec,  
                       const T& arg);  

private:  
  T arg_;  
};
```

```cpp
char c = 120;
string s0 = format("{:6}", 42); // value of s0 is " 42"
string s1 = format("{:3}", 'x'); // value of s1 is "x  
string s2 = format("{:*:6}" , 'x'); // value of s2 is "x*****
string s3 = format("{:*:6}" , 'x'); // value of s3 is "*****x"
string s4 = format("{:*:6}" , 'x'); // value of s4 is "***x**
string s5 = format("{:*:6}" , c); // value of s5 is " 120"
string s6 = format("{:*:6}" , true); // value of s6 is "true  
string s7 = format("{:*:6.3}" , "123456"); // value of s7 is "123***
string s8 = format("{:*:06}" , 1234); // value of s8 is "1234"
string s9 = format("{:*:06}" , 12); // value of s9 is "12"
string sA = format("{:*:6}" , "12345678"); // value of sA is "12345678"
string sB = format("{:*:6}" , "x") ; // value of sB is "x****
string sC = format("{:*:6}" , "12345678"); // value of sC is "12345678"
```

**Example 2:**

```cpp
double inf = numeric_limits<double>::infinity();
double nan = numeric_limits<double>::quiet_NaN();
string s0 = format("{0:},{0:+},{0:-},{0: }", 1); // value of s0 is "1,+1,1, 1"
string s1 = format("{0:},{0:+},{0:-},{0: }", -1); // value of s1 is ",-1,-1,-1"
string s2 = format("{0:},{0:inf},{0:-},{0: }", inf); // value of s2 is "inf,+inf,inf, inf"
string s3 = format("{0:},{0:+},{0:-},{0: }", nan); // value of s3 is "nan,+nan,nan, nan"
```

**Note 4:** The **fill**, **align**, and 0 options have no effect when the minimum field width is not greater than the estimated field width because padding width is 0 in that case. Since fill characters are assumed to have a field width of 1, use of a character with a different field width can produce misaligned output. The `ültf921 clown face` character has a field width of 2. The examples above that include that character illustrate the effect of the field width when that character is used as a fill character as opposed to when it is used as a formatting argument. — *end note*

### Table 69 — Meaning of **align** options  
*[tab:format.align]*

<table>
<thead>
<tr>
<th>Option</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;</td>
<td>Forces the formatted argument to be aligned to the start of the field by inserting <em>n</em> fill characters after the formatted argument where <em>n</em> is the padding width. This is the default for non-arithmetic non-pointer types, <code>charT</code>, and <code>bool</code>, unless an integer presentation type is specified.</td>
</tr>
<tr>
<td>&gt;</td>
<td>Forces the formatted argument to be aligned to the end of the field by inserting <em>n</em> fill characters before the formatted argument where <em>n</em> is the padding width. This is the default for arithmetic types other than <code>charT</code> and <code>bool</code>, pointer types, or when an integer presentation type is specified.</td>
</tr>
<tr>
<td>-</td>
<td>Forces the formatted argument to be centered within the field by inserting ( \left\lfloor \frac{n}{2} \right\rfloor ) fill characters before and ( \left\lceil \frac{n}{2} \right\rceil ) fill characters after the formatted argument, where <em>n</em> is the padding width.</td>
</tr>
</tbody>
</table>

5. The **sign** option is only valid for arithmetic types other than `charT` and `bool` or when an integer presentation type is specified. The meaning of the various options is as specified in Table 70.

6. The **sign** option applies to floating-point infinity and NaN.

**Example 2:**

```cpp
double inf = numeric_limits<double>::infinity();
double nan = numeric_limits<double>::quiet_NaN();
string s0 = format("{0:},{0:+},{0:-},{0: }", 1); // value of s0 is "1,+1,1, 1"
string s1 = format("{0:},{0:+},{0:-},{0: }", -1); // value of s1 is ",-1,-1,-1"
string s2 = format("{0:},{0:inf},{0:-},{0: }", inf); // value of s2 is "inf,+inf,inf, inf"
string s3 = format("{0:},{0:+},{0:-},{0: }", nan); // value of s3 is "nan,+nan,nan, nan"
```

§ 22.14.2.2 © ISO/IEC 829
Table 70 — Meaning of sign options [tab:format.sign]

<table>
<thead>
<tr>
<th>Option</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Indicates that a sign should be used for both non-negative and negative numbers. The + sign is inserted before the output of <code>to_chars</code> for non-negative numbers other than negative zero.</td>
</tr>
<tr>
<td></td>
<td>[Note 5: For negative numbers and negative zero the output of <code>to_chars</code> will already contain the sign so no additional transformation is performed. — end note]</td>
</tr>
<tr>
<td>-</td>
<td>Indicates that a sign should be used for negative numbers and negative zero only (this is the default behavior).</td>
</tr>
<tr>
<td>space</td>
<td>Indicates that a leading space should be used for non-negative numbers other than negative zero, and a minus sign for negative numbers and negative zero.</td>
</tr>
</tbody>
</table>

The # option causes the alternate form to be used for the conversion. This option is valid for arithmetic types other than `charT` and `bool` or when an integer presentation type is specified, and not otherwise. For integral types, the alternate form inserts the base prefix (if any) specified in Table 72 into the output after the sign character (possibly space) if there is one, or before the output of `to_chars` otherwise. For floating-point types, the alternate form causes the result of the conversion of finite values to always contain a decimal-point character, even if no digits follow it. Normally, a decimal-point character appears in the result of these conversions only if a digit follows it. In addition, for `g` and `G` conversions, trailing zeros are not removed from the result.

The 0 option is valid for arithmetic types other than `charT` and `bool`, pointer types, or when an integer presentation type is specified. For formatting arguments that have a value other than an infinity or a NaN, this option pads the formatted argument by inserting the 0 character n times following the sign or base prefix indicators (if any) where n is 0 if the align option is present and is the padding width otherwise.

For a sequence of characters in UTF-8, UTF-16, or UTF-32, an implementation should use as its field width the sum of the field widths of the first code point of each extended grapheme cluster. Extended grapheme clusters are defined by UAX #29 of the Unicode Standard. The following code points have a field width of 2:

1. any code point with the `East_Asian_Width="W"` or `East_Asian_Width="F"` Derived Extracted Property as described by UAX #44 of the Unicode Standard
2. `U+4DC0` – `U+4DFF` (Yijing Hexagram Symbols)

---

Note 6: This is the case for Windows®-based and many POSIX-based operating systems. — end note]
The field width of all other code points is 1.

For a sequence of characters in neither UTF-8, UTF-16, nor UTF-32, the field width is unspecified.

The **precision** option is valid for floating-point and string types. For floating-point types, the value of this option specifies the precision to be used for the floating-point presentation type. For string types, this option specifies the longest prefix of the formatted argument to be included in the replacement field such that the field width of the prefix is no greater than the value of this option.

If **nonnegative-integer** is used in a **precision** option, the value of the decimal integer is used as the value of the option.

When the L option is used, the form used for the conversion is called the **locale-specific form**. The L option is only valid for arithmetic types, and its effect depends upon the type.

- For integral types, the locale-specific form causes the context’s locale to be used to insert the appropriate digit group separator characters.
- For floating-point types, the locale-specific form causes the context’s locale to be used to insert the appropriate digit group and radix separator characters.
- For the textual representation of **bool**, the locale-specific form causes the context’s locale to be used to insert the appropriate string as if obtained with `numpunct::truename` or `numpunct::falsename`.

The **type** determines how the data should be presented.

The available string presentation types are specified in Table 71.

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none, s</td>
<td>Copies the string to the output.</td>
</tr>
<tr>
<td>?</td>
<td>Copies the escaped string (22.14.6.5) to the output.</td>
</tr>
</tbody>
</table>

The meaning of some non-string presentation types is defined in terms of a call to to_chars. In such cases, let \([\text{first}, \text{last})\) be a range large enough to hold the to_chars output and value be the formatting argument value. Formatting is done as if by calling to_chars as specified and copying the output through the output iterator of the format context.

**Note 7**: Additional padding and adjustments are performed prior to copying the output through the output iterator as specified by the format specifiers. —end note

The available integer presentation types for integral types other than bool and charT are specified in Table 72.

**Example 4**:

```cpp
string s0 = format("{}", 42); // value of s0 is "42"
string s1 = format("{0:b} {0:d} {0:o} {0:x}", 42); // value of s1 is "101010 42 52 2a"
string s2 = format("{0:#x} {0:#X}", 42); // value of s2 is "0x2a 0X2A"
string s3 = format("{:L}", 1234); // value of s3 can be "1,234"
```  // (depending on the locale)

—end example

The available charT presentation types are specified in Table 73.

The available bool presentation types are specified in Table 74.

The available floating-point presentation types and their meanings for values other than infinity and NaN are specified in Table 75. For lower-case presentation types, infinity and NaN are formatted as **inf** and **nan**, respectively. For upper-case presentation types, infinity and NaN are formatted as **INF** and **NAN**, respectively.

**Note 9**: In either case, a sign is included if indicated by the **sign** option. —end note

The available pointer presentation types and their mapping to to_chars are specified in Table 76.

**Note 10**: Pointer presentation types also apply to **nullptr_t**. —end note

§ 22.14.2.2

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831
Table 72 — Meaning of type options for integer types

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>to_chars(first, last, value, 2); the base prefix is 0b.</td>
</tr>
<tr>
<td>B</td>
<td>The same as b, except that the base prefix is 0B.</td>
</tr>
<tr>
<td>c</td>
<td>Copies the character static_cast&lt;charT&gt;(value) to the output. Throws format_error if value is not in the range of representable values for charT.</td>
</tr>
<tr>
<td>d</td>
<td>to_chars(first, last, value).</td>
</tr>
<tr>
<td>o</td>
<td>to_chars(first, last, value, 8); the base prefix is 0 if value is nonzero and is empty otherwise.</td>
</tr>
<tr>
<td>X</td>
<td>The same as x, except that it uses uppercase letters for digits above 9 and the base prefix is 0X.</td>
</tr>
<tr>
<td>none</td>
<td>The same as d.</td>
</tr>
</tbody>
</table>

[Note 8: If the formatting argument type is charT or bool, the default is instead c or s, respectively. —end note]

Table 73 — Meaning of type options for charT

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none, c</td>
<td>Copies the character to the output.</td>
</tr>
<tr>
<td>b, B, d, o, x, X</td>
<td>As specified in Table 72 with value converted to the unsigned version of the underlying type.</td>
</tr>
<tr>
<td>?</td>
<td>Copies the escaped character (22.14.6.5) to the output.</td>
</tr>
</tbody>
</table>

Table 74 — Meaning of type options for bool

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none, s</td>
<td>Copies textual representation, either true or false, to the output.</td>
</tr>
<tr>
<td>b, B, d, o, x, X</td>
<td>As specified in Table 72 for the value static_cast&lt;unsigned char&gt;(value).</td>
</tr>
</tbody>
</table>

22.14.3 Error reporting

Formatting functions throw format_error if an argument fmt is passed that is not a format string for args. They propagate exceptions thrown by operations of formatter specializations and iterators. Failure to allocate storage is reported by throwing an exception as described in 16.4.6.13.

22.14.4 Class template basic_format_string

```cpp
namespace std {
    template<class charT, class... Args>
    struct basic_format_string {
        private:
            basic_string_view<charT> str; // exposition only
        public:
            template<class T> consteval basic_format_string(const T& s)
                basic_format_string(runtime-format-string<charT> s) noexcept : str(s.str) {}
                constexpr basic_string_view<charT> get() const noexcept { return str; }
            
    }
}
```

1 Constraints: const T& models convertible_to<basic_string_view<charT>>.
2 Effects: Direct-non-list-initializes str with s.
Table 75 — Meaning of type options for floating-point types  [tab:format.type.float]

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>If <code>precision</code> is specified, equivalent to <code>to_chars(first, last, value, chars_format::hex, precision)</code> where <code>precision</code> is the specified formatting precision; equivalent to <code>to_chars(first, last, value, chars_format::hex)</code> otherwise.</td>
</tr>
<tr>
<td>A</td>
<td>The same as a, except that it uses uppercase letters for digits above 9 and P to indicate the exponent.</td>
</tr>
<tr>
<td>e</td>
<td>Equivalent to <code>to_chars(first, last, value, chars_format::scientific, precision)</code> where <code>precision</code> is the specified formatting precision, or 6 if <code>precision</code> is not specified.</td>
</tr>
<tr>
<td>E</td>
<td>The same as e, except that it uses E to indicate exponent.</td>
</tr>
<tr>
<td>f, F</td>
<td>Equivalent to <code>to_chars(first, last, value, chars_format::fixed, precision)</code> where <code>precision</code> is the specified formatting precision, or 6 if <code>precision</code> is not specified.</td>
</tr>
<tr>
<td>g</td>
<td>Equivalent to <code>to_chars(first, last, value, chars_format::general, precision)</code> where <code>precision</code> is the specified formatting precision, or 6 if <code>precision</code> is not specified.</td>
</tr>
<tr>
<td>G</td>
<td>The same as g, except that it uses E to indicate exponent.</td>
</tr>
<tr>
<td>none</td>
<td>If <code>precision</code> is specified, equivalent to <code>to_chars(first, last, value, chars_format::general, precision)</code> where <code>precision</code> is the specified formatting precision; equivalent to <code>to_chars(first, last, value)</code> otherwise.</td>
</tr>
</tbody>
</table>

Table 76 — Meaning of type options for pointer types  [tab:format.type.ptr]

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none, p</td>
<td>If <code>uintptr_t</code> is defined, <code>to_chars(first, last, reinterpret_cast&lt;uintptr_t&gt;(value), 16)</code> with the prefix 0x inserted immediately before the output of <code>to_chars</code>; otherwise, implementation-defined.</td>
</tr>
<tr>
<td>P</td>
<td>The same as p, except that it uses uppercase letters for digits above 9 and the base prefix is 0X.</td>
</tr>
</tbody>
</table>

Remarks: A call to this function is not a core constant expression (7.7) unless there exist `args` of types `Args` such that `str` is a format string for `args`.

22.14.5 Formatting functions  [format.functions]

In the description of the functions, operator + is used for some of the iterator categories for which it does not have to be defined. In these cases the semantics of a + n are the same as in 27.2.

```cpp
template<class... Args>
string format(format_string<Args...> fmt, Args&&... args);
```

**Effects:** Equivalent to:

```cpp
return vformat(fmt.str, make_format_args(args...));
```

```cpp
template<class... Args>
wstring format(wformat_string<Args...> fmt, Args&&... args);
```

**Effects:** Equivalent to:

```cpp
return vformat(fmt.str, make_wformat_args(args...));
```
template<class... Args>
    string format(const locale& loc, format_string<Args...> fmt, Args&&... args);

    Effects: Equivalent to:
             return vformat(loc, fmt.str, make_format_args(args...));

template<class... Args>
    wstring format(const locale& loc, wformat_string<Args...> fmt, Args&&... args);

    Effects: Equivalent to:
             return vformat(loc, fmt.str, make_wformat_args(args...));

string vformat(string_view fmt, format_args args);
wstring vformat(wstring_view fmt, format_args args);
string vformat(const locale& loc, string_view fmt, format_args args);
wstring vformat(const locale& loc, wstring_view fmt, wformat_args args);

    Returns: A string object holding the character representation of formatting arguments provided by args
             formatted according to specifications given in fmt. If present, loc is used for locale-specific formatting.

template<class Out, class... Args>
    Out format_to(Out out, format_string<Args...> fmt, Args&&... args);

    Effects: Equivalent to:
             return vformat_to(std::move(out), fmt.str, make_format_args(args...));

template<class Out, class... Args>
    Out format_to(Out out, wformat_string<Args...> fmt, Args&&... args);

    Effects: Equivalent to:
             return vformat_to(std::move(out), fmt.str, make_wformat_args(args...));

template<class Out, class... Args>
    Out format_to(Out out, const locale& loc, format_string<Args...> fmt, Args&&... args);

    Effects: Equivalent to:
             return vformat_to(std::move(out), loc, fmt.str, make_format_args(args...));

template<class Out, class... Args>
    Out format_to(Out out, const locale& loc, wformat_string<Args...> fmt, Args&&... args);

    Effects: Equivalent to:
             return vformat_to(std::move(out), loc, fmt.str, make_wformat_args(args...));

template<class Out>
    Out vformat_to(Out out, string_view fmt, format_args args);

template<class Out>
    Out vformat_to(Out out, wstring_view fmt, format_args args);

template<class Out>
    Out vformat_to(Out out, const locale& loc, string_view fmt, format_args args);

template<class Out>
    Out vformat_to(Out out, const locale& loc, wstring_view fmt, wformat_args args);

    Let charT be decltype(fmt)::value_type.

    Constraints: Out satisfies output_iterator<const charT>.

    Preconditions: Out models output_iterator<const charT>.

    Effects: Places the character representation of formatting the arguments provided by args, formatted
             according to the specifications given in fmt, into the range [out, out + N), where N is the number of
             characters in that character representation. If present, loc is used for locale-specific formatting.

    Returns: out + N.

    Throws: As specified in 22.14.3.
template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n,
        format_string<Args...> fmt, Args&&... args);

template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n,
        wformat_string<Args...> fmt, Args&&... args);

template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n,
        const locale& loc, format_string<Args...> fmt,
        Args&&... args);

template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n,
        const locale& loc, wformat_string<Args...> fmt,
        Args&&... args);

Let

— \( \text{charT} \) be \( \text{decltype(fmt.str)::value_type} \),
— \( N \) be \( \text{formatted\_size(fmt, args...)} \) for the functions without a \( \text{loc} \) parameter and \( \text{formatted\_size(loc, fmt, args...)} \) for the functions with a \( \text{loc} \) parameter, and
— \( M \) be \( \text{clamp(n, 0, N)} \).

Constraints: \( \text{Out} \) satisfies \( \text{output\_iterator<const \text{charT}t>} \).

Preconditions: \( \text{Out} \) models \( \text{output\_iterator<const \text{charT}t>} \), \( \text{and formatter<remove\_cv\_t<T,}>, charT} \) meets the \( \text{BasicFormatter} \) requirements (22.14.6.1) for each \( T_i \) in \( \text{Args} \).

Effects: Places the first \( M \) characters of the character representation of formatting the arguments provided by \( \text{args} \), formatted according to the specifications given in \( \text{fmt} \), into the range \( \text{[out, out + N]} \). If present, \( \text{loc} \) is used for locale-specific formatting.

Returns: \( \{\text{out + M, N}\} \).

Throws: As specified in 22.14.3.

Let \( \text{charT} \) be \( \text{decltype(fmt.str)::value_type} \).

Preconditions: \( \text{formatter<remove\_cv\_t<T,)}, \text{charT}\) meets the \( \text{BasicFormatter} \) requirements (22.14.6.1) for each \( T_i \) in \( \text{Args} \).

Returns: The number of characters in the character representation of formatting arguments \( \text{args} \) formatted according to specifications given in \( \text{fmt} \). If present, \( \text{loc} \) is used for locale-specific formatting.

Throws: As specified in 22.14.3.

22.14.6 Formatter

22.14.6.1 Formatter requirements

A type \( F \) meets the \( \text{BasicFormatter} \) requirements if it meets the

1. \( \text{Cpp17DefaultConstructible} \) (Table 30),
2. \( \text{Cpp17CopyConstructible} \) (Table 32),
3. \( \text{Cpp17CopyAssignable} \) (Table 34),
4. \( \text{Cpp17Swappable} \) (16.4.4.3), and
5. \( \text{Cpp17Destructible} \) (Table 35)

requirements, and the expressions shown in Table 77 are valid and have the indicated semantics.
A type \( F \) meets the *Formatter* requirements if it meets the *BasicFormatter* requirements and the expressions shown in Table 78 are valid and have the indicated semantics.

Given character type charT, output iterator type Out, and formatting argument type \( T \), in Table 77 and Table 78:

(3.1) — \( f \) is a value of type (possibly const) \( F \),

(3.2) — \( g \) is an lvalue of type \( F \),

(3.3) — \( u \) is an lvalue of type \( T \),

(3.4) — \( t \) is a value of a type convertible to (possibly const) \( T \),

(3.5) — \( PC \) is basic_format_parse_context<charT>,

(3.6) — FC is basic_format_context<Out, charT>,

(3.7) — \( pc \) is an lvalue of type PC, and

(3.8) — \( fc \) is an lvalue of type FC.

\( pc.begin() \) points to the beginning of the *format-spec* (22.14.2) of the replacement field being formatted in the format string. If *format-spec* is not present or empty then either \( pc.begin() == pc.end() \) or \( *pc.begin() == '}' \).

### Table 77 — *BasicFormatter* requirements [tab:formatter.basic]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
</table>
| \( g.parse(pc) \) | PC::iterator | Parses *format-spec* (22.14.2) for type \( T \) in the range \([pc.begin(), pc.end())\) until the first unmatched character. Throws *format_error* unless the whole range is parsed or the unmatched character is \( } \).  

[Note 1: This allows formatters to emit meaningful error messages. — end note]

Stores the parsed format specifiers in \(*this\) and returns an iterator past the end of the parsed range.

| \( f.format(u, fc) \) | FC::iterator | Formats \( u \) according to the specifiers stored in \(*this\), writes the output to \( fc.out() \), and returns an iterator past the end of the output range. The output shall only depend on \( u, fc.locale() \), \( fc.arg(n) \) for any value \( n \) of type size_t, and the range \([pc.begin(), pc.end())\) from the last call to \( f.parse(pc) \). |

### Table 78 — *Formatter* requirements [tab:formatter]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f.format(t, fc) )</td>
<td>FC::iterator</td>
<td>Formats ( t ) according to the specifiers stored in (*this), writes the output to ( fc.out() ), and returns an iterator past the end of the output range. The output shall only depend on ( t, fc.locale() ), ( fc.arg(n) ) for any value ( n ) of type size_t, and the range ([pc.begin(), pc.end())) from the last call to ( f.parse(pc) ).</td>
</tr>
</tbody>
</table>

| \( f.format(u, fc) \) | FC::iterator | As above, but does not modify \( u \). |

### 22.14.6.2 Formatter locking [format.formatter.locking]
template<class T>
constexpr bool enable_nonlocking_formatter_optimization = false;

Remarks: Pursuant to 16.4.5.2.1, users may specialize enable_nonlocking_formatter_optimization
for cv-unqualified program-defined types. Such specializations shall be usable in constant expressions
(7.7) and have type const bool.

22.14.6.3 Concept formattable

Let fmt_iter_for<charT> be an unspecified type that models output_iterator<const charT&> (25.3.4.10).

1 template<class T, class Context, class Formatter = typename Context::template formatter_type<remove_const_t<T>>>
   concept formattable-with = // exposition only
     semiregular<Formatter> &&
     requires(Formatter& f, const Formatter& cf, T&& t, Context fc,
               basic_format_parse_context<typename Context::char_type> pc)
     {
       { f.parse(pc) } -> same_as<typename decltype(pc)::iterator>;
       { cf.format(t, fc) } -> same_as<typename Context::iterator>;
     }

template<class T, class charT>
concept formattable = formattable-with<remove_reference_t<T>, basic_format_context<fmt_iter_for<charT>, charT>>;

2 A type T and a character type charT model formattable if formatter<remove_cvref_t<T>, charT> meets
the BasicFormatter requirements (22.14.6.1) and, if remove_reference_t<T> is const-qualified, the Formatter
requirements.

22.14.6.4 Formatter specializations

1 The functions defined in 22.14.5 use specializations of the class template formatter to format individual arguments.

2 Let charT be either char or wchar_t. Each specialization of formatter is either enabled or disabled, as
described below. A debug-enabled specialization of formatter additionally provides a public, constexpr,
non-static member function set_debug_format() which modifies the state of the formatter to be as if the
type of the std-format-spec parsed by the last call to parse were ?. Each header that declares the template
formatter provides the following enabled specializations:

(2.1) — The debug-enabled specializations
   template<> struct formatter<char, char>;
   template<> struct formatter<char, wchar_t>;
   template<> struct formatter<wchar_t, wchar_t>;

(2.2) — For each charT, the debug-enabled string type specializations
   template<> struct formatter<charT*, charT>;
   template<> struct formatter<charT*, wchar_t>;
   template<> struct formatter<wchar_t*, charT>;
   template<> struct formatter<wchar_t*, wchar_t>;

(2.3) — For each charT, for each cv-unqualified arithmetic type ArithmeticT other than char, wchar_t,
char8_t, char16_t, or char32_t, a specialization
   template<> struct formatter<ArithmeticT, charT>;

(2.4) — For each charT, the pointer type specializations
   template<> struct formatter<void*, charT>;
   template<> struct formatter<void*, wchar_t>;
   template<> struct formatter<const void*, charT>;
   template<> struct formatter<const void*, wchar_t>;

The parse member functions of these formatters interpret the format specification as a std-format-spec as
described in 22.14.2.2.

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Unless specified otherwise, for each type \( T \) for which a formatter specialization is provided by the library, each of the headers provides the following specialization:

```cpp
template<> inline constexpr bool enable_nonlocking_formatter_optimization<T> = true;
```

[Note 1: Specializations such as `formatter<wchar_t, char>` that would require implicit multibyte / wide string or character conversion are disabled. — end note]

The header `<format>` provides the following disabled specializations:

(4.1) — The string type specializations

```cpp
template<> struct formatter<char*, wchar_t>;
template<> struct formatter<const char*, wchar_t>;
template<typename N> struct formatter<char[N], wchar_t>;
template<class traits, class Allocator>
    struct formatter<basic_string<char, traits, Allocator>, wchar_t>;
template<class traits>
    struct formatter<basic_string_view<char, traits>, wchar_t>;
```

For any types \( T \) and \( \text{charT} \) for which neither the library nor the user provides an explicit or partial specialization of the class template `formatter`, `formatter<T, \text{charT}>` is disabled.

If the library provides an explicit or partial specialization of `formatter<T, \text{charT}>`, that specialization is enabled and meets the `Formatter` requirements except as noted otherwise.

If \( F \) is a disabled specialization of `formatter`, these values are `false`:

(7.1) — `is_default_constructible_v<F>`,
(7.2) — `is_copy_constructible_v<F>`,
(7.3) — `is_move_constructible_v<F>`,
(7.4) — `is_copy_assignable_v<F>`, and
(7.5) — `is_move_assignable_v<F>`.

An enabled specialization `formatter<T, \text{charT}>` meets the `BasicFormatter` requirements (22.14.6.1).

[Example 1:
```cpp
#include <format>
#include <string>

enum color { red, green, blue };
const char* color_names[] = { "red", "green", "blue" };

template<> struct std::formatter<color> : std::formatter<const char*> {
    auto format(color c, format_context& ctx) const {
        return formatter<const char*>::format(color_names[c], ctx);
    }
};

struct err {}

std::string s0 = std::format("\{\}", 42); // OK, library-provided formatter
std::string s1 = std::format("\{\}", L"foo"); // error: disabled formatter
std::string s2 = std::format("\{\}", red); // OK, user-provided formatter
std::string s3 = std::format("\{\}", err()); // error: disabled formatter
```
— end example]

### 22.14.6.5 Formatting escaped characters and strings [format.string.escaped]

A character or string can be formatted as escaped to make it more suitable for debugging or for logging.

The escaped string \( E \) representation of a string \( S \) is constructed by encoding a sequence of characters as follows. The associated character encoding \( CE \) for `\text{charT}` (Table 12) is used to both interpret \( S \) and construct \( E \).

(2.1) — \( \text{U+0022 QUOTATION MARK ("}) \) appended to \( E \).
(2.2) — For each code unit sequence \( X \) in \( S \) that either encodes a single character, is a shift sequence, or is a sequence of ill-formed code units, processing is in order as follows:
If $X$ encodes a single character $C$, then:

- If $C$ is one of the characters in Table 79, then the two characters shown as the corresponding escape sequence are appended to $E$.

- Otherwise, if $C$ is not $\text{u}+0020 \text{ SPACE}$ and

  - $CE$ is UTF-8, UTF-16, or UTF-32 and $C$ corresponds to a Unicode scalar value whose Unicode property General_Category has a value in the groups Separator (Z) or Other (C), as described by UAX #44 of the Unicode Standard, or

  - $CE$ is UTF-8, UTF-16, or UTF-32 and $C$ corresponds to a Unicode scalar value with the Unicode property Grapheme_Extend=Yes as described by UAX #44 of the Unicode Standard and $C$ is not immediately preceded in $S$ by a character $P$ appended to $E$ without translation to an escape sequence, or

  - $CE$ is neither UTF-8, UTF-16, nor UTF-32 and $C$ is one of an implementation-defined set of separator or non-printable characters

  then the sequence \texttt{\u{hex-digit-sequence}} is appended to $E$, where \texttt{hex-digit-sequence} is the shortest hexadecimal representation of $C$ using lower-case hexadecimal digits.

- Otherwise, $C$ is appended to $E$.

Otherwise, if $X$ is a shift sequence, the effect on $E$ and further decoding of $S$ is unspecified.

Recommended practice: A shift sequence should be represented in $E$ such that the original code unit sequence of $S$ can be reconstructed.

Otherwise ($X$ is a sequence of ill-formed code units), each code unit $U$ is appended to $E$ in order as the sequence \texttt{x\{hex-digit-sequence\}}, where \texttt{hex-digit-sequence} is the shortest hexadecimal representation of $U$ using lower-case hexadecimal digits.

Finally, $U+0022$ QUOTATION MARK (" ) is appended to $E$.

### Table 79 — Mapping of characters to escape sequences

<table>
<thead>
<tr>
<th>Character</th>
<th>Escape sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+0009 CHARACTER TABULATION</td>
<td>\t</td>
</tr>
<tr>
<td>U+000A LINE FEED</td>
<td>\n</td>
</tr>
<tr>
<td>U+000D CARRIAGE RETURN</td>
<td>\r</td>
</tr>
<tr>
<td>U+0022 QUOTATION MARK</td>
<td>&quot;</td>
</tr>
<tr>
<td>U+005C REVERSE SOLIDUS</td>
<td>\</td>
</tr>
</tbody>
</table>

3 The escaped string representation of a character $C$ is equivalent to the escaped string representation of a string of $C$, except that:

- the result starts and ends with $U+0027$ APOSTROPHE (’ ) instead of $U+0022$ QUOTATION MARK (" ), and

- if $C$ is $U+0027$ APOSTROPHE, the two characters ‘ are appended to $E$, and

- if $C$ is $U+0022$ QUOTATION MARK, then $C$ is appended unchanged.

**Example 1:**

```latex
string s0 = format([{}], "h\tll0");  // s0 has value: [h llo]
string s1 = format([?{}], "h\tll0");  // s1 has value: ['h\tll0']
string s2 = format([{}?{}], "Спасибо, Виктор♥!");  // s2 has value: ['Спасибо, Виктор♥!']
string s3 = format([{}?{}], '\{}', '\{}');  // s3 has value: ['\{}', '\{}']

// The following examples assume use of the UTF-8 encoding
string s4 = format([{}?{}], string("\0 \n \t \x02 \x1b", 9));  // s4 has value: ['\u{0} \n \t \u{2} \u{1b}""]
string s5 = format([{}?{}], "\xc3\xa8\xc298");  // invalid UTF-8, s5 has value: ['\xc3\xc298"']
string s6 = format([{}?{}], "é");  // s6 has value: ['é\u{200d}é"]
string s7 = format([{}?{}], "\u0301");  // s7 has value: ['\u0301"]
string s8 = format([{}?{}], "\\\u0301\";  // s8 has value: ['\u0301"]
string s9 = format([{}?{}], "\e\u0301\u0323\");  // s9 has value: ['é']
```

---

§ 22.14.6.5 © ISO/IEC 839
```cpp
namespace std {
    template<class charT>
    class basic_format_parse_context {
      public:
        using char_type = charT;
        using const_iterator = typename basic_string_view<charT>::const_iterator;
        using iterator = const_iterator;

      private:
        iterator begin_;  // exposition only
        iterator end_;  // exposition only
        enum indexing { unknown, manual, automatic };  // exposition only
        indexing indexing_;  // exposition only
        size_t next_arg_id_;  // exposition only
        size_t num_args_;  // exposition only

      public:
        constexpr explicit basic_format_parse_context(basic_string_view<charT> fmt) noexcept;
        basic_format_parse_context(const basic_format_parse_context&) = delete;
        basic_format_parse_context& operator=(const basic_format_parse_context&) = delete;
        constexpr const_iterator begin() const noexcept;
        constexpr const_iterator end() const noexcept;
        constexpr void advance_to(const_iterator it);
        constexpr size_t next_arg_id();
        constexpr void check_arg_id(size_t id);
        template<class... Ts>
        constexpr void check_dynamic_spec(size_t id) noexcept;
        constexpr void check_dynamic_spec_integral(size_t id) noexcept;
        constexpr void check_dynamic_spec_string(size_t id) noexcept;
      }
    }
```

1. An instance of `basic_format_parse_context` holds the format string parsing state, consisting of the format string range being parsed and the argument counter for automatic indexing.

2. If a program declares an explicit or partial specialization of `basic_format_parse_context`, the program is ill-formed, no diagnostic required.

3. **Effects**: Initializes `begin_` with `fmt.begin()`, `end_` with `fmt.end()`, `indexing_` with `unknown`, `next_arg_id_` with `0`, and `num_args_` with `0`.

   `[Note 1: Any call to `next_arg_id`, `check_arg_id`, or `check_dynamic_spec` on an instance of `basic_format_parse_context` initialized using this constructor is not a core constant expression. — end note]`

4. **Returns**: `begin_`.

5. **Returns**: `end_`.

6. **Preconditions**: `end()` is reachable from it.

7. **Effects**: Equivalent to: `begin_ = it;`

8. **Effects**: If `indexing_` != `manual` is true, equivalent to:

   ```cpp
   if (indexing_ == unknown)
   indexing_ = automatic;
   ```
return next_arg_id_++;

**Throws:** format_error if indexing_ == manual is true.

[Note 2: This indicates mixing of automatic and manual argument indexing. — end note]

**Remarks:** Let cur-arg-id be the value of next_arg_id_ prior to this call. Call expressions where cur-arg-id >= num_args_ is true are not core constant expressions (7.7).

```cpp
constexpr void check_arg_id(size_t id);
```

**Effects:** If indexing_ != automatic is true, equivalent to:

if (indexing_ == unknown)
    indexing_ = manual;

**Throws:** format_error if indexing_ == automatic is true.

[Note 3: This indicates mixing of automatic and manual argument indexing. — end note]

**Remarks:** A call to this function is a core constant expression (7.7) only if id < num_args_ is true.

```cpp
template<class... Ts>
constexpr void check_dynamic Spec(size_t id) noexcept;
```

**Mandates:** The types in Ts... are unique. Each type in Ts... is one of bool, char_type, int, unsigned int, long long int, unsigned long long int, float, double, long double, const char_type*, basic_string_view<char_type>, or const void*.

**Remarks:** A call to this function is a core constant expression only if

- id < num_args_ is true and
- the type of the corresponding format argument (after conversion to basic_format_arg<Context>) is one of the types in Ts....

```cpp
constexpr void check_dynamic_spec_integral(size_t id) noexcept;
```

**Effects:** Equivalent to:

check_dynamic_spec<int, unsigned int, long long int>(id);

```cpp
constexpr void check_dynamic_spec_string(size_t id) noexcept;
```

**Effects:** Equivalent to:

check_dynamic_spec<const char_type*, basic_string_view<char_type>>(id);

### 22.14.6.7 Class template basic_format_context

```cpp
namespace std {
    template<class Out, class charT>
    class basic_format_context {
        basic_format_args<basic_format_context> args_; // exposition only
        Out out_; // exposition only

        basic_format_context(const basic_format_context&) = delete;
        basic_format_context& operator=(const basic_format_context&) = delete;

    public:
        using iterator = Out;
        using char_type = charT;
        template<class T> using formatter_type = formatter<T, charT>;

        basic_format_arg<basic_format_context> arg(size_t id) const noexcept;
        std::locale locale();
        iterator out();
        void advance_to(iterator it);
    }
}
```

1 An instance of basic_format_context holds formatting state consisting of the formatting arguments and the output iterator.
If a program declares an explicit or partial specialization of `basic_format_context`, the program is ill-formed, no diagnostic required.

Out shall model `output_iterator<const charT&>`.

`format_context` is an alias for a specialization of `basic_format_context` with an output iterator that appends to `string`, such as `back_insert_iterator<string>`. Similarly, `wformat_context` is an alias for a specialization of `basic_format_context` with an output iterator that appends to `wstring`.

Recommended practice: For a given type `charT`, implementations should provide a single instantiation of `basic_format_context` for appending to `basic_string<charT>`, `vector<charT>`, or any other container with contiguous storage by wrapping those in temporary objects with a uniform interface (such as a `span<charT>`) and polymorphic reallocation.

```
basic_format_arg<basic_format_context> arg(size_t id) const noexcept;

std::locale locale();

iterator out();

Effects: Equivalent to: return std::move(out_);

void advance_to(iterator it);

Effects: Equivalent to: out_ = std::move(it);
```

`Example 1`:
```
struct S { int value; }

template<> struct std::formatter<S> {
    size_t width_arg_id = 0;

    // Parses a width argument id in the format { digit }.
    constexpr auto parse(format_parse_context& ctx) {
        auto iter = ctx.begin();
        auto is_digit = [auto c] { return c >= '0' && c <= '9'; };
        auto get_char = [&]() { return iter != ctx.end() ? *iter : 0; };
        if (get_char() != '{')
            return iter;
        return ++iter;
    }

    // Formats an S with width given by the argument width_arg_id.
    auto format(S s, format_context& ctx) const {
        int width = ctx.arg(width_arg_id).visit([&](auto value) -> int {
            if constexpr (!is_integral_v<decltype(value)>)
                throw format_error("width is not integral");
            else if (value < 0 || value > numeric_limits<int>::max())
                throw format_error("invalid width");
            else
                return value;
        });
        return format_to(ctx.out(), "{0:{1}}", s.value, width);
    }

    operator std::string() const {
        std::string s = std::format("{0:{1}}", S{42}, 10);  // value of s is "xxxxxxxx42"
    }
```
22.14.7 Formatting of ranges

22.14.7.1 Variable template format_kind

```cpp
template<ranges::input_range R>
requires same_as<R, remove_cvref_t<R>>
constexpr range_format format_kind<R> = see below;
```

1 A program that instantiates the primary template of format_kind is ill-formed.
2 For a type R, format_kind<R> is defined as follows:
   (2.1) — If same_as<remove_cvref_t<ranges::range_reference_t<R>>, R> is true, format_kind<R> is range_format::disabled.
   [Note 1: This prevents constraint recursion for ranges whose reference type is the same range type. For example, std::filesystem::path is a range of std::filesystem::path. — end note]
   (2.2) — Otherwise, if the qualified-id R::key_type is valid and denotes a type:
      (2.2.1) — If the qualified-id R::mapped_type is valid and denotes a type, let U be remove_cvref_t<ranges::range_reference_t<R>>. If either U is a specialization of pair or U is a specialization of tuple and tuple_size_v<U> == 2, format_kind<R> is range_format::map.
      (2.2.2) — Otherwise, format_kind<R> is range_format::set.
   (2.3) — Otherwise, format_kind<R> is range_format::sequence.

Remarks: Pursuant to 16.4.5.2.1, users may specialize format_kind for cv-unqualified program-defined types that model ranges::input_range. Such specializations shall be usable in constant expressions (7.7) and have type const range_format.

22.14.7.2 Class template range_formatter

```cpp
namespace std {
    template<class T, class charT = char>
    requires same_as<remove_cvref_t<T>, T> && formattable<T, charT>
    class range_formatter {
        formatter<T, charT> underlying_; // exposition only
        basic_string_view<charT> separator_ = STATICALLY-WIDEN<charT>(" ", ""); // exposition only
        basic_string_view<charT> opening_bracket_ = STATICALLY-WIDEN<charT>("["); // exposition only
        basic_string_view<charT> closing_bracket_ = STATICALLY-WIDEN<charT>("]"); // exposition only

        public:
            constexpr void set_separator(basic_string_view<charT> sep) noexcept; // exposition only
            constexpr void set_brackets(basic_string_view<charT> opening, basic_string_view<charT> closing) noexcept;
            constexpr formatter<T, charT>& underlying() noexcept { return underlying_; }
            constexpr const formatter<T, charT>& underlying() const noexcept { return underlying_; }

            template<class ParseContext>
            constexpr typename ParseContext::iterator parse(ParseContext& ctx);

            template<ranges::input_range R, class FormatContext>
            requires formattable<ranges::range_reference_t<R>, charT> && same_as<remove_cvref_t<ranges::range_reference_t<R>>, T>
            typename FormatContext::iterator format(R&& r, FormatContext& ctx) const;
    };
}
```

1 The class template range_formatter is a utility for implementing formatter specializations for range types.
2 range_formatter interprets format-spec as a range-format-spec. The syntax of format specifications is as follows:
   range-format-spec:
   range-fill-and-align_opt width_opt n_opt range-type_opt range-underlying-spec_opt.
range-fill-and-align:
  range-fill_opt align

range-fill:
  any character other than { or } or :

range-type:
  m
  s
  ?s

range-underlying-spec:
  : format-spec

3 For `range_formatter<T, charT>`, the `format-spec` in a `range-underlying-spec`, if any, is interpreted by `formatter<T, charT>`.

4 The `range-fill-and-align` is interpreted the same way as a `fill-and-align` (22.14.2.2). The productions `align` and `width` are described in 22.14.2.

5 The `n` option causes the range to be formatted without the opening and closing brackets.
   [Note 1: This is equivalent to invoking `set_brackets({{}, {}}). — end note]

6 The `range-type` specifier changes the way a range is formatted, with certain options only valid with certain argument types. The meaning of the various type options is as specified in Table 80.

<table>
<thead>
<tr>
<th>Option</th>
<th>Requirements</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>T shall be either a specialization of <code>pair</code> or a specialization of <code>tuple</code> such that <code>tuple_size_v&lt;T&gt;</code> is 2.</td>
<td>Indicates that the opening bracket should be {, the closing bracket should be }, the separator should be ,, and each range element should be formatted as if m were specified for its <code>tuple-type</code>. [Note 2: If the n option is provided in addition to the m option, both the opening and closing brackets are still empty. — end note]</td>
</tr>
<tr>
<td>s</td>
<td>T shall be charT.</td>
<td>Indicates that the range should be formatted as a string.</td>
</tr>
<tr>
<td>?s</td>
<td>T shall be charT.</td>
<td>Indicates that the range should be formatted as an escaped string (22.14.6.5).</td>
</tr>
</tbody>
</table>

If the `range-type` is s or ?s, then there shall be no n option and no `range-underlying-spec`.

```cpp
constexpr void set_separator(basic_string_view<charT> sep) noexcept;
```

7 **Effects:** Equivalent to: `separator_ = sep;`

```cpp
constexpr void set_brackets(basic_string_view<charT> opening, basic_string_view<charT> closing) noexcept;
```

8 **Effects:** Equivalent to:

```cpp
  opening-bracket_ = opening;
  closing-bracket_ = closing;
```

```cpp
template<class ParseContext>
constexpr typename ParseContext::iterator parse(ParseContext& ctx);
```

9 **Effects:** Parses the format specifiers as a `range-format-spec` and stores the parsed specifiers in *this. Calls `underlying_.parse(ctx)` to parse `format-spec` in `range-format-spec` or, if the latter is not present, an empty `format-spec`. The values of `opening-bracket_`, `closing-bracket_`, and `separator_` are modified if and only if required by the `range-type` or the n option, if present. If:

(9.1) — the range-type is neither s nor ?s,

(9.2) — `underlying_.set_debug_format()` is a valid expression, and
— there is no range-underlying-spec,
then calls underlying_.set_debug_format().

Returns: An iterator past the end of the range-format-spec.

```cpp
template<ranges::input_range R, class FormatContext>
requires formattable<ranges::range_reference_t<R>, charT> &&
  same_as<remove_cvref_t<ranges::range_reference_t<R>>, T>
typename FormatContext::iterator
format(R&& r, FormatContext& ctx) const;
```

Effects: Writes the following into ctx.out(), adjusted according to the range-format-spec:

1. If the range-type was s, then as if by formatting basic_string<charT>(from_range, r).
2. Otherwise, if the range-type was ?s, then as if by formatting basic_string<charT>(from_range, r) as an escaped string (22.14.6.5).
3. Otherwise,
   1. opening-bracket_,
   2. for each element e of the range r:
      1. the result of writing e via underlying_ and
      2. separator_, unless e is the last element of r, and
   3. closing-bracket_.

Returns: An iterator past the end of the output range.

### 22.14.7.3 Class template range-default-formatter

```cpp
namespace std {

  template<ranges::input_range R, class charT>
  struct range-default-formatter<range_format::sequence, R, charT> { // exposition only
    private:
      using maybe-const-r = fmt-maybe-const<R, charT>; // exposition only
      range_formatter<remove_cvref_t<ranges::range_reference_t<maybe-const-r>>, charT> underlying_; // exposition only

    public:
      constexpr void set_separator(basic_string_view<charT> sep) noexcept;
      constexpr void set_brackets(basic_string_view<charT> opening,
                                basic_string_view<charT> closing) noexcept;

      template<class ParseContext>
      constexpr typename ParseContext::iterator
      parse(ParseContext& ctx);

      template<class FormatContext>
      typename FormatContext::iterator
      format(maybe-const-r& elems, FormatContext& ctx) const;
  };

  constexpr void set_separator(basic_string_view<charT> sep) noexcept;
  Effects: Equivalent to: underlying_.set_separator(sep);

  constexpr void set_brackets(basic_string_view<charT> opening,
                              basic_string_view<charT> closing) noexcept;
  Effects: Equivalent to: underlying_.set_brackets(opening, closing);

  template<class ParseContext>
  constexpr typename ParseContext::iterator
  parse(ParseContext& ctx);
  Effects: Equivalent to: return underlying_.parse(ctx);

}```
template<class FormatContext>
    typename FormatContext::iterator
    format(maybe-const-r elems, FormatContext& ctx) const;

Effects: Equivalent to: return underlying_.format(elems, ctx);

22.14.7.4 Specialization of range-default-formatter for maps

namespace std {
    template<ranges::input_range R, class charT>
    struct range-default-formatter<range_format::map, R, charT> {
        private:
            using maybe-const-map = fmt-maybe-const<R, charT>;
            using element-type = remove_cvref_t<ranges::range_reference_t<maybe-const-map>>;
            range_formatter<element-type, charT> underlying_; // exposition only

        public:
            constexpr range-default-formatter();

            template<class ParseContext>
                typename ParseContext::iterator
                    parse(ParseContext& ctx);

            template<class FormatContext>
                typename FormatContext::iterator
                    format(maybe-const-map& r, FormatContext& ctx) const;

            constexpr
                range-default-formatter();

        public: // exposition only
            Mandates: Either:
(1.1) element-type is a specialization of pair, or
(1.2) element-type is a specialization of tuple and tuple_size_v<element-type> == 2.

        Effects: Equivalent to:
            underlying_.set_brackets(STATICALLY-WIDEN<charT>("{"), STATICALLY-WIDEN<charT>("}"));
            underlying_.underlying().set_brackets({}, {});
            underlying_.underlying().set_separator(STATICALLY-WIDEN<charT>(" : "));

            template<class ParseContext>
                typename ParseContext::iterator
                    parse(ParseContext& ctx);

            Effects: Equivalent to: return underlying_.parse(ctx);

            template<class FormatContext>
                typename FormatContext::iterator
                    format(maybe-const-map& r, FormatContext& ctx) const;

            Effects: Equivalent to: return underlying_.format(r, ctx);

    }
}

22.14.7.5 Specialization of range-default-formatter for sets

namespace std {
    template<ranges::input_range R, class charT>
    struct range-default-formatter<range_format::set, R, charT> {
        private:
            using maybe-const-set = fmt-maybe-const<R, charT>;
            range_formatter<remove_cvref_t<ranges::range_reference_t<maybe-const-set>>, charT> underlying_; // exposition only

        public:
            constexpr range-default-formatter();

        public: // exposition only
            template<class ParseContext>
                typename ParseContext::iterator
                    parse(ParseContext& ctx);

            Effects: Equivalent to: return underlying_.parse(ctx);

            template<class FormatContext>
                typename FormatContext::iterator
                    format(maybe-const-map& r, FormatContext& ctx) const;

            Effects: Equivalent to: return underlying_.format(r, ctx);

    }
}
template<class ParseContext>
    constexpr typename ParseContext::iterator
    parse(ParseContext& ctx);  
};

template<class FormatContext>
    typename FormatContext::iterator
    format(maybe-const-set r, FormatContext& ctx) const;

constexpr range-default-formatter();

Effects: Equivalent to:
    underlying_.set_brackets(STATICALLY-WIDEN<br>'{'), STATICALLY-WIDEN<br>('}'));

template<class ParseContext>
    constexpr typename ParseContext::iterator
    parse(ParseContext& ctx);  

Effects: Equivalent to: return underlying_.parse(ctx);

template<class FormatContext>
    typename FormatContext::iterator
    format(maybe-const-set r, FormatContext& ctx) const;

Effects: Equivalent to: return underlying_.format(r, ctx);

22.14.7.6 Specialization of range-default-formatter for strings

namespace std {
    template<range_format K, ranges::input_range R, class charT>
    requires (K == range_format::string || K == range_format::debug_string)
    struct range-default-formatter<K, R, charT> {
        private:
            formatter<basic_string<charT>, charT> underlying_;  // exposition only

        public:
            template<class ParseContext>
                constexpr typename ParseContext::iterator
                parse(ParseContext& ctx);  

            template<class FormatContext>
                typename FormatContext::iterator
                format(see below str, FormatContext& ctx) const;
    };

    Mandates: same_as<remove_cvref_t<range_reference_t<R>>, charT> is true.

    template<class ParseContext>
        constexpr typename ParseContext::iterator
        parse(ParseContext& ctx);  

    Effects: Equivalent to:
        auto i = underlying_.parse(ctx);
        if constexpr (K == range_format::debug_string) {
            underlying_.set_debug_format();
        }
        return i;

    template<class FormatContext>
        typename FormatContext::iterator
        format(see below r, FormatContext& ctx) const;

    The type of r is const R if ranges::input_range<const R> is true and R otherwise.

    Effects: Let s be a basic_string<charT> such that ranges::equal(s, r) is true. Equivalent to:
        return underlying_.format(s, ctx);

§ 22.14.7.6
22.14.8 Arguments

22.14.8.1 Class template basic_format_arg

namespace std {

    template<class Context>
    class basic_format_arg {
    public:
        class handle;
    
    private:
        using char_type = typename Context::char_type;
        // exposition only

        variant<monostate, bool, char_type,
            int, unsigned int, long long int, unsigned long long int,
            float, double, long double,
            const char_type*, basic_string_view<char_type>,
            const void*, handle> value;
        // exposition only

        template<class T> explicit basic_format_arg(T& v) noexcept;
        // exposition only

    public:

        basic_format_arg() noexcept;
        explicit operator bool() const noexcept;

        template<class Visitor>
        decltype(auto) visit(this basic_format_arg arg, Visitor&& vis);
        template<class R, class Visitor>
        R visit(this basic_format_arg arg, Visitor&& vis);
    };
}

An instance of basic_format_arg provides access to a formatting argument for user-defined formatters.

The behavior of a program that adds specializations of basic_format_arg is undefined.

basic_format_arg() noexcept;

Postconditions: !(*this).

template<class T> explicit basic_format_arg(T& v) noexcept;

Constraints: T satisfies formattable-with<Context>.

Preconditions: If decay_t<T> is char_type* or const char_type*, static_cast<const char_type*>(v) points to a NTCTS (3.35).

Effects: Let TD be remove_const_t<T>.

- If TD is bool or char_type, initializes value with v;
- otherwise, if TD is char and char_type is wchar_t, initializes value with static_cast<wchar_t>(static_cast<unsigned char>(v));
- otherwise, if TD is a signed integer type (6.8.2) and sizeof(TD) \leq\ sizeof(int), initializes value with static_cast<int>(v);
- otherwise, if TD is an unsigned integer type and sizeof(TD) \leq\ sizeof(unsigned int), initializes value with static_cast<unsigned int>(v);
- otherwise, if TD is a signed integer type and sizeof(TD) \leq\ sizeof(long long int), initializes value with static_cast<long long int>(v);
- otherwise, if TD is an unsigned integer type and sizeof(TD) \leq\ sizeof(unsigned long long int), initializes value with static_cast<unsigned long long int>(v);
- otherwise, if TD is a standard floating-point type, initializes value with v;
- otherwise, if TD is a specialization of basic_string_view or basic_string and TD::value_type is char_type, initializes value with basic_string_view<char_type>(v.data(), v.size());
— otherwise, if decay_t<TD> is char_type* or const char_type*, initializes value with static_cast<const char_type*>(v);

— otherwise, if is_void_v<remove_pointer_t<TD>> is true or is_null_pointer_v<TD> is true, initializes value with static_cast<const void*>(v);

— otherwise, initializes value with handle(v).

[Note 1: Constructing basic_format_arg from a pointer to a member is ill-formed unless the user provides an enabled specialization of formatter for that pointer to member type. — end note]

explicit operator bool() const noexcept;

template<class Visitor>
decltype(auto) visit(this basic_format_arg arg, Visitor&& vis);

Effects: Equivalent to: return arg.value.visit(std::forward<Visitor>(vis));

template<class R, class Visitor>
R visit(this basic_format_arg arg, Visitor&& vis);

Effects: Equivalent to: return arg.value.visit<R>(std::forward<Visitor>(vis));

The class handle allows formatting an object of a user-defined type.

namespace std {
  template<class Context>
class basic_format_arg<Context>::handle {
    const void* ptr_;  // exposition only
    void (*format_)(basic_format_parse_context<char_type>&, Context&, const void*);  // exposition only

template<class T> explicit handle(T& val) noexcept;  // exposition only

friend class basic_format_arg<Context>;

public:
  void format(basic_format_parse_context<char_type>&, Context& ctx) const;

};

} // namespace std

template<class T> explicit handle(T& val) noexcept;

Let

— TD be remove_const_t<T>.
— TQ be const TD if const TD satisfies formattable-with<Context> and TD otherwise.

Mandates: TQ satisfies formattable-with<Context>.

Effects: Initializes ptr_ with addressof(val) and format_ with

[](basic_format_parse_context<char_type>& parse_ctx,
   Context& ctx, const void* ptr) {
  typename Context::template formatter_type<TD> f;
  parse_ctx.advance_to(f.parse(parse_ctx));
  format_ctx.advance_to(f.format(*const_cast<TQ*>(static_cast<const TD*>(ptr)),
                               format_ctx));
}

void format(basic_format_parse_context<char_type>& parse_ctx, Context& format_ctx) const;

Effects: Equivalent to: format_(parse_ctx, format_ctx, ptr_);

22.14.8.2 Class template format-arg-store

namespace std {
  template<class Context, class... Args>
class format-arg-store {
    array<basic_format_arg<Context>, sizeof...(Args)> args;  // exposition only

  } // class format-arg-store

} // namespace std
An instance of \texttt{format-arg-store} stores formatting arguments.

\begin{verbatim}
};

// An instance of \texttt{format-arg-store} stores formatting arguments.

template<class Context = format_context, class... Args>
    \texttt{format-arg-store<Context, Args...> make_format_args(Args&&... fmt_args);};

\textbf{Preconditions:} The type \texttt{typename Context::template formatter_type<remove_const_t<T>>} meets the \texttt{BasicFormatter} requirements (22.14.6.1) for each \texttt{T} in \texttt{Args}.

\textbf{Returns:} An object of type \texttt{format-arg-store<Context, Args...>} whose \texttt{args} data member is initialized with \{\texttt{basic_format_arg<Context>(fmt_args)...}\}.

\begin{verbatim}
// A template for \texttt{format-arg-store<Context, Args...>}.

template<class... Args>
    \texttt{format-arg-store<wformat_context, Args...> make_wformat_args(Args&... args);};

\textbf{Effects:} Equivalent to: \texttt{return make_format_args<wformat_context>(args...);}.
\end{verbatim}

\section{22.14.8.3 Class template basic_format_args \texttt{[format.args]}}

\begin{verbatim}
namespace std {
    template<class Context>
        \texttt{class basic_format_args { }
            \texttt{size_t size_; \hfill // exposition only}
            \texttt{const basic_format_arg<Context>** data_; \hfill // exposition only}

    public:
        template<class... Args>
            \texttt{basic_format_args(const format-arg-store<Context, Args...>& store) noexcept; }

        \texttt{basic_format_arg<Context> get(size_t i) const noexcept; }
    }
}
\end{verbatim}

An instance of \texttt{basic_format_args} provides access to formatting arguments. Implementations should optimize the representation of \texttt{basic_format_args} for a small number of formatting arguments.

\textbf{[Note 1:} For example, by storing indices of type alternatives separately from values and packing the former. \textit{— end note]}\textbf{]}

\begin{verbatim}
template<class... Args>
    \texttt{basic_format_args(const format-arg-store<Context, Args...>& store) noexcept; }

\textbf{Effects:} Initializes \texttt{size_} with \texttt{sizeof...(Args)} and \texttt{data_} with \texttt{store.args.data()}.\texttt{basic_format_arg<Context> get(size_t i) const noexcept; }

\textbf{Returns:} \texttt{i < size_ ? data_[i] : basic_format_arg<Context>()}.\texttt{22.14.9 Tuple formatter \texttt{[format.tuple]}}

\begin{verbatim}
namespace std {
    template<class charT, formattable<charT>... Ts>
        \texttt{struct formatter<pair-or-tuple<Ts...>, charT> { }
            \texttt{private: }
                \texttt{tuple<formatter<remove_cvref_t<Ts>, charT>...> underlying_; \hfill // exposition only}
                \texttt{basic_string_view<charT> separator_ = STATICALLY-WIDEN\texttt{<charT>("", "); \hfill // exposition only}}
                \texttt{basic_string_view<charT> opening-bracket_ = STATICALLY-WIDEN\texttt{<charT>("("); \hfill // exposition only}}
                \texttt{basic_string_view<charT> closing-bracket_ = STATICALLY-WIDEN\texttt{<charT>(")"}); \hfill // exposition only}}

            \texttt{public:}
                \texttt{constexpr void set_separator(basic_string_view<charT> sep) noexcept;}
                \texttt{constexpr void set_brackets(basic_string_view<charT> opening,}
                    \texttt{basic_string_view<charT> closing) noexcept;}
\end{verbatim}

\section{22.14.9 Tuple formatter \texttt{[format.tuple]}}

For each of \texttt{pair} and \texttt{tuple}, the library provides the following formatter specialization where \texttt{pair-or-tuple} is the name of the template:

\begin{verbatim}
namespace std {
    template<class charT, formattable<charT>... Ts>
        \texttt{struct format<Ts...> { }
            \texttt{private: }
                \texttt{tuple<formatter<remove_cvref_t<Ts>, charT>...> underlying_; \hfill // exposition only}
                \texttt{basic_string_view<charT> separator_ = STATICALLY-WIDEN\texttt{<charT>("", "); \hfill // exposition only}}
                \texttt{basic_string_view<charT> opening-bracket_ = STATICALLY-WIDEN\texttt{<charT>("("); \hfill // exposition only}}
                \texttt{basic_string_view<charT> closing-bracket_ = STATICALLY-WIDEN\texttt{<charT>(")"}); \hfill // exposition only}}

            \texttt{public:}
                \texttt{constexpr void set_separator(basic_string_view<charT> sep) noexcept;}
                \texttt{constexpr void set_brackets(basic_string_view<charT> opening,}
                    \texttt{basic_string_view<charT> closing) noexcept;}
\end{verbatim}

\end{verbatim}
template<class ParseContext>
  constexpr typename ParseContext::iterator
  parse(ParseContext& ctx);

template<class FormatContext>
  typename FormatContext::iterator
  format(see below elems, FormatContext& ctx) const;

};

template<class... Ts>
  inline constexpr bool enable_nonlocking_formatter_optimization<pair-or-tuple<Ts...>> =
    (enable_nonlocking_formatter_optimization<Ts> && ...);

The `parse` member functions of these formatters interpret the format specification as a `tuple-format-spec` according to the following syntax:

```
tuple-format-spec:
  tuple-fill-and-align_opt width_opt tuple-type_opt

tuple-fill-and-align:
  tuple-fill_opt align

  fill:
    any character other than { or } or :

  type:
    m
    n
```

The `tuple-fill-and-align` is interpreted the same way as a `fill-and-align` (22.14.2.2). The productions `align` and `width` are described in 22.14.2.

The `tuple-type` specifier changes the way a `pair` or `tuple` is formatted, with certain options only valid with certain argument types. The meaning of the various type options is as specified in Table 81.

<table>
<thead>
<tr>
<th>Option</th>
<th>Requirements</th>
<th>Meaning</th>
</tr>
</thead>
</table>
| m      | sizeof...(Ts) == 2 | Equivalent to:  
  set_separator(STATICALLY-WIDEN<charT>(" ");  
  set_brackets({}, {}); |
| n      | none         | Equivalent to: set_brackets({}, {}); |
| none                                          | No effects |

```
constexpr void set_separator(basic_string_view<charT> sep) noexcept;
```

**Effects:** Equivalent to: `separator_ = sep;`

```
constexpr void set_brackets(basic_string_view<charT> opening,
                             basic_string_view<charT> closing) noexcept;
```

**Effects:** Equivalent to:

- `opening-bracket_ = opening;`
- `closing-bracket_ = closing;`

```
template<class ParseContext>
  constexpr typename ParseContext::iterator
  parse(ParseContext& ctx);
```

**Effects:** Parses the format specifiers as a `tuple-format-spec` and stores the parsed specifiers in `*this`. The values of `opening-bracket_`, `closing-bracket_`, and `separator_` are modified if and only if required by the `tuple-type`, if present. For each element `e` in `underlying_`, calls `e.parse(ctx)` to parse an empty `format-spec` and, if `e.set_debug_format()` is a valid expression, calls `e.set_debug_format()`.

**Returns:** An iterator past the end of the `tuple-format-spec`.  

§ 22.14.9
template<class FormatContext>
  typename FormatContext::iterator
  format(see below& elems, FormatContext& ctx) const;

  The type of elems is:
  (9.1) — If (formattable<const Ts, charT> && ...) is true, const pair-or-tuple<Ts...>&.
  (9.2) — Otherwise pair-or-tuple<Ts...>&.

  Effects: Writes the following into ctx.out(), adjusted according to the tuple-format-spec:
  (10.1) — opening-bracket_,
  (10.2) — for each index I in the [0, sizeof...(Ts)):
   (10.2.1) — if I != 0, separator_,
   (10.2.2) — the result of writing get<I>(elems) via get<I>(underlying_), and
  (10.3) — closing-bracket_.

  Returns: An iterator past the end of the output range.

22.14.10 Class format_error

namespace std {
  class format_error : public runtime_error {
    public:
      explicit format_error(const string& what_arg);
      explicit format_error(const char* what_arg);
  }; // class format_error
}

The class format_error defines the type of objects thrown as exceptions to report errors from the formatting library.

format_error(const string& what_arg);
  Postconditions: strcmp(what(), what_arg.c_str()) == 0.

format_error(const char* what_arg);
  Postconditions: strcmp(what(), what_arg) == 0.

22.15 Bit manipulation

22.15.1 General

The header <bit> provides components to access, manipulate and process both individual bits and bit sequences.

22.15.2 Header <bit> synopsis

// all freestanding
namespace std {
  // 22.15.3, bit_cast
  template<class To, class From>
  constexpr To bit_cast(const From& from) noexcept;

  // 22.15.4, byteswap
  template<class T>
  constexpr T byteswap(T value) noexcept;

  // 22.15.5, integral powers of 2
  template<class T>
  constexpr bool has_single_bit(T x) noexcept;
  template<class T>
  constexpr T bit_ceil(T x);
  template<class T>
  constexpr T bit_floor(T x) noexcept;
  template<class T>
  constexpr int bit_width(T x) noexcept;

  § 22.15.2 ©ISO/IEC 852
// 22.15.6, rotating

template<class T>
  [[nodiscard]] constexpr T rotl(T x, int s) noexcept;

template<class T>
  [[nodiscard]] constexpr T rotr(T x, int s) noexcept;

// 22.15.7, counting

template<class T>
  constexpr int countl_zero(T x) noexcept;

template<class T>
  constexpr int countl_one(T x) noexcept;

template<class T>
  constexpr int countr_zero(T x) noexcept;

template<class T>
  constexpr int countr_one(T x) noexcept;

template<class T>
  constexpr int popcount(T x) noexcept;

// 22.15.8, endian

enum class endian {
  little = see below,
  big = see below,
  native = see below
};

22.15.3 Function template bit_cast

```cpp
template<class To, class From>
  constexpr To bit_cast(const From& from) noexcept;
```

Constraints:

1. `sizeof(To) == sizeof(From)` is true;
2. `is_trivially_copyable_v<To>` is true; and
3. `is_trivially_copyable_v<From>` is true.

Returns: An object of type `To`. Implicitly creates objects nested within the result (6.7.2). Each bit of the value representation of the result is equal to the corresponding bit in the object representation of `from`. Padding bits of the result are unspecified. For the result and each object created within it, if there is no value of the object's type corresponding to the value representation produced, the behavior is undefined. If there are multiple such values, which value is produced is unspecified. A bit in the value representation of the result is indeterminate if it does not correspond to a bit in the value representation of `from` or corresponds to a bit for which the smallest enclosing object is not within its lifetime or has an indeterminate value (6.7.4). A bit in the value representation of the result is erroneous if it corresponds to a bit for which the smallest enclosing object has an erroneous value. For each bit `b` in the value representation of the result that is indeterminate or erroneous, let `u` be the smallest object containing that bit enclosing `b`:

1. If `u` is of unsigned ordinary character type or `std::byte` type, `u` has an indeterminate value if any of the bits in its value representation are indeterminate, or otherwise has an erroneous value.
2. Otherwise, if `b` is indeterminate, the behavior is undefined.
3. Otherwise, the behavior is erroneous, and the result is as specified above.

The result does not otherwise contain any indeterminate or erroneous values.

Remarks: This function is constexpr if and only if `To`, `From`, and the types of all subobjects of `To` and `From` are types `T` such that:

1. `is_union_v<T>` is false;
2. `is_pointer_v<T>` is false;
3. `is_member_pointer_v<T>` is false;
4. `is_volatile_v<T>` is false; and

§ 22.15.3 ©ISO/IEC 853
— T has no non-static data members of reference type.

### 22.15.4 byteswap

```cpp
template<class T>
constexpr T byteswap(T value) noexcept;
```

**Constraints:** T models integral.

**Mandates:** T does not have padding bits (6.8.1).

Let the sequence \( R \) comprise the bytes of the object representation of \( \text{value} \) in reverse order.

**Returns:** An object \( v \) of type T such that each byte in the object representation of \( v \) is equal to the byte in the corresponding position in \( R \).

### 22.15.5 Integral powers of 2

```cpp
template<class T>
constexpr bool has_single_bit(T x) noexcept;
```

**Constraints:** T is an unsigned integer type (6.8.2).

**Returns:** true if \( x \) is an integral power of two; false otherwise.

```cpp
template<class T>
constexpr T bit_ceil(T x);
```

**Constraints:** T is an unsigned integer type (6.8.2).

**Preconditions:** \( N \) is representable as a value of type T.

**Returns:** \( N \).

**Throws:** Nothing.

**Remarks:** A function call expression that violates the precondition in the Preconditions: element is not a core constant expression (7.7).

```cpp
template<class T>
constexpr T bit_floor(T x) noexcept;
```

**Constraints:** T is an unsigned integer type (6.8.2).

**Returns:** If \( x == 0 \), 0; otherwise the maximal value \( y \) such that has_single_bit(y) is true and \( y \leq x \).

```cpp
template<class T>
constexpr int bit_width(T x) noexcept;
```

**Constraints:** T is an unsigned integer type (6.8.2).

**Returns:** If \( x == 0 \), 0; otherwise one plus the base-2 logarithm of \( x \), with any fractional part discarded.

### 22.15.6 Rotating

In the following descriptions, let \( N \) denote numeric_limits<T>::digits.

```cpp
template<class T>
[[nodiscard]] constexpr T rotl(T x, int s) noexcept;
```

**Constraints:** T is an unsigned integer type (6.8.2).

Let \( r \) be \( s \% N \).

**Returns:** If \( r \) is 0, \( x \); if \( r \) is positive, \( (x << r) \mid (x >> (N - r)) \); if \( r \) is negative, rotr(x, -r).

```cpp
template<class T>
[[nodiscard]] constexpr T rotr(T x, int s) noexcept;
```

**Constraints:** T is an unsigned integer type (6.8.2).

Let \( r \) be \( s \% N \).

**Returns:** If \( r \) is 0, \( x \); if \( r \) is positive, \( (x >> r) \mid (x << (N - r)) \); if \( r \) is negative, rotl(x, -r).
22.15.7 Counting

In the following descriptions, let N denote `numeric_limits<T>::digits`.

```cpp
template<class T>
constexpr int countl_zero(T x) noexcept;

Constraints: T is an unsigned integer type (6.8.2).

Returns: The number of consecutive 0 bits in the value of x, starting from the most significant bit.

[Note 1: Returns N if x == 0. — end note]
```

```cpp
template<class T>
constexpr int countl_one(T x) noexcept;

Constraints: T is an unsigned integer type (6.8.2).

Returns: The number of consecutive 1 bits in the value of x, starting from the most significant bit.

[Note 2: Returns N if x == `numeric_limits<T>::max()`. — end note]
```

```cpp
template<class T>
constexpr int countr_zero(T x) noexcept;

Constraints: T is an unsigned integer type (6.8.2).

Returns: The number of consecutive 0 bits in the value of x, starting from the least significant bit.

[Note 3: Returns N if x == 0. — end note]
```

```cpp
template<class T>
constexpr int countr_one(T x) noexcept;

Constraints: T is an unsigned integer type (6.8.2).

Returns: The number of consecutive 1 bits in the value of x, starting from the least significant bit.

[Note 4: Returns N if x == `numeric_limits<T>::max()`. — end note]
```

```cpp
template<class T>
constexpr int popcount(T x) noexcept;

Constraints: T is an unsigned integer type (6.8.2).

Returns: The number of 1 bits in the value of x.
```

22.15.8 Endian

Two common methods of byte ordering in multibyte scalar types are big-endian and little-endian in the execution environment. Big-endian is a format for storage of binary data in which the most significant byte is placed first, with the rest in descending order. Little-endian is a format for storage of binary data in which the least significant byte is placed first, with the rest in ascending order. This subclause describes the endianness of the scalar types of the execution environment.

```cpp
enum class endian {
    little = see below,
    big = see below,
    native = see below
};
```

If all scalar types have size 1 byte, then all of `endian::little`, `endian::big`, and `endian::native` have the same value. Otherwise, `endian::little` is not equal to `endian::big`. If all scalar types are big-endian, `endian::native` is equal to `endian::big`. If all scalar types are little-endian, `endian::native` is equal to `endian::little`. Otherwise, `endian::native` is not equal to either `endian::big` or `endian::little`.

22.16 Debugging

22.16.1 General

Subclause 22.16 describes functionality to introspect and interact with the execution of the program.

[Note 1: The facilities provided by the debugging functionality interact with a program that could be tracing the execution of a C++ program, such as a debugger. — end note]
22.16.2 Header <debugging> synopsis

```cpp
namespace std {
    // 22.16.3, utility
    void breakpoint() noexcept;
    void breakpoint_if_debugging() noexcept;
    bool is_debugger_present() noexcept;
}
```

22.16.3 Utility

```cpp
void breakpoint() noexcept;
```

The semantics of this function are implementation-defined.

[Note 1: When invoked, the execution of the program temporarily halts and execution is handed to the debugger until such a time as: The program is terminated by the debugger, or the debugger resumes execution of the program as if the function was not invoked. —end note]

```cpp
void breakpoint_if_debugging() noexcept;
```

Effects: Equivalent to:

```cpp
if (is_debugger_present()) breakpoint();
```

```cpp
bool is_debugger_present() noexcept;
```

Replaceable: A C++ program may define a function with this function signature, and thereby displace the default version defined by the C++ standard library.

Required behavior: This function has no preconditions.

Default behavior: implementation-defined.

[Note 2: When tracing the execution of a program with a debugger, an implementation returns true. An implementation performs an immediate query, as needed, to determine if the program is traced by a debugger. On Windows or equivalent systems, this can be achieved by calling the ::IsDebuggerPresent() Win32 function. On POSIX, this can be achieved by checking for a tracer parent process, with best effort determination that such a tracer parent process is a debugger. —end note]
23  Strings library

23.1 General

This Clause describes components for manipulating sequences of any non-array trivial standard-layout (6.8.1) type. Such types are called char-like types, and objects of char-like types are called char-like objects or simply characters.

The following subclauses describe a character traits class, string classes, and null-terminated sequence utilities, as summarized in Table 82.

Table 82 — Strings library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.2</td>
<td>&lt;string&gt;</td>
</tr>
<tr>
<td>23.3</td>
<td>&lt;string_view&gt;</td>
</tr>
<tr>
<td>23.4</td>
<td>&lt;string&gt;</td>
</tr>
<tr>
<td>23.5</td>
<td>&lt;cctype&gt;, &lt;cstdlib&gt;, &lt;cstring&gt;, &lt;cuchar&gt;, &lt;cwchar&gt;, &lt;cwctype&gt;</td>
</tr>
</tbody>
</table>

23.2 Character traits

23.2.1 General

Subclause 23.2 defines requirements on classes representing character traits, and defines a class template char_traits<
charT>, along with five specializations, char_traits<char>, char_traits<char8_t>, char_traits<char16_t>, char_traits<char32_t>, and char_traits<wchar_t>, that meet those requirements.

Most classes specified in 23.4, 23.3, and Clause 31 need a set of related types and functions to complete the definition of their semantics. These types and functions are provided as a set of member typedef-names and functions in the template parameter traits used by each such template. Subclause 23.2 defines the semantics of these members.

To specialize those templates to generate a string, string view, or iostream class to handle a particular character container type (3.10) C, that and its related character traits class X are passed as a pair of parameters to the string, string view, or iostream template as parameters charT and traits. If X::char_type is not the same type as C, the program is ill-formed.

23.2.2 Character traits requirements

1 In Table 83, X denotes a traits class defining types and functions for the character container type C; c and d denote values of type C; p and q denote values of type const C*; s denotes a value of type C*; n, i and j denote values of type size_t; e and f denote values of type X::int_type; pos denotes a value of type X::pos_type; and r denotes an lvalue of type C. No expression which is part of the character traits requirements specified in 23.2.2 shall exit via an exception.

Table 83 — Character traits requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Assertion/note/pre-/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>X::char_type</td>
<td>C</td>
<td></td>
<td>compile-time</td>
</tr>
<tr>
<td>X::int_type</td>
<td></td>
<td>(described in 23.2.3)</td>
<td>compile-time</td>
</tr>
<tr>
<td>X::off_type</td>
<td></td>
<td>(described in 31.2.3 and 31.3)</td>
<td>compile-time</td>
</tr>
<tr>
<td>X::pos_type</td>
<td></td>
<td>(described in 31.2.3 and 31.3)</td>
<td>compile-time</td>
</tr>
<tr>
<td>X::state_type</td>
<td></td>
<td>(described in 23.2.3)</td>
<td>compile-time</td>
</tr>
<tr>
<td>X:eq(c,d)</td>
<td>bool</td>
<td>Returns: whether c is to be treated as equal to d.</td>
<td>constant</td>
</tr>
</tbody>
</table>
Table 83 — Character traits requirements (continued)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Assertions/Note</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>X::lt(c,d)</td>
<td>bool</td>
<td>Returns: whether c is to be treated as less than d.</td>
<td>constant</td>
</tr>
<tr>
<td>X::compare(p,q,n)</td>
<td>int</td>
<td>Returns: 0 if for each i in [0,n), X::eq(p[i],q[i]) is true; else, a negative value if, for some j in [0,n), X::lt(p[j],q[j]) is true and for each i in [0,j) X::eq(p[i],q[i]) is true; else a positive value.</td>
<td>linear</td>
</tr>
<tr>
<td>X::length(p)</td>
<td>size_t</td>
<td>Returns: the smallest i such that X::eq(p[i],charT()) is true.</td>
<td>linear</td>
</tr>
<tr>
<td>X::find(p,n,c)</td>
<td>const X::char_type*</td>
<td>Returns: the smallest q in [p,p+n) such that X::eq(*q,c) is true, nullptr otherwise.</td>
<td>linear</td>
</tr>
<tr>
<td>X::move(s,p,n)</td>
<td>X::char_type*</td>
<td>for each i in [0,n), performs X::assign(s[i],p[i]). Copies correctly even where the ranges [p,p+n) and [s,s+n) overlap. Returns: s.</td>
<td>linear</td>
</tr>
<tr>
<td>X::copy(s,p,n)</td>
<td>X::char_type*</td>
<td>Preconditions: The ranges [p,p+n) and [s,s+n) do not overlap. Returns: s. for each i in [0,n), performs X::assign(s[i],p[i]).</td>
<td>linear</td>
</tr>
<tr>
<td>X::assign(r,d)</td>
<td>(not used)</td>
<td>assigns r=d.</td>
<td>constant</td>
</tr>
<tr>
<td>X::assign(s,n,c)</td>
<td>X::char_type*</td>
<td>for each i in [0,n), performs X::assign(s[i],c). Returns: s.</td>
<td>linear</td>
</tr>
<tr>
<td>X::not_eof(e)</td>
<td>int_type</td>
<td>Returns: e if X::eq_int_type(e,X::eof()) is false, otherwise a value f such that X::eq_int_type(f,X::eof()) is false.</td>
<td>constant</td>
</tr>
<tr>
<td>X::to_char_type(e)</td>
<td>X::char_type</td>
<td>Returns: if for some c, X::eq_int_type(e,X::to_int_type(c)) is true, c; else some unspecified value.</td>
<td>constant</td>
</tr>
<tr>
<td>X::to_int_type(c)</td>
<td>X::int_type</td>
<td>Returns: some value e, constrained by the definitions of to_char_type and eq_int_type.</td>
<td>constant</td>
</tr>
</tbody>
</table>
Table 83 — Character traits requirements (continued)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Assertion/note pre-/post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>X::eq_int_type(e,f)</td>
<td>bool</td>
<td>Returns: for all c and d,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X::eq(c,d) is equal to X::eq_int_type(X::to_int_type(c), X::to_int_type(d));</td>
</tr>
<tr>
<td></td>
<td></td>
<td>otherwise, yields true if e and f</td>
</tr>
<tr>
<td></td>
<td></td>
<td>are both copies of X::eof();</td>
</tr>
<tr>
<td></td>
<td></td>
<td>otherwise, yields false if one of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e and f is a copy of X::eof() and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the other is not; otherwise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the value is unspecified.</td>
</tr>
<tr>
<td>X::eof()</td>
<td>X::int_type</td>
<td>Returns: a value e such that</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X::eq_int_type(e,X::to_int_type(c)) is false for all values c.</td>
</tr>
</tbody>
</table>

2 The class template

    template<class charT> struct char_traits;

is provided in the header `<string>` as a basis for explicit specializations.

23.2.3 Traits typedefs

using int_type = see below;

1 Preconditions: `int_type` shall be able to represent all of the valid characters converted from the
    corresponding `char_type` values, as well as an end-of-file value, `eof()`.\(^{200}\)

using state_type = see below;

2 Preconditions: `state_type` meets the Cpp17Destructible (Table 35), Cpp17CopyAssignable (Table 34),
    Cpp17CopyConstructible (Table 32), and Cpp17DefaultConstructible (Table 30) requirements.

23.2.4 char_traits specializations

23.2.4.1 General

namespace std {
    template<> struct char_traits<char> {
        using char_type = char;
        using int_type = int;
        using off_type = streamoff;
        using pos_type = streampos;
        using state_type = mbstate_t;
        using comparison_category = strong_ordering;

        static constexpr void assign(char_type& c1, const char_type& c2) noexcept;
        static constexpr bool eq(char_type c1, char_type c2) noexcept;
        static constexpr bool lt(char_type c1, char_type c2) noexcept;
    }
}

1 The header `<string>` defines five specializations of the class template char_traits: char_traits<char>,
    char_traits<char8_t>, char_traits<char16_t>, char_traits<char32_t>, and char_traits<wchar_t>.

23.2.4.2 struct char_traits<char>

namespace std {
    template<> struct char_traits<char> {
        using char_type = char;
        using int_type = int;
        using off_type = streamoff;
        using pos_type = streampos;
        using state_type = mbstate_t;
        using comparison_category = strong_ordering;

        static constexpr void assign(char_type& c1, const char_type& c2) noexcept;
        static constexpr bool eq(char_type c1, char_type c2) noexcept;
        static constexpr bool lt(char_type c1, char_type c2) noexcept;
    }
}

\(^{200}\) If `eof()` can be held in `char_type` then some iostreams operations can give surprising results.

§ 23.2.4.2 ©ISO/IEC 859
static constexpr int compare(const char_type* s1, const char_type* s2, size_t n);
static constexpr size_t length(const char_type* s);
static constexpr const char_type* find(const char_type* s, size_t n, const char_type& a);
static constexpr char_type* move(char_type* s1, const char_type* s2, size_t n);
static constexpr char_type* copy(char_type* s1, const char_type* s2, size_t n);
static constexpr char_type* assign(char_type* s, size_t n, char_type a);

static constexpr int_type not_eof(int_type c) noexcept;
static constexpr char_type to_char_type(int_type c) noexcept;
static constexpr int_type to_int_type(char_type c) noexcept;
static constexpr bool eq_int_type(int_type c1, int_type c2) noexcept;
static constexpr int_type eof() noexcept;

1 The type mbstate_t is defined in <cwchar> and can represent any of the conversion states that can occur in an implementation-defined set of supported multibyte character encoding rules.
2 The two-argument member assign is defined identically to the built-in operator =. The two-argument members eq and lt are defined identically to the built-in operators == and < for type unsigned char.
3 The member eof() returns EOF.

23.2.4.3 struct char_traits<char8_t> [char.traits.specializations.char8.t]
namespace std {
    template<> struct char_traits<char8_t> {
        using char_type = char8_t;
        using int_type = unsigned int;
        using off_type = streamoff;
        using pos_type = u8streampos;
        using state_type = mbstate_t;
        using comparison_category = strong_ordering;

        static constexpr void assign(char_type& c1, const char_type& c2) noexcept;
        static constexpr bool eq(char_type c1, char_type c2) noexcept;
        static constexpr bool lt(char_type c1, char_type c2) noexcept;
        static constexpr int compare(const char_type* s1, const char_type* s2, size_t n);
        static constexpr size_t length(const char_type* s);
        static constexpr const char_type* find(const char_type* s, size_t n, const char_type& a);
        static constexpr char_type* move(char_type* s1, const char_type* s2, size_t n);
        static constexpr char_type* copy(char_type* s1, const char_type* s2, size_t n);
        static constexpr char_type* assign(char_type* s, size_t n, char_type a);
        static constexpr int_type not_eof(int_type c) noexcept;
        static constexpr char_type to_char_type(int_type c) noexcept;
        static constexpr int_type to_int_type(char_type c) noexcept;
        static constexpr bool eq_int_type(int_type c1, int_type c2) noexcept;
        static constexpr int_type eof() noexcept;
    };
}

1 The two-argument members assign, eq, and lt are defined identically to the built-in operators =, ==, and < respectively.
2 The member eof() returns an implementation-defined constant that cannot appear as a valid UTF-8 code unit.

23.2.4.4 struct char_traits<char16_t> [char.traits.specializations.char16.t]
namespace std {
    template<> struct char_traits<char16_t> {
        using char_type = char16_t;
        using int_type = uint_least16_t;
        using off_type = streamoff;
        using pos_type = u16streampos;

    };
}

©ISO/IEC 860
using state_type = mbstate_t;
using comparison_category = strong_ordering;

static constexpr void assign(char_type& c1, const char_type& c2) noexcept;
static constexpr bool eq(char_type c1, char_type c2) noexcept;
static constexpr bool lt(char_type c1, char_type c2) noexcept;
static constexpr int compare(const char_type* s1, const char_type* s2, size_t n);
static constexpr size_t length(const char_type* s);
static constexpr const char_type* find(const char_type* s, size_t n, const char_type& a);
static constexpr char_type* move(char_type* s1, const char_type* s2, size_t n);
static constexpr char_type* copy(char_type* s1, const char_type* s2, size_t n);
static constexpr char_type* assign(char_type* s, size_t n, char_type a);
static constexpr int_type not_eof(int_type c) noexcept;
static constexpr char_type to_char_type(int_type c) noexcept;
static constexpr int_type to_int_type(char_type c) noexcept;
static constexpr bool eq_int_type(int_type c1, int_type c2) noexcept;
static constexpr int_type eof() noexcept;

1 The two-argument members assign, eq, and lt are defined identically to the built-in operators =, ==, and <, respectively.

2 The member eof() returns an implementation-defined constant that cannot appear as a Unicode code point.
23.2.4.6 struct char_traits<wchar_t> [char.traits.specializations.wchar.t]

namespace std {
    template<> struct char_traits<wchar_t> {
        using char_type = wchar_t;
        using int_type = wint_t;
        using off_type = streamoff;
        using pos_type = wstreampos;
        using state_type = mbstate_t;
        using comparison_category = strong_ordering;

        static constexpr void assign(char_type& c1, const char_type& c2) noexcept;
        static constexpr bool eq(char_type c1, char_type c2) noexcept;
        static constexpr bool lt(char_type c1, char_type c2) noexcept;
        static constexpr int compare(const char_type* s1, const char_type* s2, size_t n);
        static constexpr size_t length(const char_type* s);
        static constexpr const char_type* find(const char_type* s, size_t n, const char_type& a);
        static constexpr char_type* move(char_type* s1, const char_type* s2, size_t n);
        static constexpr char_type* copy(char_type* s1, const char_type* s2, size_t n);
        static constexpr char_type* assign(char_type* s, size_t n, char_type a);
        static constexpr int_type not_eof(int_type c) noexcept;
        static constexpr char_type to_char_type(int_type c) noexcept;
        static constexpr int_type to_int_type(char_type c) noexcept;
        static constexpr bool eq_int_type(int_type c1, int_type c2) noexcept;
        static constexpr int_type eof() noexcept;
    };
}

1 The two-argument members assign, eq, and lt are defined identically to the built-in operators =, ==, and <, respectively.

2 The member eof() returns WEOF.

23.3 String view classes [string.view]

23.3.1 General [string.view.general]

1 The class template basic_string_view describes an object that can refer to a constant contiguous sequence of char-like (23.1) objects with the first element of the sequence at position zero. In the rest of 23.3, the type of the char-like objects held in a basic_string_view object is designated by charT.

2 [Note 1: The library provides implicit conversions from const charT* and std::basic_string<charT, ...> to std::basic_string_view<charT, ...> so that user code can accept just std::basic_string_view<charT> as a non-templated parameter wherever a sequence of characters is expected. User-defined types can define their own implicit conversions to std::basic_string_view<charT> in order to interoperate with these functions. — end note]

23.3.2 Header <string_view> synopsis [string.view.synop]

// mostly freestanding
#include <compare> // see 17.11.1

namespace std {
    // 23.3.3, class template basic_string_view
    template<class charT, class traits = char_traits<charT>>
    class basic_string_view; // partially freestanding

    template<class charT, class traits>
    constexpr bool ranges::enable_view<basic_string_view<charT, traits>> = true;
    template<class charT, class traits>
    constexpr bool ranges::enable_borrowed_range<basic_string_view<charT, traits>> = true;

    // 23.3.4, non-member comparison functions
    template<class charT, class traits>
    constexpr bool operator==(basic_string_view<charT, traits> x, type_identity_t<basic_string_view<charT, traits>> y) noexcept;

§ 23.3.2 ©ISO/IEC 862
template<class charT, class traits>
constexpr see below operator<=>(basic_string_view<charT, traits> x,
    type_identity_t<basic_string_view<charT, traits>> y) noexcept;

// 23.3.5, inserters and extractors
template<class charT, class traits>
basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os,
        basic_string_view<charT, traits> str);  // hosted

// basic_string_view typedef-names
using string_view = basic_string_view<char>;
using u8string_view = basic_string_view<char8_t>;
using u16string_view = basic_string_view<char16_t>;
using u32string_view = basic_string_view<char32_t>;
using wstring_view = basic_string_view<wchar_t>;

// 23.3.6, hash support
template<class T> struct hash;
template<> struct hash<string_view>;
template<> struct hash<u8string_view>;
template<> struct hash<u16string_view>;
template<> struct hash<u32string_view>;
template<> struct hash<wstring_view>;

// 23.3.7, suffix for basic_string_view literals
constexpr string_view operator"sv(const char* str, size_t len) noexcept;
constexpr u8string_view operator"sv(const char8_t* str, size_t len) noexcept;
constexpr u16string_view operator"sv(const char16_t* str, size_t len) noexcept;
constexpr u32string_view operator"sv(const char32_t* str, size_t len) noexcept;
constexpr wstring_view operator"sv(const wchar_t* str, size_t len) noexcept;

1 The function templates defined in 22.2.2 and 25.7 are available when <string_view> is included.

23.3.3 Class template basic_string_view
[string.view.template]

23.3.3.1 General
[string.view.template.general]

namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_string_view {
        public:
            // types
            using traits_type = traits;
            using value_type = charT;
            using pointer = value_type*;
            using const_pointer = const value_type*;
            using reference = value_type&;
            using const_reference = const value_type&;
            using const_iterator = implementation-defined; // see 23.3.3.4
            using iterator = const_iterator;[201]
            using const_reverse_iterator = reverse_iterator<const_iterator>;
            using reverse_iterator = const_reverse_iterator;
            using size_type = size_t;
            using difference_type = ptrdiff_t;
            static constexpr size_type npos = size_type(-1);

    } // class basic_string_view
}

[201] Because basic_string_view refers to a constant sequence, iterator and const_iterator are the same type.
// 23.3.2, construction and assignment
constexpr basic_string_view() noexcept;
constexpr basic_string_view(const basic_string_view&) noexcept = default;
constexpr basic_string_view& operator=(const basic_string_view&) noexcept = default;
basic_string_view(const charT* str);
basic_string_view(nullptr_t) = delete;
constexpr basic_string_view(const charT* str, size_type len);
template<class It, class End>
  constexpr basic_string_view(It begin, End end);
template<class R>
  constexpr explicit basic_string_view(R&& r);

// 23.3.3.4, iterator support
constexpr const_iterator begin() const noexcept;
constexpr const_iterator end() const noexcept;
constexpr const_iterator cbegin() const noexcept;
constexpr const_iterator cend() const noexcept;
constexpr const_reverse_iterator rbegin() const noexcept;
constexpr const_reverse_iterator rend() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept;
constexpr const_reverse_iterator crend() const noexcept;

// 23.3.3.5, capacity
constexpr size_type size() const noexcept;
constexpr size_type length() const noexcept;
constexpr size_type max_size() const noexcept;
[[nodiscard]] constexpr bool empty() const noexcept;

// 23.3.3.6, element access
constexpr const_reference operator[](size_type pos) const;
constexpr const_reference at(size_type pos) const;

// freestanding-deleted
constexpr const_reference front() const;
constexpr const_reference back() const;
constexpr const_pointer data() const noexcept;

// 23.3.3.7, modifiers
constexpr void remove_prefix(size_type n);
constexpr void remove_suffix(size_type n);
constexpr void swap(basic_string_view& s) noexcept;

// 23.3.3.8, string operations
constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;

// freestanding-deleted
constexpr basic_string_view substr(size_type pos = 0, size_type n = npos) const;

// freestanding-deleted
constexpr int compare(basic_string_view s) const noexcept;
constexpr int compare(size_type pos1, size_type n1, basic_string_view s, size_type pos2, size_type n2) const;

// freestanding-deleted
constexpr int compare(const charT* s) const;
constexpr int compare(size_type pos1, size_type n1, const charT* s, size_type n2) const;

// freestanding-deleted
constexpr bool starts_with(basic_string_view x) const noexcept;
constexpr bool starts_with(charT x) const noexcept;
constexpr bool starts_with(const charT* x) const;
constexpr bool ends_with(basic_string_view x) const noexcept;
constexpr bool ends_with(charT x) const noexcept;
constexpr bool ends_with(const charT* x) const;
constexpr bool contains(basic_string_view x) const noexcept;
constexpr bool contains(charT x) const noexcept;
constexpr bool contains(const charT* x) const;

// 23.3.3.9, searching
constexpr size_type find(basic_string_view s, size_type pos = 0) const noexcept;
constexpr size_type find(charT c, size_type pos = 0) const noexcept;
constexpr size_type find(const charT* s, size_type pos, size_type n) const;
constexpr size_type find(const charT* s, size_type pos = 0) const;
constexpr size_type rfind(basic_string_view s, size_type pos = npos) const noexcept;
constexpr size_type rfind(charT c, size_type pos = npos) const noexcept;
constexpr size_type rfind(const charT* s, size_type pos, size_type n) const;
constexpr size_type rfind(const charT* s, size_type pos = npos) const;
constexpr size_type find_first_of(basic_string_view s, size_type pos = 0) const noexcept;
constexpr size_type find_first_of(charT c, size_type pos = 0) const noexcept;
constexpr size_type find_first_of(const charT* s, size_type pos, size_type n) const;
constexpr size_type find_first_of(const charT* s, size_type pos = 0) const;
constexpr size_type find_last_of(basic_string_view s, size_type pos = npos) const noexcept;
constexpr size_type find_last_of(charT c, size_type pos = npos) const noexcept;
constexpr size_type find_last_of(const charT* s, size_type pos, size_type n) const;
constexpr size_type find_last_of(const charT* s, size_type pos = npos) const;
constexpr size_type find_first_not_of(basic_string_view s, size_type pos = 0) const noexcept;
constexpr size_type find_first_not_of(charT c, size_type pos = 0) const noexcept;
constexpr size_type find_first_not_of(const charT* s, size_type pos, size_type n) const;
constexpr size_type find_first_not_of(const charT* s, size_type pos = 0) const;
constexpr size_type find_last_not_of(basic_string_view s, size_type pos = npos) const noexcept;
constexpr size_type find_last_not_of(charT c, size_type pos = npos) const noexcept;
constexpr size_type find_last_not_of(const charT* s, size_type pos, size_type n) const;
constexpr size_type find_last_not_of(const charT* s, size_type pos = npos) const;

private:
const_pointer data_;  // exposition only
size_type size_;  // exposition only

// 23.3.3.3, deduction guides
template<class It, class End>
basic_string_view(It, End) -> basic_string_view<iter_value_t<It>>;
template<class R>
basic_string_view(R&&) -> basic_string_view<ranges::range_value_t<R>>;

1 In every specialization basic_string_view<charT, traits>, the type traits shall meet the character
traits requirements (23.2).

[Note 1: The program is ill-formed if traits::char_type is not the same type as charT. — end note]

2 For a basic_string_view str, any operation that invalidates a pointer in the range
[str.data(), str.data() + str.size())
invalidates pointers, iterators, and references to elements of str.

3 The complexity of basic_string_view member functions is \(O(1)\) unless otherwise specified.

4 basic_string_view<charT, traits> is a trivially copyable type (6.8.1).

23.3.3.2 Construction and assignment

constexpr basic_string_view() noexcept;

Postconditions: size_ == 0 and data_ == nullptr.
constexpr basic_string_view(const charT* str);

**Preconditions:** \([\text{str}, \text{str} + \text{traits::length(str)})\) is a valid range.

**Effects:** Constructs a `basic_string_view`, initializing `data_` with `str` and initializing `size_` with `traits::length(str)`.

**Complexity:** \(\Theta(\text{traits::length(str)})\).

constexpr basic_string_view(const charT* str, size_type len);

**Preconditions:** \([\text{str}, \text{str} + \text{len})\) is a valid range.

**Effects:** Constructs a `basic_string_view`, initializing `data_` with `str` and initializing `size_` with `len`.

template<class It, class End>
constexpr basic_string_view(It begin, End end);

**Constraints:**
- (7.1) It satisfies `contiguous_iterator`.
- (7.2) End satisfies `sized_sentinel_for<It>`.
- (7.3) `is_same_v<\text{iter_value_t<It>, charT}>` is true.
- (7.4) `is_convertible_v<\text{End, size_type}>` is false.

**Preconditions:**
- (8.1) \([\text{begin}, \text{end})\) is a valid range.
- (8.2) It models `contiguous_iterator`.
- (8.3) End models `sized_sentinel_for<It>`.

**Effects:** Initializes `data_` with `to_address(begin)` and initializes `size_` with \(\text{end} - \text{begin}\).

**Throws:** When and what `end - begin` throws.

template<class R>
constexpr explicit basic_string_view(R&& r);

Let \(d\) be an lvalue of type `remove_cvref_t<R>`.

**Constraints:**
- (12.1) `remove_cvref_t<R>` is not the same type as `basic_string_view`.
- (12.2) R models `ranges::contiguous_range` and `ranges::sized_range`.
- (12.3) `is_same_v<\text{ranges::range_value_t<\text{R}, charT}>` is true.
- (12.4) `is_convertible_v<\text{R, const charT}>` is false, and
- (12.5) `d.operator ::std::basic_string_view<charT, traits>()` is not a valid expression.

**Effects:** Initializes `data_` with `ranges::data(r)` and `size_` with `ranges::size(r)`.

**Throws:** Any exception thrown by `ranges::data(r)` and `ranges::size(r)`.

### 23.3.3 Deduction guides

#### [string.view.deduct]

**template<class It, class End>**
basic_string_view(It, End) \(\rightarrow\) basic_string_view<\text{iter_value_t<It>}>;

**Constraints:**
- (1.1) It satisfies `contiguous_iterator`.
- (1.2) End satisfies `sized_sentinel_for<It>`.

**template<class R>**
basic_string_view(R&&) \(\rightarrow\) basic_string_view<\text{ranges::range_value_t<\text{R}>}>;

**Constraints:** R satisfies `ranges::contiguous_range`.

### 23.3.4 Iterator support

#### [string.view.iterators]

§ 23.3.4 ©ISO/IEC 866
using const_iterator = implementation-defined;

A type that meets the requirements of a constant Cpp17RandomAccessIterator (25.3.5.7), models contiguous_iterator (25.3.4.14), and meets the constexpr iterator requirements (25.3.1), whose value_type is the template parameter charT.

All requirements on container iterators (24.2) apply to basic_string_view::const_iterator as well.

constexpr const_iterator begin() const noexcept;
constexpr const_iterator cbegin() const noexcept;

Returns: An iterator such that
— if !empty(), addressof(*begin()) == data_,
— otherwise, an unspecified value such that [begin(), end()) is a valid range.

constexpr const_iterator end() const noexcept;
constexpr const_iterator cend() const noexcept;

Returns: begin() + size().

constexpr const_reverse_iterator rbegin() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept;

Returns: const_reverse_iterator(end()).

constexpr const_reverse_iterator rend() const noexcept;
constexpr const_reverse_iterator crend() const noexcept;

Returns: const_reverse_iterator(begin()).

23.3.3.5 Capacity [string.view.capacity]

constexpr size_type size() const noexcept;
constexpr size_type length() const noexcept;

Returns: size_

constexpr size_type max_size() const noexcept;

Returns: The largest possible number of char-like objects that can be referred to by a basic_string_view.

[[nodiscard]] constexpr bool empty() const noexcept;

Returns: size_ == 0.

23.3.3.6 Element access [string.view.access]

constexpr const_reference operator[](size_type pos) const;

Preconditions: pos < size().

Returns: data_[pos].

Throws: Nothing.

[Note 1: Unlike basic_string::operator[], basic_string_view::operator[](size()) has undefined behavior instead of returning charT(). — end note]

constexpr const_reference at(size_type pos) const;

Returns: data_[pos].

Throws: out_of_range if pos >= size().

constexpr const_reference front() const;

Preconditions: !empty().

Returns: data_[0].

Throws: Nothing.
constexpr const_reference back() const; 
   
Preconditions: !empty().
   Returns: data_[size() - 1].
   Throws: Nothing.

constexpr const_pointer data() const noexcept;
   Returns: data_.
   
[Note 2: Unlike basic_string::data() and string-literals, data() can return a pointer to a buffer that is not null-terminated. Therefore it is typically a mistake to pass data() to a function that takes just a const charT* and expects a null-terminated string. — end note]

23.3.3.7 Modifiers

constexpr void remove_prefix(size_type n);
   Preconditions: n <= size().
   Effects: Equivalent to: data_ += n; size_ -= n;

constexpr void remove_suffix(size_type n);
   Preconditions: n <= size().
   Effects: Equivalent to: size_ -= n;

constexpr void swap(basic_string_view& s) noexcept;
   Effects: Exchanges the values of *this and s.

23.3.3.8 String operations

constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;
   Let rlen be the smaller of n and size() - pos.
   Preconditions: [s, s + rlen) is a valid range.
   Effects: Equivalent to traits::copy(s, data() + pos, rlen).
   Returns: rlen.
   Throws: out_of_range if pos > size().
   Complexity: O(rlen).

constexpr basic_string_view substr(size_type pos = 0, size_type n = npos) const;
   Let rlen be the smaller of n and size() - pos.
   Effects: Determines rlen, the effective length of the string to reference.
   Returns: basic_string_view(data() + pos, rlen).
   Throws: out_of_range if pos > size().

constexpr int compare(basic_string_view str) const noexcept;
   Let rlen be the smaller of size() and str.size().
   Effects: Determines rlen, the effective length of the strings to compare. The function then compares the two strings by calling traits::compare(data(), str.data(), rlen).
   Returns: The nonzero result if the result of the comparison is nonzero. Otherwise, returns a value as indicated in Table 84.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Return Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>size() &lt; str.size()</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>size() == str.size()</td>
<td>0</td>
</tr>
<tr>
<td>size() &gt; str.size()</td>
<td>&gt; 0</td>
</tr>
</tbody>
</table>

§ 23.3.8
14  Complexity: \( \Theta(r_{len}) \).

constexpr int compare(size_type pos1, size_type n1, basic_string_view str) const;
Effects: Equivalent to: return substr(pos1, n1).compare(str);

constexpr int compare(size_type pos1, size_type n1, basic_string_view str,
size_type pos2, size_type n2) const;
Effects: Equivalent to: return substr(pos1, n1).compare(str.substr(pos2, n2));

constexpr int compare(const charT* s) const;
Effects: Equivalent to: return compare(basic_string_view(s));

constexpr int compare(size_type pos1, size_type n1, const charT* s) const;
Effects: Equivalent to: return substr(pos1, n1).compare(basic_string_view(s));

constexpr int compare(size_type pos1, size_type n1, const charT* s, size_type n2) const;
Effects: Equivalent to: return substr(pos1, n1).compare(basic_string_view(s, n2));

constexpr bool starts_with(basic_string_view x) const noexcept;
Effects: Equivalent to: return basic_string_view(data(), rlen) == x;

constexpr bool starts_with(charT x) const noexcept;
Effects: Equivalent to: return !empty() \&\& traits::eq(front(), x);

constexpr bool starts_with(const charT* x) const;
Effects: Equivalent to: return starts_with(basic_string_view(x));

constexpr bool ends_with(basic_string_view x) const noexcept;
Effects: Equivalent to: return basic_string_view(data() + (size() - rlen), rlen) == x;

constexpr bool ends_with(charT x) const noexcept;
Effects: Equivalent to: return !empty() \&\& traits::eq(back(), x);

constexpr bool ends_with(const charT* x) const;
Effects: Equivalent to: return ends_with(basic_string_view(x));

constexpr bool contains(basic_string_view x) const noexcept;
constexpr bool contains(charT x) const noexcept;
constexpr bool contains(const charT* x) const;
Effects: Equivalent to: return find(x) != npos;

23.3.3.9 Searching [string.view.find]

1 Member functions in this subclause have complexity \( \Theta(size() \times str.size()) \) at worst, although implementations should do better.

2 Let \( F \) be one of find, rfind, find_first_of, find_last_of, find_first_not_of, and find_last_not_of.

(2.1) Each member function of the form

  constexpr return-type \( F \)(const charT* s, size_type pos) const;
  has effects equivalent to: return \( F \)(basic_string_view(s), pos);

(2.2) Each member function of the form

  constexpr return-type \( F \)(const charT* s, size_type pos, size_type n) const;
  has effects equivalent to: return \( F \)(basic_string_view(s, n), pos);

(2.3) Each member function of the form
constexpr return-type \( F(\texttt{charT} \ c, \texttt{size_type} \ \texttt{pos}) \) const noexcept;

has effects equivalent to: \( \texttt{return} \ \texttt{F}(\texttt{basic_string_view}(	exttt{addressof(c), 1}), \texttt{pos}); \)

constexpr size-type \( \texttt{find}((\texttt{basic_string_view} \ \texttt{str}, \texttt{size_type} \ \texttt{pos} = 0) \) const noexcept;

Let \( \texttt{xpos} \) be the lowest position, if possible, such that the following conditions hold:

\begin{enumerate}
  \item \( \texttt{pos} \leq \texttt{xpos} \)
  \item \( \texttt{xpos} + \texttt{str}.\texttt{size}() \leq \texttt{size}() \)
  \item \( \text{traits}::\text{eq}(\texttt{data}[\texttt{xpos} + I], \texttt{str}[I]) \) for all elements \( I \) of the string referenced by \( \text{str} \).
\end{enumerate}

\textit{Effects:} Determines \( \texttt{xpos} \).

\textit{Returns:} \( \texttt{xpos} \) if the function can determine such a value for \( \texttt{xpos} \). Otherwise, returns \( \texttt{npos} \).

constexpr size-type \( \texttt{rfind}((\texttt{basic_string_view} \ \texttt{str}, \texttt{size_type} \ \texttt{pos} = \texttt{npos}) \) const noexcept;

Let \( \texttt{xpos} \) be the highest position, if possible, such that the following conditions hold:

\begin{enumerate}
  \item \( \texttt{xpos} \leq \texttt{pos} \)
  \item \( \texttt{xpos} + \texttt{str}.\texttt{size}() \leq \texttt{size}() \)
  \item \( \text{traits}::\text{eq}(\texttt{data}[\texttt{xpos} + I], \texttt{str}[I]) \) for all elements \( I \) of the string referenced by \( \text{str} \).
\end{enumerate}

\textit{Effects:} Determines \( \texttt{xpos} \).

\textit{Returns:} \( \texttt{xpos} \) if the function can determine such a value for \( \texttt{xpos} \). Otherwise, returns \( \texttt{npos} \).

constexpr size-type \( \texttt{find\_first\_of}((\texttt{basic_string_view} \ \texttt{str}, \texttt{size_type} \ \texttt{pos} = 0) \) const noexcept;

Let \( \texttt{xpos} \) be the lowest position, if possible, such that the following conditions hold:

\begin{enumerate}
  \item \( \texttt{pos} \leq \texttt{xpos} \)
  \item \( \texttt{xpos} < \texttt{size}() \)
  \item \( \text{traits}::\text{eq}(\texttt{data}[\texttt{xpos}], \texttt{str}[I]) \) for some element \( I \) of the string referenced by \( \text{str} \).
\end{enumerate}

\textit{Effects:} Determines \( \texttt{xpos} \).

\textit{Returns:} \( \texttt{xpos} \) if the function can determine such a value for \( \texttt{xpos} \). Otherwise, returns \( \texttt{npos} \).

constexpr size-type \( \texttt{find\_last\_of}((\texttt{basic_string_view} \ \texttt{str}, \texttt{size_type} \ \texttt{pos} = \texttt{npos}) \) const noexcept;

Let \( \texttt{xpos} \) be the highest position, if possible, such that the following conditions hold:

\begin{enumerate}
  \item \( \texttt{xpos} \leq \texttt{pos} \)
  \item \( \texttt{xpos} < \texttt{size}() \)
  \item \( \text{traits}::\text{eq}(\texttt{data}[\texttt{xpos}], \texttt{str}[I]) \) for some element \( I \) of the string referenced by \( \text{str} \).
\end{enumerate}

\textit{Effects:} Determines \( \texttt{xpos} \).

\textit{Returns:} \( \texttt{xpos} \) if the function can determine such a value for \( \texttt{xpos} \). Otherwise, returns \( \texttt{npos} \).

constexpr size-type \( \texttt{find\_first\_not\_of}((\texttt{basic_string_view} \ \texttt{str}, \texttt{size_type} \ \texttt{pos} = 0) \) const noexcept;

Let \( \texttt{xpos} \) be the lowest position, if possible, such that the following conditions hold:

\begin{enumerate}
  \item \( \texttt{pos} \leq \texttt{xpos} \)
  \item \( \texttt{xpos} < \texttt{size}() \)
  \item \( \text{traits}::\text{eq}(\texttt{data}[\texttt{xpos}], \texttt{str}[I]) \) for no element \( I \) of the string referenced by \( \text{str} \).
\end{enumerate}

\textit{Effects:} Determines \( \texttt{xpos} \).

\textit{Returns:} \( \texttt{xpos} \) if the function can determine such a value for \( \texttt{xpos} \). Otherwise, returns \( \texttt{npos} \).

constexpr size-type \( \texttt{find\_last\_not\_of}((\texttt{basic_string_view} \ \texttt{str}, \texttt{size_type} \ \texttt{pos} = \texttt{npos}) \) const noexcept;

Let \( \texttt{xpos} \) be the highest position, if possible, such that the following conditions hold:

\begin{enumerate}
  \item \( \texttt{xpos} \leq \texttt{pos} \)
  \item \( \texttt{xpos} < \texttt{size}() \)
  \item \( \text{traits}::\text{eq}(\texttt{data}[\texttt{xpos}], \texttt{str}[I]) \) for no element \( I \) of the string referenced by \( \text{str} \).
\end{enumerate}

\textit{Effects:} Determines \( \texttt{xpos} \).

\textit{Returns:} \( \texttt{xpos} \) if the function can determine such a value for \( \texttt{xpos} \). Otherwise, returns \( \texttt{npos} \).

§ 23.3.3.9
Effects: Determines xpos.
Returns: xpos if the function can determine such a value for xpos. Otherwise, returns npos.

23.3.4 Non-member comparison functions [string.view.comparison]

```cpp
template<class charT, class traits>
constexpr bool operator==(basic_string_view<charT, traits> lhs,
                        type_identity_t<basic_string_view<charT, traits>> rhs) noexcept;
```

Returns: lhs.compare(rhs) == 0.

```cpp
template<class charT, class traits>
constexpr see below operator<=>(basic_string_view<charT, traits> lhs,
                              type_identity_t<basic_string_view<charT, traits>> rhs) noexcept;
```

Let R denote the type traits::comparison_category if that qualified-id is valid and denotes a type (13.10.3), otherwise R is weak_ordering.

Mandates: R denotes a comparison category type (17.11.2).

Returns: static_cast<R>(lhs.compare(rhs) <=> 0).

[Note 1: The usage of type_identity_t as parameter ensures that an object of type basic_string_view<charT, traits> can always be compared with an object of a type T with an implicit conversion to basic_string_view<charT, traits>, and vice versa, as per 12.2.2.3. — end note]

23.3.5 Inserters and extractors [string.view.io]

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, basic_string_view<charT, traits> str);
```

Effects: Behaves as a formatted output function (31.7.6.3.1) of os. Forms a character sequence seq, initially consisting of the elements defined by the range [str.begin(), str.end()). Determines padding for seq as described in 31.7.6.3.1. Then inserts seq as if by calling os.rdbuf()->sputn(seq, n), where n is the larger of os.width() and str.size(); then calls os.width(0).

Returns: os

23.3.6 Hash support [string.view.hash]

```cpp
template<> struct hash<string_view>;
template<> struct hash<u8string_view>;
template<> struct hash<u16string_view>;
template<> struct hash<u32string_view>;
template<> struct hash<wstring_view>;
```

The specialization is enabled (22.10.19).

[Note 1: The hash value of a string view object is equal to the hash value of the corresponding string object (23.4.6). — end note]

23.3.7 Suffix for basic_string_view literals [string.view.literals]

```cpp
constexpr string_view operator"sv(const char* str, size_t len) noexcept;
```

Returns: string_view(str, len).

```cpp
constexpr u8string_view operator"sv(const char8_t* str, size_t len) noexcept;
```

Returns: u8string_view(str, len).

```cpp
constexpr u16string_view operator"sv(const char16_t* str, size_t len) noexcept;
```

Returns: u16string_view(str, len).

```cpp
constexpr u32string_view operator"sv(const char32_t* str, size_t len) noexcept;
```

Returns: u32string_view(str, len).

```cpp
constexpr wstring_view operator"sv(const wchar_t* str, size_t len) noexcept;
```

Returns: wstring_view(str, len).
23.4 String classes

23.4.1 General

The header `<string>` defines the `basic_string` class template for manipulating varying-length sequences of char-like objects and five typedef-names, `string`, `u8string`, `u16string`, `u32string`, and `wstring`, that name the specializations `basic_string<char>`, `basic_string<char8_t>`, `basic_string<char16_t>`, `basic_string<char32_t>`, and `basic_string<wchar_t>`, respectively.

23.4.2 Header `<string>` synopsis

```cpp
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2
namespace std {
    // 23.2, character traits
    template<class charT> struct char_traits; // freestanding
    template<> struct char_traits<char>; // freestanding
    template<> struct char_traits<char8_t>; // freestanding
    template<> struct char_traits<char16_t>; // freestanding
    template<> struct char_traits<char32_t>; // freestanding
    template<> struct char_traits<wchar_t>; // freestanding
    // 23.4.3, basic_string
    template<class charT, class traits = char_traits<charT>, class Allocator = allocator<charT>>
    class basic_string;

    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(const basic_string<charT, traits, Allocator>& lhs,
               const basic_string<charT, traits, Allocator>& rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(basic_string<charT, traits, Allocator>&& lhs,
               const basic_string<charT, traits, Allocator>& rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(const basic_string<charT, traits, Allocator>& lhs,
               basic_string<charT, traits, Allocator>&& rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(basic_string<charT, traits, Allocator>&& lhs,
               basic_string<charT, traits, Allocator>&& rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(const charT* lhs,
               const basic_string<charT, traits, Allocator>& rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(const charT* lhs,
               basic_string<charT, traits, Allocator>&& rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(const basic_string<charT, traits, Allocator>& lhs,
               const charT* rhs);
    template<class charT, class traits, class Allocator>
    constexpr basic_string<charT, traits, Allocator>
    operator+(const basic_string<charT, traits, Allocator>& lhs,
               const charT* rhs);

§ 23.4.2 © ISO/IEC 872
template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(basic_string<charT, traits, Allocator>&& lhs,
    const charT* rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(const basic_string<charT, traits, Allocator>& lhs,
    charT rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(basic_string<charT, traits, Allocator>&& lhs,
    const charT* rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(const basic_string<charT, traits, Allocator>& lhs,
    type_identity_t<basic_string_view<charT, traits>> rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(basic_string<charT, traits, Allocator>&& lhs,
    type_identity_t<basic_string_view<charT, traits>> rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(type_identity_t<basic_string_view<charT, traits>> lhs,
    const basic_string<charT, traits, Allocator>& rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(type_identity_t<basic_string_view<charT, traits>> lhs,
    basic_string<charT, traits, Allocator>&& rhs);

template<class charT, class traits, class Allocator>
constexpr bool
operator==(const basic_string<charT, traits, Allocator>& lhs,
    const basic_string<charT, traits, Allocator>& rhs) noexcept;

template<class charT, class traits, class Allocator>
constexpr bool
operator==(const basic_string<charT, traits, Allocator>& lhs,
    const charT* rhs);

// 23.4.4.3, swap
template<class charT, class traits, class Allocator>
constexpr void
swap(basic_string<charT, traits, Allocator>& lhs,
    basic_string<charT, traits, Allocator>& rhs) noexcept(noexcept(lhs.swap(rhs)));

// 23.4.4.4, inserters and extractors
template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>&& is,
    basic_string<charT, traits, Allocator>& str);

template<class charT, class traits, class Allocator>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os,
    const basic_string<charT, traits, Allocator>& str);

template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
getline(basic_istream<charT, traits>&& is,
    basic_string<charT, traits, Allocator>& str,

§ 23.4.2
template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
getline(basic_istream<charT, traits>&& is,
basic_string<charT, traits, Allocator>& str,
charT delim);

template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
getline(basic_istream<charT, traits>& is,
basic_string<charT, traits, Allocator>& str);

template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
getline(basic_istream<charT, traits>&& is,
basic_string<charT, traits, Allocator>& str);

// 23.4.4.5, erasure
template<class charT, class traits, class Allocator, class U = charT>
constexpr typename basic_string<charT, traits, Allocator>::size_type
erase(basic_string<charT, traits, Allocator>& c, const U& value);

template<class charT, class traits, class Allocator, class Predicate>
constexpr typename basic_string<charT, traits, Allocator>::size_type
erase_if(basic_string<charT, traits, Allocator>& c, Predicate pred);

using string = basic_string<char>;
using u8string = basic_string<char8_t>;
using u16string = basic_string<char16_t>;
using u32string = basic_string<char32_t>;
using wstring = basic_string<wchar_t>;

// 23.4.5, numeric conversions
int stoi(const string& str, size_t* idx = nullptr, int base = 10);
long stol(const string& str, size_t* idx = nullptr, int base = 10);
unsigned long stoul(const string& str, size_t* idx = nullptr, int base = 10);
long long stoll(const string& str, size_t* idx = nullptr, int base = 10);
unsigned long long stoull(const string& str, size_t* idx = nullptr, int base = 10);
float stof(const string& str, size_t* idx = nullptr);
double stod(const string& str, size_t* idx = nullptr);
long double stold(const string& str, size_t* idx = nullptr);
string to_string(int val);
string to_string(unsigned val);
string to_string(long val);
string to_string(unsigned long val);
string to_string(long long val);
string to_string(float val);
string to_string(double val);
string to_string(long double val);

int stoi(const wstring& str, size_t* idx = nullptr, int base = 10);
long stol(const wstring& str, size_t* idx = nullptr, int base = 10);
unsigned long stoul(const wstring& str, size_t* idx = nullptr, int base = 10);
long long stoll(const wstring& str, size_t* idx = nullptr, int base = 10);
unsigned long long stoull(const wstring& str, size_t* idx = nullptr, int base = 10);
float stof(const wstring& str, size_t* idx = nullptr);
double stod(const wstring& str, size_t* idx = nullptr);
long double stold(const wstring& str, size_t* idx = nullptr);
wstring to_wstring(int val);
wstring to_wstring(unsigned val);
wstring to_wstring(long val);
wstring to_wstring(unsigned long val);
wstring to_wstring(long long val);
wstring to_wstring(float val);
namespace pmr {
    template<class charT, class traits = char_traits<charT>>
    using basic_string = std::basic_string<charT, traits, polymorphic_allocator<charT>>;

    using string = basic_string<char>;
    using u8string = basic_string<char8_t>;
    using u16string = basic_string<char16_t>;
    using u32string = basic_string<char32_t>;
    using wstring = basic_string<wchar_t>;
}

// 23.4.6, hash support
template<class T> struct hash;
template<class A> struct hash<basic_string<char, char_traits<char>, A>>;
template<class A> struct hash<basic_string<char8_t, char_traits<char8_t>, A>>;
template<class A> struct hash<basic_string<char16_t, char_traits<char16_t>, A>>;
template<class A> struct hash<basic_string<char32_t, char_traits<char32_t>, A>>;
template<class A> struct hash<basic_string<wchar_t, char_traits<wchar_t>, A>>;

inline namespace literals {
    inline namespace string_literals {
        constexpr string operator"s(const char* str, size_t len);
        constexpr u8string operator"s(const char8_t* str, size_t len);
        constexpr u16string operator"s(const char16_t* str, size_t len);
        constexpr u32string operator"s(const char32_t* str, size_t len);
        constexpr wstring operator"s(const wchar_t* str, size_t len);
    }
}

23.4.3 Class template basic_string

1 The class template basic_string describes objects that can store a sequence consisting of a varying number
of arbitrary char-like objects with the first element of the sequence at position zero. Such a sequence is also
called a “string” if the type of the char-like objects that it holds is clear from context. In the rest of 23.4.3,
the type of the char-like objects held in a basic_string object is designated by charT.

2 A specialization of basic_string is a contiguous container (24.2.2.2).

3 In all cases, [data(), data() + size()] is a valid range, data() + size() points at an object with value
charT() (a “null terminator”), and size() <= capacity() is true.

namespace std {
    template<class charT, class traits = char_traits<charT>,
             class Allocator = allocator<charT>>
    class basic_string {
    public:
        // types
        using traits_type = traits;
        using value_type = charT;
        using allocator_type = Allocator;
        using size_type = typename allocator_traits<Allocator>::size_type;
        using difference_type = typename allocator_traits<Allocator>::difference_type;
        using pointer = typename allocator_traits<Allocator>::pointer;
        using const_pointer = typename allocator_traits<Allocator>::const_pointer;
        using reference = value_type&;
        using const_reference = const value_type&;

        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
    }
}
using reverse_iterator = std::reverse_iterator<iterator>;
using const_reverse_iterator = std::reverse_iterator<const_iterator>;
static constexpr size_type npos = size_type(-1);

// 23.4.3.3, construct/copy/destroy
constexpr basic_string() noexcept(noexcept(Allocator())) : basic_string(Allocator()) { }
constexpr explicit basic_string(const Allocator& a) noexcept;
constexpr basic_string(const basic_string& str);
constexpr basic_string(basic_string&& str) noexcept;
constexpr basic_string(const basic_string& str, size_type pos, const Allocator& a = Allocator());
constexpr basic_string(const basic_string& str, size_type pos, size_type n, const Allocator& a = Allocator());
constexpr basic_string(basic_string&& str, size_type pos, const Allocator& a = Allocator());
constexpr basic_string(basic_string&& str, size_type pos, size_type n, const Allocator& a = Allocator());
template<class T>
  constexpr basic_string(const T& t, size_type pos, size_type n, const Allocator& a = Allocator());
template<class T>
  constexpr explicit basic_string(const T& t, const Allocator& a = Allocator());
constexpr basic_string(const charT* s, size_type n, const Allocator& a = Allocator());
constexpr basic_string(const charT* s, const Allocator& a = Allocator());
basic_string(nullptr_t) = delete;
constexpr basic_string(size_type n, charT c, const Allocator& a = Allocator());
template<class InputIterator>
  constexpr basic_string(InputIterator begin, InputIterator end, const Allocator& a = Allocator());
template<container-compatible-range<CharT> R>
  constexpr basic_string(from_range_t, R&& rg, const Allocator& a = Allocator());
constexpr basic_string(initializer_list<charT>, const Allocator& = Allocator());
constexpr basic_string(basic_string&&, const Allocator&);
custom basic_string& operator=(const basic_string& str);
constexpr basic_string& operator=(basic_string&& str) noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
  allocator_traits<Allocator>::is_always_equal::value);
template<class T>
  constexpr basic_string& operator=(const T& t);
constexpr basic_string& operator=(const charT* s);
basic_string& operator=(nullptr_t) = delete;
constexpr basic_string& operator=(charT c);
constexpr basic_string& operator=(initializer_list<charT>);

// 23.4.3.4, iterators
constexpr iterator begin() noexcept;
constexpr const_iterator begin() const noexcept;
constexpr iterator end() noexcept;
constexpr const_iterator end() const noexcept;
constexpr reverse_iterator rbegin() noexcept;
constexpr const_reverse_iterator rbegin() const noexcept;
constexpr reverse_iterator rend() noexcept;
constexpr const_reverse_iterator rend() const noexcept;
constexpr const_iterator cbegin() const noexcept;
constexpr const_iterator cend() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept;
constexpr const_reverse_iterator crend() const noexcept;
// 23.4.3.5, capacity
constexpr size_type size() const noexcept;
constexpr size_type length() const noexcept;
constexpr size_type max_size() const noexcept;
constexpr void resize(size_type n, charT c);
constexpr void resize(size_type n);
template<class Operation> constexpr void resize_and_overwrite(size_type n, Operation op);
constexpr size_type capacity() const noexcept;
constexpr void reserve(size_type res_arg);
constexpr void shrink_to_fit();
constexpr void clear() noexcept;
[[nodiscard]] constexpr bool empty() const noexcept;

// 23.4.3.6, element access
constexpr const_reference operator[](size_type pos) const;
constexpr reference operator[](size_type pos);
constexpr const_reference at(size_type n) const;
constexpr reference at(size_type n);
constexpr const_charT& front() const;
constexpr charT& front();
constexpr const_charT& back() const;
constexpr charT& back();

// 23.4.3.7, modifiers
constexpr basic_string& operator+=(const basic_string& str);
template<class T>
constexpr basic_string& operator+=(const T& t);
constexpr basic_string& operator+=(const charT* s);
constexpr basic_string& operator+=(charT c);
constexpr basic_string& append(const basic_string& str);
constexpr basic_string& append(const basic_string& str, size_type pos, size_type n = npos);
template<class T>
constexpr basic_string& append(const T& t);
template<class T>
constexpr basic_string& append(const T& t, size_type pos, size_type n = npos);
constexpr basic_string& append(const charT* s, size_type n);
constexpr basic_string& append(const charT* s);
constexpr basic_string& append(size_type n, charT c);
template<class InputIterator>
constexpr basic_string& append(InputIterator first, InputIterator last);
template<container-compatible-range<charT> R>
constexpr basic_string& append_range(R&& rg);
constexpr basic_string& append(initializer_list<charT>);

constexpr void push_back(charT c);
constexpr basic_string& assign(const basic_string& str);
constexpr basic_string& assign(basic_string&& str)
noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
allocator_traits<Allocator>::is_always_equal::value);
constexpr basic_string& assign(const basic_string& str, size_type pos, size_type n = npos);
template<class T>
constexpr basic_string& assign(const T& t);
template<class T>
constexpr basic_string& assign(const T& t, size_type pos, size_type n = npos);
constexpr basic_string& assign(const charT* s, size_type n);
constexpr basic_string& assign(const charT* s);
constexpr basic_string& assign(size_type n, charT c);
template<class InputIterator>
constexpr basic_string& assign(InputIterator first, InputIterator last);
template<container-compatible-range<charT> R>
constexpr basic_string& assign_range(R&& rg);
constexpr basic_string& assign(initializer_list<charT>);  
constexpr basic_string& insert(size_type pos, const basic_string& str);  
constexpr basic_string& insert(size_type pos1, const basic_string& str,  
    size_type pos2, size_type n = npos);  
template<class T>  
    constexpr basic_string& insert(size_type pos, const T& t);  
template<class T>  
    constexpr basic_string& insert(size_type pos1, const T& t,  
        size_type pos2, size_type n = npos);  
constexpr basic_string& insert(size_type pos, const charT* s, size_type n);  
constexpr basic_string& insert(size_type pos, const charT* s);  
constexpr basic_string& insert(size_type pos, size_type n, charT c);  
constexpr basic_string& insert(const_iterator p, charT c);  
constexpr basic_string& insert(const_iterator p, size_type n, charT c);  
template<class InputIterator>  
    constexpr iterator insert(const_iterator p, InputIterator first, InputIterator last);  
template<container-compatible-range<charT> R>  
    constexpr iterator insert_range(const_iterator p, R&& rg);  
constexpr basic_string& erase(size_type pos = 0, size_type n = npos);  
constexpr iterator erase(const_iterator p);  
constexpr iterator erase(const_iterator first, const_iterator last);  

constexpr basic_string& erase(size_type pos, size_type n1, const basic_string& str);  
constexpr basic_string& erase(size_type pos1, size_type n1, const basic_string& str,  
    size_type pos2, size_type n2 = npos);  
template<class T>  
    constexpr basic_string& erase(size_type pos1, size_type n1, const T& t);  
template<class T>  
    constexpr basic_string& erase(size_type pos1, size_type n1, const T& t,  
        size_type pos2, size_type n2 = npos);  
constexpr basic_string& replace(size_type pos1, size_type n1, const charT* s, size_type n2);  
constexpr basic_string& replace(size_type pos, size_type n1, const charT* s);  
constexpr basic_string& replace(size_type pos, size_type n1, size_type n2, charT c);  
constexpr basic_string& replace(const_iterator i1, const_iterator i2,  
    const basic_string& str);  
template<class T>  
    constexpr basic_string& replace(const_iterator i1, const_iterator i2, const T& t);  
constexpr basic_string& replace(const_iterator i1, const_iterator i2, const charT* s,  
    size_type n);  
constexpr basic_string& replace(const_iterator i1, const_iterator i2, const charT* s);  
constexpr basic_string& replace(const_iterator i1, const_iterator i2, size_type n, charT c);  
template<class InputIterator>  
    constexpr basic_string& replace(const_iterator i1, const_iterator i2,  
        InputIterator j1, InputIterator j2);  
template<container-compatible-range<charT> R>  
    constexpr basic_string& replace_with_range(const_iterator i1, const_iterator i2, R&& rg);  
constexpr basic_string& replace_with_range(const_iterator i1, const_iterator i2, initializer_list<charT>);  

constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;  

constexpr void swap(basic_string& str)  
    noexcept(allocator_traits<Allocator>::propagate_on_container_swap::value ||  
        allocator_traits<Allocator>::is_always_equal::value);  

// 23.4.3.8, string operations  
constexpr const charT* c_str() const noexcept;  
constexpr const charT* data() const noexcept;  
constexpr charT* data() noexcept;  
constexpr operator basic_string_view<charT, traits>() const noexcept;
constexpr allocator_type get_allocator() const noexcept;

template<class T>
constexpr size_type find(const T& t, size_type pos = 0) const noexcept;
constexpr size_type find(const basic_string& str, size_type pos = 0) const noexcept;
constexpr size_type find(const charT* s, size_type pos, size_type n) const;
constexpr size_type find(charT c, size_type pos = 0) const noexcept;

template<class T>
constexpr size_type rfind(const T& t, size_type pos = npos) const noexcept;
constexpr size_type rfind(const basic_string& str, size_type pos = npos) const noexcept;
constexpr size_type rfind(const charT* s, size_type pos, size_type n) const;
constexpr size_type rfind(charT c, size_type pos = npos) const noexcept;

template<class T>
constexpr size_type find_first_of(const T& t, size_type pos = 0) const noexcept;
constexpr size_type find_first_of(const basic_string& str, size_type pos = 0) const noexcept;
constexpr size_type find_first_of(const charT* s, size_type pos, size_type n) const;
constexpr size_type find_first_of(charT c, size_type pos = 0) const noexcept;

template<class T>
constexpr size_type find_last_of(const T& t, size_type pos = npos) const noexcept;
constexpr size_type find_last_of(const basic_string& str, size_type pos = npos) const noexcept;
constexpr size_type find_last_of(const charT* s, size_type pos, size_type n) const;
constexpr size_type find_last_of(charT c, size_type pos = npos) const noexcept;

constexpr basic_string substr(size_type pos = 0, size_type n = npos) const &;
constexpr basic_string substr(size_type pos = 0, size_type n = npos) &&;

template<class T>
constexpr int compare(const T& t) const noexcept;
template<class T>
constexpr int compare(size_type pos1, size_type n1, const T& t) const;

template<class T>
constexpr int compare(const basic_string& str, size_type pos1, size_type n1, const T& t) const;

template<class T>
constexpr int compare(const charT* s) const;
constexpr int compare(size_type pos1, size_type n1, const charT* s) const;

§ 23.4.3.1
constexpr bool starts_with(basic_string_view<charT, traits> x) const noexcept;
constexpr bool starts_with(charT x) const noexcept;
constexpr bool starts_with(const charT* x) const;
constexpr bool ends_with(basic_string_view<charT, traits> x) const noexcept;
constexpr bool ends_with(charT x) const noexcept;
constexpr bool ends_with(const charT* x) const;
constexpr bool contains(basic_string_view<charT, traits> x) const noexcept;
constexpr bool contains(charT x) const noexcept;
constexpr bool contains(const charT* x) const;

};

template<class InputIterator, 
    class Allocator = allocator<typename iterator_traits<InputIterator>::value_type>>
    basic_string(InputIterator, InputIterator, Allocator = Allocator())
    -> basic_string<typename iterator_traits<InputIterator>::value_type, 
    char_traits<typename iterator_traits<InputIterator>::value_type>, 
    Allocator>;

template<ranges::input_range R, 
    class Allocator = allocator<ranges::range_value_t<R>>> 
    basic_string(from_range_t, R&&, Allocator = Allocator())
    -> basic_string<ranges::range_value_t<R>, char_traits<ranges::range_value_t<R>>, 
    Allocator>;

template<class charT, 
    class traits, 
    class Allocator = allocator<charT>>
    explicit basic_string(basic_string_view<charT, traits>, const Allocator& = Allocator())
    -> basic_string<charT, traits, Allocator>;

template<class charT, 
    class traits, 
    class Allocator = allocator<charT>>
    basic_string(basic_string_view<charT, traits>, 
        typename see below::size_type, typename see below::size_type, 
        const Allocator& = Allocator())
    -> basic_string<charT, traits, Allocator>;

A size_type parameter type in a basic_string deduction guide refers to the size_type member type of the type deduced by the deduction guide.

The types iterator and const_iterator meet the constexpr iterator requirements (25.3.1).

23.4.3.2 General requirements [string.require]

1 If any operation would cause size() to exceed max_size(), that operation throws an exception object of type length_error.

2 If any member function or operator of basic_string throws an exception, that function or operator has no other effect on the basic_string object.

3 Every object of type basic_string<charT, traits, Allocator> uses an object of type Allocator to allocate and free storage for the contained charT objects as needed. The Allocator object used is obtained as described in 24.2.2.2. In every specialization basic_string<charT, traits, Allocator>, the type traits shall meet the character traits requirements (23.2).

[Note 1: Every specialization basic_string<charT, traits, Allocator> is an allocator-aware container (24.2.2.5), but does not use the allocator’s construct and destroy member functions (24.2.1). The program is ill-formed if Allocator::value_type is not the same type as charT. — end note]

[Note 2: The program is ill-formed if traits::char_type is not the same type as charT. — end note]

4 References, pointers, and iterators referring to the elements of a basic_string sequence may be invalidated by the following uses of that basic_string object:
— Passing as an argument to any standard library function taking a reference to non-const basic_string as an argument.\(^{202}\)

— Calling non-const member functions, except operator[], at, data, front, back, begin, rbegin, end, and rend.

### 23.4.3.3 Constructors and assignment operators

```cpp
constexpr explicit basic_string(const Allocator& a) noexcept;
1
Postconditions: size() is equal to 0.
```

```cpp
constexpr basic_string(const basic_string& str);
2
`Effects: Constructs an object whose value is that of str prior to this call.
Remarks: In the second form, str is left in a valid but unspecified state.
```

```cpp
constexpr basic_string(const basic_string& str, size_type pos,
            const Allocator& a = Allocator());
4
Let
— s be the value of str prior to this call and
— rlen be pos + min(n, s.size() - pos) for the overloads with parameter n, and s.size() otherwise.
5
`Effects: Constructs an object whose initial value is the range [s.data() + pos, s.data() + rlen].
Throws: out_of_range if pos > s.size().
Remarks: For the overloads with a basic_string& parameter, str is left in a valid but unspecified state.
Recommended practice: For the overloads with a basic_string& parameter, implementations should avoid allocation if s.get_allocator() == a is true.
```

```cpp
template<class T>
constexpr basic_string(const T& t, size_type pos, size_type n, const Allocator& a = Allocator());
9
Constraints: is_convertible_v<const T&, basic_string_view<charT, traits>> is true.
10
`Effects: Creates a variable, sv, as if by basic_string_view<charT, traits> sv = t; and then behaves the same as:
basic_string(sv.substr(pos, n), a);
```

```cpp
template<class T>
constexpr explicit basic_string(const T& t, const Allocator& a = Allocator());
11
Constraints:
(11.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(11.2) — is_convertible_v<const T&, const charT*> is false.
12
`Effects: Creates a variable, sv, as if by basic_string_view<charT, traits> sv = t; and then behaves the same as basic_string(sv.data(), sv.size(), a).
```

```cpp
constexpr basic_string(const charT* s, size_type n, const Allocator& a = Allocator());
13
Preconditions: [s, s + n) is a valid range.
Effects: Constructs an object whose initial value is the range [s, s + n).
```

\(^{202}\) For example, as an argument to non-member functions swap() (23.4.4.3), operator>>() (23.4.4.4), and getline() (23.4.4.4), or as an argument to basic_string::swap().

§ 23.4.3.3 ©ISO/IEC 881
Postconditions: size() is equal to n, and traits::compare(data(), s, n) is equal to 0.

constexpr basic_string(const charT* s, const Allocator& a = Allocator());

Constraints: Allocator is a type that qualifies as an allocator (24.2.2.2).

[Note 1: This affects class template argument deduction. — end note]

Effects: Equivalent to: basic_string(s, traits::length(s), a).

constexpr basic_string(size_type n, charT c, const Allocator& a = Allocator());

Constraints: Allocator is a type that qualifies as an allocator (24.2.2.2).

[Note 2: This affects class template argument deduction. — end note]

Effects: Constructs an object whose value consists of n copies of c.

template<class InputIterator>
constexpr basic_string(InputIterator begin, InputIterator end, const Allocator& a = Allocator());

Constraints: InputIterator is a type that qualifies as an input iterator (24.2.2.2).

Effects: Constructs a string from the values in the range [begin,end), as specified in 24.2.4.

template<container-compatible-range<charT> R>
constexpr basic_string(from_range_t<R>, R&& rg, const Allocator& a = Allocator());

Effects: Constructs a string from the values in the range rg, as specified in 24.2.4.

constexpr basic_string(initializer_list<charT> il, const Allocator& a = Allocator());

Effects: Equivalent to basic_string(il.begin(), il.end(), a).

constexpr basic_string(const basic_string& str, const Allocator& alloc);
constexpr basic_string(basic_string&& str, const Allocator& a);

Effects: Constructs an object whose value is that of str prior to this call. The stored allocator is constructed from alloc. In the second form, str is left in a valid but unspecified state.

Returns: The second form throws nothing if alloc == str.get_allocator().

template<class InputIterator, class Allocator = allocator<typename iterator_traits<InputIterator>::value_type>>
 basic_string<InputIterator, Allocator> = basic_string<typename iterator_traits<InputIterator>::value_type, char_traits<typename iterator_traits<InputIterator>::value_type>, Allocator>();

Constraints: InputIterator is a type that qualifies as an input iterator, and Allocator is a type that qualifies as an allocator (24.2.2.2).

template<class charT, class traits, class Allocator = allocator<charT>>
 explicit basic_string(basic_string_view<charT, traits>, const Allocator& = Allocator())
 -> basic_string<charT, traits, Allocator>;

template<class charT, class traits, class Allocator = allocator<charT> >
 basic_string_view(basic_string_view<charT, traits>)
 , typename see below::size_type, typename see below::size_type,
 const Allocator& = Allocator() 
 -> basic_string<charT, traits, Allocator>;

Constraints: Allocator is a type that qualifies as an allocator (24.2.2.2).

constexpr basic_string& operator=(const basic_string& str);

Effects: If *this and str are the same object, has no effect. Otherwise, replaces the value of *this with a copy of str.

Returns: *this.
constexpr basic_string& operator=(basic_string&& str)
  noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
  allocator_traits<Allocator>::is_always_equal::value);

Effects: Move assigns as a sequence container (24.2.4), except that iterators, pointers and references may be invalidated.

Returns: *this.

template<class T>
constexpr basic_string& operator=(const T& t);

Constraints:
— is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
— is_convertible_v<const T&, const charT*> is false.

Effects: Equivalent to:
  basic_string_view<charT, traits> sv = t;
  return assign(sv);

constexpr basic_string& operator=(const charT* s);

Effects: Equivalent to: return *this = basic_string_view<charT, traits>(s);

constexpr basic_string& operator=(charT c);

Effects: Equivalent to:
  return *this = basic_string_view<charT, traits>(addressof(c), 1);

constexpr basic_string& operator=(initializer_list<charT> il);

Effects: Equivalent to:
  return *this = basic_string_view<charT, traits>(il.begin(), il.size());

23.4.3.4 Iterator support

constexpr iterator begin() noexcept;
constexpr const_iterator begin() const noexcept;
constexpr const_iterator cbegin() const noexcept;

Returns: An iterator referring to the first character in the string.

constexpr iterator end() noexcept;
constexpr const_iterator end() const noexcept;
constexpr const_iterator cend() const noexcept;

Returns: An iterator which is the past-the-end value.

constexpr reverse_iterator rbegin() noexcept;
constexpr const_reverse_iterator rbegin() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept;

Returns: An iterator which is semantically equivalent to reverse_iterator(end()).

constexpr reverse_iterator rend() noexcept;
constexpr const_reverse_iterator rend() const noexcept;
constexpr const_reverse_iterator crend() const noexcept;

Returns: An iterator which is semantically equivalent to reverse_iterator(begin()).

23.4.3.5 Capacity

constexpr size_type size() const noexcept;
constexpr size_type length() const noexcept;

Returns: A count of the number of char-like objects currently in the string.

Complexity: Constant time.
```cpp
constexpr size_type max_size() const noexcept;

Returns: The largest possible number of char-like objects that can be stored in a basic_string.

Complexity: Constant time.

constexpr void resize(size_type n, charT c);

Effects: Alters the value of *this as follows:
- If \( n \leq \text{size()} \), erases the last \( \text{size()} - n \) elements.
- If \( n > \text{size()} \), appends \( n - \text{size()} \) copies of \( c \).

constexpr void resize(size_type n);

Effects: Equivalent to \( \text{resize}(n, \text{charT}()) \).

template<class Operation> constexpr void resize_and_overwrite(size_type n, Operation op);

Let
- \( o = \text{size()} \) before the call to \( \text{resize_and_overwrite} \).
- \( k = \min(o, n) \).
- \( p \) be a value of type \( \text{charT*} \) or \( \text{charT* const} \), such that the range \([p, p + n]\) is valid and \( \text{this->compare}(0, k, p, k) == 0 \) is true before the call. The values in the range \([p + k, p + n]\) may be indeterminate (6.7.4).
- \( m \) be a value of type \( \text{size_type} \) or \( \text{const size_type} \) equal to \( n \).
- \( OP \) be the expression \( \text{std::move}(op)(p, m) \).
- \( r = OP \).

Mandates: \( OP \) has an integer-like type (25.3.4.4).

Preconditions:
- \( OP \) does not throw an exception or modify \( p \) or \( m \).
- \( r \geq 0 \).
- \( r \leq m \).
- After evaluating \( OP \) there are no indeterminate values in the range \([p, p + r]\).

Effects: Evaluates \( OP \), replaces the contents of \( *\text{this} \) with \([p, p + r]\), and invalidates all pointers and references to the range \([p, p + n]\).

Recommended practice: Implementations should avoid unnecessary copies and allocations by, for example, making \( p \) a pointer into internal storage and by restoring \( *(p + r) \) to \( \text{charT}() \) after evaluating \( OP \).

constexpr size_type capacity() const noexcept;

Returns: The size of the allocated storage in the string.

Complexity: Constant time.

constexpr void reserve(size_type res_arg);

Effects: A directive that informs a basic_string of a planned change in size, so that the storage allocation can be managed accordingly. Following a call to \( \text{reserve} \), \( \text{capacity()} \) is greater or equal to the argument of \( \text{reserve} \) if reallocation happens; and equal to the previous value of \( \text{capacity()} \) otherwise. Reallocation happens at this point if and only if the current capacity is less than the argument of \( \text{reserve} \).

Throws: \text{length_error} if \( \text{res_arg} > \text{max_size()} \) or any exceptions thrown by allocator_traits<Allocator>::allocate.

constexpr void shrink_to_fit();

Effects: \( \text{shrink_to_fit} \) is a non-binding request to reduce \( \text{capacity()} \) to \( \text{size()} \).

[Note 1: The request is non-binding to allow latitude for implementation-specific optimizations. — end note]
It does not increase \( \text{capacity()} \), but may reduce \( \text{capacity()} \) by causing reallocation.
```
Complexity: If the size is not equal to the old capacity, linear in the size of the sequence; otherwise constant.

Remarks: Reallocation invalidates all the references, pointers, and iterators referring to the elements in the sequence, as well as the past-the-end iterator.

[Note 2: If no reallocation happens, they remain valid. — end note]

```cpp
constexpr void clear() noexcept;
```

Effects: Equivalent to: `erase(begin(), end());`

```cpp
[[nodiscard]] constexpr bool empty() const noexcept;
```

Effects: Equivalent to: `return size() == 0;`

23.4.3.6 Element access

```cpp
constexpr const_reference operator[](size_type pos) const;  
constexpr reference operator[](size_type pos);  

Preconditions: pos <= size().

Returns: *(begin() + pos) if pos < size(). Otherwise, returns a reference to an object of type charT with value charT(), where modifying the object to any value other than charT() leads to undefined behavior.

Throws: Nothing.

Complexity: Constant time.
```

```cpp
constexpr const_reference at(size_type pos) const;  
constexpr reference at(size_type pos);
```

Returns: `operator[](pos).`

Throws: `out_of_range` if pos >= size().

```cpp
constexpr const charT& front() const;  
constexpr charT& front();  
```

Preconditions: `!empty()`. Effects: Equivalent to: `return operator[](0);`

```cpp
constexpr const charT& back() const;  
constexpr charT& back();
```

Preconditions: `!empty()`. Effects: Equivalent to: `return operator[](size() - 1);`

23.4.3.7 Modifiers

23.4.3.7.1 basic_string::operator+=

```cpp
constexpr basic_string& operator+=(const basic_string& str);
```

Effects: Equivalent to: `return append(str);`

```cpp
template<class T>  
constexpr basic_string& operator+=(const T& t);
```

Effects: Equivalent to: `basic_string_view<charT, traits> sv = t; return append(sv);`

```cpp
constexpr basic_string& operator+=(const charT* s);
```

Effects: Equivalent to: `return append(s);`
constexpr basic_string& operator+=(charT c);
Effects: Equivalent to: return append(size_type{1}, c);

constexpr basic_string& operator+=(initializer_list<charT> il);
Effects: Equivalent to:
return append(il);

23.4.3.7.2 basic_string::append
[string.append]

constexpr basic_string& append(const basic_string& str);
Effects: Equivalent to: return append(str.data(), str.size());

constexpr basic_string& append(const basic_string& str, size_type pos, size_type n = npos);
Effects: Equivalent to:
return append(basic_string_view<charT, traits>(str).substr(pos, n));

template<class T>
constexpr basic_string& append(const T& t);
Constraints:
(3.1) is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(3.2) is_convertible_v<const T&, const charT*> is false.
Effects: Equivalent to:
basic_string_view<charT, traits> sv = t;
return append(sv.data(), sv.size());

template<class T>
constexpr basic_string& append(const T& t, size_type pos, size_type n = npos);
Constraints:
(5.1) is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(5.2) is_convertible_v<const T&, const charT*> is false.
Effects: Equivalent to:
basic_string_view<charT, traits> sv = t;
return append(sv.substr(pos, n));

constexpr basic_string& append(const charT* s, size_type n);
Preconditions: [s, s + n) is a valid range.
Effects: Appends a copy of the range [s, s + n) to the string.
Returns: *this.

constexpr basic_string& append(const charT* s);
Effects: Equivalent to: return append(s, traits::length(s));

constexpr basic_string& append(size_type n, charT c);
Effects: Appends n copies of c to the string.
Returns: *this.

template<class InputIterator>
constexpr basic_string& append(InputIterator first, InputIterator last);
Constraints: InputIterator is a type that qualifies as an input iterator (24.2.2.2).
Effects: Equivalent to: return append(basic_string(first, last, get_allocator()));

template<container-compatible-range<charT> R>
constexpr basic_string& append_range(R&& rg);
Effects: Equivalent to: return append(basic_string(from_range, std::forward<R>(rg), get_allocator()));
constexpr basic_string& append(initializer_list<charT> il);

Effects: Equivalent to: return append(il.begin(), il.size());

constexpr void push_back(charT c);

Effects: Equivalent to: append(size_type{1}, c).

§ 23.4.3.7.3 basic_string::assign

constexpr basic_string& assign(const basic_string& str);

Effects: Equivalent to: return *this = str;

constexpr basic_string& assign(basic_string&& str)

noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
 allocator_traits<Allocator>::is_always_equal::value);

Effects: Equivalent to: return *this = std::move(str);

constexpr basic_string& assign(const basic_string& str, size_type pos, size_type n = npos);

Effects: Equivalent to:

return assign(basic_string_view<charT, traits>(str).substr(pos, n));

template<class T>
constexpr basic_string& assign(const T& t);

Constraints:

— is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
— is_convertible_v<const T&, const charT*> is false.

Effects: Equivalent to:

basic_string_view<charT, traits> sv = t;
return assign(sv.data(), sv.size());

template<class T>
constexpr basic_string& assign(const T& t, size_type pos, size_type n = npos);

Constraints:

— is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
— is_convertible_v<const T&, const charT*> is false.

Effects: Equivalent to:

basic_string_view<charT, traits> sv = t;
return assign(sv.substr(pos, n));

constexpr basic_string& assign(const charT* s, size_type n);

Preconditions: [s, s + n) is a valid range.

Effects: Replaces the string controlled by *this with a copy of the range [s, s + n).

Returns: *this.

constexpr basic_string& assign(const charT* s);

Effects: Equivalent to: return assign(s, traits::length(s));

constexpr basic_string& assign(initializer_list<charT> il);

Effects: Equivalent to: return assign(il.begin(), il.size());

constexpr basic_string& assign(size_type n, charT c);

Effects: Equivalent to:

clear();
resize(n, c);
return *this;
template<class InputIterator>
constexpr basic_string& assign(InputIterator first, InputIterator last);

Constraints: InputIterator is a type that qualifies as an input iterator (24.2.2.2).

Effects: Equivalent to: return assign(basic_string(first, last, get_allocator()));

template<container-compatible-range<charT> R>
constexpr basic_string& assign_range(R&& rg);

Effects: Equivalent to: return assign(basic_string(from_range, std::forward<R>(rg), get_allocator()));

23.4.3.7.4 basic_string::insert

constexpr basic_string& insert(size_type pos, const basic_string& str);

Effects: Equivalent to: return insert(pos, str.data(), str.size());

constexpr basic_string& insert(size_type pos1, const basic_string& str,
    size_type pos2, size_type n = npos);

Effects: Equivalent to:
    return insert(pos1, basic_string_view<charT, traits>(str), pos2, n);

template<class T>
constexpr basic_string& insert(size_type pos, const T& t);

Constraints:
(3.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(3.2) — is_convertible_v<const T&, const charT*> is false.

Effects: Equivalent to:
    basic_string_view<charT, traits> sv = t;
    return insert(pos, sv.data(), sv.size());

template<class T>
constexpr basic_string& insert(size_type pos1, const T& t,
    size_type pos2, size_type n = npos);

Constraints:
(5.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(5.2) — is_convertible_v<const T&, const charT*> is false.

Effects: Equivalent to:
    basic_string_view<charT, traits> sv = t;
    return insert(pos1, sv.substr(pos2, n));

constexpr basic_string& insert(size_type pos, const charT* s, size_type n);

Preconditions: [s, s + n] is a valid range.

Effects: Inserts a copy of the range [s, s + n] immediately before the character at position pos if pos < size(), or otherwise at the end of the string.

Returns: *this.

Throws:
(10.1) — out_of_range if pos > size(),
(10.2) — length_error if n > max_size() - size(), or
(10.3) — any exceptions thrown by allocator_traits<Allocator>::allocate.

constexpr basic_string& insert(size_type pos, const charT* s);

Effects: Equivalent to: return insert(pos, s, traits::length(s));
constexpr basic_string& insert(size_type pos, size_type n, charT c);

Effects: Inserts n copies of c before the character at position pos if pos < size(), or otherwise at the end of the string.

Returns: *this

Throws:
(14.1) — out_of_range if pos > size(),
(14.2) — length_error if n > max_size() - size(), or
(14.3) — any exceptions thrown by allocator_traits<Allocator>::allocate.

constexpr iterator insert(const_iterator p, charT c);

Preconditions: p is a valid iterator on *this.
Effects: Inserts a copy of c at the position p.
Returns: An iterator which refers to the inserted character.

constexpr iterator insert(const_iterator p, size_type n, charT c);

Preconditions: p is a valid iterator on *this.
Effects: Inserts n copies of c at the position p.
Returns: An iterator which refers to the first inserted character, or p if n == 0.

template<class InputIterator>
constexpr iterator insert(const_iterator p, InputIterator first, InputIterator last);

Constraints: InputIterator is a type that qualifies as an input iterator (24.2.2.2).
Preconditions: p is a valid iterator on *this.
Effects: Equivalent to insert(p - begin(), basic_string(first, last, get_allocator())).
Returns: An iterator which refers to the first inserted character, or p if first == last.

template<container-compatible-range<charT> R>
constexpr iterator insert_range(const_iterator p, R&& rg);

Preconditions: p is a valid iterator on *this.
Effects: Equivalent to insert(p - begin(), basic_string(from_range, std::forward<R>(rg), get_allocator())).
Returns: An iterator which refers to the first inserted character, or p if rg is empty.

constexpr iterator insert(const_iterator p, initializer_list<charT> il);

Effects: Equivalent to: return insert(p, il.begin(), il.end());

23.4.3.7.5 basic_string::erase

constexpr basic_string& erase(size_type pos = 0, size_type n = npos);

Effects: Determines the effective length xlen of the string to be removed as the smaller of n and size() - pos. Removes the characters in the range [begin() + pos, begin() + pos + xlen).

Returns: *this.

Throws: out_of_range if pos > size().

constexpr iterator erase(const_iterator p);

Preconditions: p is a valid dereferenceable iterator on *this.
Effects: Removes the character referred to by p.
Returns: An iterator which points to the element immediately following p prior to the element being erased. If no such element exists, end() is returned.

Throws: Nothing.


```cpp
constexpr iterator erase(const_iterator first, const_iterator last);

**Preconditions:** first and last are valid iterators on *this. [first, last) is a valid range.

**Effects:** Removes the characters in the range [first, last).

**Returns:** An iterator which points to the element pointed to by last prior to the other elements being erased. If no such element exists, end() is returned.

**Throws:** Nothing.

```cpp
c constexpr void pop_back();

**Preconditions:** !empty().

**Effects:** Equivalent to erase(end() - 1).

**Throws:** Nothing.

### 23.4.3.7.6 basic_string::replace

```cpp
constexpr basic_string& replace(size_type pos1, size_type n1, const basic_string& str);

**Effects:** Equivalent to: return replace(pos1, n1, str.data(), str.size());

```cpp
c constexpr basic_string& replace(size_type pos1, size_type n1, const basic_string& str, size_type pos2, size_type n2 = npos);

**Effects:** Equivalent to:

- return replace(pos1, n1, basic_string_view<charT, traits>(str).substr(pos2, n2));

```cpp
template<class T>
c constexpr basic_string& replace(size_type pos1, size_type n1, const T& t);

**Constraints:**

- (3.1) is_convertible_v<const T&., basic_string_view<charT, traits>> is true and
- (3.2) is_convertible_v<const T&., const charT*> is false.

**Effects:** Equivalent to:

- basic_string_view<charT, traits> sv = t;
- return replace(pos1, n1, sv.data(), sv.size());

```cpp
template<class T>
c constexpr basic_string& replace(size_type pos1, size_type n1, const T& t, size_type pos2, size_type n2 = npos);

**Constraints:**

- (5.1) is_convertible_v<const T&., basic_string_view<charT, traits>> is true and
- (5.2) is_convertible_v<const T&., const charT*> is false.

**Effects:** Equivalent to:

- basic_string_view<charT, traits> sv = t;
- return replace(pos1, n1, sv.substr(pos2, n2));

```cpp
c constexpr basic_string& replace(size_type pos1, size_type n1, const charT* s, size_type n2);

**Preconditions:** [s, s + n2) is a valid range.

**Effects:** Determines the effective length xlen of the string to be removed as the smaller of n1 and size() - pos1. If size() - xlen >= max_size() - n2 throws length_error. Otherwise, the function replaces the characters in the range [begin() + pos1, begin() + pos1 + xlen) with a copy of the range [s, s + n2).

**Returns:** *this.

**Throws:**

- (10.1) out_of_range if pos1 > size(),
- (10.2) length_error if the length of the resulting string would exceed max_size(), or
- (10.3) any exceptions thrown by allocator_traits<Allocator>::allocate.

§ 23.4.3.7.6 ©ISO/IEC 890
constexpr basic_string& replace(size_type pos, size_type n, const charT* s);
11  Effects: Equivalent to: return replace(pos, n, s, traits::length(s));

constexpr basic_string& replace(size_type pos1, size_type n1, size_type n2, charT c);
12  Effects: Determines the effective length xlen of the string to be removed as the smaller of n1 and size() - pos1. If size() - xlen >= max_size() - n2 throws length_error. Otherwise, the function replaces the characters in the range [begin() + pos1, begin() + pos1 + xlen) with n2 copies of c.
13  Returns: *this.
14  Throws:
(14.1)  out_of_range if pos1 > size(),
(14.2)  length_error if the length of the resulting string would exceed max_size(), or
(14.3)  any exceptions thrown by allocator_traits<Allocator>::allocate.

constexpr basic_string& replace(const_iterator i1, const_iterator i2, const basic_string& str);
15  Effects: Equivalent to: return replace(i1, i2, basic_string_view<charT, traits>(str));

template<class T>
constexpr basic_string& replace(const_iterator i1, const_iterator i2, const T& t);
16  Constraints:
(16.1)  is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(16.2)  is_convertible_v<const T&, const charT*> is false.
17  Preconditions: [begin(), i1) and [i1, i2) are valid ranges.
18  Effects: Equivalent to:
  basic_string_view<charT, traits> sv = t;
  return replace(i1 - begin(), i2 - i1, sv.data(), sv.size());

constexpr basic_string& replace(const_iterator i1, const_iterator i2, const charT* s, size_type n);
19  Effects: Equivalent to: return replace(i1, i2, basic_string_view<charT, traits>(s, n));

constexpr basic_string& replace(const_iterator i1, const_iterator i2, const charT* s);
20  Effects: Equivalent to: return replace(i1, i2, basic_string_view<charT, traits>(s));

constexpr basic_string& replace(const_iterator i1, const_iterator i2, const_iterator i1, const_iterator i2, const basic_string& str);
21  Effects: Equivalent to: return replace(i1, i2, basic_string_view<charT, traits>(str));

template<container-compatible-range<charT> R>
constexpr basic_string& replace_with_range(const_iterator i1, const_iterator i2, R&& rg);
22  Effects: Equivalent to:
  return replace(i1, i2, basic_string(from_range, std::forward<R>(rg), get_allocator()));

23.4.3.7.7 basic_string::copy
23  [string.copy]
constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;
23  Effects: Equivalent to: return basic_string_view<charT, traits>(*this).copy(s, n, pos);

§ 23.4.3.7.7 ©ISO/IEC 891
23.4.3.7.8 basic_string::swap

```cpp
constexpr void swap(basic_string& s)
    noexcept(allocator_traits<Allocator>::propagate_on_container_swap::value ||
                allocator_traits<Allocator>::is_always_equal::value);
```

**Preconditions:**
- `allocator_traits<Allocator>::propagate_on_container_swap::value` is true or `get_allocator() == s.get_allocator()`.

**Postconditions:**
- `*this` contains the same sequence of characters that was in `s`, `s` contains the same
  sequence of characters that was in `*this`.

**Throws:** Nothing.

**Complexity:** Constant time.

23.4.3.8 String operations

23.4.3.8.1 Accessors

```cpp
constexpr const charT* c_str() const noexcept;
constexpr const charT* data() const noexcept;
```

**Returns:**
- A pointer `p` such that `p + i == addressof(operator[](i))` for each `i` in `[0, size()]`.

**Complexity:** Constant time.

**Remarks:** The program shall not modify any of the values stored in the character array; otherwise, the
behavior is undefined.

```cpp
constexpr charT* data() noexcept;
```

**Returns:**
- A pointer `p` such that `p + i == addressof(operator[](i))` for each `i` in `[0, size()]`.

**Complexity:** Constant time.

**Remarks:** The program shall not modify the value stored at `p + size()` to any value other than
`charT();` otherwise, the behavior is undefined.

```cpp
constexpr operator basic_string_view<charT, traits>() const noexcept;
```

**Effects:** Equivalent to:
- `return basic_string_view<charT, traits>(data(), size());`;

```cpp
constexpr allocator_type get_allocator() const noexcept;
```

**Returns:** A copy of the `Allocator` object used to construct the string or, if that allocator has been
replaced, a copy of the most recent replacement.

23.4.3.8.2 Searching

Let `F` be one of `find`, `rfind`, `find_first_of`, `find_last_of`, `find_first_not_of`, and `find_last_not_of`.

1. Each member function of the form
   ```cpp
   constexpr size_type F(const basic_string& str, size_type pos) const noexcept;
   ```
   has effects equivalent to:
   ```cpp
   return F(basic_string_view<charT, traits>(str), pos);
   ```

2. Each member function of the form
   ```cpp
   constexpr size_type F(const charT* s, size_type pos) const;
   ```
   has effects equivalent to:
   ```cpp
   return F(basic_string_view<charT, traits>(s), pos);
   ```

3. Each member function of the form
   ```cpp
   constexpr size_type F(const charT* s, size_type pos, size_type n) const;
   ```
   has effects equivalent to:
   ```cpp
   return F(basic_string_view<charT, traits>(s, n), pos);
   ```

4. Each member function of the form
   ```cpp
   constexpr size_type F(charT c, size_type pos) const noexcept;
   ```
   has effects equivalent to:
   ```cpp
   return F(basic_string_view<charT, traits>(addressof(c), 1), pos);
   ```
template<class T>
    constexpr size_type find(const T& t, size_type pos = 0) const noexcept;
    constexpr size_type rfind(const T& t, size_type pos = npos) const noexcept;
    constexpr size_type find_first_of(const T& t, size_type pos = 0) const noexcept;
    constexpr size_type find_last_of(const T& t, size_type pos = npos) const noexcept;
    constexpr size_type find_first_not_of(const T& t, size_type pos = 0) const noexcept;
    constexpr size_type find_last_not_of(const T& t, size_type pos = npos) const noexcept;

2 Constraints:
(2.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true
(2.2) — is_convertible_v<const T&, const charT*> is false.

3 Effects: Let \( G \) be the name of the function. Equivalent to:

\[
\text{basic_string_view<charT, traits> s = *this, sv = t; return s.}G(\text{sv, pos});
\]

4 Remarks: The exception specification is equivalent to is_nothrow_convertible_v<const T&, basic_string_view<charT, traits>>.

23.4.3.8.3 basic_string::substr

constexpr basic_string substr(size_type pos = 0, size_type n = npos) const &;

Effects: Equivalent to:

\[
\text{return basic_string(*this, pos, n);}
\]

constexpr basic_string substr(size_type pos = 0, size_type n = npos) &&;

Effects: Equivalent to:

\[
\text{return basic_string(std::move(*this), pos, n);}
\]

23.4.3.8.4 basic_string::compare

template<class T>
    constexpr int compare(const T& t) const noexcept;

1 Constraints:
(1.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(1.2) — is_convertible_v<const T&, const charT*> is false.

2 Effects: Equivalent to:

\[
\text{return basic_string_view<charT, traits>(*this).compare(t);}\]

3 Remarks: The exception specification is equivalent to is_nothrow_convertible_v<const T&, basic_string_view<charT, traits>>.

template<class T>
    constexpr int compare(size_type pos1, size_type n1, const T& t) const;

4 Constraints:
(4.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(4.2) — is_convertible_v<const T&, const charT*> is false.

5 Effects: Equivalent to:

\[
\text{return basic_string_view<charT, traits>(*this).substr(pos1, n1).compare(t);}
\]

template<class T>
    constexpr int compare(size_type pos1, size_type n1, const T& t, size_type pos2, size_type n2 = npos) const;

6 Constraints:
(6.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(6.2) — is_convertible_v<const T&, const charT*> is false.
Effects: Equivalent to:

\[
\text{basic_string\_view<charT, traits> } s = *\text{this, } sv = t;
\text{return } s.\text{substr}(\text{pos}, n).\text{compare}(sv.\text{substr}(\text{pos2}, n2));
\]

Effects: Equivalent to: return \text{compare(basic_string\_view<charT, traits>(str));}

Effects: Equivalent to: return \text{compare(size_type pos1, size_type n1, const basic_string& str) const;}

Effects: Equivalent to: return \text{compare(pos1, n1, basic_string\_view<charT, traits>(str));}

Effects: Equivalent to: return \text{compare(size_type pos1, size_type n1, const basic_string& str, size_type pos2, size_type n2 = npos) const;}

Effects: Equivalent to: return \text{compare(pos1, n1, basic_string\_view<charT, traits>(str), pos2, n2);}

Effects: Equivalent to: return \text{compare(const charT* s) const;}

Effects: Equivalent to: return \text{compare(basic_string\_view<charT, traits>(s));}

Effects: Equivalent to: return \text{compare(pos, n1, basic_string\_view<charT, traits>(s));}

Effects: Equivalent to: return \text{compare(size_type pos, size_type n1, const charT* s, size_type n2) const;}

Effects: Equivalent to: return \text{compare(pos, n1, basic_string\_view<charT, traits>(s), pos2, n2);}

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{starts\_with}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{ends\_with}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{contains}(x);
\]

effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{starts\_with}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{ends\_with}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{contains}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{starts\_with}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{ends\_with}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{contains}(x);
\]

Effects: Equivalent to:

\[
\text{return basic_string\_view<charT, traits>}(data(), size()).\text{starts\_with}(x);
\]
basic_string<
charT,
traits,
Allocator>
r = lhs;
r.append(rhs);
return r;

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(basic_string<
charT,
traits,
Allocator>&& lhs,
const basic_string<
charT,
traits,
Allocator>& rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(basic_string<
charT,
traits,
Allocator>&& lhs, const charT* rhs);

Effects: Equivalent to:

lhs.append(rhs);
return std::move(lhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(const basic_string<
charT,
traits,
Allocator>& lhs,
basic_string<
charT,
traits,
Allocator>&& rhs);

Effects: Equivalent to:

lhs.append(rhs);
return std::move(lhs);

except that both lhs and rhs are left in valid but unspecified states.

[Note 1: If lhs and rhs have equal allocators, the implementation can move from either. —end note]

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(const charT* lhs, basic_string<
charT,
traits,
Allocator>&& rhs);

Effects: Equivalent to:

rhs.insert(0, lhs);
return std::move(rhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(const charT* lhs, const basic_string<
charT,
traits,
Allocator>& rhs);

Effects: Equivalent to:

basic_string<
charT,
traits,
Allocator> r = rhs;
r.insert(0, lhs);
return r;

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(charT lhs, const basic_string<
charT,
traits,
Allocator>& rhs);

Effects: Equivalent to:

basic_string<
charT,
traits,
Allocator> r = rhs;
r.insert(r.begin(), lhs);
return r;

template<class charT, class traits, class Allocator>
constexpr basic_string<
charT,
traits,
Allocator>
operator+(charT lhs, basic_string<
charT,
traits,
Allocator>&& rhs);

Effects: Equivalent to:

rhs.insert(rhs.begin(), lhs);
return std::move(rhs);
template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(const basic_string<charT, traits, Allocator>& lhs, charT rhs);

Effects: Equivalent to:
basic_string<charT, traits, Allocator> r = lhs;
r.push_back(rhs);
return r;

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(basic_string<charT, traits, Allocator>&& lhs, charT rhs);

Effects: Equivalent to:
lhs.push_back(rhs);
return std::move(lhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(const basic_string<charT, traits, Allocator>& lhs, type_identity_t<basic_string_view<charT, traits>> rhs);

Equivalent to:
basic_string<charT, traits, Allocator> r = lhs;
r.append(rhs);
return r;

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(basic_string<charT, traits, Allocator>&& lhs, type_identity_t<basic_string_view<charT, traits>> rhs);

Equivalent to:
lhs.append(rhs);
return std::move(lhs);

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(type_identity_t<basic_string_view<charT, traits>> lhs, const basic_string<charT, traits, Allocator>& rhs);

Equivalent to:
basic_string<charT, traits, Allocator> r = rhs;
r.insert(0, lhs);
return r;

template<class charT, class traits, class Allocator>
constexpr basic_string<charT, traits, Allocator>
operator+(type_identity_t<basic_string_view<charT, traits>> lhs, basic_string<charT, traits, Allocator>&& rhs);

Equivalent to:
rhs.insert(0, lhs);
return std::move(rhs);

[Note 2: Using a specialization of type_identity_t as a parameter type ensures that an object of type basic_string<charT, traits, Allocator> can be concatenated with an object of a type T having an implicit conversion to basic_string_view<charT, traits> (12.2.2.3). —end note]

23.4.4.2 Non-member comparison operator functions [string.cmp]

template<class charT, class traits, class Allocator>
constexpr bool
operator==(const basic_string<charT, traits, Allocator>& lhs, const basic_string<charT, traits, Allocator>& rhs) noexcept;
template<class charT, class traits, class Allocator>
constexpr bool operator==(const basic_string<charT, traits, Allocator>& lhs,
const charT* rhs);

template<class charT, class traits, class Allocator>
constexpr
see below
operator<=>(const basic_string<charT, traits, Allocator>& lhs,
const charT* rhs);

Effects: Let \( \text{op} \) be the operator. Equivalent to:
\[
\text{return basic_string_view<charT, traits>(lhs) \text{ op } basic_string_view<charT, traits>(rhs);}\
\]

23.4.4.3 swap

template<class charT, class traits, class Allocator>
constexpr
see below
operator<=>(const basic_string<charT, traits, Allocator>& lhs,
const basic_string<charT, traits, Allocator>& rhs) noexcept;

Effects: Equivalent to \( \text{lhs} . \text{swap}(\text{rhs}) \).

23.4.4.4 Inserters and extractors

template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>&& is, basic_string<charT, traits, Allocator>& str);

Effects: Behaves as a formatted input function (31.7.5.3.1). After constructing a \text{sentry} object, if the \text{sentry} object returns \text{true} when converted to a value of type \text{bool}, calls \text{str.erase()} and then extracts characters from \text{is} and appends them to \text{str} as if by calling \text{str.append}(1, c). If \text{is.width()} is greater than zero, the maximum number \( n \) of characters appended is \text{is.width()}; otherwise \( n \) is \text{str.max_size()}. Characters are extracted and appended until any of the following occurs:

1. \( n \) characters are stored;
2. end-of-file occurs on the input sequence;
3. \( \text{isspace}(c, \text{is.getloc()}) \) is \text{true} for the next available input character \( c \).

After the last character (if any) is extracted, \text{is.width}(0) is called and the \text{sentry} object is destroyed.

If the function extracts no characters, \text{ios_base::failbit} is set in the input function’s local error state before \text{setstate} is called.

Returns: \text{is}.

5

Effects: Equivalent to: \text{return os} \text{ << basic_string_view<charT, traits>(str);}\

template<class charT, class traits, class Allocator>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os,
const basic_string<charT, traits, Allocator>& str);

Effects: Behaves as an unformatted input function (31.7.5.4), except that it does not affect the value returned by subsequent calls to \text{basic_istream<>::gcount()}. After constructing a \text{sentry} object, if the \text{sentry} object returns \text{true} when converted to a value of type \text{bool}, calls \text{str.erase()} and then

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extracts characters from is and appends them to str as if by calling `str.append(1, c)` until any of the following occurs:

- end-of-file occurs on the input sequence;
- `traits::eq(c, delim)` for the next available input character c (in which case, c is extracted but not appended);
- `str.max_size()` characters are stored (in which case, `ios_base::failbit` is set in the input function’s local error state).

The conditions are tested in the order shown. In any case, after the last character is extracted, the sentry object is destroyed.

If the function extracts no characters, `ios_base::failbit` is set in the input function’s local error state before `setstate` is called.

Returns: is.

```cpp
template<class charT, class traits, class Allocator>
basic_istream<charT, traits>&
getline(basic_istream<charT, traits>& is,
basic_string<charT, traits, Allocator>& str);
```

Returns: `getline(is, str, is.widen(’\n’))`.

### 23.4.4.5 Erasure

```cpp
template<class charT, class traits, class Allocator, class U = charT>
constexpr typename basic_string<charT, traits, Allocator>::size_type
erase(basic_string<charT, traits, Allocator>& c, const U& value);
```

Effects: Equivalent to:

```cpp
auto it = remove(c.begin(), c.end(), value);
auto r = distance(it, c.end());
c.erase(it, c.end());
return r;
```

```cpp
template<class charT, class traits, class Allocator, class Predicate>
constexpr typename basic_string<charT, traits, Allocator>::size_type
erase_if(basic_string<charT, traits, Allocator>& c, Predicate pred);
```

Effects: Equivalent to:

```cpp
auto it = remove_if(c.begin(), c.end(), pred);
auto r = distance(it, c.end());
c.erase(it, c.end());
return r;
```

### 23.4.5 Numeric conversions

```cpp
int stoi(const string& str, size_t* idx = nullptr, int base = 10);
long stol(const string& str, size_t* idx = nullptr, int base = 10);
unsigned long stoul(const string& str, size_t* idx = nullptr, int base = 10);
long long stoll(const string& str, size_t* idx = nullptr, int base = 10);
unsigned long long stoull(const string& str, size_t* idx = nullptr, int base = 10);
```

Effects: The first two functions call `strtol(str.c_str(), ptr, base)`, and the last three functions call `strtoul(str.c_str(), ptr, base)`, `strtol(str.c_str(), ptr, base)`, and `strtoull(str.c_str(), ptr, base)`, respectively. Each function returns the converted result, if any. The argument `ptr` designates a pointer to an object internal to the function that is used to determine what to store at `*idx`. If the function does not throw an exception and `idx` != `nullptr`, the function stores in `*idx` the index of the first unconverted element of `str`.

Returns: The converted result.
Throws: invalid_argument if `strtol`, `strtoul`, `strtoll`, or `strtoull` reports that no conversion can be performed. Throws out_of_range if `strtol`, `strtoul`, `strtoll` or `strtoull` sets `errno` to ERANGE, or if the converted value is outside the range of representable values for the return type.

```cpp
float stof(const string& str, size_t* idx = nullptr);
double stod(const string& str, size_t* idx = nullptr);
long double stold(const string& str, size_t* idx = nullptr);
```

Effects: These functions call `strtof(str.c_str(), ptr)`, `strtod(str.c_str(), ptr)`, and `stold(str.c_str(), ptr)`, respectively. Each function returns the converted result, if any. The argument `ptr` designates a pointer to an object internal to the function that is used to determine what to store at `*idx`. If the function does not throw an exception and `idx != nullptr`, the function stores in `*idx` the index of the first unconverted element of `str`.

Returns: The converted result.

Throws: invalid_argument if `strtof`, `strtod`, or `stold` reports that no conversion can be performed. Throws out_of_range if `strtof`, `strtod`, or `stold` sets `errno` to ERANGE or if the converted value is outside the range of representable values for the return type.

```cpp
string to_string(int val);
string to_string(unsigned val);
string to_string(long val);
string to_string(unsigned long val);
string to_string(long long val);
string to_string(float val);
string to_string(double val);
```

Returns: `format("{0}", val)`.

```cpp
int stoi(const wstring& str, size_t* idx = nullptr, int base = 10);
long stol(const wstring& str, size_t* idx = nullptr, int base = 10);
unsigned long stoul(const wstring& str, size_t* idx = nullptr, int base = 10);
long long stoll(const wstring& str, size_t* idx = nullptr, int base = 10);
unsigned long long stoull(const wstring& str, size_t* idx = nullptr, int base = 10);
```

Effects: The first two functions call `wcstol(str.c_str(), ptr, base)`, and the last three functions call `wcstoul(str.c_str(), ptr, base)`, `wcstoll(str.c_str(), ptr, base)`, and `wcstoull(str.c_str(), ptr, base)`, respectively. Each function returns the converted result, if any. The argument `ptr` designates a pointer to an object internal to the function that is used to determine what to store at `*idx`. If the function does not throw an exception and `idx != nullptr`, the function stores in `*idx` the index of the first unconverted element of `str`.

Returns: The converted result.

Throws: invalid_argument if `wcstol`, `wcstoul`, `wcstoll`, or `wcstoull` reports that no conversion can be performed. Throws out_of_range if the converted value is outside the range of representable values for the return type.

```cpp
float stof(const wstring& str, size_t* idx = nullptr);
double stod(const wstring& str, size_t* idx = nullptr);
long double stold(const wstring& str, size_t* idx = nullptr);
```

Effects: These functions call `wcstof(str.c_str(), ptr)`, `wcstod(str.c_str(), ptr)`, and `wcstold(str.c_str(), ptr)`, respectively. Each function returns the converted result, if any. The argument `ptr` designates a pointer to an object internal to the function that is used to determine what to store at `*idx`. If the function does not throw an exception and `idx != nullptr`, the function stores in `*idx` the index of the first unconverted element of `str`.

Returns: The converted result.

Throws: invalid_argument if `wcstof`, `wcstod`, or `wcstold` reports that no conversion can be performed. Throws out_of_range if `wcstof`, `wcstod`, or `wcstold` sets `errno` to ERANGE.
wstring to_wstring(long val);
wstring to_wstring(unsigned long val);
wstring to_wstring(long long val);
wstring to_wstring(unsigned long long val);
wstring to_wstring(float val);
wstring to_wstring(double val);
wstring to_wstring(long double val);

Returns: format(L"{}", val).

23.4.6 Hash support

template<class A> struct hash<basic_string<char, char_traits<char>, A>>;
template<class A> struct hash<basic_string<char8_t, char_traits<char8_t>, A>>;
template<class A> struct hash<basic_string<char16_t, char_traits<char16_t>, A>>;
template<class A> struct hash<basic_string<char32_t, char_traits<char32_t>, A>>;
template<class A> struct hash<basic_string<wchar_t, char_traits<wchar_t>, A>>;

1 If S is one of these string types, SV is the corresponding string view type, and s is an object of type S, then hash<S>()(s) == hash<SV>()(SV(s)).

23.4.7 Suffix for basic_string literals

constexpr string operator"s(const char* str, size_t len);

1 Returns: string{str, len}.

constexpr u8string operator"s(const char8_t* str, size_t len);

2 Returns: u8string{str, len}.

constexpr u16string operator"s(const char16_t* str, size_t len);

3 Returns: u16string{str, len}.

constexpr u32string operator"s(const char32_t* str, size_t len);

4 Returns: u32string{str, len}.

constexpr wstring operator"s(const wchar_t* str, size_t len);

5 Returns: wstring{str, len}.

6 [Note 1: The same suffix s is used for chrono::duration literals denoting seconds but there is no conflict, since duration suffixes apply to numbers and string literal suffixes apply to character array literals. — end note]

23.5 Null-terminated sequence utilities

23.5.1 Header <cctype> synopsis

namespace std {
    int isalnum(int c);
    int isalpha(int c);
    int isblank(int c);
    int iscntrl(int c);
    int isdigit(int c);
    int isgraph(int c);
    int islower(int c);
    int isprint(int c);
    int ispunct(int c);
    int isspace(int c);
    int isupper(int c);
    int isxdigit(int c);
    int tolower(int c);
    int toupper(int c);
}

1 The contents and meaning of the header <cctype> are the same as the C standard library header <ctype.h>. See also: ISO/IEC 9899:2018, 7.4
23.5.2 Header `<cwctype>` synopsis

```cpp
namespace std {
    using wint_t = see below;
    using wctrans_t = see below;
    using wctype_t = see below;

    int iswalnum(wint_t wc);
    int iswalpha(wint_t wc);
    int iswblank(wint_t wc);
    int iswcntrl(wint_t wc);
    int iswdigit(wint_t wc);
    int iswgraph(wint_t wc);
    int iswlower(wint_t wc);
    int iswprint(wint_t wc);
    int iswpunct(wint_t wc);
    int iswspace(wint_t wc);
    int iswupper(wint_t wc);
    int iswxdigit(wint_t wc);
    wctype_t wctype(const char* property);
    wint_t towlower(wint_t wc);
    wint_t towupper(wint_t wc);
    wint_t towctrans(wint_t wc, wctrans_t desc);
    wctrans_t wctrans(const char* property);
}
```

#define WEOF see below

1 The contents and meaning of the header `<cwctype>` are the same as the C standard library header `<wctype.h>`.

See also: ISO/IEC 9899:2018, 7.30

23.5.3 Header `<cstring>` synopsis

```cpp
namespace std {
    using size_t = see 17.2.4;

    void* memcpy(void* s1, const void* s2, size_t n);
    char* strcpy(char* s1, const char* s2);
    char* strncpy(char* s1, const char* s2, size_t n);
    char* strcat(char* s1, const char* s2);
    int memcmp(const void* s1, const void* s2, size_t n);
    int strcmp(const char* s1, const char* s2);
    int strcoll(const char* s1, const char* s2);
    int strcspn(const char* s1, const char* s2, size_t n);
    const char* strpbrk(const char* s1, const char* s2);
    char* strchr(const char* s, int c);
    size_t strspn(const char* s1, const char* s2);
    const char* strstr(const char* s1, const char* s2);
    char* strtok(char* s1, const char* s2);
    void* memset(void* s, int c, size_t n);
    char* strerror(int errnum);
    size_t strlen(const char* s);
}
```

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#define NULL see 17.2.3 // freestanding

1 The contents and meaning of the header `<cstring>` are the same as the C standard library header `<string.h>.

2 The functions `strerror` and `strtok` are not required to avoid data races (16.4.6.10).

3 The functions `memcpy` and `memmove` are signal-safe (17.13.5). Both functions implicitly create objects (6.7.2) in the destination region of storage immediately prior to copying the sequence of characters to the destination.

4 [Note 1: The functions `strchr`, `strpbrk`, `strrchr`, `strstr`, and `memchr`, have different signatures in this document, but they have the same behavior as in the C standard library (16.2). — end note]

See also: ISO/IEC 9899:2018, 7.24

23.5.4 Header `<cwchar>` synopsis [cwchar.syn]

namespace std {
    using size_t = see 17.2.4; // freestanding
    using mbstate_t = see below; // freestanding
    using wint_t = see below; // freestanding

    struct tm;

    int fwprintf(FILE* stream, const wchar_t* format, ...);
    int fwidth(FILE* stream, const wchar_t* format, ...);
    int swprintf(wchar_t* s, size_t n, const wchar_t* format, ...);
    int swscanf(const wchar_t* s, const wchar_t* format, va_list arg);
    int vfwprintf(FILE* stream, const wchar_t* format, va_list arg);
    int vfwscanf(FILE* stream, const wchar_t* format, va_list arg);
    int vswprintf(wchar_t* s, size_t n, const wchar_t* format, va_list arg);
    int vswscanf(const wchar_t* s, const wchar_t* format, va_list arg);
    int vfwprintf(const wchar_t* format, va_list arg);
    int vfwscanf(const wchar_t* format, va_list arg);
    int vswprintf(const wchar_t* format, va_list arg);
    int vswscanf(const wchar_t* format, va_list arg);
    int vfprintf(const wchar_t* format, va_list arg);
    int vscanf(const wchar_t* format, va_list arg);
    wchar_t* fgetwc(FILE* stream);
    wchar_t* fgetws(wchar_t* s, int n, FILE* stream);
    int fputwc(wchar_t c, FILE* stream);
    int fputws(const wchar_t* s, FILE* stream);
    int fwide(FILE* stream, int mode);
    wchar_t* getwc(FILE* stream);
    wchar_t* getwchar();
    int putwc(wchar_t c, FILE* stream);
    int putwchar(wchar_t c);
    wchar_t* ungetwc(wchar_t c, FILE* stream);
    double wcstod(const wchar_t* nptr, wchar_t** endptr);
    float wcstof(const wchar_t* nptr, wchar_t** endptr);
    long double wcstold(const wchar_t* nptr, wchar_t** endptr, int base);
    long int wcstol(const wchar_t* nptr, wchar_t** endptr, int base);
    unsigned long int wcstoul(const wchar_t* nptr, wchar_t** endptr, int base);
    unsigned long long int wcstoull(const wchar_t* nptr, wchar_t** endptr, int base);
    wchar_t* wcsncpy(wchar_t* s1, const wchar_t* s2);
    wchar_t* wcsncat(wchar_t* s1, const wchar_t* s2, size_t n);
    wchar_t* wcsncpy(const wchar_t* s1, const wchar_t* s2, size_t n);
    wchar_t* wmemmove(const wchar_t* s1, const wchar_t* s2, size_t n);
    wchar_t* wcscat(wchar_t* s1, const wchar_t* s2);
    wchar_t* wcsncat(const wchar_t* s1, const wchar_t* s2, size_t n);
    size_t wcsxfrm(const wchar_t* s1, const wchar_t* s2, size_t n);
    int wcscmp(const wchar_t* s1, const wchar_t* s2);
    int wcscmp(const wchar_t* s1, const wchar_t* s2, size_t n);
    int wcscmp(const wchar_t* s1, const wchar_t* s2, size_t n);
    int wcscmp(const wchar_t* s1, const wchar_t* s2, size_t n);
    const wchar_t* wcschr(const wchar_t* s, wchar_t c);
    const wchar_t* wcschr(const wchar_t* s, wchar_t c);
    const wchar_t* wcspbrk(const wchar_t* s1, const wchar_t* s2);
    const wchar_t* wcspbrk(const wchar_t* s1, const wchar_t* s2);
}

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902
```cpp
wchar_t* wcspbrk(wchar_t* s1, const wchar_t* s2);
// freestanding; see 16.2
const wchar_t* wcsrchr(const wchar_t* s, wchar_t c);
// freestanding; see 16.2
size_t wcsspn(const wchar_t* s1, const wchar_t* s2);
// freestanding
const wchar_t* wcsstr(const wchar_t* s1, const wchar_t* s2);
// freestanding; see 16.2
wchar_t* wcsstr(wchar_t* s1, const wchar_t* s2);
// freestanding; see 16.2
wchar_t* wcstok(wchar_t* s1, const wchar_t* s2, wchar_t** ptr);
// freestanding
const wchar_t* wmemchr(const wchar_t* s, wchar_t c, size_t n);
// freestanding; see 16.2
wchar_t* wmemchr(wchar_t* s, wchar_t c, size_t n);
// freestanding; see 16.2
size_t wcslen(const wchar_t* s);
// freestanding
wchar_t* wmemset(wchar_t* s, wchar_t c, size_t n);
// freestanding
size_t wcsftime(wchar_t* s, size_t maxsize, const wchar_t* format, const tm* timeptr);
wint_t btowc(int c);
int wctob(wint_t c);
```

1. The contents and meaning of the header `<cwchar>` are the same as the C standard library header `<wchar.h>`, except that it does not declare a type `wchar_t`.

2. [Note 1: The functions `wcschr`, `wcspbrk`, `wcsrchr`, `wcsstr`, and `wmemchr` have different signatures in this document, but they have the same behavior as in the C standard library (16.2). — end note]

---

### 23.5.5 Header `<cuchar>` synopsis

```cpp
namespace std {
    using mbstate_t = see below;
    using size_t = see 17.2.4;

    size_t mbbrtoc8(char8_t* pc8, const char* s, size_t n, mbstate_t* ps);
    size_t c8rtomb(char* s, char8_t c8, mbstate_t* ps);
    size_t mbbrtoc16(char16_t* pc16, const char* s, size_t n, mbstate_t* ps);
    size_t c16rtomb(char* s, char16_t c16, mbstate_t* ps);
    size_t mbbrtoc32(char32_t* pc32, const char* s, size_t n, mbstate_t* ps);
    size_t c32rtomb(char* s, char32_t c32, mbstate_t* ps);
}
```

1. The contents and meaning of the header `<cuchar>` are the same as the C standard library header `<uchar.h>`, except that it declares the additional `mbbrtoc8` and `c8rtomb` functions and does not declare types `char16_t` nor `char32_t`.

---

### 23.5.6 Multibyte / wide string and character conversion functions

1. [Note 1: The headers `<cstdlib>` (17.2.2), `<cuchar>` (23.5.5), and `<cwchar>` (23.5.4) declare the functions described in this subclause. — end note]

```cpp
int mbsinit(const mbstate_t* ps);
int mblen(const char* s, size_t n);
size_t mbstowcs(wchar_t* pwcs, const char* s, size_t n);
size_t wcstombs(char* s, const wchar_t* pwcs, size_t n);
```

2. **Effects:** These functions have the semantics specified in the C standard library.
**See also:** ISO/IEC 9899:2018, 7.22.7.1, 7.22.8, 7.29.6.2.1

```c
int mbtowc(wchar_t* pwc, const char* s, size_t n);
int wctomb(char* s, wchar_t wchar);
```

3. **Effects:** These functions have the semantics specified in the C standard library.

4. **Remarks:** Calls to these functions may introduce a data race (16.4.6.10) with other calls to the same function.

**See also:** ISO/IEC 9899:2018, 7.22.7

```c
size_t mbrlen(const char* s, size_t n, mbstate_t* ps);
size_t mbtowc(const char* s, wchar_t* pwc, size_t n, mbstate_t* ps);
size_t wcsrtowcs(const wchar_t* src, const char* dst, size_t len, mbstate_t* ps);
size_t mbsrtowcs(const char* src, size_t len, mbstate_t* ps);
```

5. **Effects:** These functions have the semantics specified in the C standard library.

6. **Remarks:** Calling these functions with an `mbstate_t*` argument that is a null pointer value may introduce a data race (16.4.6.10) with other calls to the same function with an `mbstate_t*` argument that is a null pointer value.

**See also:** ISO/IEC 9899:2018, 7.29.6.3

```c
size_t mbtowc8(char8_t* pc8, const char* s, size_t n, mbstate_t* ps);
```

7. **Effects:** If `s` is a null pointer, equivalent to `mbtowc8(nullptr, ",", 1, ps)`. Otherwise, the function inspects at most `n` bytes beginning with the byte pointed to by `s` to determine the number of bytes needed to complete the next multibyte character (including any shift sequences). If the function determines that the next multibyte character is complete and valid, it determines the values of the corresponding UTF-8 code units and then, if `pc8` is not a null pointer, stores the value of the first (or only) such code unit in the object pointed to by `pc8`. Subsequent calls will store successive UTF-8 code units without consuming any additional input until all the code units have been stored. If the corresponding Unicode character is \U0000 NULL, the resulting state described is the initial conversion state.

8. **Returns:** The first of the following that applies (given the current conversion state):

- (8.1) 0, if the next `n` or fewer bytes complete the multibyte character that corresponds to the \U0000 NULL Unicode character (which is the value stored).
- (8.2) between 1 and `n` (inclusive), if the next `n` or fewer bytes complete a valid multibyte character (whose first (or only) code unit is stored); the value returned is the number of bytes that complete the multibyte character.
- (8.3) `(size_t)(-3)`, if the next code unit resulting from a previous call has been stored (no bytes from the input have been consumed by this call).
- (8.4) `(size_t)(-2)`, if the next `n` bytes contribute to an incomplete (but potentially valid) multibyte character, and all `n` bytes have been processed (no value is stored).
- (8.5) `(size_t)(-1)`, if an encoding error occurs, in which case the next `n` or fewer bytes do not contribute to a complete and valid multibyte character (no value is stored); the value of the macro EILSEQ is stored in `errno`, and the conversion state is unspecified.

```c
size_t c8rtomb(char8_t* c8, const char* s, size_t n, mbstate_t* ps);
```

9. **Effects:** If `s` is a null pointer, equivalent to `c8rtomb(buf, u8'\0', ps)` where `buf` is an internal buffer. Otherwise, if `c8` completes a sequence of valid UTF-8 code units, determines the number of bytes needed to represent the multibyte character (including any shift sequences), and stores the multibyte character representation in the array whose first element is pointed to by `s`. At most MB_CUR_MAX bytes are stored. If the multibyte character is a null character, a null byte is stored, preceded by any shift sequence needed to restore the initial shift state; the resulting state described is the initial conversion state.

10. **Returns:** The number of bytes stored in the array object (including any shift sequences). If `c8` does not contribute to a sequence of `char8_t` corresponding to a valid multibyte character, the value of the macro EILSEQ is stored in `errno`, `(size_t)(-1)` is returned, and the conversion state is unspecified.
Remarks: Calls to `c8rtomb` with a null pointer argument for `s` may introduce a data race (16.4.6.10) with other calls to `c8rtomb` with a null pointer argument for `s`. 
24 Containers library

24.1 General

This Clause describes components that C++ programs may use to organize collections of information.

The following subclauses describe container requirements, and components for sequence containers and associative containers, as summarized in Table 85.

Table 85 — Containers library summary

<table>
<thead>
<tr>
<th>Subclause Header</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.2 Requirements</td>
<td></td>
</tr>
<tr>
<td>24.3 Sequence containers</td>
<td>&lt;array&gt;, &lt;deque&gt;, &lt;forward_list&gt;, &lt;inplace_vector&gt;, &lt;list&gt;, &lt;vector&gt;</td>
</tr>
<tr>
<td>24.4 Associative containers</td>
<td>&lt;map&gt;, &lt;set&gt;</td>
</tr>
<tr>
<td>24.5 Unordered associative containers</td>
<td>&lt;unordered_map&gt;, &lt;unordered_set&gt;</td>
</tr>
<tr>
<td>24.6 Container adaptors</td>
<td>&lt;queue&gt;, &lt;stack&gt;, &lt;flat_map&gt;, &lt;flat_set&gt;</td>
</tr>
<tr>
<td>24.7 Views</td>
<td>&lt;span&gt;, &lt;mdspan&gt;</td>
</tr>
</tbody>
</table>

24.2 Requirements

24.2.1 Preamble

Containers are objects that store other objects. They control allocation and deallocation of these objects through constructors, destructors, insert and erase operations.

All of the complexity requirements in this Clause are stated solely in terms of the number of operations on the contained objects.

[Example 1: The copy constructor of type vector<vector<int>> has linear complexity, even though the complexity of copying each contained vector<int> is itself linear. — end example]

Allocator-aware containers (24.2.2.5) other than basic_string construct elements using the function allocator_traits<allocator_type>::rebind_traits<U>::construct and destroy elements using the function allocator_traits<allocator_type>::rebind_traits<U>::destroy (20.2.9.3), where U is either allocator_type::value_type or an internal type used by the container. These functions are called only for the container’s element type, not for internal types used by the container.

[Note 1: This means, for example, that a node-based container would need to construct nodes containing aligned buffers and call construct to place the element into the buffer. — end note]

24.2.2 General containers

24.2.2.1 Introduction

In 24.2.2,

1. X denotes a container class containing objects of type T,
2. a denotes a value of type X,
3. b and c denote values of type (possibly const) X,
4. i and j denote values of type (possibly const) X::iterator,
5. u denotes an identifier,
6. v denotes an lvalue of type (possibly const) X or an rvalue of type const X,
7. s and t denote non-const lvalues of type X, and
8. rv denotes a non-const rvalue of type X.

The following exposition-only concept is used in the definition of containers:
template<class R, class T>
concept container-compatible-range = // exposition only
ranges::input_range<R> && convertible_to<ranges::range_reference_t<R>, T>;

24.2.2.2 Container requirements [container.reqmts]

A type `X` meets the `container` requirements if the following types, statements, and expressions are well-formed and have the specified semantics.

typename `X::value_type`

*Result:* `T`

*Preconditions*: `T` is `Cpp17Erasable` from `X` (see 24.2.2.5, below).

typename `X::reference`

*Result:* `T&`

typename `X::const_reference`

*Result:* `const T&`

typename `X::iterator`

*Result:* A type that meets the forward iterator requirements (25.3.5.5) with value type `T`. The type `X::iterator` is convertible to `X::const_iterator`.

typename `X::const_iterator`

*Result:* A type that meets the requirements of a constant iterator and those of a forward iterator with value type `T`.

typename `X::difference_type`

*Result:* A signed integer type, identical to the difference type of `X::iterator` and `X::const_iterator`.

typename `X::size_type`

*Result:* An unsigned integer type that can represent any non-negative value of `X::difference_type`.

```
X u;
X u = X();

Postconditions: u.empty()

Complexity: Constant.

X u(v);
X u = v;

Preconditions: T is Cpp17CopyInsertable into X (see below).
Postconditions: u == v.

Complexity: Linear.

X u(rv);
X u = rv;

Postconditions: u is equal to the value that rv had before this construction.
Complexity: Linear for array and inplace_vector and constant for all other standard containers.

t = v;

Result: Xk.

Postconditions: t == v.

Complexity: Linear.

```

t = rv

*Result:* Xk.

*Effects:* All existing elements of `t` are either move assigned to or destroyed.
Postconditions: If \( t \) and \( rv \) do not refer to the same object, \( t \) is equal to the value that \( rv \) had before this assignment.

Complexity: Linear.

a. \(~X()\)
   
   Result: void.
   
   Effects: Destroys every element of \( a \); any memory obtained is deallocated.
   
   Complexity: Linear.

b. \begin{()\}
   
   Result: iterator; const_iterator for constant \( b \).
   
   Returns: An iterator referring to the first element in the container.
   
   Complexity: Constant.

b. \end{()\}
   
   Result: iterator; const_iterator for constant \( b \).
   
   Returns: An iterator which is the past-the-end value for the container.
   
   Complexity: Constant.

b. \cbegin{()\}
   
   Result: const_iterator.
   
   Returns: const_cast<X const&>(b).begin()
   
   Complexity: Constant.

b. \cend{()\}
   
   Result: const_iterator.
   
   Returns: const_cast<X const&>(b).end()
   
   Complexity: Constant.

i \leftrightarrow j
   
   Result: strong_ordering.
   
   Constraints: \( X::iterator \) meets the random access iterator requirements.
   
   Complexity: Constant.

c == b
   
   Preconditions: \( T \) meets the \textit{Cpp17EqualityComparable} requirements.
   
   Result: bool.
   
   Returns: equal(c.begin(), c.end(), b.begin(), b.end())
   
   \[\text{Note 1: The algorithm equal is defined in 27.6.13. — end note}\]
   
   Complexity: Constant if \( c.size() \neq b.size() \), linear otherwise.
   
   Remarks: \( == \) is an equivalence relation.

c != b
   
   Effects: Equivalent to \( !(c == b) \).

t.swap(s)
   
   Result: void.
   
   Effects: Exchanges the contents of \( t \) and \( s \).
   
   Complexity: Linear for \textit{array} and \textit{inplace_vector}, and constant for all other standard containers.
swap(t, s)

Effects: Equivalent to \(t\text{.swap}(s)\).

c.size()

Result: size\_type.

Returns: \(\text{distance}(c\text{.begin()}, c\text{.end()})\), i.e., the number of elements in the container.

Complexity: Constant.

Remarks: The number of elements is defined by the rules of constructors, inserts, and erases.

c.max\_size()

Result: size\_type.

Returns: \(\text{distance}(\text{begin()}, \text{end()})\) for the largest possible container.

Complexity: Constant.

c.empty()

Result: bool.

Returns: \(c\text{.begin()} == c\text{.end()}\)

Complexity: Constant.

Remarks: If the container is empty, then \(c\text{.empty()}\) is \text{true}.

In the expressions

\[i == j\]
\[i != j\]
\[i < j\]
\[i <= j\]
\[i >= j\]
\[i > j\]
\[i <=> j\]
\[i - j\]

where \(i\) and \(j\) denote objects of a container’s iterator type, either or both may be replaced by an object of the container’s \text{const\_iterator} type referring to the same element with no change in semantics.

Unless otherwise specified, all containers defined in this Clause obtain memory using an allocator (see 16.4.4.6).

[Note 2: In particular, containers and iterators do not store references to allocated elements other than through the allocator’s pointer type, i.e., as objects of type \(P\) or \text{pointer\_traits}<\text{template rebinding\_unspecified}>, where \(P\) is \text{allocator\_traits}<\text{allocator\_type}>::\text{pointer}. — end note]

Copy constructors for these container types obtain an allocator by calling \text{allocator\_traits}<\text{allocator\_type}>::\text{select\_on\_container\_copy\_construction} on the allocator belonging to the container being copied. Move constructors obtain an allocator by move construction from the allocator belonging to the container being moved. Such move construction of the allocator shall not exit via an exception. All other constructors for these container types take a \text{const allocator\_type&} argument.

[Note 3: If an invocation of a constructor uses the default value of an optional allocator argument, then the allocator type must support value-initialization. — end note]

A copy of this allocator is used for any memory allocation and element construction performed, by these constructors and by all member functions, during the lifetime of each container object or until the allocator is replaced. The allocator may be replaced only via assignment or \text{swap()}. Allocator replacement is performed by copy assignment, move assignment, or swapping of the allocator only if

\[\text{allocator\_traits}<\text{allocator\_type}>::\text{propagate\_on\_container\_copy\_assignment}::\text{value},\]
\[\text{allocator\_traits}<\text{allocator\_type}>::\text{propagate\_on\_container\_move\_assignment}::\text{value},\]

or

\[\text{allocator\_traits}<\text{allocator\_type}>::\text{propagate\_on\_container\_swap}::\text{value}\]

is \text{true} within the implementation of the corresponding container operation. In all container types defined in this Clause, the member \text{get\_allocator()} returns a copy of the allocator used to construct the container or, if that allocator has been replaced, a copy of the most recent replacement.

§ 24.2.2.2 ©ISO/IEC 909
The expression `a.swap(b)`, for containers `a` and `b` of a standard container type other than `array` and `inplace_vector`, shall exchange the values of `a` and `b` without invoking any move, copy, or swap operations on the individual container elements. Any `Compare`, `Pred`, or `Hash` types belonging to `a` and `b` shall meet the `Cpp17Swappable` requirements and shall be exchanged by calling `swap` as described in 16.4.4.3. If allocator traits::propagate_on_container_swap::value is true, then allocator_type shall meet the `Cpp17Swappable` requirements and the allocators of `a` and `b` shall also be exchanged by calling `swap` as described in 16.4.4.3. Otherwise, the allocators shall not be swapped, and the behavior is undefined unless `a.get_allocator() == b.get_allocator()`. Every iterator referring to an element in one container before the swap shall refer to the same element in the other container after the swap. It is unspecified whether an iterator with value `a.end()` before the swap will have value `b.end()` after the swap.

Unless otherwise specified (see 24.2.7.2, 24.2.8.2, 24.3.9.4, 24.3.14.5, and 24.3.12.5) all container types defined in this Clause meet the following additional requirements:

1. If an exception is thrown by an `insert()` or `emplace()` function while inserting a single element, that function has no effects.
2. If an exception is thrown by a `push_back()`, `push_front()`, `emplace_back()`, or `emplace_front()` function, that function has no effects.
3. No `erase()`, `clear()`, `pop_back()` or `pop_front()` function throws an exception.
4. No copy constructor or assignment operator of a returned iterator throws an exception.
5. No `swap()` function invalidates any references, pointers, or iterators referring to the elements of the containers being swapped.

[Note 4: The `end()` iterator does not refer to any element, so it can be invalidated. — end note]

Unless otherwise specified (either explicitly or by defining a function in terms of other functions), invoking a container member function or passing a container as an argument to a library function shall not invalidate iterators to, or change the values of, objects within that container.

A contiguous container is a container whose member types `iterator` and `const_iterator` meet the `Cpp17RandomAccessIterator` requirements (25.3.5.7) and model `contiguous_iterator` (25.3.4.14).

The behavior of certain container member functions and deduction guides depends on whether types qualify as input iterators or allocators. The extent to which an implementation determines that a type cannot be an input iterator is unspecified, except that as a minimum integral types shall not qualify as input iterators. Likewise, the extent to which an implementation determines that a type cannot be an allocator is unspecified, except that as a minimum a type `A` shall not qualify as an allocator unless it meets both of the following conditions:

1. The qualified-id `A::value_type` is valid and denotes a type (13.10.3).
2. The expression `declval<A&>().allocate(size_t{0})` is well-formed when treated as an unevaluated operand.

24.2.2.3 Reversible container requirements

A type `X` meets the reversible container requirements if `X` meets the container requirements, the iterator type of `X` belongs to the bidirectional or random access iterator categories (25.3), and the following types and expressions are well-formed and have the specified semantics.

```cpp
typename X::reverse_iterator
```

**Result:** The type `reverse_iterator<X::iterator>`, an iterator type whose value type is `T`.

```cpp
typename X::const_reverse_iterator
```

**Result:** The type `reverse_iterator<X::const_iterator>`, a constant iterator type whose value type is `T`.

```cpp
a.rbegin()
```

**Result:** `reverse_iterator; const_reverse_iterator` for constant `a`.

**Returns:** `reverse_iterator(end())`

**Complexity:** Constant.
a.rend()

Result: reverse_iterator; const_reverse_iterator for constant a.
Returns: reverse_iterator(begin())
Complexity: Constant.

a.crbegin()
Result: const_reverse_iterator.
Returns: const_cast<X const&>(a).rbegin()
Complexity: Constant.

a.crend()
Result: const_reverse_iterator.
Returns: const_cast<X const&>(a).rend()
Complexity: Constant.

24.2.2.4 Optional container requirements

The following operations are provided for some types of containers but not others. Those containers for which
the listed operations are provided shall implement the semantics as described unless otherwise stated. If the
iterators passed to lexicographical_compare_three_way meet the constexpr iterator requirements (25.3.1)
then the operations described below are implemented by constexpr functions.

a <=> b
Result: synth-three-way-result<X::value_type>.
Preconditions: Either T models three_way_comparable, or < is defined for values of type (possibly const) T and < is a total ordering relationship.
Returns: lexicographical_compare_three_way(a.begin(), a.end(), b.begin(), b.end(), synth-three-way)
[Note 1: The algorithm lexicographical_compare_three_way is defined in Clause 27. — end note]
Complexity: Linear.

24.2.2.5 Allocator-aware containers

Except for array and inplace_vector, all of the containers defined in Clause 24, 19.6.4, 23.4.3, and 32.9
meet the additional requirements of an allocator-aware container, as described below.

Given an allocator type A and given a container type X having a value_type identical to T and an allocator_type identical to allocator_traits<A>::rebind_alloc<T> and given an lvalue m of type A, a pointer p of type T*, an expression v that denotes an lvalue of type T or const T or an rvalue of type const T, and an rvalue rv of type T, the following terms are defined. If X is not allocator-aware or is a specialization of basic_string, the terms below are defined as if A were allocator<T> — no allocator object needs to be created and user specializations of allocator<T> are not instantiated:

(2.1) — T is Cpp17DefaultInsertable into X means that the following expression is well-formed:
allocator_traits<A>::construct(m, p)

(2.2) — An element of X is default-inserted if it is initialized by evaluation of the expression
allocator_traits<A>::construct(m, p)
where p is the address of the uninitialized storage for the element allocated within X.

(2.3) — T is Cpp17MoveInsertable into X means that the following expression is well-formed:
allocator_traits<A>::construct(m, p, rv)
and its evaluation causes the following postcondition to hold: The value of *p is equivalent to the value
of rv before the evaluation.
[Note 1: rv remains a valid object. Its state is unspecified. — end note]
— T is Cpp17CopyInsertable into X means that, in addition to T being Cpp17MoveInsertable into X, the following expression is well-formed:

\[
\text{allocator_traits<A>::construct(m, p, v)}
\]

and its evaluation causes the following postcondition to hold: The value of v is unchanged and is equivalent to \( *p \).

— T is Cpp17EmplaceConstructible into X from args, for zero or more arguments args, means that the following expression is well-formed:

\[
\text{allocator_traits<A>::construct(m, p, args)}
\]

[Note 2: A container calls allocator_traits<A>::construct(m, p, args) to construct an element at p using args, with m == get_allocator(). The default construct in allocator will call \( ::\text{new}((\text{void}*)p)\ T(\text{args}) \), but specialized allocators can choose a different definition. — end note]

In this subclause,

— X denotes an allocator-aware container class with a value_type of T using an allocator of type A,
— u denotes a variable,
— a and b denote non-const lvalues of type X,
— c denotes an lvalue of type const X,
— t denotes an lvalue or a const rvalue of type X, and
— m is a value of type A.

A type X meets the allocator-aware container requirements if X meets the container requirements and the following types, statements, and expressions are well-formed and have the specified semantics.

typename X::allocator_type

Result: A

Mandates: allocator_type::value_type is the same as X::value_type.

c.get_allocator()

Result: A

Complexity: Constant.

X u;
X u = X();

Preconditions: A meets the Cpp17DefaultConstructible requirements.

Postconditions: u.empty() returns true, u.get_allocator() == A().

Complexity: Constant.

X u(m);

Postconditions: u.empty() returns true, u.get_allocator() == m.

Complexity: Constant.

X u(t, m);

Preconditions: T is Cpp17CopyInsertable into X.

Postconditions: u == t, u.get_allocator() == m

Complexity: Linear.

X u(rv);

Postconditions: u has the same elements as rv had before this construction; the value of u.get_allocator() is the same as the value of rv.get_allocator() before this construction.

Complexity: Constant.
X u(rv, m);

Preconditions: T is Cpp17MoveInsertable into X.
Postconditions: u has the same elements, or copies of the elements, that rv had before this construction,
u.get_allocator() == m.
Complexity: Constant if m == rv.get_allocator(), otherwise linear.

a = t
Result: Xk.
Preconditions: T is Cpp17CopyInsertable into X and Cpp17CopyAssignable.
Postconditions: a == t is true.
Complexity: Linear.

a = rv
Result: Xk.
Preconditions: If allocator_traits<allocator_type>::propagate_on_container_move_assign-
ment::value is false, T is Cpp17MoveInsertable into X and Cpp17MoveAssignable.
Effects: All existing elements of a are either move assigned to or destroyed.
Postconditions: If a and rv do not refer to the same object, a is equal to the value that rv had before
this assignment.
Complexity: Linear.

a.swap(b)
Result: void
Effects: Exchanges the contents of a and b.
Complexity: Constant.

24.2.3 Container data races
For purposes of avoiding data races (16.4.6.10), implementations shall consider the following functions to be
cost: begin, end, rbegin, rend, front, back, data, find, lower_bound, upper_bound, equal_range, at
and, except in associative or unordered associative containers, operator[].
Notwithstanding 16.4.6.10, implementations are required to avoid data races when the contents of the contained
object in different elements in the same container, excepting vector<bool>, are modified concurrently.
[Note 1: For a vector<int> x with a size greater than one, x[1] = 5 and *x.begin() = 10 can be executed
concurrently without a data race, but x[0] = 5 and *x.begin() = 10 executed concurrently can result in a data race.
As an exception to the general rule, for a vector<bool> y, y[0] = true can race with y[1] = true. — end note]

24.2.4 Sequence containers
A sequence container organizes a finite set of objects, all of the same type, into a strictly linear arrangement.
The library provides the following basic kinds of sequence containers: vector, inplace_vector, forward-
list, list, and deque. In addition, array is provided as a sequence container which provides limited
sequence operations because it has a fixed number of elements. The library also provides container adaptors
that make it easy to construct abstract data types, such as stacks, queues, flat_maps, flat_multimaps,
flat_sets, or flat_multisets, out of the basic sequence container kinds (or out of other program-defined
sequence containers).
In this subclause,
(2.1) — X denotes a sequence container class,
(2.2) — a denotes a value of type X containing elements of type T,
(2.3) — u denotes the name of a variable being declared,
(2.4) — A denotes X::allocator_type if the qualified-id X::allocator_type is valid and denotes a type
(13.10.3) and allocator<T> if it doesn’t,
i and j denote iterators that meet the Cpp17InputIterator requirements and refer to elements implicitly convertible to value_type,

[i, j) denotes a valid range,

rg denotes a value of a type R that models container-compatible-range<T>,

il designates an object of type initializer_list<value_type>,

n denotes a value of type X::size_type,

p denotes a valid constant iterator to a,

[q1, q2) denotes a valid range of constant iterators in a,

t denotes an lvalue or a const rvalue of X::value_type, and

rv denotes a non-const rvalue of X::value_type.

Args denotes a template parameter pack;

args denotes a function parameter pack with the pattern Args&&.

The complexities of the expressions are sequence dependent.

A type X meets the sequence container requirements if X meets the container requirements and the following statements and expressions are well-formed and have the specified semantics.

X u(n, t);

Preconditions: T is Cpp17CopyInsertable into X.

Effects: Constructs a sequence container with n copies of t.

Postconditions: distance(u.begin(), u.end()) == n is true.

X u(i, j);

Preconditions: T is Cpp17EmplaceConstructible into X from *i. For vector, if the iterator does not meet the Cpp17ForwardIterator requirements (25.3.5.5), T is also Cpp17MoveInsertable into X.

Effects: Constructs a sequence container equal to the range [i, j). Each iterator in the range [i, j) is dereferenced exactly once.

Postconditions: distance(u.begin(), u.end()) == distance(i, j) is true.

X(from_range, rg)

Preconditions: T is Cpp17EmplaceConstructible into X from *ranges::begin(rg). For vector, if R models neither ranges::sized_range nor ranges::forward_range, T is also Cpp17MoveInsertable into X.

Effects: Constructs a sequence container equal to the range rg. Each iterator in the range rg is dereferenced exactly once.

Postconditions: distance(begin(), end()) == ranges::distance(rg) is true.

X(il)

Effects: Equivalent to X(il.begin(), il.end()).

a = il

Result: X&.

Preconditions: T is Cpp17CopyInsertable into X and Cpp17CopyAssignable.

Effects: Assigns the range [il.begin(), il.end()) into a. All existing elements of a are either assigned to or destroyed.

Returns: *this.

a.emplace(p, args)

Result: iterator.
Preconditions: \( T \) is \( \text{Cpp17EmplaceConstructible} \) into \( X \) from \( \text{args} \). For \( \text{vector} \) and \( \text{deque} \), \( T \) is also \( \text{Cpp17MoveInsertable} \) into \( X \) and \( \text{Cpp17MoveAssignable} \).

Effects: Inserts an object of type \( T \) constructed with \( \text{std::forward<Args>(args)} \ldots \) before \( p \).

[Note 1: \( \text{args} \) can directly or indirectly refer to a value in \( a \). — end note]

Returns: An iterator that points to the new element constructed from \( \text{args} \) into \( a \).

\[
a.insert(p, t)
\]

Result: iterator.

Preconditions: \( T \) is \( \text{Cpp17CopyInsertable} \) into \( X \). For \( \text{vector} \), \( \text{inplace_vector} \), and \( \text{deque} \), \( T \) is also \( \text{Cpp17CopyAssignable} \).

Effects: Inserts a copy of \( t \) before \( p \).

Returns: An iterator that points to the copy of \( t \) inserted into \( a \).

\[
a.insert(p, rv)
\]

Result: iterator.

Preconditions: \( T \) is \( \text{Cpp17MoveInsertable} \) into \( X \). For \( \text{vector} \), \( \text{inplace_vector} \), and \( \text{deque} \), \( T \) is also \( \text{Cpp17MoveAssignable} \).

Effects: Inserts a copy of \( \text{rv} \) before \( p \).

Returns: An iterator that points to the copy of \( \text{rv} \) inserted into \( a \).

\[
a.insert(p, i, j)
\]

Result: iterator.

Preconditions: \( T \) is \( \text{Cpp17EmplaceConstructible} \) into \( X \) from \(*i\). For \( \text{vector} \), \( \text{inplace_vector} \), and \( \text{deque} \), \( T \) is also \( \text{Cpp17MoveInsertable} \) into \( X \), and \( T \) meets the \( \text{Cpp17MoveConstructible} \), \( \text{Cpp17MoveAssign-}
\)

Effects: Inserts copies of elements in \( [i, j) \) before \( p \). Each iterator in the range \( [i, j) \) shall be dereferenced exactly once.

Returns: An iterator that points to the copy of the first element inserted into \( a \), or \( p \) if \( n == 0 \).

\[
a.insert_range(p, rg)
\]

Result: iterator.

Preconditions: \( T \) is \( \text{Cpp17EmplaceConstructible} \) into \( X \) from \(*ranges::begin(rg)\). For \( \text{vector} \), \( \text{inplace_vector} \), and \( \text{deque} \), \( T \) is also \( \text{Cpp17MoveInsertable} \) into \( X \), and \( T \) meets the \( \text{Cpp17MoveCon-
\)

Effects: Inserts copies of elements in \( rg \) before \( p \). Each iterator in the range \( rg \) is dereferenced exactly once.

Returns: An iterator that points to the copy of the first element inserted into \( a \), or \( p \) if \( rg \) is empty.

\[
a.insert(p, il)
\]

Effects: Equivalent to \( a.insert(p, il.begin(), il.end()) \).

\[
a.erase(q)
\]

Result: iterator.

Preconditions: For \( \text{vector} \), \( \text{inplace_vector} \), and \( \text{deque} \), \( T \) is \( \text{Cpp17MoveAssignable} \).

§ 24.2.4 © ISO/IEC 915
Effects: Erases the element pointed to by q.

Returns: An iterator that points to the element immediately following q prior to the element being erased. If no such element exists, a.end() is returned.

\( \text{a.erase(q1, q2)} \)

Result: iterator.

Preconditions: For vector, inplace_vector, and deque, T is Cpp17MoveAssignable.

Effects: Erases the elements in the range \([q1, q2)\).

Returns: An iterator that points to the element pointed to by q2 prior to any elements being erased. If no such element exists, a.end() is returned.

\( \text{a.clear()} \)

Result: void

Effects: Destroys all elements in a. Invalidates all references, pointers, and iterators referring to the elements of a and may invalidate the past-the-end iterator.

Postconditions: a.empty() is true.

Complexity: Linear.

\( \text{a.assign(i, j)} \)

Result: void

Preconditions: T is Cpp17EmplaceConstructible into X from \(*i\) and assignable from \(*i\). For vector, if the iterator does not meet the forward iterator requirements (25.3.5.5), T is also Cpp17MoveInsertable into X. Neither i nor j are iterators into a.

Effects: Replaces elements in a with a copy of \([i, j)\). Invalidates all references, pointers and iterators referring to the elements of a. For vector and deque, also invalidates the past-the-end iterator. Each iterator in the range \([i, j)\) is dereferenced exactly once.

\( \text{a.assign_range(rg)} \)

Result: void

Mandates: assignable_from<T&, ranges::range_reference_t<R>> is modeled.

Preconditions: T is Cpp17EmplaceConstructible into X from \(*ranges::begin(rg)\). For vector, if R models neither ranges::sized_range nor ranges::forward_range, T is also Cpp17MoveInsertable into X. rg and a do not overlap.

Effects: Replaces elements in a with a copy of each element in rg. Invalidates all references, pointers, and iterators referring to the elements of a. For vector and deque, also invalidates the past-the-end iterator. Each iterator in the range rg is dereferenced exactly once.

\( \text{a.assign(il)} \)

Effects: Equivalent to a.assign(il.begin(), il.end()).

\( \text{a.assign(n, t)} \)

Result: void

Preconditions: T is Cpp17CopyInsertable into X and Cpp17CopyAssignable. t is not a reference into a.

Effects: Replaces elements in a with n copies of t. Invalidates all references, pointers and iterators referring to the elements of a. For vector and deque, also invalidates the past-the-end iterator.

For every sequence container defined in this Clause and in Clause 23:

(67.1) — If the constructor

\[
\begin{align*}
\text{template<class InputIterator>}
\text{X(InputIterator first, InputIterator last,}
\text{ const allocator_type& alloc = allocator_type());}
\end{align*}
\]

is called with a type InputIterator that does not qualify as an input iterator, then the constructor shall not participate in overload resolution.
If the member functions of the forms:

\[
\text{template<class InputIterator>}
\text{return-type } F \text{(const_iterator } p, \text{ InputIterator first, InputIterator last);} \quad \text{// such as insert}
\]

\[
\text{template<class InputIterator>}
\text{return-type } F \text{(InputIterator first, InputIterator last);} \quad \text{// such as append, assign}
\]

\[
\text{template<class InputIterator>}
\text{return-type } F \text{(const_iterator i1, const_iterator i2, InputIterator first, InputIterator last);} \quad \text{// such as replace}
\]

are called with a type \text{InputIterator} that does not qualify as an input iterator, then these functions shall not participate in overload resolution.

A deduction guide for a sequence container shall not participate in overload resolution if it has an \text{InputIterator} template parameter and a type that does not qualify as an input iterator is deduced for that parameter, or if it has an \text{Allocator} template parameter and a type that does not qualify as an allocator is deduced for that parameter.

The following operations are provided for some types of sequence containers but not others. Operations other than \text{prepend_range} and \text{append_range} are implemented so as to take amortized constant time.

\[\text{a.front()}\]

\text{Result: reference; const_reference} for constant \text{a}.

\text{Returns: *a.begin()}

\text{Remarks: Required for basic_string, array, deque, forward_list, inplace_vector, list, and vector.}

\[\text{a.back()}\]

\text{Result: reference; const_reference} for constant \text{a}.

\text{Effects: Equivalent to:}
\begin{verbatim}
auto tmp = a.end();
--tmp;
return *tmp;
\end{verbatim}

\text{Remarks: Required for basic_string, array, deque, inplace_vector, list, and vector.}

\[\text{a.emplace_front(args)}\]

\text{Result: reference}

\text{Preconditions: T is Cpp17EmplaceConstructible} into \text{X} from \text{args}.

\text{Effects: Prepends an object of type } T \text{ constructed with std::forward<Args>(args)....}

\text{Returns: a.front().}

\text{Remarks: Required for deque, forward_list, and list.}

\[\text{a.emplace_back(args)}\]

\text{Result: reference}

\text{Preconditions: T is Cpp17EmplaceConstructible} into \text{X} from \text{args}. For \text{vector}, \text{T} is also \text{Cpp17MoveInsertable} into \text{X}.

\text{Effects: Appends an object of type } T \text{ constructed with std::forward<Args>(args)....}

\text{Returns: a.back().}

\text{Remarks: Required for deque, inplace_vector, list, and vector.}

\[\text{a.push_front(t)}\]

\text{Result: void}

\text{Preconditions: T is Cpp17CopyInsertable} into \text{X}.

\text{Effects: Prepends a copy of } t.
Remarks: Required for deque, forward_list, and list.

\(a.\text{push}\_\text{front}(rv)\)

Result: void

Preconditions: \(T\) is \text{Cpp17MoveInsertable} into \(X\).

Effects: Prepends a copy of \(rv\).

Remarks: Required for deque, forward_list, and list.

\(a.\text{prepend}\_\text{range}(rg)\)

Result: void

Preconditions: \(T\) is \text{Cpp17EmplaceConstructible} into \(X\) from \*ranges::begin(rg). For deque, \(T\) is also \text{Cpp17MoveInsertable} into \(X\), and \(T\) meets the \text{Cpp17MoveConstructible}, \text{Cpp17MoveAssignable}, and \text{Cpp17Swappable} (16.4.4.3) requirements.

Effects: Inserts copies of elements in \(rg\) before \text{begin()}. Each iterator in the range \(rg\) is dereferenced exactly once.

[Note 2: The order of elements in \(rg\) is not reversed. — end note]

Remarks: Required for deque, forward_list, and list.

\(a.\text{push}\_\text{back}(t)\)

Result: void

Preconditions: \(T\) is \text{Cpp17CopyInsertable} into \(X\).

Effects: Appends a copy of \(t\).

Remarks: Required for basic_string, deque, inplace_vector, list, and vector.

\(a.\text{push}\_\text{back}(rv)\)

Result: void

Preconditions: \(T\) is \text{Cpp17MoveInsertable} into \(X\).

Effects: Appends a copy of \(rv\).

Remarks: Required for basic_string, deque, inplace_vector, list, and vector.

\(a.\text{append}\_\text{range}(rg)\)

Result: void

Preconditions: \(T\) is \text{Cpp17EmplaceConstructible} into \(X\) from \*ranges::begin(rg). For vector, \(T\) is also \text{Cpp17MoveInsertable} into \(X\).

Effects: Inserts copies of elements in \(rg\) before \text{end()}. Each iterator in the range \(rg\) is dereferenced exactly once.

Remarks: Required for deque, inplace_vector, list, and vector.

\(a.\text{pop}\_\text{front}()\)

Result: void

Preconditions: \(a.\text{empty() is false.}\)

Effects: Destroys the first element.

Remarks: Required for deque, forward_list, and list.

\(a.\text{pop}\_\text{back}()\)

Result: void

Preconditions: \(a.\text{empty() is false.}\)

Effects: Destroys the last element.

Remarks: Required for basic_string, deque, inplace_vector, list, and vector.
N4986

[282x799]N4986
[64x761]a[n]
[44x747]Result: reference; const_reference for constant a
Effects: Equivalent to: return *(a.begin() + n);
Remarks: Required for basic_string, array, deque, inplace_vector, and vector.

a.at(n)
Result: reference; const_reference for constant a
Returns: *(a.begin() + n)
Throws: out_of_range if n >= a.size().
Remarks: Required for basic_string, array, deque, inplace_vector, and vector.

24.2.5 Node handles
24.2.5.1 Overview

A node handle is an object that accepts ownership of a single element from an associative container (24.2.7) or an unordered associative container (24.2.8). It may be used to transfer that ownership to another container with compatible nodes. Containers with compatible nodes have the same node handle type. Elements may be transferred in either direction between container types in the same row of Table 86.

Table 86 — Container types with compatible nodes

<table>
<thead>
<tr>
<th>map&lt;K, T, C1, A&gt;</th>
<th>map&lt;K, T, C2, A&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>map&lt;K, T, C1, A&gt;</td>
<td>multimap&lt;K, T, C2, A&gt;</td>
</tr>
<tr>
<td>set&lt;K, C1, A&gt;</td>
<td>set&lt;K, C2, A&gt;</td>
</tr>
<tr>
<td>set&lt;K, C1, A&gt;</td>
<td>multiset&lt;K, C2, A&gt;</td>
</tr>
<tr>
<td>unordered_map&lt;K, T, H1, E1, A&gt;</td>
<td>unordered_map&lt;K, T, H2, E2, A&gt;</td>
</tr>
<tr>
<td>unordered_map&lt;K, T, H1, E1, A&gt;</td>
<td>unordered_multimap&lt;K, T, H2, E2, A&gt;</td>
</tr>
<tr>
<td>unordered_set&lt;K, H1, E1, A&gt;</td>
<td>unordered_set&lt;K, H2, E2, A&gt;</td>
</tr>
<tr>
<td>unordered_set&lt;K, H1, E1, A&gt;</td>
<td>unordered_multiset&lt;K, H2, E2, A&gt;</td>
</tr>
</tbody>
</table>

If a node handle is not empty, then it contains an allocator that is equal to the allocator of the container when the element was extracted. If a node handle is empty, it contains no allocator.

Class node-handle is for exposition only.

If a user-defined specialization of pair exists for pair<const Key, T> or pair<Key, T>, where Key is the container’s key_type and T is the container’s mapped_type, the behavior of operations involving node handles is undefined.

template<unspec> class node-handle {
  public:
    // These type declarations are described in 24.2.7 and 24.2.8.
    using value_type = see below; // not present for map containers
    using key_type = see below; // not present for set containers
    using mapped_type = see below; // not present for set containers
    using allocator_type = see below;
    // exposition only

    using container_node_type = unspecified;
    using ator_traits = allocator_traits<allocator_type>;
    // exposition only

typename ator_traits::template
    rebind_traits<container_node_type>::pointer ptr_; // exposition only
    optional<allocator_type> alloc_; // exposition only

    public:
    // 24.2.5.2, constructors, copy, and assignment
    constexpr node-handle() noexcept = default;
    node-handle(node-handle&&) noexcept = default;
    node-handle(const node-handle&); // exposition only
    node-handle(node-handle&); // exposition only
    node-handle(const node-handle&); // exposition only

    template<unspecified> node-handle(const node-handle& h, allocator_type a)
    {
      this->ptr_ = &h.ptr_;
      this->alloc_ = a;
    }

    static node-handle& get_node_handle
      (node-handle& h, allocator_type a)
    {
      // exposition only
      node-handle& handle = h;
      handle.ptr_ = &h.ptr_;
      handle.alloc_ = a;
      return handle;
    }

    static node-handle& get_node_handle
      (node-handle& h)
    {
      // exposition only
      node-handle& handle = h;
      handle.alloc_ = h.alloc_;
      return handle;
    }

    // exposition only
    template<unspecified>
    node-handle(node-handle const& x)
    { // exposition only
      this->ptr_ = &x.ptr_;
      this->alloc_ = x.alloc_;
    }

    template<unspecified> node-handle(node-handle const& x)
node-handle& operator=(node-handle&&);

// 24.2.5.3, destructor
~node-handle();

// 24.2.5.4, observers
value_type& value() const; // not present for map containers
key_type& key() const; // not present for set containers
mapped_type& mapped() const; // not present for set containers

allocator_type get_allocator() const;
explicit operator bool() const noexcept;
[[nodiscard]] bool empty() const noexcept;

// 24.2.5.5, modifiers
void swap(node-handle&);
friend void swap(node-handle x, node-handle y) noexcept(noexcept(x.swap(y))) {
  x.swap(y);
}

24.2.5.2 Constructors, copy, and assignment

node-handle(node-handle&& nh) noexcept;

Effects: Constructs a node-handle object initializing ptr_ with nh.ptr_. Move constructs alloc_ with nh.alloc_. Assigns nullptr to nh.ptr_ and assigns nullopt to nh.alloc_.

node-handle& operator=(node-handle&& nh);

Preconditions: Either !alloc_, or ator_traits::propagate_on_container_move_assignment::value is true, or alloc_ == nh.alloc_.

Effects:
(3.1) — If ptr_ != nullptr, destroys the value_type subobject in the container_node_type object pointed to by ptr_ by calling ator_traits::destroy, then deallocates ptr_ by calling ator_traits::template rebind_traits<container_node_type>::deallocate.
(3.2) — Assigns nh.ptr_ to ptr_.
(3.3) — If !alloc_ or ator_traits::propagate_on_container_move_assignment::value is true, move assigns nh.alloc_ to alloc_.
(3.4) — Assigns nullptr to nh.ptr_ and assigns nullopt to nh.alloc_.

Returns: *this.

Throws: Nothing.

24.2.5.3 Destructor

~node-handle();

Effects: If ptr_ != nullptr, destroys the value_type subobject in the container_node_type object pointed to by ptr_ by calling ator_traits::destroy, then deallocates ptr_ by calling ator_traits::template rebind_traits<container_node_type>::deallocate.

24.2.5.4 Observers

value_type& value() const;

Preconditions: empty() == false.

Returns: A reference to the value_type subobject in the container_node_type object pointed to by ptr_.

Throws: Nothing.
key_type& key() const;

Preconditions: empty() == false.

Returns: A non-const reference to the key_type member of the value_type subobject in the container_node_type object pointed to by ptr_.

Throws: Nothing.

Remarks: Modifying the key through the returned reference is permitted.

mapped_type& mapped() const;

Preconditions: empty() == false.

Returns: A reference to the mapped_type member of the value_type subobject in the container_node_type object pointed to by ptr_.

Throws: Nothing.

allocator_type get_allocator() const;

Preconditions: empty() == false.

Returns: *alloc_.

Throws: Nothing.

explicit operator bool() const noexcept;

Returns: ptr_ != nullptr.

[[nodiscard]] bool empty() const noexcept;

Returns: ptr_ == nullptr.

24.2.5.5 Modifiers

void swap(node-handle& nh)

noexcept(ator_traits::propagate_on_container_swap::value ||
ator_traits::is_always_equal::value);

Preconditions: !alloc_, or !nh.alloc_, or ator_traits::propagate_on_container_swap::value is true, or alloc_ == nh.alloc_.

Effects: Calls swap(ptr_, nh.ptr_). If !alloc_, or !nh.alloc_, or ator_traits::propagate_on_container_swap::value is true calls swap(alloc_, nh.alloc_).

24.2.6 Insert return type

The associative containers with unique keys and the unordered containers with unique keys have a member function insert that returns a nested type insert_return_type. That return type is a specialization of the template specified in this subclause.

template<class Iterator, class NodeType>
struct insert-return-type
{
    Iterator position;
    bool inserted;
    NodeType node;
};

The name insert-return-type is exposition only. insert-return-type has the template parameters, data members, and special members specified above. It has no base classes or members other than those specified.

24.2.7 Associative containers

24.2.7.1 General

Associative containers provide fast retrieval of data based on keys. The library provides four basic kinds of associative containers: set, multiset, map and multimap. The library also provides container adaptors that make it easy to construct abstract data types, such as flat_maps, flat_multimaps, flat_sets, or
flat_multisets, out of the basic sequence container kinds (or out of other program-defined sequence containers).

Each associative container is parameterized on Key and an ordering relation Compare that induces a strict weak ordering (27.8) on elements of Key. In addition, map and multimap associate an arbitrary mapped type T with the Key. The object of type Compare is called the comparison object of a container.

The phrase “equivalence of keys” means the equivalence relation imposed by the comparison object. That is, two keys k1 and k2 are considered to be equivalent if for the comparison object comp, comp(k1, k2) == false && comp(k2, k1) == false.

[Note 1: This is not necessarily the same as the result of k1 == k2. — end note]

For any two keys k1 and k2 in the same container, calling comp(k1, k2) shall always return the same value.

An associative container supports unique keys if it may contain at most one element for each key. Otherwise, it supports equivalent keys. The set and map classes support unique keys; the multiset and multimap classes support equivalent keys. For multiset and multimap, insert, emplace, and erase preserve the relative ordering of equivalent elements.

For set and multiset the value type is the same as the key type. For map and multimap it is equal to pair<const Key, T>.

iterator of an associative container is of the bidirectional iterator category. For associative containers where the value type is the same as the key type, both iterator and const_iterator are constant iterators. It is unspecified whether or not iterator and const_iterator are the same type.

[Note 2: iterator and const_iterator have identical semantics in this case, and iterator is convertible to const_iterator. Users can avoid violating the one-definition rule by always using const_iterator in their function parameter lists. — end note]

In this subclause,

- X denotes an associative container class,
- a denotes a value of type X,
- a2 denotes a value of a type with nodes compatible with type X (Table 86),
- b denotes a value of type X or const X,
- u denotes the name of a variable being declared,
- a_uniq denotes a value of type X when X supports unique keys,
- a_eq denotes a value of type X when X supports multiple keys,
- a_tran denotes a value of type X or const X when the qualified-id X::key_compare::is_transparent is valid and denotes a type (13.10.3),
- i and j meet the Cpp17InputIterator requirements and refer to elements implicitly convertible to value_type,
- [i, j) denotes a valid range,
- rg denotes a value of a type R that models container-compatible-range<value_type>,
- p denotes a valid constant iterator to a,
- q denotes a valid dereferenceable constant iterator to a,
- r denotes a valid dereferenceable iterator to a,
- [q1, q2) denotes a valid range of constant iterators in a,
- il designates an object of type initializer_list<value_type>,
- t denotes a value of type X::value_type,
- k denotes a value of type X::key_type, and
- c denotes a value of type X::key_compare or const X::key_compare;
- k1 is a value such that a is partitioned (27.8) with respect to c(x, k1), with x the key value of e and e in a;
- ku is a value such that a is partitioned with respect to !c(ku, x), with x the key value of e and e in a;
ke is a value such that a is partitioned with respect to c(x, ke) and !c(ke, x), with c(x, ke) implying !c(ke, x) and with x the key value of e and e in a;

kx is a value such that

— a is partitioned with respect to c(x, kx) and !c(kx, x), with c(x, kx) implying !c(kx, x) and with x the key value of e and e in a, and

kx is not convertible to either iterator or const_iterator; and

— A denotes the storage allocator used by X, if any, or allocator<X::value_type> otherwise,

— m denotes an allocator of a type convertible to A, and nh denotes a non-const rvalue of type X::node_type.

A type X meets the associative container requirements if X meets all the requirements of an allocator-aware container (24.2.2.2) and the following types, statements, and expressions are well-formed and have the specified semantics, except that for map and multimap, the requirements placed on value_type in 24.2.2.5 apply instead to key_type and mapped_type.

[Note 3: For example, in some cases key_type and mapped_type need to be Cpp17CopyAssignable even though the associated value_type, pair<const key_type, mapped_type>, is not Cpp17CopyAssignable. — end note]

typename X::key_type

   Result: Key.

typename X::mapped_type

   Result: T.

   Remarks: For map and multimap only.

typename X::value_type

   Result: Key for set and multiset only; pair<const Key, T> for map and multimap only.

   Preconditions: X::value_type is Cpp17Erasable from X.

typename X::key_compare

   Result: Compare.

   Preconditions: key_compare is Cpp17CopyConstructible.

typename X::value_compare

   Result: A binary predicate type. It is the same as key_compare for set and multiset; is an ordering relation on pairs induced by the first component (i.e., Key) for map and multimap.

   Preconditions: X::value_type is Cpp17CopyComparable.

typename X::node_type

   Result: A specialization of the node-handle class template (24.2.5), such that the public nested types are the same types as the corresponding types in X.

X(c)

   Effects: Constructs an empty container. Uses a copy of c as a comparison object.

   Complexity: Constant.

X u = X();
X u;

   Preconditions: key_compare meets the Cpp17DefaultConstructible requirements.

   Effects: Constructs an empty container. Uses Compare() as a comparison object.

   Complexity: Constant.

X(i, j, c)

   Preconditions: value_type is Cpp17EmplaceConstructible into X from *i.

   Effects: Constructs an empty container and inserts elements from the range [i, j) into it; uses c as a comparison object.
Complexity: $N \log N$ in general, where $N$ has the value $\text{distance}(i, j)$; linear if $[i, j]$ is sorted with respect to $\text{value\_comp}()$.

$X(i, j)$

Preconditions: $\text{key\_compare}$ meets the $\text{Cpp17DefaultConstructible}$ requirements. $\text{value\_type}$ is $\text{Cpp17EmplaceConstructible}$ into $X$ from $i$.

Effects: Constructs an empty container and inserts elements from the range $[i, j]$ into it; uses $\text{Compare}()$ as a comparison object.

Complexity: $N \log N$ in general, where $N$ has the value $\text{distance}(i, j)$; linear if $[i, j]$ is sorted with respect to $\text{value\_comp}()$.

$X(\text{from\_range}, \text{rg}, c)$

Preconditions: $\text{value\_type}$ is $\text{Cpp17EmplaceConstructible}$ into $X$ from $\text{ranges::begin}(\text{rg})$.

Effects: Constructs an empty container and inserts each element from $\text{rg}$ into it. Uses $c$ as the comparison object.

Complexity: $N \log N$ in general, where $N$ has the value $\text{ranges::distance}(\text{rg})$; linear if $\text{rg}$ is sorted with respect to $\text{value\_comp}()$.

$X(\text{from\_range}, \text{rg})$

Preconditions: $\text{key\_compare}$ meets the $\text{Cpp17DefaultConstructible}$ requirements. $\text{value\_type}$ is $\text{Cpp17EmplaceConstructible}$ into $X$ from $\text{ranges::begin}(\text{rg})$.

Effects: Constructs an empty container and inserts each element from $\text{rg}$ into it. Uses $\text{Compare}()$ as the comparison object.

Complexity: Same as $X(\text{from\_range}, \text{rg}, c)$.

$X(\text{il}, c)$

Effects: Equivalent to $X(\text{il}.\text{begin()}, \text{il}.\text{end()}, c)$.

$X(\text{il})$

Effects: Equivalent to $X(\text{il}.\text{begin()}, \text{il}.\text{end()}).

$\text{a} = \text{il}$

Result: $X$\&

Preconditions: $\text{value\_type}$ is $\text{Cpp17CopyInsertable}$ into $X$ and $\text{Cpp17CopyAssignable}$.

Effects: Assigns the range $[\text{il}.\text{begin()}, \text{il}.\text{end()}]$ into $\text{a}$. All existing elements of $\text{a}$ are either assigned to or destroyed.

Complexity: $N \log N$ in general, where $N$ has the value $\text{il}.\text{size}() + \text{a}.\text{size}()$; linear if $[\text{il}.\text{begin()}, \text{il}.\text{end()}]$ is sorted with respect to $\text{value\_comp}()$.

$\text{b.key\_comp}()$

Result: $X::\text{key\_compare}$

Returns: The comparison object out of which $\text{b}$ was constructed.

Complexity: Constant.

$\text{b.value\_comp}()$

Result: $X::\text{value\_compare}$

Returns: An object of $\text{value\_compare}$ constructed out of the comparison object.

Complexity: Constant.

$\text{a\_uniq}.\text{emplace}(\text{args})$

Result: $\text{pair<iterator, bool>}$

Preconditions: $\text{value\_type}$ is $\text{Cpp17EmplaceConstructible}$ into $X$ from $\text{args}$.
**Effects:** Inserts a value_type object \( t \) constructed with `std::forward<Args>(args)`... if and only if there is no element in the container with key equivalent to the key of \( t \).

**Returns:** The bool component of the returned pair is **true** if and only if the insertion takes place, and the iterator component of the pair points to the element with key equivalent to the key of \( t \).

**Complexity:** Logarithmic.

\begin{verbatim}
a_eq.emplace(args)
\end{verbatim}

**Result:** iterator

**Preconditions:** value_type is **Cpp17EmplaceConstructible** into \( X \) from args.

**Effects:** Inserts a value_type object \( t \) constructed with `std::forward<Args>(args)`... If a range containing elements equivalent to \( t \) exists in \( a_eq \), \( t \) is inserted at the end of that range.

**Returns:** An iterator pointing to the newly inserted element.

**Complexity:** Logarithmic.

\begin{verbatim}
a.emplace_hint(p, args)
\end{verbatim}

**Result:** iterator

**Effects:** Equivalent to `a.emplace(std::forward<Args>(args))`, except that the element is inserted as close as possible to the position just prior to \( p \).

**Returns:** An iterator pointing to the element with the key equivalent to the newly inserted element.

**Complexity:** Logarithmic.

\begin{verbatim}
a_uniq.insert(t)
\end{verbatim}

**Result:** pair<iterator, bool>

**Preconditions:** If \( t \) is a non-const rvalue, value_type is **Cpp17MoveInsertable** into \( X \); otherwise, value_type is **Cpp17CopyInsertable** into \( X \).

**Effects:** Inserts \( t \) if and only if there is no element in the container with key equivalent to the key of \( t \).

**Returns:** The bool component of the returned pair is **true** if and only if the insertion takes place, and the iterator component of the pair points to the element with key equivalent to the key of \( t \).

**Complexity:** Logarithmic in general, but amortized constant if the element is inserted right before \( p \).

\begin{verbatim}
a.insert(p, t)
\end{verbatim}

**Result:** iterator

**Preconditions:** If \( t \) is a non-const rvalue, value_type is **Cpp17MoveInsertable** into \( X \); otherwise, value_type is **Cpp17CopyInsertable** into \( X \).

**Effects:** Inserts \( t \) if and only if there is no element with key equivalent to the key of \( t \) in containers with unique keys; always inserts \( t \) in containers with equivalent keys. \( t \) is inserted as close as possible to the position just prior to \( p \).

**Returns:** An iterator pointing to the element with key equivalent to the key of \( t \).

**Complexity:** Logarithmic in general, but amortized constant if \( t \) is inserted right before \( p \).

\begin{verbatim}
a.insert(i, j)
\end{verbatim}

**Result:** void
Preconditions: value_type is Cpp17EmplaceConstructible into X from *i. Neither i nor j are iterators into a.

Effects: Inserts each element from the range [i, j) if and only if there is no element with key equivalent to the key of that element in containers with unique keys; always inserts that element in containers with equivalent keys.

Complexity: N log(a.size() + N), where N has the value distance(i, j).

a.insert_range(rg)

Result: void

Preconditions: value_type is Cpp17EmplaceConstructible into X from *ranges::begin(rg). rg and a do not overlap.

Effects: Inserts each element from rg if and only if there is no element with key equivalent to the key of that element in containers with unique keys; always inserts that element in containers with equivalent keys.

Complexity: N log(a.size() + N), where N has the value ranges::distance(rg).

a.insert(il)

Effects: Equivalent to a.insert(il.begin(), il.end()).

a_uniq.insert(nh)

Result: insert_return_type

Preconditions: nh is empty or a_uniq.get_allocator() == nh.get_allocator() is true.

Effects: If nh is empty, has no effect. Otherwise, inserts the element owned by nh if and only if there is no element in the container with a key equivalent to nh.key().

Returns: If nh is empty, inserted is false, position is end(), and node is empty. Otherwise if the insertion took place, inserted is true, position points to the inserted element, and node is empty; if the insertion failed, inserted is false, node has the previous value of nh, and position points to an element with a key equivalent to nh.key().

Complexity: Logarithmic.

a_eq.insert(nh)

Result: iterator

Preconditions: nh is empty or a_eq.get_allocator() == nh.get_allocator() is true.

Effects: If nh is empty, has no effect and returns a_eq.end(). Otherwise, inserts the element owned by nh and returns an iterator pointing to the newly inserted element. If a range containing elements with keys equivalent to nh.key() exists in a_eq, the element is inserted at the end of that range.

Postconditions: nh is empty.

Complexity: Logarithmic.

a.insert(p, nh)

Result: iterator

Preconditions: nh is empty or a.get_allocator() == nh.get_allocator() is true.

Effects: If nh is empty, has no effect and returns a.end(). Otherwise, inserts the element owned by nh if and only if there is no element with key equivalent to nh.key() in containers with unique keys; always inserts the element owned by nh in containers with equivalent keys. The element is inserted as close as possible to the position just prior to p.

Postconditions: nh is empty if insertion succeeds, unchanged if insertion fails.

Returns: An iterator pointing to the element with key equivalent to nh.key().

Complexity: Logarithmic in general, but amortized constant if the element is inserted right before p.

a.extract(k)

Result: node_type
**Effects**: Removes the first element in the container with key equivalent to \(k\).

**Returns**: A `node_type` owning the element if found, otherwise an empty `node_type`.

**Complexity**: \(\log(a.size())\)

\[\text{a.tran.extract(kx)}\]

**Result**: `node_type`

**Effects**: Removes the first element in the container with key \(r\) such that \(!c(r, kx) \&\& !c(kx, r)\) is true.

**Returns**: A `node_type` owning the element if found, otherwise an empty `node_type`.

**Complexity**: \(\log(a.tran.size())\)

\[\text{a.extract(q)}\]

**Result**: `node_type`

**Effects**: Removes the element pointed to by \(q\).

**Returns**: A `node_type` owning that element.

**Complexity**: Amortized constant.

\[\text{a.merge(a2)}\]

**Result**: `void`

**Preconditions**: \(a.get_allocator() == a2.get_allocator()\).

**Effects**: Attempts to extract each element in \(a2\) and insert it into \(a\) using the comparison object of \(a\). In containers with unique keys, if there is an element in \(a\) with key equivalent to the key of an element from \(a2\), then that element is not extracted from \(a2\).

**Postconditions**: Pointers and references to the transferred elements of \(a2\) refer to those same elements but as members of \(a\). Iterators referring to the transferred elements will continue to refer to their elements, but they now behave as iterators into \(a\), not into \(a2\).

**Throws**: Nothing unless the comparison object throws.

**Complexity**: \(N\log(a.size()+N),\) where \(N\) has the value \(a2.size()\).

\[\text{a.erase(k)}\]

**Result**: `size_type`

**Effects**: Erases all elements in the container with key equivalent to \(k\).

**Returns**: The number of erased elements.

**Complexity**: \(\log(a.size()) + a.count(k)\)

\[\text{a.tran.erase(kx)}\]

**Result**: `size_type`

**Effects**: Erases all elements in the container with key \(r\) such that \(!c(r, kx) \&\& !c(kx, r)\) is true.

**Returns**: The number of erased elements.

**Complexity**: \(\log(a.tran.size()) + a.tran.count(kx)\)

\[\text{a.erase(q)}\]

**Result**: `iterator`

**Effects**: Erases the element pointed to by \(q\).

**Returns**: An iterator pointing to the element immediately following \(q\) prior to the element being erased. If no such element exists, returns `a.end()`.

**Complexity**: Amortized constant.

\[\text{a.erase(r)}\]

**Result**: `iterator`
Effects: Erases the element pointed to by \( r \).

Returns: An iterator pointing to the element immediately following \( r \) prior to the element being erased. If no such element exists, returns \( a.\text{end()} \).

Complexity: Amortized constant.

\[ a.\text{erase}(q1, q2) \]

Result: iterator

Effects: Erases all the elements in the range \([q1, q2)\).

Returns: An iterator pointing to the element pointed to by \( q2 \) prior to any elements being erased. If no such element exists, \( a.\text{end()} \) is returned.

Complexity: log(\( a.\text{size()} \)) + \( N \), where \( N \) has the value distance(\( q1, q2) \).

\[ a.\text{clear()} \]

Effects: Equivalent to \( a.\text{erase}(a.\text{begin()}, a.\text{end()} \).

Postconditions: \( a.\text{empty()} \) is true.

Complexity: Linear in \( a.\text{size()} \).

\[ b.\text{find}(k) \]

Result: iterator; const_iterator for constant \( b \).

Returns: An iterator pointing to an element with the key equivalent to \( k \), or \( b.\text{end()} \) if such an element is not found.

Complexity: Logarithmic.

\[ a.\text{tran}.\text{find}(ke) \]

Result: iterator; const_iterator for constant \( a.\text{tran} \).

Returns: An iterator pointing to an element with key \( r \) such that \( !c(r, ke) \) \&\& \( !c(ke, r) \) is true, or \( a.\text{tran}.\text{end()} \) if such an element is not found.

Complexity: Logarithmic.

\[ b.\text{count}(k) \]

Result: size_type

Returns: The number of elements with key equivalent to \( k \).

Complexity: log(\( b.\text{size()} \)) + \( b.\text{count}(k) \)

\[ a.\text{tran}.\text{count}(ke) \]

Result: size_type

Returns: The number of elements with key \( r \) such that \( !c(r, ke) \) \&\& \( !c(ke, r) \).

Complexity: log(\( a.\text{tran}.\text{size()} \)) + \( a.\text{tran}.\text{count}(ke) \)

\[ b.\text{contains}(k) \]

Result: bool

Effects: Equivalent to: return \( b.\text{find}(k) \) != \( b.\text{end()} \);

\[ a.\text{tran}.\text{contains}(ke) \]

Result: bool

Effects: Equivalent to: return \( a.\text{tran}.\text{find}(ke) \) != \( a.\text{tran}.\text{end()} \);

\[ b.\text{lower_bound}(k) \]

Result: iterator; const_iterator for constant \( b \).

Returns: An iterator pointing to the first element with key not less than \( k \), or \( b.\text{end()} \) if such an element is not found.

Complexity: Logarithmic.
a_tran.lower_bound(kl)

Result: iterator; const_iterator for constant a_tran.

Returns: An iterator pointing to the first element with key r such that !c(r, kl), or a_tran.end() if such an element is not found.

Complexity: Logarithmic.

b.upper_bound(k)

Result: iterator; const_iterator for constant b.

Returns: An iterator pointing to the first element with key greater than k, or b.end() if such an element is not found.

Complexity: Logarithmic,

a_tran.upper_bound(ku)

Result: iterator; const_iterator for constant a_tran.

Returns: An iterator pointing to the first element with key r such that c(ku, r), or a_tran.end() if such an element is not found.

Complexity: Logarithmic.

b.equal_range(k)

Result: pair<iterator, iterator>; pair<const_iterator, const_iterator> for constant b.

Effects: Equivalent to: return make_pair(b.lower_bound(k), b.upper_bound(k));

Complexity: Logarithmic.

a_tran.equal_range(ke)

Result: pair<iterator, iterator>; pair<const_iterator, const_iterator> for constant a_tran.

Effects: Equivalent to: return make_pair(a_tran.lower_bound(ke), a_tran.upper_bound(ke));

Complexity: Logarithmic.

The insert, insert_range, and emplace members shall not affect the validity of iterators and references to the container, and the erase members shall invalidate only iterators and references to the erased elements.

The extract members invalidate only iterators to the removed element; pointers and references to the removed element remain valid. However, accessing the element through such pointers and references while the element is owned by a node_type is undefined behavior. References and pointers to an element obtained while it is owned by a node_type are invalidated if the element is successfully inserted.

The fundamental property of iterators of associative containers is that they iterate through the containers in the non-descending order of keys where non-descending is defined by the comparison that was used to construct them. For any two dereferenceable iterators i and j such that distance from i to j is positive, the following condition holds:

value_comp(*j, *i) == false

For associative containers with unique keys the stronger condition holds:

value_comp(*i, *j) != false

When an associative container is constructed by passing a comparison object the container shall not store a pointer or reference to the passed object, even if that object is passed by reference. When an associative container is copied, through either a copy constructor or an assignment operator, the target container shall then use the comparison object from the container being copied, as if that comparison object had been passed to the target container in its constructor.

The member function templates find, count, contains, lower_bound, upper_bound, equal_range, erase, and extract shall not participate in overload resolution unless the qualified-id Compare::is_transparent is valid and denotes a type (13.10.3). Additionally, the member function templates extract and erase shall not participate in overload resolution if is_convertible_v<K&&, iterator> || is_convertible_v<K&&, const_iterator> is true, where K is the type substituted as the first template argument.

A deduction guide for an associative container shall not participate in overload resolution if any of the following are true:

§ 24.2.7.1
It has an **InputIterator** template parameter and a type that does not qualify as an input iterator is deduced for that parameter.

It has an **Allocator** template parameter and a type that does not qualify as an allocator is deduced for that parameter.

It has a **Compare** template parameter and a type that qualifies as an allocator is deduced for that parameter.

### 24.2.7.2 Exception safety guarantees

For associative containers, no `clear()` function throws an exception. `erase(k)` does not throw an exception unless that exception is thrown by the container’s `Compare` object (if any).

For associative containers, if an exception is thrown by any operation from within an `insert` or `emplace` function inserting a single element, the insertion has no effect.

For associative containers, no `swap` function throws an exception unless that exception is thrown by the swap of the container’s `Compare` object (if any).

### 24.2.8 Unordered associative containers

**General**

Unordered associative containers provide an ability for fast retrieval of data based on keys. The worst-case complexity for most operations is linear, but the average case is much faster. The library provides four unordered associative containers: `unordered_set`, `unordered_map`, `unordered_multiset`, and `unordered_multimap`.

Unordered associative containers conform to the requirements for Containers (24.2), except that the expressions `a == b` and `a != b` have different semantics than for the other container types.

Each unordered associative container is parameterized by `Key`, by a function object type `Hash` that meets the C++17 requirements (16.4.4.5) and acts as a hash function for argument values of type `Key`, and by a binary predicate `Pred` that induces an equivalence relation on values of type `Key`. Additionally, `unordered_map` and `unordered_multimap` associate an arbitrary mapped type `T` with the `Key`.

The container’s object of type `Hash` — denoted by `hash` — is called the `hash function` of the container. The container’s object of type `Pred` — denoted by `pred` — is called the `key equality predicate` of the container.

Two values `k1` and `k2` are considered equivalent if the container’s key equality predicate `pred(k1, k2)` is valid and returns `true` when passed those values. If `k1` and `k2` are equivalent, the container’s hash function shall return the same value for both.

[Note 1: Thus, when an unordered associative container is instantiated with a non-default `Pred` parameter it usually needs a non-default `Hash` parameter as well. — end note]

For any two keys `k1` and `k2` in the same container, calling `pred(k1, k2)` shall always return the same value. For any key `k` in a container, calling `hash(k)` shall always return the same value.

An unordered associative container supports `unique keys` if it may contain at most one element for each key. Otherwise, it supports `equivalent keys`. `unordered_set` and `unordered_map` support unique keys. `unordered_multiset` and `unordered_multimap` support equivalent keys. In containers that support equivalent keys, elements with equivalent keys are adjacent to each other in the iteration order of the container. Thus, although the absolute order of elements in an unordered container is not specified, its elements are grouped into `equivalent-key groups` such that all elements of each group have equivalent keys. Mutating operations on unordered containers shall preserve the relative order of elements within each equivalent-key group unless otherwise specified.

For `unordered_set` and `unordered_multiset` the value type is the same as the key type. For `unordered_map` and `unordered_multimap` it is `pair<const Key, T>`.

For unordered containers where the value type is the same as the key type, both `iterator` and `const_iterator` are constant iterators. It is unspecified whether or not `iterator` and `const_iterator` are the same type.

[Note 2: `iterator` and `const_iterator` have identical semantics in this case, and `iterator` is convertible to `const_iterator`. Users can avoid violating the one-definition rule by always using `const_iterator` in their function parameter lists. — end note]
The elements of an unordered associative container are organized into buckets. Keys with the same hash code appear in the same bucket. The number of buckets is automatically increased as elements are added to an unordered associative container, so that the average number of elements per bucket is kept below a bound. Rehashing invalidates iterators, changes ordering between elements, and changes which buckets elements appear in, but does not invalidate pointers or references to elements. For unordered_multiset and unordered_multimap, rehashing preserves the relative ordering of equivalent elements.

In this subclause,

1. X denotes an unordered associative container class,
2. a denotes a value of type X,
3. a2 denotes a value of a type with nodes compatible with type X (Table 86),
4. b denotes a value of type X or const X,
5. a_uniq denotes a value of type X when X supports unique keys,
6. a_eq denotes a value of type X when X supports equivalent keys,
7. a_tran denotes a value of type X or const X when the qualified-ids X::key_equal::is_transparent and X::hasher::is_transparent are both valid and denote types (13.10.3),
8. i and j denote input iterators that refer to value_type,
9. [i, j) denotes a valid range,
10. rg denotes a value of a type R that models container-compatible-range<value_type>,
11. p and q2 denote valid constant iterators to a,
12. q and q1 denote valid dereferenceable constant iterators to a,
13. r denotes a valid dereferenceable iterator to a,
14. [q1, q2) denotes a valid range in a,
15. il denotes a value of type initializer_list<value_type>,
16. t denotes a value of type X::value_type,
17. k denotes a value of type key_type,
18. hf denotes a value of type hasher or const hasher,
19. eq denotes a value of type key_equal or const key_equal,
20. ke is a value such that
   1. eq(r1, ke) == eq(ke, r1),
   2. hf(r1) == hf(ke) if eq(r1, ke) is true, and
   3. if any two of eq(r1, ke), eq(r2, ke), and eq(r1, r2) are true, then all three are true,
   where r1 and r2 are keys of elements in a_tran,
   4. kx is a value such that
      1. eq(r1, kx) == eq(kx, r1),
      2. hf(r1) == hf(kx) if eq(r1, kx) is true,
      3. if any two of eq(r1, kx), eq(r2, kx), and eq(r1, r2) are true, then all three are true, and
      4. kx is not convertible to either iterator or const_iterator,
   where r1 and r2 are keys of elements in a_tran,
21. n denotes a value of type size_type,
22. z denotes a value of type float, and
23. nh denotes an rvalue of type X::node_type.

A type X meets the unordered associative container requirements if X meets all the requirements of an allocator-aware container (24.2.2.2) and the following types, statements, and expressions are well-formed and have the specified semantics, except that for unordered_map and unordered_multimap, the requirements placed on value_type in 24.2.2.5 apply instead to key_type and mapped_type.
[Note 3: For example, `key_type` and `mapped_type` sometimes need to be `Cpp17CopyAssignable` even though the associated `value_type`, `pair<const key_type, mapped_type>`, is not `Cpp17CopyAssignable`. — end note]

typename X::key_type

Result: Key.

typedef X::mapped_type

Result: T.

Remarks: For unordered_map and unordered_multimap only.

typename X::value_type

Result: Key for unordered_set and unordered_multiset only; `pair<const Key, T>` for unordered_map and unordered_multimap only.

Preconditions: `value_type` is `Cpp17Erasable` from X.

typename X::hasher

Result: Hash.

Preconditions: Hash is a unary function object type such that the expression `hf(k)` has type `size_t`.

typename X::key_equal

Result: Pred.

Preconditions: Pred meets the `Cpp17CopyConstructible` requirements. Pred is a binary predicate that takes two arguments of type Key. Pred is an equivalence relation.

typename X::local_iterator

Result: An iterator type whose category, value type, difference type, and pointer and reference types are the same as X::iterator's.

[Note 4: A local_iterator object can be used to iterate through a single bucket, but cannot be used to iterate across buckets. — end note]

typename X::const_local_iterator

Result: An iterator type whose category, value type, difference type, and pointer and reference types are the same as X::const_iterator's.

[Note 5: A const_local_iterator object can be used to iterate through a single bucket, but cannot be used to iterate across buckets. — end note]

typename X::node_type

Result: A specialization of a node-handle class template (24.2.5), such that the public nested types are the same types as the corresponding types in X.

X(n, hf, eq)

Effects: Constructs an empty container with at least n buckets, using hf as the hash function and eq as the key equality predicate.

Complexity: $O(n)$

X(n, hf)

Preconditions: key_equal meets the `Cpp17DefaultConstructible` requirements.

Effects: Constructs an empty container with at least n buckets, using hf as the hash function and key_equal() as the key equality predicate.

Complexity: $O(n)$

X(n)

Preconditions: hasher and key_equal meet the `Cpp17DefaultConstructible` requirements.

Effects: Constructs an empty container with at least n buckets, using hasher() as the hash function and key_equal() as the key equality predicate.
Complexity: $\Theta(n)$

```cpp
X a = X();
X a;
```

**Preconditions**: \(\text{hasher}\) and \(\text{key\_equal}\) meet the \textit{Cpp17DefaultConstructible} requirements.

**Effects**: Constructs an empty container with an unspecified number of buckets, using \(\text{hasher}\) as the hash function and \(\text{key\_equal}\) as the key equality predicate.

**Complexity**: Constant.

```
X(i, j, n, hf, eq)
```

**Preconditions**: \textit{value\_type} is \textit{Cpp17EmplaceConstructible} into \(X\) from \(*i\).

**Effects**: Constructs an empty container with at least \(n\) buckets, using \(hf\) as the hash function and \(eq\) as the key equality predicate, and inserts elements from \([i, j]\) into it.

**Complexity**: Average case \(\Theta(N)\) (\(N\) is \(\text{distance}(i, j)\)), worst case \(\Theta(N^2)\).

```
X(i, j, n, hf)
```

**Preconditions**: \textit{key\_equal} meets the \textit{Cpp17DefaultConstructible} requirements. \textit{value\_type} is \textit{Cpp17EmplaceConstructible} into \(X\) from \(*i\).

**Effects**: Constructs an empty container with at least \(n\) buckets, using \(hf\) as the hash function and \(key\_equal\) as the key equality predicate, and inserts elements from \([i, j]\) into it.

**Complexity**: Average case \(\Theta(N)\) (\(N\) is \(\text{distance}(i, j)\)), worst case \(\Theta(N^2)\).

```
X(i, j, n)
```

**Preconditions**: \textit{hasher} and \textit{key\_equal} meet the \textit{Cpp17DefaultConstructible} requirements. \textit{value\_type} is \textit{Cpp17EmplaceConstructible} into \(X\) from \(*i\).

**Effects**: Constructs an empty container with at least \(n\) buckets, using \(\text{hasher}\) as the hash function and \(\text{key\_equal}\) as the key equality predicate, and inserts elements from \([i, j]\) into it.

**Complexity**: Average case \(\Theta(N)\) (\(N\) is \(\text{distance}(i, j)\)), worst case \(\Theta(N^2)\).

```
X(from\_range, rg, n, hf, eq)
```

**Preconditions**: \textit{value\_type} is \textit{Cpp17EmplaceConstructible} into \(X\) from \(*\text{ranges}\_\text{begin}(rg)\).

**Effects**: Constructs an empty container with at least \(n\) buckets, using \(hf\) as the hash function and \(eq\) as the key equality predicate, and inserts elements from \(rg\) into it.

**Complexity**: Average case \(\Theta(N)\) (\(N\) is \(\text{ranges}\_\text{distance}(rg)\)), worst case \(\Theta(N^2)\).

```
X(from\_range, rg, n, hf)
```

**Preconditions**: \textit{key\_equal} meets the \textit{Cpp17DefaultConstructible} requirements. \textit{value\_type} is \textit{Cpp17EmplaceConstructible} into \(X\) from \(*\text{ranges}\_\text{begin}(rg)\).

**Effects**: Constructs an empty container with at least \(n\) buckets, using \(hf\) as the hash function and \(key\_equal\) as the key equality predicate, and inserts elements from \(rg\) into it.

**Complexity**: Average case \(\Theta(N)\) (\(N\) is \(\text{ranges}\_\text{distance}(rg)\)), worst case \(\Theta(N^2)\).

```
X(from\_range, rg, n)
```

**Preconditions**: \textit{hasher} and \textit{key\_equal} meet the \textit{Cpp17DefaultConstructible} requirements. \textit{value\_type} is \textit{Cpp17EmplaceConstructible} into \(X\) from \(*\text{ranges}\_\text{begin}(rg)\).
Effects: Constructs an empty container with at least \( n \) buckets, using \texttt{hasher()} as the hash function and \texttt{key_equal()} as the key equality predicate, and inserts elements from \( \texttt{rg} \) into it.

Complexity: Average case \( \theta(N) \) (\( N \) is \texttt{ranges::distance(rg)}), worst case \( \theta(N^2) \).

\( \texttt{X(from\_range, \texttt{rg})} \)

Preconditions: \texttt{hasher} and \texttt{key_equal} meet the \texttt{Cpp17DefaultConstructible} requirements. \texttt{value\_type} is \texttt{Cpp17EmplaceConstructible} into \( \texttt{X} \) from \texttt{*ranges::begin(rg)}.

Effects: Constructs an empty container with an unspecified number of buckets, using \texttt{hasher()} as the hash function and \texttt{key_equal()} as the key equality predicate, and inserts elements from \( \texttt{rg} \) into it.

Complexity: Average case \( \theta(N) \) (\( N \) is \texttt{ranges::distance(rg)}), worst case \( \theta(N^2) \).

\( \texttt{X(il)} \)

Effects: Equivalent to \( \texttt{X(il.begin(), il.end())} \).

\( \texttt{X(il, n)} \)

Effects: Equivalent to \( \texttt{X(il.begin(), il.end(), n)} \).

\( \texttt{X(il, n, hf)} \)

Effects: Equivalent to \( \texttt{X(il.begin(), il.end(), n, hf)} \).

\( \texttt{X(il, n, hf, eq)} \)

Effects: Equivalent to \( \texttt{X(il.begin(), il.end(), n, hf, eq)} \).

\( \texttt{X(b)} \)

Effects: In addition to the container requirements (24.2.2.2), copies the hash function, predicate, and maximum load factor.

Complexity: Average case linear in \( b.size() \), worst case quadratic.

\( a = b \)

Result: \( \texttt{X\&} \)

Effects: In addition to the container requirements, copies the hash function, predicate, and maximum load factor.

Complexity: Average case linear in \( b.size() \), worst case quadratic.

\( a = \texttt{il} \)

Result: \( \texttt{X\&} \)

Preconditions: \texttt{value\_type} is \texttt{Cpp17CopyInsertable} into \( \texttt{X} \) and \texttt{Cpp17CopyAssignable}.

Effects: Assigns the range \([\texttt{il.begin()}, \texttt{il.end()}]\) into \( a \). All existing elements of \( a \) are either assigned to or destroyed.

Complexity: Average case linear in \( il.size() \), worst case quadratic.

\( \texttt{b.hash\_function()} \)

Result: \texttt{hasher}

Returns: \( b \)’s hash function.

Complexity: Constant.

\( \texttt{b.key\_eq()} \)

Result: \texttt{key\_equal}

Returns: \( b \)’s key equality predicate.

Complexity: Constant.

\( \texttt{a\_uniq.emplace(args)} \)

Result: \texttt{pair<iterator, bool>}

Preconditions: \texttt{value\_type} is \texttt{Cpp17EmplaceConstructible} into \( \texttt{X} \) from \( \texttt{args} \).
Effects: Inserts a value_type object \( t \) constructed with \texttt{std::forward<Args>(args)...} if and only if there is no element in the container with key equivalent to the key of \( t \).

Returns: The \texttt{bool} component of the returned pair is \texttt{true} if and only if the insertion takes place, and the iterator component of the pair points to the element with key equivalent to the key of \( t \).

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\textunderscore uniq.size()) \).

\texttt{a\_eq.insert(t)}

Result: iterator

Preconditions: If \( t \) is a non-const rvalue, \texttt{value_type} is \texttt{Cpp17MoveInsertable} into \( X \); otherwise, \texttt{value_type} is \texttt{Cpp17CopyInsertable} into \( X \).

Effects: Inserts \( t \) if and only if there is no element in the container with key equivalent to the key of \( t \).

Returns: An iterator pointing to the newly inserted element.

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\textunderscore eq.size()) \).

\texttt{a\_eq.insert(p, t)}

Result: iterator

Preconditions: If \( t \) is a non-const rvalue, \texttt{value_type} is \texttt{Cpp17MoveInsertable} into \( X \); otherwise, \texttt{value_type} is \texttt{Cpp17CopyInsertable} into \( X \).

Effects: Equivalent to \texttt{a\_eq.insert(t)}. The iterator \( p \) is a hint pointing to where the search should start. Implementations are permitted to ignore the hint.

Returns: An iterator pointing to the element with the key equivalent to that of \( t \).

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\textunderscore eq.size()) \).

\texttt{a\_eq.insert(args)}

Result: iterator

Preconditions: \texttt{value_type} is \texttt{Cpp17EmplaceConstructible} into \( X \) from \texttt{args}.

Effects: Inserts a value_type object \( t \) constructed with \texttt{std::forward<Args>(args)...}.

Returns: An iterator pointing to the newly inserted element.

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\textunderscore eq.size()) \).

\texttt{a\_eq.emplace_hint(p, args)}

Result: iterator

Preconditions: \texttt{value_type} is \texttt{Cpp17EmplaceConstructible} into \( X \) from \texttt{args}.

Effects: Equivalent to \texttt{a\_eq.emplace(std::forward<Args>(args)...)}.

Returns: An iterator pointing to the element with the key equivalent to the newly inserted element. The const_iterator \( p \) is a hint pointing to where the search should start. Implementations are permitted to ignore the hint.

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\textunderscore size()) \).

\texttt{a\_uniq.insert(t)}

Result: pair<iterator, bool>

Preconditions: If \( t \) is a non-const rvalue, \texttt{value_type} is \texttt{Cpp17MoveInsertable} into \( X \); otherwise, \texttt{value_type} is \texttt{Cpp17CopyInsertable} into \( X \).

Effects: Inserts \( t \) if and only if there is no element in the container with key equivalent to the key of \( t \).

Returns: The \texttt{bool} component of the returned pair indicates whether the insertion takes place, and the iterator component points to the element with key equivalent to the key of \( t \).

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\textunderscore uniq.size()) \).

\texttt{a\_uniq.insert(i, j)}

Result: void
Preconditions: value_type is Cpp17EmplaceConstructible into X from *i. Neither i nor j are iterators into a.

Effects: Equivalent to a.insert(t) for each element in [i, j).

Complexity: Average case $\Theta(N)$, where $N$ is distance(i, j), worst case $\Theta(N(a.size() + 1))$.

\[ \text{a.insert\_range}(rg) \]

Result: void

Preconditions: value_type is Cpp17EmplaceConstructible into X from *ranges::begin(rg). rg and a do not overlap.

Effects: Equivalent to a.insert(t) for each element t in rg.

Complexity: Average case $\Theta(N)$, where $N$ is ranges::distance(rg), worst case $\Theta(N(a.size() + 1))$.

\[ \text{a.insert}(il) \]

Effects: Equivalent to a.insert(il.begin(), il.end()).

\[ \text{a_uniq.insert}(nh) \]

Result: insert\_return\_type

Preconditions: nh is empty or a_uniq.get_allocator() == nh.get_allocator() is true.

Effects: If nh is empty, has no effect. Otherwise, inserts the element owned by nh if and only if there is no element in the container with a key equivalent to nh.key().

Postconditions: If nh is empty, inserted is false, position is end(), and node is empty. Otherwise if the insertion took place, inserted is true, position points to the inserted element, and node is empty; if the insertion failed, inserted is false, node has the previous value of nh, and position points to an element with a key equivalent to nh.key().

Complexity: Average case $\Theta(1)$, worst case $\Theta(a_uniq.size())$.

\[ \text{a_eq.insert}(nh) \]

Result: iterator

Preconditions: nh is empty or a_eq.get_allocator() == nh.get_allocator() is true.

Effects: If nh is empty, has no effect and returns a_eq.end(). Otherwise, inserts the element owned by nh and returns an iterator pointing to the newly inserted element.

Postconditions: nh is empty.

Complexity: Average case $\Theta(1)$, worst case $\Theta(a_eq.size())$.

\[ \text{a.insert}(q, nh) \]

Result: iterator

Preconditions: nh is empty or a.get_allocator() == nh.get_allocator() is true.

Effects: If nh is empty, has no effect and returns a.end(). Otherwise, inserts the element owned by nh if and only if there is no element with key equivalent to nh.key() in containers with unique keys; always inserts the element owned by nh in containers with equivalent keys. The iterator q is a hint pointing to where the search should start. Implementations are permitted to ignore the hint.

Postconditions: nh is empty if insertion succeeds, unchanged if insertion fails.

Returns: An iterator pointing to the element with key equivalent to nh.key().

Complexity: Average case $\Theta(1)$, worst case $\Theta(a.size())$.

\[ \text{a.extract}(k) \]

Result: node_type

Effects: Removes an element in the container with key equivalent to k.

Returns: A node_type owning the element if found, otherwise an empty node_type.

Complexity: Average case $\Theta(1)$, worst case $\Theta(a.size())$. 

§ 24.2.8.1
a_tran.extract(kx)

Result: node_type
Effects: Removes an element in the container with key equivalent to kx.
Returns: A node_type owning the element if found, otherwise an empty node_type.
Complexity: Average case $\Theta(1)$, worst case $\Theta(a\_tran.size())$.

a.extract(q)

Result: node_type
Effects: Removes the element pointed to by q.
Returns: A node_type owning that element.
Complexity: Average case $\Theta(1)$, worst case $\Theta(a.size())$.

a.merge(a2)

Result: void
Preconditions: a.get_allocator() == a2.get_allocator().
Effects: Attempts to extract each element in a2 and insert it into a using the hash function and key equality predicate of a. In containers with unique keys, if there is an element in a with key equivalent to the key of an element from a2, then that element is not extracted from a2.
Postconditions: Pointers and references to the transferred elements of a2 refer to those same elements but as members of a. Iterators referring to the transferred elements and all iterators referring to a will be invalidated, but iterators to elements remaining in a2 will remain valid.
Complexity: Average case $\Theta(N)$, where N is a2.size(), worst case $\Theta(N*a.size() + N)$.

a.erase(k)

Result: size_type
Effects: Erases all elements with key equivalent to k.
Returns: The number of elements erased.
Complexity: Average case $\Theta(a.count(k))$, worst case $\Theta(a.size())$.

a_tran.erase(kx)

Result: size_type
Effects: Erases all elements with key equivalent to kx.
Returns: The number of elements erased.
Complexity: Average case $\Theta(a\_tran.count(kx))$, worst case $\Theta(a\_tran.size())$.

a.erase(q)

Result: iterator
Effects: Erases the element pointed to by q.
Returns: The iterator immediately following q prior to the erasure.
Complexity: Average case $\Theta(1)$, worst case $\Theta(a.size())$.

a.erase(r)

Result: iterator
Effects: Erases the element pointed to by r.
Returns: The iterator immediately following r prior to the erasure.
Complexity: Average case $\Theta(1)$, worst case $\Theta(a.size())$.

a.erase(q1, q2)

Result: iterator
Effects: Erases all elements in the range [q1, q2).
Returns: The iterator immediately following the erased elements prior to the erasure.

Complexity: Average case linear in distance(q1, q2), worst case \( \Theta(a.size()) \).

\[ a.clear() \]

Result: void

Effects: Erases all elements in the container.

Postconditions: \( a.empty() \) is true.

Complexity: Linear in \( a.size() \).

\[ b.find(k) \]

Result: iterator; const_iterator for constant \( b \).

Returns: An iterator pointing to an element with key equivalent to \( k \), or \( b.end() \) if no such element exists.

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(b.size()) \).

\[ a_tran.find(ke) \]

Result: iterator; const_iterator for constant \( a\_tran \).

Returns: An iterator pointing to an element with key equivalent to \( ke \), or \( a\_tran.end() \) if no such element exists.

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(a\_tran.size()) \).

\[ b.count(k) \]

Result: size_type

Returns: The number of elements with key equivalent to \( k \).

Complexity: Average case \( \Theta(b.count(k)) \), worst case \( \Theta(b.size()) \).

\[ a\_tran.count(ke) \]

Result: size_type

Returns: The number of elements with key equivalent to \( ke \).

Complexity: Average case \( \Theta(a\_tran.count(ke)) \), worst case \( \Theta(a\_tran.size()) \).

\[ b.contains(k) \]

Effects: Equivalent to \( b.find(k) \neq b.end() \).

\[ a\_tran.contains(ke) \]

Effects: Equivalent to \( a\_tran.find(ke) \neq a\_tran.end() \).

\[ b.equal_range(k) \]

Result: pair<iterator, iterator>; pair<const_iterator, const_iterator> for constant \( b \).

Returns: A range containing all elements with keys equivalent to \( k \). Returns \( \text{make_pair}(b.end(), b.end()) \) if no such elements exist.

Complexity: Average case \( \Theta(b.count(k)) \), worst case \( \Theta(b.size()) \).

\[ a\_tran.equal_range(ke) \]

Result: pair<iterator, iterator>; pair<const_iterator, const_iterator> for constant \( a\_tran \).

Returns: A range containing all elements with keys equivalent to \( ke \). Returns \( \text{make_pair}(a\_tran.end(), a\_tran.end()) \) if no such elements exist.

Complexity: Average case \( \Theta(a\_tran.count(ke)) \), worst case \( \Theta(a\_tran.size()) \).

\[ b.bucket_count() \]

Result: size_type

Returns: The number of buckets that \( b \) contains.
Complexity: Constant.

\[ b.\text{max\_bucket\_count()} \]

**Result**: \( \text{size\_type} \)

**Returns**: An upper bound on the number of buckets that \( b \) can ever contain.

Complexity: Constant.

\[ b.\text{bucket}(k) \]

**Result**: \( \text{size\_type} \)

**Preconditions**: \( b.\text{bucket\_count()} > 0 \).

**Returns**: The index of the bucket in which elements with keys equivalent to \( k \) would be found, if any such element existed. The return value is in the range \( [0, b.\text{bucket\_count()}) \).

Complexity: Constant.

\[ a.\text{tran}.\text{bucket}(ke) \]

**Result**: \( \text{size\_type} \)

**Preconditions**: \( a.\text{tran}.\text{bucket\_count()} > 0 \).

**Postconditions**: The return value is in the range \( [0, a.\text{tran}.\text{bucket\_count()}) \).

**Returns**: The index of the bucket in which elements with keys equivalent to \( ke \) would be found, if any such element existed.

Complexity: Constant.

\[ b.\text{bucket\_size}(n) \]

**Result**: \( \text{size\_type} \)

**Preconditions**: \( n \) shall be in the range \( [0, b.\text{bucket\_count()}) \).

**Returns**: The number of elements in the \( n \)th bucket.

Complexity: \( \Theta(b.\text{bucket\_size}(n)) \)

\[ b.\text{begin}(n) \]

**Result**: \( \text{local\_iterator}; \text{const\_local\_iterator} \) for constant \( b \).

**Preconditions**: \( n \) is in the range \( [0, b.\text{bucket\_count()}) \).

**Returns**: An iterator referring to the first element in the bucket. If the bucket is empty, then \( b.\text{begin}(n) == b.\text{end}(n) \).

Complexity: Constant.

\[ b.\text{end}(n) \]

**Result**: \( \text{local\_iterator}; \text{const\_local\_iterator} \) for constant \( b \).

**Preconditions**: \( n \) is in the range \( [0, b.\text{bucket\_count()}) \).

**Returns**: An iterator which is the past-the-end value for the bucket.

Complexity: Constant.

\[ b.\text{cbegin}(n) \]

**Result**: \( \text{const\_local\_iterator} \)

**Preconditions**: \( n \) shall be in the range \( [0, b.\text{bucket\_count()}) \).

**Returns**: An iterator referring to the first element in the bucket. If the bucket is empty, then \( b.\text{cbegin}(n) == b.\text{cend}(n) \).

Complexity: Constant.

\[ b.\text{cend}(n) \]

**Result**: \( \text{const\_local\_iterator} \)

**Preconditions**: \( n \) is in the range \( [0, b.\text{bucket\_count()}) \).
Returns: An iterator which is the past-the-end value for the bucket.

Complexity: Constant.

\texttt{b.load_factor()}

\textbf{Result: float}

Returns: The average number of elements per bucket.

Complexity: Constant.

\texttt{b.max_load_factor()}

\textbf{Result: float}

Returns: A positive number that the container attempts to keep the load factor less than or equal to. The container automatically increases the number of buckets as necessary to keep the load factor below this number.

Complexity: Constant.

\texttt{a.max_load_factor(z)}

\textbf{Result: void}

Preconditions: \( z \) is positive. May change the container’s maximum load factor, using \( z \) as a hint.

Complexity: Constant.

\texttt{a.rehash(n)}

\textbf{Result: void}

Postconditions: \( a.bucket\_count() \geq a.size() / a.max\_load\_factor() \) and \( a.bucket\_count() \geq n \).

Complexity: Average case linear in \( a.size() \), worst case quadratic.

\texttt{a.reserve(n)}

Effects: Equivalent to \( a.rehash(\text{ceil}(n / a.max\_load\_factor())) \).

Two unordered containers \( a \) and \( b \) compare equal if \( a.size() == b.size() \) and, for every equivalent-key group \( [E_{a1}, E_{a2}] \) obtained from \( a.equal\_range(Ea1) \), there exists an equivalent-key group \( [E_{b1}, E_{b2}] \) obtained from \( b.equal\_range(Ea1) \), such that \( \text{is\_permutation(Ea1, Ea2, Eb1, Eb2)} \) returns true. For \texttt{unordered\_set} and \texttt{unordered\_map}, the complexity of \texttt{operator==} (i.e., the number of calls to the == operator of the value\_type, to the predicate returned by \texttt{key\_eq()}, and to the hasher returned by \texttt{hash\_function()}) is proportional to \( N \) in the average case and to \( N^2 \) in the worst case, where \( N == a.size() \). For \texttt{unordered\_multiset} and \texttt{unordered\_multimap}, the complexity of \texttt{operator==} is proportional to \( \sum E_i^2 \) in the average case and to \( N^2 \) in the worst case, where \( N == a.size() \), and \( E_i \) is the size of the \( i \)-th equivalent-key group in \( a \). However, if the respective elements of each corresponding pair of equivalent-key groups \( E_{ai} \) and \( E_{bi} \) are arranged in the same order (as is commonly the case, e.g., if \( a \) and \( b \) are unmodified copies of the same container), then the average-case complexity for \texttt{unordered\_multiset} and \texttt{unordered\_multimap} becomes proportional to \( N \) (but worst-case complexity remains \( \Theta(N^2) \), e.g., for a pathologically bad hash function). The behavior of a program that uses \texttt{operator==} or \texttt{operator!=} on unordered containers is undefined unless the \texttt{Pred} function object has the same behavior for both containers and the equality comparison function for Key is a refinement of the partition into equivalent-key groups produced by \texttt{Pred}.

The iterator types \texttt{iterator} and \texttt{const\_iterator} of an unordered associative container are of at least the forward iterator category. For unordered associative containers where the key type and value type are the same, both \texttt{iterator} and \texttt{const\_iterator} are constant iterators.

The \texttt{insert}, \texttt{insert\_range}, and \texttt{emplace} members shall not affect the validity of references to container elements, but may invalidate all iterators to the container. The \texttt{erase} members shall invalidate only iterators and references to the erased elements, and preserve the relative order of the elements that are not erased.

The \texttt{insert}, \texttt{insert\_range}, and \texttt{emplace} members shall not affect the validity of iterators if \( (N+n) \leq z * B \), where \( N \) is the number of elements in the container prior to the insert operation, \( n \) is the number of elements inserted, \( B \) is the container’s bucket count, and \( z \) is the container’s maximum load factor.

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\textsuperscript{203) Equality comparison is a refinement of partitioning if no two objects that compare equal fall into different partitions.}
246 The extract members invalidate only iterators to the removed element, and preserve the relative order of
the elements that are not erased; pointers and references to the removed element remain valid. However,
accessing the element through such pointers and references while the element is owned by a node_type
is undefined behavior. References and pointers to an element obtained while it is owned by a node_type
are invalidated if the element is successfully inserted.
247 The member function templates find, count, equal_range, contains, extract, erase, and bucket shall not
participate in overload resolution unless the qualified-ids Pred::is_transparent and Hash::is_transparent
are both valid and denote types (13.10.3). Additionally, the member function templates extract and erase
shall not participate in overload resolution if is_convertible_v<K&&, iterator> || is_convertible_v<K&&,
const_iterator> is true, where K is the type substituted as the first template argument.
248 A deduction guide for an unordered associative container shall not participate in overload resolution if any of
the following are true:

(a) It has an InputIterator template parameter and a type that does not qualify as an input iterator is
deduced for that parameter.
(b) It has an Allocator template parameter and a type that does not qualify as an allocator is deduced
for that parameter.
(c) It has a Hash template parameter and an integral type or a type that qualifies as an allocator is deduced
for that parameter.
(d) It has a Pred template parameter and a type that qualifies as an allocator is deduced for that parameter.

24.2.8.2 Exception safety guarantees [unord.req.except]
1 For unordered associative containers, no clear() function throws an exception. erase(k) does not throw an
exception unless that exception is thrown by the container’s Hash or Pred object (if any).
2 For unordered associative containers, if an exception is thrown by any operation other than the container’s
hash function from within an insert or emplace function inserting a single element, the insertion has no
effect.
3 For unordered associative containers, no swap function throws an exception unless that exception is thrown
by the swap of the container’s Hash or Pred object (if any).
4 For unordered associative containers, if an exception is thrown from within a rehash() function other than
by the container’s hash function or comparison function, the rehash() function has no effect.

24.3 Sequence containers [sequences]
24.3.1 General [sequences.general]
1 The headers <array> (24.3.2), <deque> (24.3.3), <forward_list> (24.3.4), <inplace_vector> (24.3.7),
<list> (24.3.5), and <vector> (24.3.6) define class templates that meet the requirements for sequence
containers.
2 The following exposition-only alias template may appear in deduction guides for sequence containers:

```cpp
template<class InputIterator>
using iter-value-type = typename iterator_traits<InputIterator>::value_type; // exposition only
```

24.3.2 Header <array> synopsis [array.syn]

```cpp
// mostly freestanding
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
   // 24.3.8, class template array
   template<class T, size_t N> struct array; // partially freestanding

   template<class T, size_t N>
   constexpr bool operator==(const array<T, N>& x, const array<T, N>& y);

   template<class T, size_t N>
   constexpr synth-three-way-result<T>
   operator<=>(const array<T, N>& x, const array<T, N>& y);

```
template<class T, size_t N>
    constexpr void swap(array<T, N>& x, array<T, N>& y) noexcept(noexcept(x.swap(y)));

template<class T, size_t N>
    constexpr array<remove_cv_t<T>, N> to_array(T (&a)[N]);

template<class T, size_t N>
    constexpr array<remove_cv_t<T>, N> to_array(T (&&a)[N]);

template<class T, size_t N>
    constexpr tuple_size<array<T, N>>;

template<size_t I, class T, size_t N>
    constexpr tuple_element<I, array<T, N>>;

template<size_t I, class T, size_t N>
    constexpr T& get(array<T, N>&) noexcept;

template<size_t I, class T, size_t N>
    constexpr T&& get(array<T, N>&&) noexcept;

namespace std {
    template<class T, class Allocator = allocator<T>> class deque;

    template<class T, class Allocator>
        bool operator==(const deque<T, Allocator>& x, const deque<T, Allocator>& y);

    template<class T, class Allocator>
        synth-three-way-result<T> operator<=>(const deque<T, Allocator>& x, const deque<T, Allocator>& y);

    template<class T, class Allocator>
        void swap(deque<T, Allocator>& x, deque<T, Allocator>& y) noexcept(noexcept(x.swap(y)));

    template<class T, class Allocator, class U = T>
        typename deque<T, Allocator>::size_type erase(deque<T, Allocator>&& x, const U& value);

    template<class T, class Allocator, class Predicate>
        typename deque<T, Allocator>::size_type erase_if(deque<T, Allocator>&& x, Predicate pred);

    namespace pmr {
        template<class T>
            using deque = std::deque<T, polymorphic_allocator<T>>;
    }
}

24.3.4 Header <forward_list> synopsis

#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    template<class T, class Allocator = allocator<T>> class forward_list;

    template<class T, class Allocator>
        bool operator==(const forward_list<T, Allocator>& x, const forward_list<T, Allocator>& y);

    template<class T, class Allocator>
        synth-three-way-result<T> operator<=>(const forward_list<T, Allocator>& x, const forward_list<T, Allocator>& y);

    template<class T, class Allocator>
        void swap(forward_list<T, Allocator>& x, forward_list<T, Allocator>& y) noexcept(noexcept(x.swap(y)));

    template<class T, class Allocator, class U = T>
        typename forward_list<T, Allocator>::size_type erase(forward_list<T, Allocator>&& x, const U& value);

    template<class T, class Allocator, class Predicate>
        typename forward_list<T, Allocator>::size_type erase_if(forward_list<T, Allocator>&& x, Predicate pred);

    namespace pmr {
        template<class T>
            using forward_list = std::forward_list<T, polymorphic_allocator<T>>;
    }
}
namespace std {
    // 24.3.10, class template forward_list
    template<class T, class Allocator = allocator<T>> class forward_list;

    template<class T, class Allocator>
    bool operator==(const forward_list<T, Allocator>& x, const forward_list<T, Allocator>& y);
    template<class T, class Allocator>
    synth-three-way-result<T> operator<=>(const forward_list<T, Allocator>& x, const forward_list<T, Allocator>& y);

    template<class T, class Allocator>
    void swap(forward_list<T, Allocator>& x, forward_list<T, Allocator>& y)
        noexcept(noexcept(x.swap(y)));

    // 24.3.10.7, erasure
    template<class T, class Allocator, class U = T>
    typename forward_list<T, Allocator>::size_type
    erase(forward_list<T, Allocator>& c, const U& value);
    template<class T, class Allocator, class Predicate>
    typename forward_list<T, Allocator>::size_type
    erase_if(forward_list<T, Allocator>& c, Predicate pred);

    namespace pmr {
        template<class T>
        using forward_list = std::forward_list<T, polymorphic_allocator<T>>;
    }
}

24.3.5 Header <list> synopsis

#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 24.3.11, class template list
    template<class T, class Allocator = allocator<T>> class list;

    template<class T, class Allocator>
    bool operator==(const list<T, Allocator>& x, const list<T, Allocator>& y);
    template<class T, class Allocator>
    synth-three-way-result<T> operator<=>(const list<T, Allocator>& x, const list<T, Allocator>& y);

    template<class T, class Allocator>
    void swap(list<T, Allocator>& x, list<T, Allocator>& y)
        noexcept(noexcept(x.swap(y)));

    // 24.3.11.6, erasure
    template<class T, class Allocator, class U = T>
    typename list<T, Allocator>::size_type
    erase(list<T, Allocator>& c, const U& value);
    template<class T, class Allocator, class Predicate>
    typename list<T, Allocator>::size_type
    erase_if(list<T, Allocator>& c, Predicate pred);

    namespace pmr {
        template<class T>
        using list = std::list<T, polymorphic_allocator<T>>;
    }
}

24.3.6 Header <vector> synopsis

#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

§ 24.3.6 ©ISO/IEC 943
namespace std {
    // 24.3.12, class template vector
    template<class T, class Allocator = allocator<T>> class vector;

    template<class T, class Allocator>
    constexpr bool operator==(const vector<T, Allocator>& x, const vector<T, Allocator>& y);

    template<class T, class Allocator>
    constexpr synth-three-way-result<T> operator<=>(const vector<T, Allocator>& x, const vector<T, Allocator>& y);

    template<class T, class Allocator>
    constexpr void swap(vector<T, Allocator>& x, vector<T, Allocator>& y)
    noexcept(noexcept(x.swap(y)));

    // 24.3.12.6, erasure
    template<class T, class Allocator, class U = T>
    constexpr typename vector<T, Allocator>::size_type
    erase(vector<T, Allocator>& c, const U& value);

    template<class T, class Allocator, class Predicate>
    constexpr typename vector<T, Allocator>::size_type
    erase_if(vector<T, Allocator>& c, Predicate pred);

    namespace pmr {
        template<class T>
        using vector = std::vector<T, polymorphic_allocator<T>>;
    }

    // 24.3.13, specialization of vector for bool
    // 24.3.13.1, partial class template specialization vector<bool, Allocator>
    class vector<bool, Allocator>;

    template<class T>
    constexpr bool is-vector-bool-reference = see below;  // exposition only

    // hash support
    template<class T> struct hash;

    // 24.3.14, class template inplace_vector
    template<class T, size_t N> class inplace_vector;

    // 24.3.14.6, erasure
    template<class T, size_t N, class U>
    constexpr typename inplace_vector<T, N>::size_type
    erase(inplace_vector<T, N>& c, const U& value);

    template<class T, size_t N, class Predicate>
    constexpr typename inplace_vector<T, N>::size_type
    erase_if(inplace_vector<T, N>& c, Predicate pred);
}

24.3.7 Header <inplace_vector> synopsis

// mostly freestanding
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
    // 24.3.14, class template inplace_vector
    template<class T, size_t N> class inplace_vector;  // partially freestanding

    // 24.3.14.6, erasure
    template<class T, size_t N, class U>
    constexpr typename inplace_vector<T, N>::size_type
    erase(inplace_vector<T, N>& c, const U& value);

    template<class T, size_t N, class Predicate>
    constexpr typename inplace_vector<T, N>::size_type
    erase_if(inplace_vector<T, N>& c, Predicate pred);
}
24.3.8 Class template array

24.3.8.1 Overview

1. The header <array> defines a class template for storing fixed-size sequences of objects. An array is a contiguous container (24.2.2.2). An instance of array<T, N> stores N elements of type T, so that size() == N is an invariant.

2. An array is an aggregate (9.4.2) that can be list-initialized with up to N elements whose types are convertible to T.

3. An array meets all of the requirements of a container (24.2.2.2) and of a reversible container (24.2.2.3), except that a default constructed array object is not empty if N > 0. An array meets some of the requirements of a sequence container (24.2.4). Descriptions are provided here only for operations on array that are not described in one of these tables and for operations where there is additional semantic information.

4. array<T, N> is a structural type (13.2) if T is a structural type. Two values a1 and a2 of type array<T, N> are template-argument-equivalent (13.6) if and only if each pair of corresponding elements in a1 and a2 are template-argument-equivalent.

5. The types iterator and const_iterator meet the constexpr iterator requirements (25.3.1).

```cpp
namespace std {
    template<class T, size_t N>
    struct array {
        // types
        using value_type = T;
        using pointer = T*;
        using const_pointer = const T*;
        using reference = T&;
        using const_reference = const T&;
        using size_type = size_t;
        using difference_type = ptrdiff_t;
        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
        using reverse_iterator = std::reverse_iterator<iterator>;
        using const_reverse_iterator = std::reverse_iterator<const_iterator>;

        // no explicit construct/copy/destroy for aggregate type
        constexpr void fill(const T& u);
        constexpr void swap(array&) noexcept(is_nothrow_swappable_v<T>);

        // iterators
        constexpr iterator begin() noexcept;
        constexpr const_iterator begin() const noexcept;
        constexpr iterator end() noexcept;
        constexpr const_iterator end() const noexcept;
        constexpr reverse_iterator rbegin() noexcept;
        constexpr const_reverse_iterator rbegin() const noexcept;
        constexpr reverse_iterator rend() noexcept;
        constexpr const_reverse_iterator rend() const noexcept;
        constexpr const_iterator cbegin() const noexcept;
        constexpr const_iterator cend() const noexcept;
        constexpr const_reverse_iterator crbegin() const noexcept;
        constexpr const_reverse_iterator crend() const noexcept;

        // capacity
        [[nodiscard]] constexpr bool empty() const noexcept;
        constexpr size_type size() const noexcept;
        constexpr size_type max_size() const noexcept;

        // element access
        constexpr reference operator[](size_type n);
        constexpr const_reference operator[](size_type n) const;
    }
}
```
24.3.8.2 Constructors, copy, and assignment

The conditions for an aggregate (9.4.2) shall be met. Class array relies on the implicitly-declared special member functions (11.4.5.2, 11.4.7, 11.4.5.3) to conform to the container requirements table in 24.2. In addition to the requirements specified in the container requirements table, the implicit move constructor and move assignment operator for array require that \( T \) be \texttt{Cpp17MoveConstructible} or \texttt{Cpp17MoveAssignable}, respectively.

24.3.8.3 Member functions

24.3.8.4 Specialized algorithms

24.3.8.5 Zero-sized arrays
24.3.8.6 Array creation functions

```cpp
template<class T, size_t N>
constexpr array<remove_cv_t<T>, N> to_array(T (&a)[N]);
```

1. **Mandates:** `is_array_v<T>` is false and `is_constructible_v<T, T&>` is true.
2. **Preconditions:** `T` meets the `Cpp17CopyConstructible` requirements.
3. **Returns:** `{ { a[0], ..., a[N - 1] } }`.

```cpp
template<class T, size_t N>
constexpr array<remove_cv_t<T>, N> to_array(T (&&a)[N]);
```

4. **Mandates:** `is_array_v<T>` is false and `is_move_constructible_v<T>` is true.
5. **Preconditions:** `T` meets the `Cpp17MoveConstructible` requirements.
6. **Returns:** `{ { std::move(a[0]), ..., std::move(a[N - 1]) } }`.

### 24.3.8.7 Tuple interface

```cpp
template<class T, size_t N>
struct tuple_size<array<T, N>> : integral_constant<size_t, N> { };
```

```cpp
template<size_t I, class T, size_t N>
struct tuple_element<I, array<T, N>> {
    using type = T;
};
```

1. **Mandates:** `I < N` is true.

```cpp
template<size_t I, class T, size_t N>
constexpr T& get(array<T, N>& a) noexcept;
```

```cpp
template<size_t I, class T, size_t N>
constexpr T&& get(array<T, N>&& a) noexcept;
```

```cpp
template<size_t I, class T, size_t N>
constexpr const T& get(const array<T, N>& a) noexcept;
```

```cpp
template<size_t I, class T, size_t N>
constexpr const T&& get(const array<T, N>&& a) noexcept;
```

2. **Mandates:** `I < N` is true.

3. **Returns:** A reference to the `I`th element of `a`, where indexing is zero-based.

### 24.3.9 Class template deque

#### 24.3.9.1 Overview

A deque is a sequence container that supports random access iterators (25.3.5.7). In addition, it supports constant time insert and erase operations at the beginning or the end; insert and erase in the middle take linear time. That is, a deque is especially optimized for pushing and popping elements at the beginning and end. Storage management is handled automatically.

A deque meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), and of a sequence container, including the optional sequence container requirements (24.2.4). Descriptions are provided here only for operations on deque that are not described in one of these tables or for operations where there is additional semantic information.

```cpp
namespace std {
    template<class T, class Allocator = allocator<T>>
    class deque {
    public:
        // types
        using value_type = T;
        using allocator_type = Allocator;
        using pointer = typename allocator_traits<Allocator>::pointer;
        using const_pointer = typename allocator_traits<Allocator>::const_pointer;
        using reference = value_type&;
        using const_reference = const value_type&;
        using size_type = implementation-defined; // see 24.2
        using difference_type = implementation-defined; // see 24.2
```
using iterator = implementation-defined; // see 24.2
using const_iterator = implementation-defined; // see 24.2
using reverse_iterator = std::reverse_iterator<iterator>;
using const_reverse_iterator = std::reverse_iterator<const_iterator>;

// 24.3.9.2, construct/copy/destroy
deque() : deque(Allocator()) {}
explicit deque(const Allocator&);
explicit deque(size_type n, const Allocator& = Allocator());
deqe(size_type n, const T& value, const Allocator& = Allocator());
template<class InputIterator>
deque(InputIterator first, InputIterator last, const Allocator& = Allocator());
template<container-compatible-range<T> R>
deque(from_range_t, R&& rg, const Allocator& = Allocator());
deque(const deque& x);
deque(deque&&);
deque(const deque&, const type_identity_t<Allocator>&);
deque(deque&&, const type_identity_t<Allocator>&);
deque(initializer_list<T>, const Allocator& = Allocator());
~deque();
deque& operator=(const deque& x);
deque& operator=(deque&& x);
   noexcept(allocator_traits<Allocator>::is_always_equal::value);
deqe& operator=(initializer_list<T>);
template<class InputIterator>
void assign(InputIterator first, InputIterator last);
template<container-compatible-range<T> R>
void assign_range(R&& rg);
void assign(size_type n, const T& t);
void assign(initializer_list<T>);
allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// 24.3.9.3, capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;
void resize(size_type sz);
void resize(size_type sz, const T& c);
void shrink_to_fit();

// element access
reference operator[](size_type n);
const_reference operator[](size_type n) const;
reference at(size_type n);
const_reference at(size_type n) const;
reference front();
const_reference front() const;
reference back();

§ 24.3.9.1
const_reference back() const;

// 24.3.9.4, modifiers
template<class... Args> reference emplace_front(Args&&... args);
template<class... Args> reference emplace_back(Args&&... args);
template<class... Args> iterator emplace(const_iterator position, Args&&... args);

void push_front(const T& x);
void push_front(T&& x);
template<container-compatible-range<T> R>
  void prepend_range(R&& rg);
void push_back(const T& x);
void push_back(T&& x);
template<container-compatible-range<T> R>
  void append_range(R&& rg);

iterator insert(const_iterator position, const T& x);
iterator insert(const_iterator position, T&& x);
iterator insert(const_iterator position, size_type n, const T& x);
template<class InputIterator>
  iterator insert(const_iterator position, InputIterator first, InputIterator last);
template<container-compatible-range<T> R>
  iterator insert_range(const_iterator position, R&& rg);
iterator insert(const_iterator position, initializer_list<T>);

void pop_front();
void pop_back();

iterator erase(const_iterator position);
iterator erase(const_iterator first, const_iterator last);

void swap(deque&) noexcept(allocator_traits<Allocator>::is_always_equal::value);

24.3.9.2 Constructors, copy, and assignment [deque.cons]

explicit deque(const Allocator&);

Effects: Constructs an empty deque, using the specified allocator.
Complexity: Constant.

explicit deque(size_type n, const Allocator& = Allocator());

Preconditions: T is Cpp17DefaultInsertable into *this.

Effects: Constructs a deque with n default-inserted elements using the specified allocator.
Complexity: Linear in n.

deque(size_type n, const T& value, const Allocator& = Allocator());

Preconditions: T is Cpp17CopyInsertable into *this.

Effects: Constructs a deque with n copies of value, using the specified allocator.
Complexity: Linear in n.
template<class InputIterator>
    deque(InputIterator first, InputIterator last, const Allocator& = Allocator());

    **Effects:** Constructs a deque equal to the range \([\text{first}, \text{last}]\), using the specified allocator.

    **Complexity:** Linear in \text{distance}(\text{first}, \text{last}).

template<container-compatible-range<T> R>
    deque(from_range_t, R&& rg, const Allocator& = Allocator());

    **Effects:** Constructs a deque with the elements of the range \(\text{rg}\), using the specified allocator.

    **Complexity:** Linear in \text{ranges::distance(rg)}.

### 24.3.9.3 Capacity

#### void resize(size_type sz);

    **Preconditions:** \(T\) is Cpp17MoveInsertable and Cpp17DefaultInsertable into *this.

    **Effects:** If \(sz < \text{size()}\), erases the last \(\text{size()} - sz\) elements from the sequence. Otherwise, appends \(sz - \text{size()}\) default-inserted elements to the sequence.

#### void resize(size_type sz, const T& c);

    **Preconditions:** \(T\) is Cpp17CopyInsertable into *this.

    **Effects:** If \(sz < \text{size()}\), erases the last \(\text{size()} - sz\) elements from the sequence. Otherwise, appends \(sz - \text{size()}\) copies of \(c\) to the sequence.

#### void shrink_to_fit();

    **Preconditions:** \(T\) is Cpp17MoveInsertable into *this.

    **Effects:** \text{shrink_to_fit} is a non-binding request to reduce memory use but does not change the size of the sequence.

    **Note 1:** The request is non-binding to allow latitude for implementation-specific optimizations. — *end note*

    If the size is equal to the old capacity, or if an exception is thrown other than by the move constructor of a non-Cpp17CopyInsertable \(T\), then there are no effects.

    **Complexity:** If the size is not equal to the old capacity, linear in the size of the sequence; otherwise constant.

    **Remarks:** If the size is not equal to the old capacity, then invalidates all the references, pointers, and iterators referring to the elements in the sequence, as well as the past-the-end iterator.

### 24.3.9.4 Modifiers

#### iterator insert(const_iterator position, const T& x);

#### iterator insert(const_iterator position, T&& x);

#### iterator insert(const_iterator position, size_type n, const T& x);

    **template<class InputIterator>**
        iterator insert(const_iterator position,
                        InputIterator first, InputIterator last);

    **template<container-compatible-range<T> R>**
        iterator insert_range(const_iterator position, R&& rg);

    **iterator insert(const_iterator position, initializer_list<T>);**

    **template<class... Args>** reference emplace_front(Args&&... args);

    **template<class... Args>** reference emplace_back(Args&&... args);

    **template<class... Args>** iterator emplace(const_iterator position, Args&&... args);

    **void push_front(const T& x);**

    **void push_front(T&& x);**

    **template<container-compatible-range<T> R>**
        void prepend_range(R&& rg);

    **void push_back(const T& x);**

    **void push_back(T&& x);**
template<container-compatible-range<T> R>
void append_range(R&& rg);

Effects: An insertion in the middle of the deque invalidates all the iterators and references to elements of the deque. An insertion at either end of the deque invalidates all the iterators to the deque, but has no effect on the validity of references to elements of the deque.

Complexity: The complexity is linear in the number of elements inserted plus the lesser of the distances to the beginning and end of the deque. Inserting a single element at either the beginning or end of a deque always takes constant time and causes a single call to a constructor of T.

Remarks: If an exception is thrown other than by the copy constructor, move constructor, assignment operator, or move assignment operator of T there are no effects. If an exception is thrown while inserting a single element at either end, there are no effects. Otherwise, if an exception is thrown by the move constructor of a non-Cpp17CopyInsertable T, the effects are unspecified.

iterator erase(const_iterator position);
iterator erase(const_iterator first, const_iterator last);
void pop_front();
void pop_back();

Effects: An erase operation that erases the last element of a deque invalidates only the past-the-end iterator and all iterators and references to the erased elements. An erase operation that erases the first element of a deque but not the last element invalidates only iterators and references to the erased elements. An erase operation that erases neither the first element nor the last element of a deque invalidates the past-the-end iterator and all iterators and references to all the elements of the deque.

[Note 1: pop_front and pop_back are erase operations. — end note]

Throws: Nothing unless an exception is thrown by the assignment operator of T.

Complexity: The number of calls to the destructor of T is the same as the number of elements erased, but the number of calls to the assignment operator of T is no more than the lesser of the number of elements before the erased elements and the number of elements after the erased elements.

24.3.9.5 Erasure [deque.erasure]

template<class T, class Allocator, class U = T>
type name deque<T, Allocator>::size_type
erase(deque<T, Allocator>& c, const U& value);

Effects: Equivalent to:
  auto it = remove(c.begin(), c.end(), value);
  auto r = distance(it, c.end());
  c.erase(it, c.end());
  return r;

template<class T, class Allocator, class Predicate>
type name deque<T, Allocator>::size_type
erase_if(deque<T, Allocator>& c, Predicate pred);

Effects: Equivalent to:
  auto it = remove_if(c.begin(), c.end(), pred);
  auto r = distance(it, c.end());
  c.erase(it, c.end());
  return r;

24.3.10 Class template forward_list [forward.list]

24.3.10.1 Overview [forward.list.overview]

A forward_list is a container that supports forward iterators and allows constant time insert and erase operations anywhere within the sequence, with storage management handled automatically. Fast random access to list elements is not supported.

[Note 1: It is intended that forward_list have zero space or time overhead relative to a hand-written C-style singly linked list. Features that would conflict with that goal have been omitted. — end note]
A `forward_list` meets all of the requirements of a container (24.2.2.2), except that the `size()` member function is not provided and `operator==` has linear complexity. A `forward_list` also meets all of the requirements for an allocator-aware container (24.2.2.5). In addition, a `forward_list` provides the assign member functions and several of the optional sequence container requirements (24.2.4). Descriptions are provided here only for operations on `forward_list` that are not described in that table or for operations where there is additional semantic information.

[Note 2: Modifying any list requires access to the element preceding the first element of interest, but in a `forward_list` there is no constant-time way to access a preceding element. For this reason, `erase_after` and `splice_after` take fully-open ranges, not semi-open ranges. — end note]

namespace std {
    template<class T, class Allocator = allocator<T>>
    class forward_list {
        public:
            // types
            using value_type = T;
            using allocator_type = Allocator;
            using pointer = typename allocator_traits<Allocator>::pointer;
            using const_pointer = typename allocator_traits<Allocator>::const_pointer;
            using reference = value_type&;
            using const_reference = const value_type&;
            using size_type = implementation_defined; // see 24.2
            using difference_type = implementation_defined; // see 24.2
            using iterator = implementation_defined; // see 24.2
            using const_iterator = implementation_defined; // see 24.2
            // 24.3.10.2, construct/copy/destroy
            forward_list() : forward_list(Allocator()) { }
            explicit forward_list(const Allocator&);
            explicit forward_list(size_type n, const Allocator& = Allocator());
            forward_list(size_type n, const T& value, const Allocator& = Allocator());
            template<class InputIterator>
            forward_list(InputIterator first, InputIterator last, const Allocator& = Allocator());
            template<container-compatible-range<T> R>
            forward_list(from_range_t, R&& rg, const Allocator& = Allocator());
            forward_list(const forward_list& x);
            forward_list(forward_list&& x);
            forward_list(const forward_list& x, const type_identity_t<Allocator>&);
            forward_list(forward_list&& x, const type_identity_t<Allocator>&);
            forward_list(initializer_list<T>, const Allocator& = Allocator());
            ~forward_list();
            forward_list& operator=(const forward_list& x);
            forward_list& operator=(forward_list&& x)
                noexcept(allocator_traits<Allocator>::is_always_equal::value);
            forward_list& operator=(initializer_list<T>);
            template<class InputIterator>
            void assign(InputIterator first, InputIterator last);
            template<container-compatible-range<T> R>
            void assign_range(R&& rg);
            void assign(size_type n, const T& t);
            void assign(initializer_list<T>);
            allocator_type get_allocator() const noexcept;
            // 24.3.10.3, iterators
            iterator before_begin() noexcept;
            const_iterator before_begin() const noexcept;
            iterator begin() noexcept;
            const_iterator begin() const noexcept;
            iterator end() noexcept;
            const_iterator end() const noexcept;
            iterator cbegin() const noexcept;
            const_iterator cbegin() const noexcept;
            iterator cend() const noexcept;
        }
    }

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// capacity
[[nodiscard]] bool empty() const noexcept;
size_type max_size() const noexcept;

// 24.3.10.4, element access
reference front();
const_reference front() const;

// 24.3.10.5, modifiers
template<class... Args> reference emplace_front(Args&&... args);
void push_front(const T& x);
void push_front(T&& x);
template<container-compatible-range<T> R>
  void prepend_range(R&& rg);
void pop_front();

template<class... Args> iterator emplace_after(const_iterator position, Args&&... args);
iterator insert_after(const_iterator position, const T& x);
iterator insert_after(const_iterator position, T&& x);
iterator insert_after(const_iterator position, size_type n, const T& x);
template<class InputIterator>
  iterator insert_after(const_iterator position, InputIterator first, InputIterator last);
iterator insert_after(const_iterator position, initializer_list<T> il);
template<container-compatible-range<T> R>
  iterator insert_range_after(const_iterator position, R&& rg);

iterator erase_after(const_iterator position);
iterator erase_after(const_iterator position, const_iterator last);
void swap(forward_list&) noexcept;
void resize(size_type sz);
void resize(size_type sz, const value_type& c);
void clear() noexcept;

// 24.3.10.6, forward_list operations
void splice_after(const_iterator position, forward_list& x);
void splice_after(const_iterator position, forward_list&& x);
void splice_after(const_iterator position, forward_list& x, const_iterator i);
void splice_after(const_iterator position, forward_list&& x, const_iterator i);
void splice_after(const_iterator position, forward_list& x, const_iterator first, const_iterator last);
void splice_after(const_iterator position, forward_list&& x, const_iterator first, const_iterator last);

size_type remove(const T& value);
template<class Predicate> size_type remove_if(Predicate pred);

size_type unique();
template<class BinaryPredicate> size_type unique(BinaryPredicate binary_pred);

void merge(forward_list& x);
void merge(forward_list&& x);
template<class Compare> void merge(forward_list& x, Compare comp);
template<class Compare> void merge(forward_list&& x, Compare comp);

void sort();
template<class Compare> void sort(Compare comp);

void reverse() noexcept;
An incomplete type T may be used when instantiating `forward_list` if the allocator meets the allocator completeness requirements (16.4.4.6.2). T shall be complete before any member of the resulting specialization of `forward_list` is referenced.

### 24.3.10.2 Constructors, copy, and assignment

**explicit forward_list(const Allocator&);**

*Effects*: Constructs an empty `forward_list` object using the specified allocator.

*Complexity*: Constant.

**explicit forward_list(size_type n, const Allocator& = Allocator());**

*Preconditions*: T is Cpp17DefaultInsertable into `*this`.

*Effects*: Constructs a `forward_list` object with n default-inserted elements using the specified allocator.

*Complexity*: Linear in n.

**forward_list(size_type n, const T& value, const Allocator& = Allocator());**

*Preconditions*: T is Cpp17CopyInsertable into `*this`.

*Effects*: Constructs a `forward_list` object with n copies of value using the specified allocator.

*Complexity*: Linear in n.

**template<class InputIterator>**

`forward_list(InputIterator first, InputIterator last, const Allocator& = Allocator());`

*Effects*: Constructs a `forward_list` object equal to the range `[first, last)`.

*Complexity*: Linear in distance(first, last).

**template<container-compatible-range<T> R>**

`forward_list(from_range_t, R&& rg, const Allocator& = Allocator());`

*Effects*: Constructs a `forward_list` object with the elements of the range `rg`.

*Complexity*: Linear in `ranges::distance(rg)`.

### 24.3.10.3 Iterators

**iterator before_begin() noexcept;**

**const_iterator before_begin() const noexcept;**

**const_iterator cbefore_begin() const noexcept;**

*Effects*: `cbefore_begin()` is equivalent to `const_cast<forward_list const&>(*this).before_begin()`.

*Returns*: A non-dereferenceable iterator that, when incremented, is equal to the iterator returned by `begin()`.

*Remarks*: `before_begin()` == `end()` shall equal `false`.

### 24.3.10.4 Element access

**reference front();**

**const_reference front() const;**

*Returns*: `*begin()`
24.3.10.5 Modifiers

None of the overloads of `insert_after` shall affect the validity of iterators and references, and `erase_after` shall invalidate only iterators and references to the erased elements. If an exception is thrown during `insert_after` there shall be no effect. Inserting \( n \) elements into a `forward_list` is linear in \( n \), and the number of calls to the copy or move constructor of \( T \) is exactly equal to \( n \). Erasing \( n \) elements from a `forward_list` is linear in \( n \) and the number of calls to the destructor of type \( T \) is exactly equal to \( n \).

```
template<class... Args> reference emplace_front(Args&&... args);
```

**Effects**: Inserts an object of type `value_type` constructed with `value_type(std::forward<Args>(...)` at the beginning of the list.

```
void push_front(const T& x);
void push_front(T&& x);
```

**Effects**: Inserts a copy of \( x \) at the beginning of the list.

```
template<container-compatible-range<T> R>
    void prepend_range(R&& rg);
```

**Effects**: Inserts a copy of each element of \( rg \) at the beginning of the list.

```
[Note 1: The order of elements is not reversed. — end note]
void pop_front();
```

**Effects**: As if by `erase_after(before_begin())`.

```
iterator insert_after(const_iterator position, const T& x);
```

**Preconditions**: \( T \) is `Cpp17CopyInsertable` into `forward_list`. \( position \) is `before_begin()` or is a dereferenceable iterator in the range `[begin(), end())`.

**Effects**: Inserts a copy of \( x \) after \( position \).

**Returns**: An iterator pointing to the copy of \( x \).

```
iterator insert_after(const_iterator position, T&& x);
```

**Preconditions**: \( T \) is `Cpp17MoveInsertable` into `forward_list`. \( position \) is `before_begin()` or is a dereferenceable iterator in the range `[begin(), end())`.

**Effects**: Inserts a copy of \( x \) after \( position \).

**Returns**: An iterator pointing to the copy of \( x \).

```
iterator insert_after(const_iterator position, size_type n, const T& x);
```

**Preconditions**: \( T \) is `Cpp17CopyInsertable` into `forward_list`. \( position \) is `before_begin()` or is a dereferenceable iterator in the range `[begin(), end())`.

**Effects**: Inserts \( n \) copies of \( x \) after \( position \).

**Returns**: An iterator pointing to the last inserted copy of \( x \), or \( position \) if \( n == 0 \) is true.

```
template<class InputIterator>
    iterator insert_after(const_iterator position, InputIterator first, InputIterator last);
```

**Preconditions**: \( T \) is `Cpp17EmplaceConstructible` into `forward_list` from `*first`. \( position \) is `before_begin()` or is a dereferenceable iterator in the range `[begin(), end())`. Neither \( first \) nor \( last \) are iterators in `*this`.

**Effects**: Inserts copies of elements in `[first, last)` after \( position \).

**Returns**: An iterator pointing to the last inserted element, or \( position \) if `first == last` is true.

```
template<container-compatible-range<T> R>
    iterator insert_range_after(const_iterator position, R&& rg);
```

**Preconditions**: \( T \) is `Cpp17EmplaceConstructible` into `forward_list` from `*ranges::begin(rg)`. \( position \) is `before_begin()` or is a dereferenceable iterator in the range `[begin(), end())`. \( rg \) and `*this` do not overlap.

**Effects**: Inserts copies of elements in the range `rg` after `position`. 

§ 24.3.10.5 © ISO/IEC 955
Returns: An iterator pointing to the last inserted element, or position if rg is empty.

iterator insert_after(const_iterator position, initializer_list<T> il);

Effects: Equivalent to: return insert_after(position, il.begin(), il.end());

template<class... Args>
it iterator emplace_after(const_iterator position, Args&&... args);

Preconditions: T is Cpp17EmplaceConstructible into forward_list from std::forward<Args>(args)... position is before_begin() or is a dereferenceable iterator in the range [begin(), end()).

Effects: Inserts an object of type value_type direct-non-list-initialized with std::forward<Args>(args)... after position.

Returns: An iterator pointing to the new object.

iterator erase_after(const_iterator position);

Preconditions: The iterator following position is dereferenceable.

Effects: Erases the element pointed to by the iterator following position.

Returns: An iterator pointing to the element following the one that was erased, or end() if no such element exists.

Throws: Nothing.

iterator erase_after(const_iterator position, const_iterator last);

Preconditions: All iterators in the range (position, last) are dereferenceable.

Effects: Erases the elements in the range (position, last).

Returns: last.

Throws: Nothing.

void resize(size_type sz);

Preconditions: T is Cpp17DefaultInsertable into *this.

Effects: If sz < distance(begin(), end()), erases the last distance(begin(), end()) - sz elements from the list. Otherwise, inserts sz - distance(begin(), end()) default-inserted elements at the end of the list.

void resize(size_type sz, const value_type& c);

Preconditions: T is Cpp17CopyInsertable into *this.

Effects: If sz < distance(begin(), end()), erases the last distance(begin(), end()) - sz elements from the list. Otherwise, inserts sz - distance(begin(), end()) copies of c at the end of the list.

void clear() noexcept;

Effects: Erases all elements in the range [begin(), end()).

Remarks: Does not invalidate past-the-end iterators.

24.3.10.6 Operations [forward.list.ops]

In this subclause, arguments for a template parameter named Predicate or BinaryPredicate shall meet the corresponding requirements in 27.2. The semantics of i + n, where i is an iterator into the list and n is an integer, are the same as those of next(i, n). The expression i - n, where i is an iterator into the list and n is an integer, means an iterator j such that j + n == i is true. For merge and sort, the definitions and requirements in 27.8 apply.

void splice_after(const_iterator position, forward_list& x);
void splice_after(const_iterator position, forward_list&& x);

Preconditions: position is before_begin() or is a dereferenceable iterator in the range [begin(), end()). get_allocator() == x.get_allocator() is true. addressof(x) != this is true.
**Effects:** Inserts the contents of \(x\) after \(\text{position}\), and \(x\) becomes empty. Pointers and references to the moved elements of \(x\) now refer to those same elements but as members of \(*\text{this}\). Iterators referring to the moved elements will continue to refer to their elements, but they now behave as iterators into \(*\text{this}\), not into \(x\).

**Throws:** Nothing.

**Complexity:** \(\Theta(\text{distance}(x\begin{end}, x\end()))\)

```cpp
void splice_after(const_iterator position, forward_list& x, const_iterator i);
void splice_after(const_iterator position, forward_list&& x, const_iterator i);
```

**Preconditions:** \(\text{position}\) is \(\text{before_begin()}\) or is a dereferenceable iterator in the range \([\text{begin()},\ \text{end()})\). The iterator following \(i\) is a dereferenceable iterator in \(x\). \(\text{get allocator}() = x.\text{get allocator}()\) is true.

**Effects:** Inserts the element following \(i\) into \(*\text{this}\), following \(\text{position}\), and removes it from \(x\). The result is unchanged if \(\text{position} = i\) or \(\text{position} = ++i\). Pointers and references to \(+i\) continue to refer to the same element but as a member of \(*\text{this}\). Iterators to \(+i\) continue to refer to the same element, but now behave as iterators into \(*\text{this}\), not into \(x\).

**Throws:** Nothing.

**Complexity:** \(\Theta(1)\)

```cpp
void splice_after(const_iterator position, forward_list& x, const_iterator first, const_iterator last);
void splice_after(const_iterator position, forward_list&& x, const_iterator first, const_iterator last);
```

**Preconditions:** \(\text{position}\) is \(\text{before_begin()}\) or is a dereferenceable iterator in the range \([\text{begin()},\ \text{end()})\). \((\text{first},\ \text{last})\) is a valid range in \(x\), and all iterators in the range \((\text{first},\ \text{last})\) are dereferenceable. \(\text{position}\) is not an iterator in the range \((\text{first},\ \text{last})\). \(\text{get allocator}() = x.\text{get allocator}()\) is true.

**Effects:** Inserts elements in the range \((\text{first},\ \text{last})\) after \(\text{position}\) and removes the elements from \(x\). Pointers and references to the moved elements of \(x\) now refer to those same elements but as members of \(*\text{this}\). Iterators referring to the moved elements will continue to refer to their elements, but they now behave as iterators into \(*\text{this}\), not into \(x\).

**Complexity:** \(\Theta(\text{distance}(\text{first},\ \text{last}))\)

```cpp
size_type remove(const T& value);
template<class Predicate> size_type remove_if(Predicate pred);
```

**Effects:** Erases all the elements in the list referred to by a list iterator \(i\) for which the following conditions hold: \(*i = value\) (for remove()), \(\text{pred}(i)\) is true (for remove_if()). Invalidates only the iterators and references to the erased elements.

**Returns:** The number of elements erased.

**Throws:** Nothing unless an exception is thrown by the equality comparison or the predicate.

**Complexity:** Exactly \(\text{distance(\begin{}}, \text{end})\) applications of the corresponding predicate.

**Remarks:** Stable (16.4.6.8).

```cpp
size_type unique();
template<class BinaryPredicate> size_type unique(BinaryPredicate binary_pred);
```

Let \(\text{binary pred}\) be \text{equal_to<>{}}\) for the first overload.

**Preconditions:** \(\text{binary pred}\) is an equivalence relation.

**Effects:** Erases all but the first element from every consecutive group of equivalent elements. That is, for a nonempty list, erases all elements referred to by the iterator \(i\) in the range \([\text{begin() + 1}, \text{end()}\) for which \(\text{binary pred}(i, \ast(i - 1))\) is true. Invalidates only the iterators and references to the erased elements.

**Returns:** The number of elements erased.

**Throws:** Nothing unless an exception is thrown by the predicate.
Complexity: If `empty()` is false, exactly `{distance(begin(), end()) - 1}` applications of the corresponding predicate, otherwise no applications of the predicate.

```cpp
void merge(forward_list& x);
void merge(forward_list&& x);
template<class Compare> void merge(forward_list& x, Compare comp);
template<class Compare> void merge(forward_list&& x, Compare comp);
```

Let `comp` be `less<` for the first two overloads.

Preconditions: `*this` and `x` are both sorted with respect to the comparator `comp`, and `get_allocator()` == `x.get_allocator()` is true.

Effects: If `addressof(x) == this`, there are no effects. Otherwise, merges the two sorted ranges `[begin(), end())` and `[x.begin(), x.end())`. The result is a range that is sorted with respect to the comparator `comp`. Pointers and references to the moved elements of `x` now refer to those same elements but as members of `*this`. Iterators referring to the moved elements will continue to refer to their elements, but they now behave as iterators into `*this`, not into `x`.

Complexity: At most `{distance(begin(), end()) + distance(x.begin(), x.end()) - 1}` comparisons if `addressof(x) != this`; otherwise, no comparisons are performed.

Remarks: Stable (16.4.6.8). If `addressof(x) != this`, `x` is empty after the merge. No elements are copied by this operation. If an exception is thrown other than by a comparison, there are no effects.

```cpp
void sort();
template<class Compare> void sort(Compare comp);
```

Effects: Sorts the list according to the `operator<` or the `comp` function object. If an exception is thrown, the order of the elements in `*this` is unspecified. Does not affect the validity of iterators and references.

Complexity: Approximately \(N \log N\) comparisons, where \(N\) is `distance(begin(), end())`.

Remarks: Stable (16.4.6.8).

```cpp
void reverse() noexcept;
```

Effects: Reverses the order of the elements in the list. Does not affect the validity of iterators and references.

Complexity: Linear time.

### 24.3.10.7 Erasure

```cpp
template<class T, class Allocator, class U = T>
typename forward_list<T, Allocator>::size_type
erase(forward_list<T, Allocator>::size_type & c, const U & value);
```

Effects: Equivalent to: `return erase_if(c, [k](auto& elem) { return elem == value; });`

```cpp
template<class T, class Allocator, class Predicate>
typecut<T, class Allocator> size_type
erase_if(forward_list<T, Allocator>& c, Predicate pred);
```

Effects: Equivalent to: `return c.remove_if(pred);`

### 24.3.11 Class template list

#### 24.3.11.1 Overview

A list is a sequence container that supports bidirectional iterators and allows constant time insert and erase operations anywhere within the sequence, with storage management handled automatically. Unlike vectors (24.3.12) and deques (24.3.9), fast random access to list elements is not supported, but many algorithms only need sequential access anyway.

A list meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), and of a sequence container, including most of the optional sequence container requirements (24.2.4). The exceptions are the `operator []` and `at` member functions, which are
not provided. Descriptions are provided here only for operations on `list` that are not described in one of these tables or for operations where there is additional semantic information.

```cpp
namespace std {
    template<class T, class Allocator = allocator<T>>
    class list {
    public:
        // types
        using value_type = T;
        using allocator_type = Allocator;
        using pointer = typename allocator_traits<Allocator>::pointer;
        using const_pointer = typename allocator_traits<Allocator>::const_pointer;
        using reference = value_type&;
        using const_reference = const value_type&;
        using size_type = implementation-defined; // see 24.2
        using difference_type = implementation-defined; // see 24.2
        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
        using reverse_iterator = std::reverse_iterator<iterator>;
        using const_reverse_iterator = std::reverse_iterator<const_iterator>;
        // 24.3.11.2, construct/copy/destroy
        list() : list(Allocator()) { }
        explicit list(const Allocator&);
        explicit list(size_type n, const Allocator& = Allocator());
        list(size_type n, const T& value, const Allocator& = Allocator());
        template<class InputIterator>
            list(InputIterator first, InputIterator last, const Allocator& = Allocator());
        template<
            container-compatible-range<T> R>
            list(from_range_t, R&& rg, const Allocator& = Allocator());
        list(const list& x);
        list(list&& x);
        list(const list&, const type_identity_t<Allocator>&);
        list(list&&, const type_identity_t<Allocator>&);
        list(initializer_list<T>, const Allocator& = Allocator());
        ~list();
        list& operator=(const list& x);
        list& operator=(list&& x);
        list& operator=(const list& x);
        list& operator=(list&& x);
        noexcept(allocator_traits<Allocator>::is_always_equal::value);
        list& operator=(initializer_list<T>);
        template<class InputIterator>
            void assign(InputIterator first, InputIterator last);
        template<
            container-compatible-range<T> R>
            void assign_range(R&& rg);
        void assign(size_type n, const T& t);
        void assign(initializer_list<T>);
        allocator_type get_allocator() const noexcept;
        // iterators
        iterator begin() noexcept;
        const_iterator begin() const noexcept;
        iterator end() noexcept;
        const_iterator end() const noexcept;
        reverse_iterator rbegin() noexcept;
        const_reverse_iterator rbegin() const noexcept;
        reverse_iterator rend() noexcept;
        const_reverse_iterator rend() const noexcept;
        const_iterator cbegin() const noexcept;
        const_iterator cend() const noexcept;
        const_reverse_iterator crbegin() const noexcept;
        const_reverse_iterator crend() const noexcept;
    }
}
```

204) These member functions are only provided by containers whose iterators are random access iterators.
// 24.3.11.3, capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;
void resize(size_type sz);
void resize(size_type sz, const T& c);

// element access
reference front();
const_reference front() const;
reference back();
const_reference back() const;

// 24.3.11.4, modifiers
template<class... Args> reference emplace_front(Args&&... args);
template<class... Args> reference emplace_back(Args&&... args);
void push_front(const T& x);
void push_front(T&& x);
template<typename container-compatible-range<T> R>
  void prepend_range(R&& rg);
void pop_front();
void push_back(const T& x);
void push_back(T&& x);
template<typename container-compatible-range<T> R>
  void append_range(R&& rg);
void pop_back();

template<class... Args> iterator emplace(const_iterator position, Args&&... args);
iterator insert(const_iterator position, const T& x);
iterator insert(const_iterator position, T&& x);
iterator insert(const_iterator position, size_type n, const T& x);
template<class InputIterator>
  iterator insert(const_iterator position, InputIterator first, InputIterator last);
template<typename container-compatible-range<T> R>
  iterator insert_range(const_iterator position, R&& rg);
iterator insert(const_iterator position, initializer_list<T> il);

iterator erase(const_iterator position);
iterator erase(const_iterator position, const_iterator last);
void swap(list&) noexcept(allocator_traits<Allocator>::is_always_equal::value);
void clear() noexcept;

// 24.3.11.5, list operations
void splice(const_iterator position, list& x);
void splice(const_iterator position, list&& x);
void splice(const_iterator position, list& x, const_iterator i);
void splice(const_iterator position, list&& x, const_iterator i);
void splice(const_iterator position, list& x, const_iterator first, const_iterator last);
void splice(const_iterator position, list&& x, const_iterator first, const_iterator last);

size_type remove(const T& value);
template<class Predicate> size_type remove_if(Predicate pred);

size_type unique();
template<class BinaryPredicate>
  size_type unique(BinaryPredicate binary_pred);

void merge(list& x);
void merge(list&& x);
template<class Compare> void merge(list& x, Compare comp);
template<class Compare> void merge(list&& x, Compare comp);

void sort();
template<class Compare> void sort(Compare comp);
# 24.3.11.2 Constructors, copy, and assignment

**explicit list(const Allocator&);**

*Effects*: Constructs an empty list, using the specified allocator.

*Complexity*: Constant.

**explicit list(size_type n, const Allocator& = Allocator());**

*Preconditions*: T is `Cpp17DefaultInsertable` into *this.

*Effects*: Constructs a list with n default-inserted elements using the specified allocator.

*Complexity*: Linear in n.

**list(size_type n, const T& value, const Allocator& = Allocator());**

*Preconditions*: T is `Cpp17CopyInsertable` into *this.

*Effects*: Constructs a list with n copies of value, using the specified allocator.

*Complexity*: Linear in n.

**template<class InputIterator>**

```c++
list(InputIterator first, InputIterator last, const Allocator& = Allocator());
```

*Effects*: Constructs a list equal to the range `[first, last)`.

*Complexity*: Linear in distance(first, last).

**template<container-compatible-range<T> R>**

```c++
list(from_range_t, R&&, Allocator = Allocator());
```

*Effects*: Constructs a list object with the elements of the range rg.

*Complexity*: Linear in `ranges::distance(rg)`.

# 24.3.11.3 Capacity

**void resize(size_type sz);**

*Preconditions*: T is `Cpp17DefaultInsertable` into *this.

*Effects*: If size() < sz, appends sz - size() default-inserted elements to the sequence. If sz <= size(), equivalent to:

```c++
list<T>::iterator it = begin();
advance(it, sz);
erase(it, end());
```

**void resize(size_type sz, const T& c);**

*Preconditions*: T is `Cpp17CopyInsertable` into *this.

*Effects*: As if by:

```c++
if (sz > size())
    insert(end(), sz-size(), c);
```
else if (sz < size()) {
    iterator i = begin();
    advance(i, sz);
    erase(i, end());
}
else
    // do nothing

24.3.11.4 Modifiers

iterator insert(const_iterator position, const T& x);
iterator insert(const_iterator position, T&& x);
iterator insert(const_iterator position, size_type n, const T& x);
template<class InputIterator>
    iterator insert(const_iterator position, InputIterator first,
                   InputIterator last);
template<container-compatible-range<T> R>
    iterator insert_range(const_iterator position, R&& rg);
iterator insert(const_iterator position, initializer_list<T>);
template<class... Args> reference emplace_front(Args&&... args);
template<class... Args> reference emplace_back(Args&&... args);
template<class... Args> iterator emplace(const_iterator position, Args&&... args);
void push_front(const T& x);
void push_front(T&& x);
template<container-compatible-range<T> R>
    void prepend_range(R&& rg);
void push_back(const T& x);
void push_back(T&& x);
template<container-compatible-range<T> R>
    void append_range(R&& rg);

1. Complexity: Insertion of a single element into a list takes constant time and exactly one call to a
   constructor of T. Insertion of multiple elements into a list is linear in the number of elements inserted,
   and the number of calls to the copy constructor or move constructor of T is exactly equal to the number
   of elements inserted.

2. Remarks: Does not affect the validity of iterators and references. If an exception is thrown there are no
   effects.

iterator erase(const_iterator position);
iterator erase(const_iterator first, const_iterator last);
void pop_front();
void pop_back();
void clear() noexcept;

3. Effects: Invalidates only the iterators and references to the erased elements.


5. Complexity: Erasing a single element is a constant time operation with a single call to the destructor
   of T. Erasing a range in a list is linear time in the size of the range and the number of calls to the
   destructor of type T is exactly equal to the size of the range.

24.3.11.5 Operations

1. Since lists allow fast insertion and erasing from the middle of a list, certain operations are provided specifically
   for them. In this subclause, arguments for a template parameter named Predicate or BinaryPredicate
   shall meet the corresponding requirements in 27.2. The semantics of i + n and i - n, where i is an iterator
   into the list and n is an integer, are the same as those of next(i, n) and prev(i, n), respectively. For
   merge and sort, the definitions and requirements in 27.8 apply.

2. list provides three splice operations that destructively move elements from one list to another. The behavior
   of splice operations is undefined if get_allocator() != x.get_allocator().
void splice(const_iterator position, list& x);
void splice(const_iterator position, list&& x);

3    Preconditions: addressof(x) != this is true.
4    Effects: Inserts the contents of x before position and x becomes empty. Pointers and references to the
5    moved elements of x now refer to those same elements but as members of *this. Iterators referring to
6    the moved elements will continue to refer to their elements, but they now behave as iterators into
7    *this, not into x.
8    Throws: Nothing.
9    Complexity: Constant time.

void splice(const_iterator position, list& x, const_iterator i);
void splice(const_iterator position, list&& x, const_iterator i);

7    Preconditions: i is a valid dereferenceable iterator of x.
8    Effects: Inserts an element pointed to by i from list x before position and removes the element from
9    x. The result is unchanged if position == i or position == ++i. Pointers and references to *i
10   continue to refer to this same element but as a member of *this. Iterators to *i (including i itself)
11   continue to refer to the same element, but now behave as iterators into *this, not into x.
12   Throws: Nothing.
13   Complexity: Constant time.

void splice(const_iterator position, list& x, const_iterator first,
const_iterator last);
void splice(const_iterator position, list&& x, const_iterator first,
const_iterator last);

11   Preconditions: [first, last) is a valid range in x. position is not an iterator in the range [first,
12   last).
13   Effects: Inserts elements in the range [first,last) before position and removes the elements from x.
14   Pointers and references to the moved elements of x now refer to those same elements but as members
15   of *this. Iterators referring to the moved elements will continue to refer to their elements, but they
16   now behave as iterators into *this, not into x.
17   Throws: Nothing.
18   Complexity: Constant time if addressof(x) == this; otherwise, linear time.

size_type remove(const T& value);
template<class Predicate> size_type remove_if(Predicate pred);

15   Effects: Erases all the elements in the list referred to by a list iterator i for which the following
16   conditions hold: *i == value, pred(*i) != false. Invalidates only the iterators and references to
17   the erased elements.
18   Returns: The number of elements erased.
19   Throws: Nothing unless an exception is thrown by *i == value or pred(*i) != false.
20   Complexity: Exactly size() applications of the corresponding predicate.
21   Remarks: Stable (16.4.6.8).

size_type unique();
template<class BinaryPredicate> size_type unique(BinaryPredicate binary_pred);

20   Let binary_pred be equal_to<>{} for the first overload.
21   Preconditions: binary_pred is an equivalence relation.
22   Effects: Erases all but the first element from every consecutive group of equivalent elements. That is,
23   for a nonempty list, erases all elements referred to by the iterator i in the range [begin() + 1, end())
24   for which binary_pred(*i, *(i - 1)) is true. Invalidates only the iterators and references to the
25   erased elements.
26   Returns: The number of elements erased.
27   Throws: Nothing unless an exception is thrown by the predicate.
Complexity: If empty() is false, exactly size() - 1 applications of the corresponding predicate, otherwise no applications of the predicate.

```c++
void merge(list& x);
void merge(list&& x);
template<class Compare> void merge(list& x, Compare comp);
template<class Compare> void merge(list&& x, Compare comp);
```

Let comp be less<> for the first two overloads.

**Preconditions**: *this and x are both sorted with respect to the comparator comp, and get_allocator() == x.get_allocator() is true.

**Effects**: If addressof(x) == this, there are no effects. Otherwise, merges the two sorted ranges [begin(), end()) and [x.begin(), x.end()). The result is a range that is sorted with respect to the comparator comp. Pointers and references to the moved elements of x now refer to those same elements but as members of *this. Iterators referring to the moved elements will continue to refer to their elements, but they now behave as iterators into *this, not into x.

Complexity: At most size() + x.size() - 1 comparisons if addressof(x) != this; otherwise, no comparisons are performed.

**Remarks**: Stable (16.4.6.8). If addressof(x) != this, x is empty after the merge. No elements are copied by this operation. If an exception is thrown other than by a comparison there are no effects.

```c++
void reverse() noexcept;
```

**Effects**: Reverses the order of the elements in the list. Does not affect the validity of iterators and references.

**Complexity**: Linear time.

```c++
void sort();
template<class Compare> void sort(Compare comp);
```

**Effects**: Sorts the list according to the operator< or a Compare function object. If an exception is thrown, the order of the elements in *this is unspecified. Does not affect the validity of iterators and references.

**Complexity**: Approximately N log N comparisons, where N == size().

**Remarks**: Stable (16.4.6.8).

### 24.3.11.6 Erasure

```c++
template<class T, class Allocator, class U = T>
typename list<T, Allocator>::size_type erase(list<T, Allocator>& c, const U& value);
```

**Effects**: Equivalent to: return erase_if(c, [] { return elem == value; });

```c++
template<class T, class Allocator, class Predicate>
typename list<T, Allocator>::size_type erase_if(list<T, Allocator>& c, Predicate pred);
```

**Effects**: Equivalent to: return c.remove_if(pred);

### 24.3.12 Class template vector

**Overview**

A vector is a sequence container that supports (amortized) constant time insert and erase operations at the end; insert and erase in the middle take linear time. Storage management is handled automatically, though hints can be given to improve efficiency.

A vector meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), of a sequence container, including most of the optional sequence container requirements (24.2.4), and, for an element type other than bool, of a contiguous container (24.2.2.2). The exceptions are the push_front, prepend_range, pop_front, and emplace_front member functions, which are not provided. Descriptions are provided here only for operations on vector that are not described in one of these tables or for operations where there is additional semantic information.
The types `iterator` and `const_iterator` meet the constexpr iterator requirements (25.3.1).

```cpp
namespace std {
  template<class T, class Allocator = allocator<T>>
  class vector {
  public:
    // types
    using value_type = T;
    using allocator_type = Allocator;
    using pointer = typename allocator_traits<Allocator>::pointer;
    using const_pointer = typename allocator_traits<Allocator>::const_pointer;
    using reference = value_type&;
    using const_reference = const value_type&;
    using size_type = implementation-defined; // see 24.2
    using difference_type = implementation-defined; // see 24.2
    using iterator = implementation-defined; // see 24.2
    using const_iterator = implementation-defined; // see 24.2
    using reverse_iterator = std::reverse_iterator<iterator>;
    using const_reverse_iterator = std::reverse_iterator<const_iterator>;
    // 24.3.12.2, construct/copy/destroy
    constexpr vector() noexcept(noexcept(Allocator())) : vector(Allocator()) { }
    constexpr explicit vector(const Allocator&) noexcept;
    constexpr explicit vector(size_type n, const Allocator& = Allocator());
    constexpr vector(size_type n, const T& value, const Allocator& = Allocator());
    template<class InputIterator>
    constexpr vector(InputIterator first, InputIterator last, const Allocator& = Allocator());
    template<container-compatible-range<T> R>
    constexpr vector(from_range_t, R&& rg, const Allocator& = Allocator());
    constexpr vector(const vector& x);
    constexpr vector(vector&&) noexcept;
    constexpr vector(const vector&, const type_identity_t<Allocator>&);
    constexpr vector(vector&&, const type_identity_t<Allocator>&);
    constexpr vector(initializer_list<T>, const Allocator& = Allocator());
    constexpr ~vector();
    constexpr vector& operator=(const vector& x);
    constexpr vector& operator=(vector&& x) noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
                                             allocator_traits<Allocator>::is_always_equal::value);
    constexpr vector& operator=(initializer_list<T>);
    template<class InputIterator>
    constexpr void assign(InputIterator first, InputIterator last);
    template<container-compatible-range<T> R>
    constexpr void assign_range(R&& rg);
    constexpr void assign(size_type n, const T& u);
    constexpr void assign(initializer_list<T>);
    constexpr allocator_type get_allocator() const noexcept;
    // iterators
    constexpr iterator begin() noexcept;
    constexpr const_iterator begin() const noexcept;
    constexpr iterator end() noexcept;
    constexpr const_iterator end() const noexcept;
    constexpr reverse_iterator rbegin() noexcept;
    constexpr const_reverse_iterator rbegin() const noexcept;
    constexpr reverse_iterator rend() noexcept;
    constexpr const_reverse_iterator rend() const noexcept;
    constexpr const_iterator cbegin() const noexcept;
    constexpr const_iterator cend() const noexcept;
    constexpr const_reverse_iterator crbegin() const noexcept;
    constexpr const_reverse_iterator crend() const noexcept;
  }
```

§ 24.3.12.1
// 24.3.12.3, capacity
[[nodiscard]] constexpr bool empty() const noexcept;
constexpr size_type size() const noexcept;
constexpr size_type max_size() const noexcept;
constexpr size_type capacity() const noexcept;
constexpr void resize(size_type sz);
constexpr void resize(size_type sz, const T& c);
constexpr void reserve(size_type n);
constexpr void shrink_to_fit();

// element access
constexpr reference operator[](size_type n);
constexpr const_reference operator[](size_type n) const;
constexpr const_reference at(size_type n) const;
constexpr reference at(size_type n);
constexpr reference front();
constexpr const_reference front() const;
constexpr reference back();
constexpr const_reference back() const;

// 24.3.12.4, data access
constexpr T* data() noexcept;
constexpr const T* data() const noexcept;

// 24.3.12.5, modifiers
template<class... Args> constexpr reference emplace_back(Args&&... args);
constexpr void push_back(const T& x);
constexpr void push_back(T&& x);
template<
  container-compatible-range<T> R>
  constexpr void append_range(R&& rg);
constexpr void pop_back();
template<class... Args> constexpr iterator emplace(const_iterator position, Args&&... args);
constexpr iterator insert(const_iterator position, const T& x);
constexpr iterator insert(const_iterator position, T&& x);
constexpr iterator insert(const_iterator position, size_type n, const T& x);
template<class InputIterator>
  constexpr iterator insert(const_iterator position,
    InputIterator first, InputIterator last);
template<
  container-compatible-range<T> R>
  constexpr iterator insert_range(const_iterator position, R&& rg);
constexpr iterator insert(const_iterator position, initializer_list<T> il);
constexpr iterator erase(const_iterator position);
constexpr iterator erase(const_iterator first, const_iterator last);
constexpr void swap(vector&);

  noexcept(allocator_traits<Allocator>::propagate_on_container_swap::value ||
    allocator_traits<Allocator>::is_always_equal::value);
constexpr void clear() noexcept;
};

template<class InputIterator, class Allocator = allocator<
  iter-value-type<InputIterator>>>
  vector<InputIterator, InputIterator, Allocator>
    -> vector<iter-value-type<InputIterator>, Allocator>;

template<ranges::input_range R, class Allocator = allocator<
  ranges::range_value_t<R>>>
  vector<from_range_t, R&&, Allocator>
    -> vector<ranges::range_value_t<R>, Allocator>;
}

4 An incomplete type T may be used when instantiating vector if the allocator meets the allocator completeness requirements (16.4.4.6.2). T shall be complete before any member of the resulting specialization of vector is referenced.
24.3.12.2 Constructors

```cpp
constexpr explicit vector(const Allocator&) noexcept;
```

**Effects:** Constructs an empty `vector`, using the specified allocator.

**Complexity:** Constant.

```cpp
constexpr explicit vector(size_type n, const Allocator& = Allocator());
```

**Preconditions:** `T` is `Cpp17DefaultInsertable` into `*this`.

**Effects:** Constructs a `vector` with `n` default-inserted elements using the specified allocator.

**Complexity:** Linear in `n`.

```cpp
constexpr vector(size_type n, const T& value, const Allocator& = Allocator());
```

**Preconditions:** `T` is `Cpp17CopyInsertable` into `*this`.

**Effects:** Constructs a `vector` with `n` copies of `value`, using the specified allocator.

**Complexity:** Linear in `n`.

```cpp
template<class InputIterator>
constexpr vector(InputIterator first, InputIterator last, const Allocator& = Allocator());
```

**Effects:** Constructs a `vector` equal to the range `[first, last)`, using the specified allocator.

**Complexity:** Makes only `N` calls to the copy constructor of `T` (where `N` is the distance between `first` and `last`) and no reallocations if iterators `first` and `last` are of forward, bidirectional, or random access categories. It makes order `N` calls to the copy constructor of `T` and order \( \log N \) reallocations if they are just input iterators.

```cpp
template<container-compatible-range<T> R>
constexpr vector(from_range_t, R&& rg, const Allocator& = Allocator());
```

**Effects:** Constructs a `vector` object with the elements of the range `rg`, using the specified allocator.

**Complexity:** Initializes exactly `N` elements from the results of dereferencing successive iterators of `rg`, where `N` is \( \text{ranges:}:\text{distance}(rg) \). Performs no reallocations if `R` models `ranges:>:\text{forward_range}` or `ranges:>:\text{sized_range}`; otherwise, performs order \( \log N \) reallocations and order `N` calls to the copy or move constructor of `T`.

24.3.12.3 Capacity

```cpp
constexpr size_type capacity() const noexcept;
```

**Returns:** The total number of elements that the vector can hold without requiring reallocation.

**Complexity:** Constant time.

```cpp
constexpr void reserve(size_type n);
```

**Preconditions:** `T` is `Cpp17MoveInsertable` into `*this`.

**Effects:** A directive that informs a `vector` of a planned change in size, so that it can manage the storage allocation accordingly. After `reserve()`, `capacity()` is greater or equal to the argument of `reserve` if reallocation happens; and equal to the previous value of `capacity()` otherwise. Reallocation happens at this point if and only if the current capacity is less than the argument of `reserve()`. If an exception is thrown other than by the move constructor of a non-`Cpp17CopyInsertable` type, there are no effects.

**Throws:** `length_error` if `n > max_size()`.

**Complexity:** It does not change the size of the sequence and takes at most linear time in the size of the sequence.

**Remarks:** Reallocation invalidates all the references, pointers, and iterators referring to the elements in the sequence, as well as the past-the-end iterator.

[Note 1: If no reallocation happens, they remain valid. — end note]

---

246) `reserve()` uses `Allocator::allocate()` which can throw an appropriate exception.
No reallocation shall take place during insertions that happen after a call to `reserve()` until an insertion would make the size of the vector greater than the value of `capacity()`.

```cpp
constexpr void shrink_to_fit();
```

**Preconditions:** `T` is `Cpp17MoveInsertable` into `*this`.

**Effects:** `shrink_to_fit` is a non-binding request to reduce `capacity()` to `size()`.

[Note 2: The request is non-binding to allow latitude for implementation-specific optimizations. — end note]

It does not increase `capacity()`, but may reduce `capacity()` by causing reallocation. If an exception is thrown other than by the move constructor of a non-`Cpp17CopyInsertable` `T` there are no effects.

**Complexity:** If reallocation happens, linear in the size of the sequence.

**Remarks:** Reallocation invalidates all the references, pointers, and iterators referring to the elements in the sequence as well as the past-the-end iterator.

[Note 3: If no reallocation happens, they remain valid. — end note]

```cpp
constexpr void swap(vector& x)
    noexcept(allocator_traits<Allocator>::propagate_on_container_swap::value ||
              allocator_traits<Allocator>::is_always_equal::value);
```

**Effects:** Exchanges the contents and `capacity()` of `*this` with that of `x`.

**Complexity:** Constant time.

```cpp
constexpr void resize(size_type sz);
```

**Preconditions:** `T` is `Cpp17MoveInsertable` and `Cpp17DefaultInsertable` into `*this`.

**Effects:** If `sz < size()`, erases the last `size() - sz` elements from the sequence. Otherwise, appends `sz - size()` default-inserted elements to the sequence.

**Remarks:** If an exception is thrown other than by the move constructor of a non-`Cpp17CopyInsertable` `T` there are no effects.

```cpp
constexpr void resize(size_type sz, const T& c);
```

**Preconditions:** `T` is `Cpp17CopyInsertable` into `*this`.

**Effects:** If `sz < size()`, erases the last `size() - sz` elements from the sequence. Otherwise, appends `sz - size()` copies of `c` to the sequence.

**Remarks:** If an exception is thrown there are no effects.

### 24.3.12.4 Data

```cpp
constexpr T* data() noexcept;
constexpr const T* data() const noexcept;
```

**Returns:** A pointer such that `[data(), data() + size()]` is a valid range. For a non-empty vector, `data() == addressof(front())` is true.

**Complexity:** Constant time.

### 24.3.12.5 Modifiers

```cpp
constexpr iterator insert(const_iterator position, const T& x);
constexpr iterator insert(const_iterator position, T&& x);
constexpr iterator insert(const_iterator position, size_type n, const T& x);
template<class InputIterator>
constexpr iterator insert(const_iterator position, InputIterator first, InputIterator last);
template<container-compatible-range<T> R>
constexpr iterator insert_range(const_iterator position, R&& rg);
constexpr iterator insert(const_iterator position, initializer_list<T>);
template<class... Args> constexpr reference emplace_back(Args&&... args);
template<class... Args> constexpr iterator emplace(const_iterator position, Args&&... args);
constexpr void push_back(const T& x);
constexpr void push_back(T&& x);
```
template<container-compatible-range<T> R>
constexpr void append_range(R& rg);

Complexity: If reallocation happens, linear in the number of elements of the resulting vector; otherwise, linear in the number of elements inserted plus the distance to the end of the vector.

Remarks: Causes reallocation if the new size is greater than the old capacity. Reallocation invalidates all the references, pointers, and iterators referring to the elements in the sequence, as well as the past-the-end iterator. If no reallocation happens, then references, pointers, and iterators before the insertion point remain valid but those at or after the insertion point, including the past-the-end iterator, are invalidated. If an exception is thrown other than by the copy constructor, move constructor, assignment operator, or move assignment operator of T or by any InputIterator operation there are no effects. If an exception is thrown while inserting a single element at the end and T is Cpp17CopyInsertable or is_nothrow_move_constructible_v<T> is true, there are no effects. Otherwise, if an exception is thrown by the move constructor of a non-Cpp17CopyInsertable T, the effects are unspecified.

namespace std {
    template<class T, class Allocator, class U = T>
    constexpr typename vector<T, Allocator>::size_type erase(vector<T, Allocator>& c, const U& value);  

    Effects: Equivalent to:
    auto it = remove(c.begin(), c.end(), value);
    auto r = distance(it, c.end());
    c.erase(it, c.end());
    return r;

    template<class T, class Allocator, class Predicate>
    constexpr typename vector<T, Allocator>::size_type erase_if(vector<T, Allocator>& c, Predicate pred);

    Effects: Equivalent to:
    auto it = remove_if(c.begin(), c.end(), pred);
    auto r = distance(it, c.end());
    c.erase(it, c.end());
    return r;
}
using difference_type = implementation-defined; // see 24.2
using iterator = implementation-defined; // see 24.2
using const_iterator = implementation-defined; // see 24.2
using reverse_iterator = std::reverse_iterator<iterator>;
using const_reverse_iterator = std::reverse_iterator<const_iterator>;

// bit reference
class reference {
friend class vector;
constexpr reference() noexcept;
public:
constexpr reference(const reference&) = default;
constexpr ~reference();
constexpr operator bool() const noexcept;
constexpr reference& operator=(bool x) noexcept;
constexpr reference& operator=(const reference& x) noexcept;
constexpr const reference& operator=(bool x) const noexcept;
constexpr void flip() noexcept; // flips the bit;
};

// construct/copy/destroy
constexpr vector() noexcept(noexcept(Allocator())) : vector(Allocator()) { }
constexpr explicit vector(const Allocator&) noexcept;
constexpr explicit vector(size_type n, const Allocator& = Allocator());
constexpr vector(const Allocator& value, const Allocator& = Allocator());
template<class InputIterator>
constexpr vector(InputIterator first, InputIterator last, const Allocator& = Allocator());
template<container-compatible-range<bool> R>
constexpr vector(from_range_t, R&& rg, const Allocator& = Allocator());
constexpr vector(const vector& x);
constexpr vector(vector&& x) noexcept;
constexpr vector(const vector&, const type_identity_t<Allocator>&);
constexpr vector(vector&&, const type_identity_t<Allocator>&);
constexpr vector(initializer_list<bool>, const Allocator& = Allocator());
constexpr ~vector();
constexpr vector& operator=(const vector& x);
constexpr vector& operator=(vector&& x) noexcept(allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
allocator_traits<Allocator>::is_always_equal::value);
constexpr vector& operator=(initializer_list<bool>);
template<class InputIterator>
constexpr void assign(InputIterator first, InputIterator last);
template<container-compatible-range<bool> R>
constexpr void assign_range(R&& rg);
constexpr void assign(size_type n, const bool& t);
constexpr void assign(initializer_list<bool>);
constexpr allocator_type get_allocator() const noexcept;

// iterators
constexpr iterator begin() noexcept;
constexpr const_iterator begin() const noexcept;
constexpr iterator end() noexcept;
constexpr const_iterator end() const noexcept;
constexpr reverse_iterator rbegin() noexcept;
constexpr const_reverse_iterator rbegin() const noexcept;
constexpr reverse_iterator rend() noexcept;
constexpr const_reverse_iterator rend() const noexcept;
constexpr const_iterator cbegin() const noexcept;
constexpr const_iterator cend() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept;
constexpr const_reverse_iterator crend() const noexcept;
// capacity
[[nodiscard]] constexpr bool empty() const noexcept;
constexpr size_type size() const noexcept;
constexpr size_type max_size() const noexcept;
constexpr size_type capacity() const noexcept;
constexpr void resize(size_type sz, bool c = false);
constexpr void reserve(size_type n);
constexpr void shrink_to_fit();

// element access
constexpr reference operator[](size_type n);
constexpr const_reference operator[](size_type n) const;
constexpr const_reference at(size_type n) const;
constexpr reference at(size_type n);
constexpr reference front();
constexpr const_reference front() const;
constexpr reference back();
constexpr const_reference back() const;

// modifiers
template<class... Args> constexpr reference emplace_back(Args&&... args);
constexpr void push_back(const bool& x);
template<container-compatible-range<br>& R> constexpr void append_range(R&& rg);
constexpr void pop_back();
template<class... Args> constexpr iterator emplace(const_iterator position, Args&&... args);
constexpr iterator insert(const_iterator position, const bool& x);
constexpr iterator insert(const_iterator position, size_type n, const bool& x);
template<class InputIterator> constexpr iterator insert(const_iterator position,
InputIterator first, InputIterator last);
template<container-compatible-range<br>& R> constexpr iterator insert_range(const_iterator position, R&& rg);
constexpr iterator insert(const_iterator position, initializer_list<bool> il);
constexpr iterator erase(const_iterator position);
constexpr iterator erase(const_iterator first, const_iterator last);
constexpr void swap(vector&) noexcept(allocator_traits<Allocator>::propagate_on_container_swap::value ||
allocator_traits<Allocator>::is_always_equal::value);
static constexpr void swap(reference x, reference y) noexcept;
constexpr void flip() noexcept; // flips all bits
constexpr void clear() noexcept;
};

2 Unless described below, all operations have the same requirements and semantics as the primary vector template, except that operations dealing with the bool value type map to bit values in the container storage and allocator_traits::construct (20.2.9.3) is not used to construct these values.

3 There is no requirement that the data be stored as a contiguous allocation of bool values. A space-optimized representation of bits is recommended instead.

4 reference is a class that simulates the behavior of references of a single bit in vector<br>. The conversion function returns true when the bit is set, and false otherwise. The assignment operators set the bit when the argument is (convertible to) true and clear it otherwise. flip reverses the state of the bit.

constexpr void flip() noexcept;
5 Effects: Replaces each element in the container with its complement.

static constexpr void swap(reference x, reference y) noexcept;
6 Effects: Exchanges the contents of x and y as if by:
bool b = x;
x = y;
\[ y = b; \]

template<class Allocator> struct hash<vector<bool, Allocator>>;

The specialization is enabled (22.10.19).

template<class T>
constexpr bool is-vector-bool-reference = see below;

The expression \texttt{is-vector-bool-reference<T>} is true if \( T \) denotes the type \texttt{vector<bool, Alloc>::reference} for some type \texttt{Alloc} and \texttt{vector<bool, Alloc>} is not a program-defined specialization.

### 24.3.13.2 Formatter specialization for vector<bool>

[vector.bool.fmt]

```cpp
namespace std {
    template<class T, class charT>
    requires is-vector-bool-reference<T>
    struct formatter<T, charT> {
        private:
            formatter<bool, charT> underlying_; // exposition only

        public:
            template<class ParseContext>
            constexpr typename ParseContext::iterator
            parse(ParseContext& ctx);

            template<class FormatContext>
            typename FormatContext::iterator
            format(const T& ref, FormatContext& ctx) const;
    };
}
```

template<class ParseContext>
constexpr typename ParseContext::iterator
parse(ParseContext& ctx);

Equivalent to: \texttt{return underlying_.parse(ctx);}.

```cpp
template<class FormatContext>
typename FormatContext::iterator
format(const T& ref, FormatContext& ctx) const;
```

Equivalent to: \texttt{return underlying_.format(ref, ctx)};

### 24.3.14 Class template inplace_vector

[inplace.vector]

#### 24.3.14.1 Overview

[inplace.vector.overview]

An \texttt{inplace_vector} is a contiguous container. Its capacity is fixed and its elements are stored within the \texttt{inplace_vector} object itself.

An \texttt{inplace_vector} meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of a contiguous container, and of a sequence container, including most of the optional sequence container requirements (24.2.4). The exceptions are the \texttt{push_front}, \texttt{prepend_range}, \texttt{pop_front}, and \texttt{emplace_front} member functions, which are not provided. Descriptions are provided here only for operations on \texttt{inplace_vector} that are not described in one of these tables or for operations where there is additional semantic information.

For any \( N \), \texttt{inplace_vector<T, N>::iterator} and \texttt{inplace_vector<T, N>::const_iterator} meet the \texttt{contextexpr} iterator requirements.

For any \( N > 0 \), if \texttt{is_trivial_v<T>} is false, then no \texttt{inplace_vector<T, N>} member functions are usable in constant expressions.

Any member function of \texttt{inplace_vector<T, N>} that would cause the size to exceed \( N \) throws an exception of type \texttt{bad_alloc}.

Let \( IV \) denote a specialization of \texttt{inplace_vector<T, N>}. If \( N \) is zero, then \( IV \) is both trivial and empty. Otherwise:

\begin{itemize}
    \item If \texttt{is_trivially_copy_constructible_v<T>} is true, then \( IV \) has a trivial copy constructor.
\end{itemize}
If `is_trivially_move_constructible_v<T>` is true, then IV has a trivial move constructor.

If `is_trivially_destructible_v<T>` is true, then:

- IV has a trivial destructor.

If

```
if (is_trivially_copy_constructible_v<T> && is_trivially_copyAssignable_v<T>)
```

is true, then IV has a trivial copy assignment operator.

If

```
if (is_trivially_move_constructible_v<T> && is_trivially_moveAssignable_v<T>)
```

is true, then IV has a trivial move assignment operator.

```cpp
namespace std {
    template<class T, size_t N>
class inplace_vector {
public:
    // types:
    using value_type = T;
    using pointer = T*;
    using const_pointer = const T*;
    using reference = value_type&;
    using const_reference = const value_type&;
    using size_type = size_t;
    using difference_type = ptrdiff_t;
    using iterator = implementation-defined; // see 24.2
    using const_iterator = implementation-defined; // see 24.2
    using reverse_iterator = std::reverse_iterator<iterator>;
    using const_reverse_iterator = std::reverse_iterator<const_iterator>;

    constexpr inplace_vector() noexcept; // freestanding-deleted
    constexpr explicit inplace_vector(size_type n);
    constexpr inplace_vector(size_type n, const T& value);
    template<class InputIterator>
    constexpr inplace_vector(InputIterator first, InputIterator last);
    template<container-compatible-range<T> R>
    constexpr inplace_vector(from_range_t, R&& rg);
    constexpr inplace_vector(const inplace_vector&);
    constexpr inplace_vector(inplace_vector&&) noexcept(N == 0 || is_nothrow_move_constructible_v<T>);
    constexpr inplace_vector(initializer_list<T> il);
    constexpr ~inplace_vector(); // freestanding-deleted
    constexpr inplace_vector& operator=(const inplace_vector& other);
    constexpr inplace_vector& operator=(inplace_vector&& other) noexcept(N == 0 || (is_nothrow_moveAssignable_v<T> &&
    is_nothrow_moveConstructible_v<T>));
    constexpr inplace_vector& operator=(initializer_list<T> il); // freestanding-deleted
    template<class InputIterator>
    constexpr void assign(InputIterator first, InputIterator last); // freestanding-deleted
    template<container-compatible-range<T> R>
    constexpr void assign_range(R&& rg); // freestanding-deleted
    constexpr void assign(size_type n, const T& u); // freestanding-deleted
    constexpr void assign(initializer_list<T> il); // freestanding-deleted

    // iterators
    constexpr iterator begin() noexcept;
    constexpr const_iterator begin() const noexcept;
    constexpr iterator end() noexcept;
    constexpr const_iterator end() const noexcept;
    constexpr reverse_iterator rbegin() noexcept;
    constexpr const_reverse_iterator rbegin() const noexcept;
    constexpr reverse_iterator rend() noexcept;
    constexpr const_reverse_iterator rend() const noexcept;
}
```
constexpr const_iterator cbegin() const noexcept;
constexpr const_iterator cend() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept;
constexpr const_reverse_iterator crend() const noexcept;

// 24.3.14.3 size/capacity
constexpr bool empty() const noexcept;
constexpr size_type size() const noexcept;
static constexpr size_type max_size() noexcept;
static constexpr size_type capacity() noexcept;
constexpr void resize(size_type sz); // freestanding-deleted
constexpr void resize(size_type sz, const T& c); // freestanding-deleted
static constexpr void reserve(size_type n); // freestanding-deleted
static constexpr void shrink_to_fit() noexcept;

// element access
constexpr reference operator[](size_type n); // freestanding-deleted
constexpr const_reference operator[](size_type n) const;
constexpr reference at(size_type n); // freestanding-deleted
constexpr const_reference at(size_type n) const; // freestanding-deleted
constexpr reference front();
constexpr const_reference front() const;
constexpr reference back();
constexpr const_reference back() const;

// 24.3.14.4, data access
constexpr T* data() noexcept;
constexpr const T* data() const noexcept;

// 24.3.14.5, modifiers
template<class... Args>
constexpr reference emplace_back(Args&&... args); // freestanding-deleted
constexpr reference push_back(const T& x); // freestanding-deleted
constexpr reference push_back(T&& x); // freestanding-deleted
template<container-compatible-range<T> R>
constexpr void append_range(R&& rg); // freestanding-deleted
constexpr void pop_back();

template<class... Args>
constexpr pointer try_emplace_back(Args&&... args);
constexpr pointer try_push_back(const T& x);
constexpr pointer try_push_back(T&& x);
template<container-compatible-range<T> R>
constexpr ranges::borrowed_iterator_t<R> try_append_range(R&& rg); // freestanding-deleted

template<class... Args>
constexpr reference unchecked_emplace_back(Args&&... args);
constexpr reference unchecked_push_back(const T& x);
constexpr reference unchecked_push_back(T&& x);

template<class... Args>
constexpr iterator emplace(const_iterator position, Args&&... args); // freestanding-deleted
constexpr iterator insert(const_iterator position, const T& x); // freestanding-deleted
constexpr iterator insert(const_iterator position, T&& x); // freestanding-deleted
constexpr iterator insert(const_iterator position, size_type n, const T& x); // freestanding-deleted

template<class InputIterator>
constexpr iterator insert(const_iterator position, InputIterator first, InputIterator last);

template<container-compatible-range<T> R>
constexpr iterator insert_range(const_iterator position, R&& rg); // freestanding-deleted
constexpr iterator insert(const_iterator position, initializer_list<T> il);
constexpr iterator erase(const_iterator position);

§ 24.3.14.1
constexpr iterator erase(const_iterator first, const_iterator last);
constexpr void swap(inplace_vector& x)
    noexcept(N == 0 || (is_nothrow_swappable_v<T> &&
                      is_nothrow_move_constructible_v<T>));
constexpr void clear() noexcept;
constexpr friend bool operator==(const inplace_vector& x,
                                const inplace_vector& y);
constexpr friend
    synth-three-way-result<T>
operator<=>(const inplace_vector& x, const inplace_vector& y);
constexpr friend void swap(inplace_vector& x, inplace_vector& y)
    noexcept(N == 0 || (is_nothrow_swappable_v<T> &&
                      is_nothrow_move_constructible_v<T>))
    { x.swap(y); }
};

24.3.14.2 Constructors

constexpr explicit inplace_vector(size_type n);
  
  Preconditions: T is Cpp17DefaultInsertable into *this.
  
  Effects: Constructs an inplace_vector with n default-inserted elements.
  
  Complexity: Linear in n.

constexpr inplace_vector(size_type n, const T& value);
  
  Preconditions: T is Cpp17CopyInsertable into *this.
  
  Effects: Constructs an inplace_vector with n copies of value.
  
  Complexity: Linear in n.

template<class InputIterator>
constexpr inplace_vector(InputIterator first, InputIterator last);
  
  Effects: Constructs an inplace_vector equal to the range [first, last).
  
  Complexity: Linear in distance(first, last).

template<container-compatible-range<T> R>
constexpr inplace_vector(from_range_t, R&& rg);
  
  Effects: Constructs an inplace_vector object with the elements of the range rg.
  
  Complexity: Linear in ranges::distance(rg).

24.3.14.3 Size and capacity

static constexpr size_type capacity() noexcept;
static constexpr size_type max_size() noexcept;
  
  Returns: N.

constexpr void resize(size_type sz);
  
  Preconditions: T is Cpp17DefaultInsertable into *this.
  
  Effects: If sz < size(), erases the last size() - sz elements from the sequence. Otherwise, appends
          sz - size() default-inserted elements to the sequence.
  
  Remarks: If an exception is thrown, there are no effects on *this.

constexpr void resize(size_type sz, const T& c);
  
  Preconditions: T is Cpp17CopyInsertable into *this.
  
  Effects: If sz < size(), erases the last size() - sz elements from the sequence. Otherwise, appends
          sz - size() copies of c to the sequence.
  
  Remarks: If an exception is thrown, there are no effects on *this.
24.3.14.4 Data

constexpr T* data() noexcept;
constexpr const T* data() const noexcept;

Returns: A pointer such that \([\text{data()}, \text{data()} + \text{size()}]\) is a valid range. For a non-empty inplace_vector, \(\text{data()} == \text{addressof(front())}\) is true.

Complexity: Constant time.

24.3.14.5 Modifiers

constexpr iterator insert(const_iterator position, const T& x);
constexpr iterator insert(const_iterator position, T&& x);
constexpr iterator insert(const_iterator position, size_type n, const T& x);
template<class InputIterator>
constexpr iterator insert(const_iterator position, InputIterator first, InputIterator last);
template<\text{vector-compatible-range} <T> R>
constexpr iterator insert_range(const_iterator position, R&& rg);
constexpr iterator insert(const_iterator position, initializer_list<T> il);
template<class... Args>
constexpr iterator emplace(const_iterator position, Args&&... args);
template<\text{vector-compatible-range} <T> R>
constexpr void append_range(R&& rg);

1. Let \(n\) be value of \(\text{size()}\) before this call for the \text{append_range} overload, and \(\text{distance}()\) otherwise.

Complexity: Linear in the number of elements inserted plus the distance to the end of the vector.

2. Remarks: If an exception is thrown other than by the copy constructor, move constructor, assignment operator, or move assignment operator of \(T\) or by any \text{InputIterator} operation, there are no effects. Otherwise, if an exception is thrown, then \(\text{size()} \geq n\) and elements in the range \(\text{begin()} + [0,n)\) are not modified.

constexpr reference push_back(const T& x);
constexpr reference push_back(T&& x);
template<class... Args>
constexpr reference emplace_back(Args&&... args);

Returns: \(\text{back()}\).

Throws: \text{bad_alloc} or any exception thrown by initialization of inserted element.

Complexity: Constant.

Remarks: If an exception is thrown there are no effects on \(*\text{this}\).

template<class... Args>
constexpr pointer try_emplace_back(Args&&... args);
constexpr pointer try_push_back(const T& x);
constexpr pointer try_push_back(T&& x);

Let \(\text{vals}\) denote a pack:

\begin{align*}
1&:\quad &\text{std::forward<Args>}(\text{args})... \text{for the first overload,} \\
2&:\quad &\text{x} \text{for the second overload,} \\
3&:\quad &\text{set::move}(\text{x}) \text{for the third overload.}
\end{align*}

Preconditions: \(\text{value_type}\) is \text{Cpp17EmplaceConstructible}\ into \text{inplace_vector}\ from \text{vals}...\.

Effects: If \(\text{size()} < \text{capacity()}\) is \text{true}, appends an object of type \(T\) direct-non-list-initialized with \text{vals}...\ Otherwise, there are no effects.

Returns: \text{nullptr} if \(\text{size()} == \text{capacity()}\) is \text{true}, otherwise \text{addressof(back())}.

Throws: Nothing unless an exception is thrown by initialization of inserted element.

Complexity: Constant.

Remarks: If an exception is thrown there are no effects on \(*\text{this}\.\)
1. template<container-compatible-range<T> R>
   constexpr ranges::borrowed_iterator_t<R> try_append_range(R&& rg);

   Preconditions: value_type is Cpp17EmplaceConstructible into inplace_vector from
   *ranges::begin(rg).

   Effects: Appends copies of initial elements in rg before end(), until all elements are inserted or size() == capacity() is true. Each iterator in the range rg is dereferenced at most once.

   Returns: An iterator pointing to the first element of rg that was not inserted into *this, or
   ranged::end(rg) if no such element exists.

   Complexity: Linear in the number of elements inserted.

   Remarks: Let n be the value of size() prior to this call. If an exception is thrown after the insertion
   of k elements, then size() equals n + k, elements in the range begin() + [0, n) are not modified, and
   elements in the range begin() + [n, n + k) correspond to the inserted elements.

2. template<class... Args>
   constexpr reference unchecked_emplace_back(Args&&... args);

   Preconditions: size() < capacity() is true.

   Effects: Equivalent to: return *try_emplace_back(std::forward<Args>(args)...);

3. constexpr reference unchecked_push_back(const T& x);
   constexpr reference unchecked_push_back(T&& x);

   Preconditions: size() < capacity() is true.

   Effects: Equivalent to: return *try_push_back(std::forward<decltype(x)>(x));

4. static constexpr void reserve(size_type n);

   Effects: None.

   Throws: bad_alloc if n > capacity() is true.

5. static constexpr void shrink_to_fit() noexcept;

   Effects: None.

6. constexpr iterator erase(const_iterator position);
   constexpr iterator erase(const_iterator first, const_iterator last);
   constexpr void pop_back();

   Effects: Invalidates iterators and references at or after the point of the erase.

   Throws: Nothing unless an exception is thrown by the assignment operator or move assignment operator
   of T.

   Complexity: The destructor of T is called the number of times equal to the number of the elements
   erased, but the assignment operator of T is called the number of times equal to the number of elements
   after the erased elements.

24.3.14.6 Erasure

   template<class T, size_t N, class U = T>
   constexpr size_t erase(inplace_vector<T, N>& c, const U& value);

1. Effects: Equivalent to:
   auto it = remove(c.begin(), c.end(), value);
   auto r = distance(it, c.end());
   c.erase(it, c.end());
   return r;

2. template<class T, size_t N, class Predicate>
   constexpr size_t erase_if(inplace_vector<T, N>& c, Predicate pred);

2. Effects: Equivalent to:
   auto it = remove_if(c.begin(), c.end(), pred);
   auto r = distance(it, c.end());
   c.erase(it, c.end());
24.4 Associative containers

24.4.1 General

The header `<map>` defines the class templates `map` and `multimap`; the header `<set>` defines the class templates `set` and `multiset`.

The following exposition-only alias templates may appear in deduction guides for associative containers:

```cpp
template<class InputIterator>
using iter_value_type = typename iterator_traits<InputIterator>::value_type; // exposition only

template<class InputIterator>
using iter_key_type = remove_const_t<
tuple_element_t<0, iter_value_type<InputIterator>>; // exposition only

template<class InputIterator>
using iter_mapped_type =
tuple_element_t<1, iter_value_type<InputIterator>>; // exposition only

template<class InputIterator>
using iter_to_alloc_type = pair<
add_const_t<tuple_element_t<0, iter_value_type<InputIterator>>>,
tuple_element_t<1, iter_value_type<InputIterator>>; // exposition only

template<ranges::input_range Range>
using range_key_type = remove_const_t<typename ranges::range_value_t<Range>::first_type; // exposition only

template<ranges::input_range Range>
using range_mapped_type = typename ranges::range_value_t<Range>::second_type; // exposition only

template<ranges::input_range Range>
using range_to_alloc_type =
pair<add_const_t<typename ranges::range_value_t<Range>::first_type>,
type_name ranges::range_value_t<Range>::second_type; // exposition only
```

24.4.2 Header `<map>` synopsis

```cpp
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 24.4.4, class template map
template<class Key, class T, class Compare = less<Key>,
class Allocator = allocator<pair<const Key, T>>>
class map;

template<class Key, class T, class Compare, class Allocator>
bool operator==(const map<Key, T, Compare, Allocator>& x,
const map<Key, T, Compare, Allocator>& y);

template<class Key, class T, class Compare, class Allocator>
synth-three-way-result<
pair<const Key, T>>,
operator<=>(const map<Key, T, Compare, Allocator>& x,
const map<Key, T, Compare, Allocator>& y);

template<class Key, class T, class Compare, class Allocator>
void swap(map<Key, T, Compare, Allocator>& x,
map<Key, T, Compare, Allocator>& y)
noexcept(noexcept(x.swap(y)));

// 24.4.4.5, erasure for map
template<class Key, class T, class Compare, class Allocator, class Predicate>
type_name map<Key, T, Compare, Allocator>::size_type
erase_if(map<Key, T, Compare, Allocator>& c, Predicate pred);

// 24.4.5, class template multimap
template<class Key, class T, class Compare = less<Key>,
class Allocator = allocator<pair<const Key, T>>>
class multimap;
```
template<class Key, class T, class Compare, class Allocator>
bool operator==(const multimap<Key, T, Compare, Allocator>& x,
    const multimap<Key, T, Compare, Allocator>& y);

template<class Key, class T, class Compare, class Allocator>
synth-three-way-result<
pair<const Key, T>>
operator<=>(const multimap<Key, T, Compare, Allocator>& x,
    const multimap<Key, T, Compare, Allocator>& y);

template<class Key, class T, class Compare, class Allocator>
void swap(multimap<Key, T, Compare, Allocator>& x,
    multimap<Key, T, Compare, Allocator>& y)
    noexcept(noexcept(x.swap(y)));

// 24.4.5.4, erasure for multimap

template<class Key, class T, class Compare, class Allocator, class Predicate>
typename multimap<Key, T, Compare, Allocator>::size_type
    erase_if(multimap<Key, T, Compare, Allocator>& c, Predicate pred);

namespace pmr {
    template<class Key, class T, class Compare = less<Key>>
        using map = std::map<Key, T, Compare,
        polymorphic_allocator<pair<const Key, T>>;}

namespace std {
    template<class Key, class T, class Compare = less<Key>, class Allocator = allocator<Key>>
        class set;

    template<class Key, class Compare, class Allocator>
        bool operator==(const set<Key, Compare, Allocator>& x,
            const set<Key, Compare, Allocator>& y);

    template<class Key, class Compare, class Allocator>
synth-three-way-result<Key>
        operator<=>(const set<Key, Compare, Allocator>& x,
            const set<Key, Compare, Allocator>& y);

    template<class Key, class Compare, class Allocator>
        void swap(set<Key, Compare, Allocator>& x,
            set<Key, Compare, Allocator>& y)
            noexcept(noexcept(x.swap(y)));

    // 24.4.6.3, erasure for set

template<class Key, class Compare, class Allocator, class Predicate>
typename set<Key, Compare, Allocator>::size_type
    erase_if(set<Key, Compare, Allocator>& c, Predicate pred);

    // 24.4.7, class template multiset

template<class Key, class Compare = less<Key>, class Allocator = allocator<Key>>
        class multiset;

    template<class Key, class Compare, class Allocator>
        bool operator==(const multiset<Key, Compare, Allocator>& x,
            const multiset<Key, Compare, Allocator>& y);

24.4.3 Header <set> synopsis [associative.set.syn]

#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 24.4.6, class template set

template<class Key, class Compare = less<Key>, class Allocator = allocator<Key>>
        class set;

    template<class Key, class Compare, class Allocator>
        bool operator==(const set<Key, Compare, Allocator>& x,
            const set<Key, Compare, Allocator>& y);

    template<class Key, class Compare, class Allocator>
synth-three-way-result<Key>
        operator<=>(const set<Key, Compare, Allocator>& x,
            const set<Key, Compare, Allocator>& y);

    template<class Key, class Compare, class Allocator>
        void swap(set<Key, Compare, Allocator>& x,
            set<Key, Compare, Allocator>& y)
            noexcept(noexcept(x.swap(y)));

    // 24.4.6.3, erasure for set

template<class Key, class Compare, class Allocator, class Predicate>
typename set<Key, Compare, Allocator>::size_type
    erase_if(set<Key, Compare, Allocator>& c, Predicate pred);

    // 24.4.7, class template multiset

    template<class Key, class Compare = less<Key>, class Allocator = allocator<Key>>
        class multiset;

    template<class Key, class Compare, class Allocator>
        bool operator==(const multiset<Key, Compare, Allocator>& x,
            const multiset<Key, Compare, Allocator>& y);
template<class Key, class Compare, class Allocator>
    synth-three-way-result<Key> operator<=>(const multiset<Key, Compare, Allocator>& x,
        const multiset<Key, Compare, Allocator>& y);

template<class Key, class Compare, class Allocator>
void swap(multiset<Key, Compare, Allocator>& x,
        multiset<Key, Compare, Allocator>& y)
    noexcept(noexcept(x.swap(y)));

// 24.4.7.3, erasure for multiset
template<class Key, class Compare, class Allocator, class Predicate>
    typename multiset<Key, Compare, Allocator>::size_type
    erase_if(multiset<Key, Compare, Allocator>& c, Predicate pred);

namespace pmr {
    template<class Key, class Compare = less<Key>>
        using set = std::set<Key, Compare, polymorphic_allocator<Key>>;
    template<class Key, class Compare = less<Key>>
        using multiset = std::multiset<Key, Compare, polymorphic_allocator<Key>>;
}

24.4.4 Class template map

24.4.4.1 Overview

A map is an associative container that supports unique keys (i.e., contains at most one of each key value) and provides for fast retrieval of values of another type T based on the keys. The map class supports bidirectional iterators.

A map meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), and of an associative container (24.2.7). A map also provides most operations described in 24.2.7 for unique keys. This means that a map supports the a_uniq operations in 24.2.7 but not the a_eq operations. For a map<Key,T> the key_type is Key and the value_type is pair<const Key,T>. Descriptions are provided here only for operations on map that are not described in one of those tables or for operations where there is additional semantic information.

namespace std {
    template<class Key, class T, class Compare = less<Key>,
         class Allocator = allocator<pair<const Key, T>>> class map {
public:
    // types
    using key_type = Key;
    using mapped_type = T;
    using value_type = pair<const Key, T>;
    using key_compare = Compare;
    using allocator_type = Allocator;
    using pointer = typename allocator_traits<Allocator>::pointer;
    using const_pointer = typename allocator_traits<Allocator>::const_pointer;
    using reference = value_type&;
    using const_reference = const value_type&;
    using size_type = implementation-defined; // see 24.2
    using difference_type = implementation-defined; // see 24.2
    using iterator = implementation-defined; // see 24.2
    using const_iterator = implementation-defined; // see 24.2
    using reverse_iterator = std::reverse_iterator<iterator>;
    using const_reverse_iterator = std::reverse_iterator<const_iterator>;
    using node_type = unspecified;
    using insert_return_type = insert-return-type<iterator, node_type>;

    class value_compare {
        friend class map;
        protected:
            Compare comp;
        ...
    };

    ...

```
value_compare(Compare c) : comp(c) {}

public:
    bool operator()(const value_type& x, const value_type& y) const {
        return comp(x.first, y.first);
    }
};

// 24.4.4.2, construct/copy/destroy
map() : map(Compare()) {}
explicit map(Compare comp, const Allocator& = Allocator());
template<class InputIterator>
    map(InputIterator first, InputIterator last,
        const Compare& comp = Compare(), const Allocator& = Allocator());
template<container-compatible-range<value_type> R>
    map(from_range_t, R&& rg, const Compare& comp = Compare(), const Allocator& = Allocator());
map(const map& x);
map(map&& x);
explicit map(const Allocator&);
map(const map&, const type_identity_t<Allocator>&);
map(map&&, const type_identity_t<Allocator>&);
map(initializer_list<value_type>,
    const Compare& comp = Compare(),
    const Allocator& = Allocator());
template<class InputIterator>
    map(InputIterator first, InputIterator last, const Allocator& a)
    : map(first, last, Compare(), a) {}
template<container-compatible-range<value_type> R>
    map(from_range_t, R&& rg, const Allocator& a)
    : map(from_range, std::forward<R>(rg), Compare(), a) {}
map(initializer_list<value_type> il, const Allocator& a)
    : map(il, Compare(), a) {}
~map();
map& operator=(const map& x);
map& operator=(map&& x)
    noexcept(allocator_traits<Allocator>::is_always_equal::value &&
             is_nothrow_move_assignable_v<Compare>);
map& operator=(initializer_list<value_type>);
allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.4.4.3, element access
mapped_type& operator[](const key_type& x);
mapped_type& operator[](key_type&& x);
template<
    class K
> mapped_type& operator[](
    K&& x);  
const mapped_type& at(const key_type& x) const;

template<
    class K
> mapped_type& at(const K& x);  
template<
    class K
> const mapped_type& at(const K& x) const;

// 24.4.4.4, modifiers

template<
    class... Args
> pair<
    iterator, bool
> emplace(Args&&... args);

template<
    class... Args
> iterator emplace_hint(cons
ter_iterator position, Args&&... args);

pair<
    iterator, bool
> insert(const value_type& x);

pair<
    iterator, bool
> insert(value_type&& x);

iterator insert(const_iterator position, const value_type& x);

iterator insert(const_iterator position, value_type&& x);

template<
    class P
>
    iterator insert(const_iterator position, P&& x);

template<
    class P
>
    void insert(InputIterator first, InputIterator last);

template<
    
    container-compatible-range
    <value_type> R
>
    void insert_range(R&& rg);

    void insert(initializer_list<value_type>);

node_type extract(const_iterator position);

node_type extract(const key_type& x);

insert_return_type insert(node_type&& nh);

iterator insert(const_iterator position, const value_type& x);

iterator insert(const_iterator position, value_type&& x);

template<
    class... Args
>
    iterator insert(const_iterator position, P&& x);

template<
    class... Args
> void insert(InputIterator first, InputIterator last);

template<
    container-compatible-range
    <value_type> R
> void insert_range(R&& rg);

    void insert(initializer_list<value_type>);

node_type extract(const_iterator position);

node_type extract(const key_type& x);

insert_return_type insert(node_type&& nh);

iterator insert(const_iterator position, const value_type& x);

iterator insert(const_iterator position, value_type&& x);

template<
    class... Args
> iterator insert(const_iterator position, P&& x);

template<
    class... Args
> iterator insert(const_iterator position, P&& x);

template<
    class M
>
    iterator insert_or_assign(const_iterator position, M&& obj);

template<
    class M
>
    iterator insert_or_assign(const_iterator position, M& obj);

template<
    class M
>
    iterator insert_or_assign(const_iterator position, M&& obj);

template<
    class M
>
    iterator insert_or_assign(const_iterator position, M& obj);

    iterator insert_or_assign(const_iterator position, M&& obj);

    iterator insert_or_assign(const_iterator position, M& obj);

    iterator insert_or_assign(const_iterator position, M&& obj);

iterator erase(iterator position);

iterator erase(const_iterator position);

size_type erase(const key_type& x);

template<
    class K
> size_type erase(K&& x);

iterator erase(const_iterator first, const_iterator last);

void swap(map&);

    noexcept(allocator_traits<
        Allocator>::is_always_equal::value &&
        is_nothrow_swappable_v<
            Compare>);

    void clear() noexcept;
template<class C2>
    void merge(map<Key, T, C2, Allocator>& source);
template<class C2>
    void merge(map<Key, T, C2, Allocator>&& source);
template<class C2>
    void merge(multimap<Key, T, C2, Allocator>& source);
template<class C2>
    void merge(multimap<Key, T, C2, Allocator>&& source);

// observers
    key_compare key_comp() const;
    value_compare value_comp() const;

// map operations
    iterator find(const key_type& x);
    const_iterator find(const key_type& x) const;
    template<class K> iterator find(const K& x);
    template<class K> const_iterator find(const K& x) const;
    size_type count(const key_type& x) const;
    template<class K> size_type count(const K& x) const;
    bool contains(const key_type& x) const;
    template<class K> bool contains(const K& x) const;
    iterator lower_bound(const key_type& x);
    const_iterator lower_bound(const key_type& x) const;
    template<class K> iterator lower_bound(const K& x);
    template<class K> const_iterator lower_bound(const K& x) const;
    iterator upper_bound(const key_type& x);
    const_iterator upper_bound(const key_type& x) const;
    template<class K> iterator upper_bound(const K& x);
    template<class K> const_iterator upper_bound(const K& x) const;
    pair<iterator, iterator> equal_range(const key_type& x);
    pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
    template<class K> pair<iterator, iterator> equal_range(const K& x);
    template<class K> pair<const_iterator, const_iterator> equal_range(const K& x) const;

};

template<class InputIterator, class Compare = less<
    iter-key-type<
        InputIterator>>,
    class Allocator = allocator<
        iter-to-alloc-type<
            InputIterator>>> map(InputIterator, InputIterator, Compare = Compare(), Allocator = Allocator())
        -> map<
            iter-key-type<
                InputIterator>,
            iter-mapped-type<
                InputIterator>,
            Compare, Allocator>;

template<ranges::input_range R, class Compare = less<
    range-key-type<
        R>>,
    class Allocator = allocator<
        range-to-alloc-type<
            R>>> map(from_range_t, R&&, Compare = Compare(), Allocator = Allocator())
        -> map<
            range-key-type<
                R>,
            range-mapped-type<
                R>,
            Compare, Allocator>;

template<class Key, class T, class Compare = less<Key>,
    class Allocator = allocator<pair<const Key, T>>> map(initializer_list<pair<Key, T>>, Compare = Compare(), Allocator = Allocator())
        -> map<Key, T, Compare, Allocator>;

template<class InputIterator, class Allocator>
    map(InputIterator, InputIterator, Allocator)
        -> map<
            iter-key-type<
                InputIterator>,
            iter-mapped-type<
                InputIterator>,
            less<
                iter-key-type<
                    InputIterator>>,
            Allocator>;

§ 24.4.4.1
24.4.4.2 Constructors, copy, and assignment

```cpp
explicit map(const Compare& comp, const Allocator& = Allocator());
```

**Effects**: Constructs an empty `map` using the specified comparison object and allocator.

**Complexity**: Constant.

```cpp
template<class InputIterator>
map(InputIterator first, InputIterator last,
    const Compare& comp = Compare(), const Allocator& = Allocator());
```

**Effects**: Constructs an empty `map` using the specified comparison object and allocator, and inserts elements from the range `[first, last)`.  
**Complexity**: Linear in \(N\) if the range `[first, last)` is already sorted with respect to `comp` and otherwise \(N \log N\), where \(N = \text{last} - \text{first}\).

```cpp
template<container-compatible-range<R> R>
map(from_range_t, R&& rg, const Compare& comp = Compare(), const Allocator& = Allocator());
```

**Effects**: Constructs an empty `map` using the specified comparison object and allocator, and inserts elements from the range `rg`.  
**Complexity**: Linear in \(N\) if `rg` is already sorted with respect to `comp` and otherwise \(N \log N\), where \(N = \text{ranges::distance}(rg)\).

### 24.4.4.3 Element access

```cpp
mapped_type& operator[](const key_type& x);
```

**Effects**: Equivalent to: `return try_emplace(x).first->second;`

```cpp
mapped_type& operator[](key_type&& x);
```

**Effects**: Equivalent to: `return try_emplace(std::move(x)).first->second;`

```cpp
template<class K> mapped_type& operator[](K&& x);
```

**Constraints**: The qualified-id `Compare::is_transparent` is valid and denotes a type.

**Effects**: Equivalent to: `return try_emplace(std::forward<K>(x)).first->second;`

```cpp
mapped_type& at(const key_type& x);
const mapped_type& at(const key_type& x) const;
```

**Returns**: A reference to the `mapped_type` corresponding to `x` in `*this`.  
**Throws**: An exception object of type `out_of_range` if no such element is present.

**Complexity**: Logarithmic.

```cpp
template<class K> mapped_type& at(const K& x);
template<class K> const mapped_type& at(const K& x) const;
```

**Constraints**: The qualified-id `Compare::is_transparent` is valid and denotes a type.

**Preconditions**: The expression `find(x)` is well-formed and has well-defined behavior.

**Returns**: A reference to `find(x)->second`.  
**Throws**: An exception object of type `out_of_range` if `find(x) == end()` is true.

**Complexity**: Logarithmic.
24.4.4.4 Modifiers

```cpp
template<class P>
pair<iterator, bool> insert(P&& x);

template<class P>
iterator insert(const_iterator position, P&& x);
```

**Constraints:**

- `is_constructible_v<value_type, P&&>` is true.

**Effects:** The first form is equivalent to return `emplace(std::forward<P>(x))`. The second form is equivalent to return `emplace_hint(position, std::forward<P>(x))`.

```cpp
template<class... Args>
pair<iterator, bool> try_emplace(const key_type& k, Args&&... args);

template<class... Args>
iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);
```

**Preconditions:**

- `value_type` is `Cpp17EmplaceConstructible` into map from `piecewise_construct, forward_as_tuple(k), forward_as_tuple(std::forward<Args>(args))`.

**Effects:**

- If the map already contains an element whose key is equivalent to `k`, there is no effect. Otherwise, inserts an object of type `value_type` constructed with `piecewise_construct, forward_as_tuple(k), forward_as_tuple(std::forward<Args>(args))`.

**Returns:**

- In the first overload, the bool component of the returned pair is `true` if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to `k`.

**Complexity:**

- The same as `emplace` and `emplace_hint`, respectively.

```cpp
template<class... Args>
pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);

template<class... Args>
iterator try_emplace(const_iterator hint, key_type&& k, Args&&... args);
```

**Preconditions:**

- `value_type` is `Cpp17EmplaceConstructible` into map from `piecewise_construct, forward_as_tuple(std::move(k)), forward_as_tuple(std::forward<Args>(args))`.

**Effects:**

- If the map already contains an element whose key is equivalent to `k`, there is no effect. Otherwise, inserts an object of type `value_type` constructed with `piecewise_construct, forward_as_tuple(std::move(k)), forward_as_tuple(std::forward<Args>(args))`.

**Returns:**

- In the first overload, the bool component of the returned pair is `true` if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to `k`.

**Complexity:**

- The same as `emplace` and `emplace_hint`, respectively.

```cpp
template<class K, class... Args>
pair<iterator, bool> try_emplace(K&& k, Args&&... args);

template<class K, class... Args>
iterator try_emplace(const_iterator hint, K&& k, Args&&... args);
```

**Constraints:**

- The qualified-id `Compare::is_transparent` is valid and denotes a type. For the first overload, `is_convertible_v<K&&, const_iterator>` and `is_convertible_v<K&&, iterator>` are both `false`.

**Preconditions:**

- `value_type` is `Cpp17EmplaceConstructible` into map from `piecewise_construct, forward_as_tuple(std::forward<K>(k)), forward_as_tuple(std::forward<Args>(args))`.

**Effects:**

- If the map already contains an element whose key is equivalent to `k`, there is no effect. Otherwise, let `r` be `equal_range(k)`. Constructs an object `u` of type `value_type` with `piecewise_construct, forward_as_tuple(std::forward<K>(k)), forward_as_tuple(std::forward<Args>(args))`. If `equal_range(u.first) == r` is `false`, the behavior is undefined. Inserts `u` into *this.

**Returns:**

- For the first overload, the bool component of the returned pair is `true` if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to `k`.

**Complexity:**

- The same as `emplace` and `emplace_hint`, respectively.

```cpp
template<class M>
pair<iterator, bool> insert_or_assign(const key_type& k, M&& obj);
```
**24.4.4.5 Erasure**

```cpp
template<class Key, class T, class Compare, class Allocator, class Predicate>
typename map<Key, T, Compare, Allocator>::size_type
erase_if(map<Key, T, Compare, Allocator>& c, Predicate pred);
```

**Effects:** Equivalent to:

```cpp
auto original_size = c.size();
for (auto i = c.begin(), last = c.end(); i != last; i++) {
    if (pred(*i)) {
        i = c.erase(i);
    } else {
        ++i;
    }
}
```
A *multimap* is an associative container that supports equivalent keys (i.e., possibly containing multiple copies of the same key value) and provides for fast retrieval of values of another type \( T \) based on the keys. The *multimap* class supports bidirectional iterators.

A *multimap* meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), and of an associative container (24.2.7). A *multimap* also provides most operations described in 24.2.7 for equal keys. This means that a *multimap* supports the `a_eq` operations in 24.2.7 but not the `a_uniq` operations. For a `multimap<Key,T>` the key type is `Key` and the value type is `pair<const Key,T>`.

```
namespace std {
    template<class Key, class T, class Compare = less<Key>,
             class Allocator = allocator<pair<const Key, T>>>
    class multimap {
public:
    // types
    using key_type = Key;
    using mapped_type = T;
    using value_type = pair<const Key, T>;
    using key_compare = Compare;
    using allocator_type = Allocator;
    using pointer = typename allocator_traits<Allocator>::pointer;
    using const_pointer = typename allocator_traits<Allocator>::const_pointer;
    using reference = value_type&;
    using const_reference = const value_type&;
    using size_type = implementation-defined; // see 24.2
    using difference_type = implementation-defined; // see 24.2
    using iterator = implementation-defined; // see 24.2
    using const_iterator = implementation-defined; // see 24.2
    using reverse_iterator = std::reverse_iterator<iterator>;
    using const_reverse_iterator = std::reverse_iterator<const_iterator>;
    using node_type = unspecified;

    class value_compare {
        friend class multimap;
        protected:
            Compare comp;
        value_compare(Compare c) : comp(c) { }
    public:
        bool operator()(const value_type& x, const value_type& y) const {
            return comp(x.first, y.first);
        }
    };

    // 24.4.5.2, construct/copy/destroy
    multimap() : multimap(Compare()) { }
    explicit multimap(const Compare& comp, const Allocator& = Allocator());
    template<class InputIterator>
    multimap(InputIterator first, InputIterator last,
             const Compare& comp = Compare(),
             const Allocator& = Allocator());
    template<container-compatible-range<value_type> R>
    multimap(from_range_t, R&& rg,
             const Compare& comp = Compare(), const Allocator& = Allocator());
    multimap(const multimap& x);
    multimap(multimap&& x);
    explicit multimap(const Allocator&);
}
```
multimap(const multimap&, const type_identity_t<Allocator>&);
multimap(multimap&&, const type_identity_t<Allocator>&);
multimap(initializer_list<value_type>,
    const Compare& = Compare(),
    const Allocator& = Allocator());
template<class InputIterator>
    multimap(InputIterator first, InputIterator last, const Allocator& a)
    : multimap(first, last, Compare(), a) { }
template<container-compatible-range<value_type> R>
    multimap(from_range_t, R&& rg, const Allocator& a))
    : multimap(from_range, std::forward<R>(rg), Compare(), a) { }
multimap(initializer_list<value_type> il, const Allocator& a)
    : multimap(il, Compare(), a) { }
~multimap();
multimap& operator=(const multimap& x);
multimap& operator=(multimap&& x)
    noexcept(allocator_traits<Allocator>::is_always_equal::value &&
              is_nothrow_move_assignable_v<Compare>);
multimap& operator=(initializer_list<value_type> il, const Allocator& a)
    allocator_type get_allocator() const noexcept;

    // iterators
    iterator begin() noexcept;
    const_iterator begin() const noexcept;
    iterator end() noexcept;
    const_iterator end() const noexcept;
    reverse_iterator rbegin() noexcept;
    const_reverse_iterator rbegin() const noexcept;
    reverse_iterator rend() noexcept;
    const_reverse_iterator rend() const noexcept;
    const_iterator cbegin() const noexcept;
    const_iterator cend() const noexcept;
    const_reverse_iterator crbegin() const noexcept;
    const_reverse_iterator crend() const noexcept;

    // capacity
    [[nodiscard]] bool empty() const noexcept;
    size_type size() const noexcept;
    size_type max_size() const noexcept;

    // 24.4.5.3, modifiers
    template<class... Args> iterator emplace(Args&&... args);
    template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
    iterator insert(const value_type& x);
    iterator insert(value_type&& x);
    template<class P> iterator insert(P&& x);
    iterator insert(const_iterator position, const value_type& x);
    iterator insert(const_iterator position, value_type&& x);
    template<class P> iterator insert(const_iterator position, P&& x);
    template<class InputIterator>
        void insert(InputIterator first, InputIterator last);
    template<container-compatible-range<value_type> R>
        void insert_range(R&& rg);
    void insert(initializer_list<value_type> il);
    node_type extract(const_iterator position);
    node_type extract(const key_type& x);
    template<class K> node_type extract(K& x);
    iterator insert(node_type&& nh);
    iterator insert(const_iterator hint, node_type&& nh);
iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);
void swap(multimap&);
    noexcept(allocator_traits<Allocator>::is_always_equal::value && is_nothrow_swappable_v<Compare>);
void clear() noexcept;

template<class C2>
    void merge(multimap<Key, T, C2, Allocator>& source);
    void merge(multimap<Key, T, C2, Allocator>&& source);
    void merge(map<Key, T, C2, Allocator>& source);
    void merge(map<Key, T, C2, Allocator>&& source);

// observers
    key_compare key_comp() const;
    value_compare value_comp() const;

// map operations
    iterator find(const key_type& x);
    const_iterator find(const key_type& x) const;
    template<class K> iterator find(const K& x);
    template<class K> const_iterator find(const K& x) const;
    size_type count(const key_type& x) const;
    template<class K> size_type count(const K& x) const;
    bool contains(const key_type& x) const;
    template<class K> bool contains(const K& x) const;
    iterator lower_bound(const key_type& x);
    const_iterator lower_bound(const key_type& x) const;
    template<class K> iterator lower_bound(const K& x);
    template<class K> const_iterator lower_bound(const K& x) const;
    iterator upper_bound(const key_type& x);
    const_iterator upper_bound(const key_type& x) const;
    template<class K> iterator upper_bound(const K& x);
    template<class K> const_iterator upper_bound(const K& x) const;
    pair<iterator, iterator> equal_range(const key_type& x);
    pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
    template<class K>
        pair<iterator, iterator> equal_range(const K& x);
        template<class K>
            pair<const_iterator, const_iterator> equal_range(const K& x) const;
    
    template<class InputIterator, class Compare = less<
        iter-key-type<
            InputIterator>,
        class Allocator = allocator<
            iter-to-alloc-type<
                InputIterator>>>
        multimap(InputIterator, InputIterator, Compare = Compare(), Allocator = Allocator())
        -> multimap<
            iter-key-type<
                InputIterator>,
            iter-to-alloc-type<
                InputIterator>, Compare, Allocator>;

    template<ranges::input_range R, class Compare = less<
        range-key-type<R>,
        class Allocator = allocator<
            range-to-alloc-type<R>>>
        multimap(from_range_t, R&&, Compare = Compare(), Allocator = Allocator())
        -> multimap<
            range-key-type<R>,
            range-to-alloc-type<R>, Compare, Allocator>;

§ 24.4.5.1
template<class Key, class T, class Compare = less<Key>,
class Allocator = allocator<pair<const Key, T>>>
multimap(initializer_list<pair<Key, T>>, Compare = Compare(), Allocator = Allocator())
  -> multimap<Key, T, Compare, Allocator>;

template<class InputIterator, class Allocator>
multimap(InputIterator, InputIterator, Allocator)
  -> multimap<iter-key-type<InputIterator>, iter-mapped-type<InputIterator>,
               less<iter-key-type<InputIterator>>, Allocator>;

template<ranges::input_range R, class Allocator>
multimap(from_range_t, R&&, Allocator)
  -> multimap<range-key-type<R>, range-mapped-type<R>, less<range-key-type<R>>, Allocator>;

template<class Key, class T, class Allocator>
multimap(initializer_list<pair<Key, T>>, Allocator)
  -> multimap<Key, T, less<Key>, Allocator>;

§ 24.4.5.2 Constructors [multimap.cons]
explicit multimap(const Compare& comp, const Allocator& = Allocator());
  Effects: Constructs an empty multimap using the specified comparison object and allocator.
  Complexity: Constant.

template<class InputIterator>
multimap(InputIterator first, InputIterator last,
         const Compare& comp = Compare(),
         const Allocator& = Allocator());
  Effects: Constructs an empty multimap using the specified comparison object and allocator, and inserts
          elements from the range [first,last).
  Complexity: Linear in \( N \) if the range [first,last) is already sorted with respect to \( \text{comp} \) and otherwise
              \( N \log N \), where \( N \) is last - first.

template<container-compatible-range<value_type> R>
multimap(from_range_t, R&& rg, const Compare& comp = Compare(), const Allocator& = Allocator());
  Effects: Constructs an empty multimap using the specified comparison object and allocator, and inserts
           elements from the range rg.
  Complexity: Linear in \( N \) if \( \text{rg} \) is already sorted with respect to \( \text{comp} \) and otherwise \( N \log N \), where \( N \)
              is ranges::distance(rg).

§ 24.4.5.3 Modifiers [multimap.modifiers]
template<class P> iterator insert(P&& x);
template<class P> iterator insert(const_iterator position, P&& x);
  Constraints: is_constructible_v<value_type, P&&> is true.
  Effects: The first form is equivalent to return emplace(std::forward<P>(x)). The second form is
equivalent to return emplace_hint(position, std::forward<P>(x)).

§ 24.4.5.4 Erasure [multimap.erasure]
template<class Key, class T, class Compare, class Allocator, class Predicate>
typename multimap<Key, T, Compare, Allocator>::size_type
  erase_if(multimap<Key, T, Compare, Allocator>& c, Predicate pred);
  Effects: Equivalent to:
          auto original_size = c.size();
          for (auto i = c.begin(), last = c.end(); i != last; ) {
            if (pred(*i)) {
              i = c.erase(i);
            } else {
              
§ 24.4.5.4
++i;

} // c

return original_size - c.size();

24.4.6 Class template set

24.4.6.1 Overview

A set is an associative container that supports unique keys (i.e., contains at most one of each key value) and provides for fast retrieval of the keys themselves. The set class supports bidirectional iterators.

A set meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), and of an associative container (24.2.7). A set also provides most operations described in 24.2.7 for unique keys. This means that a set supports the a_uniq operations in 24.2.7 but not the a_eq operations. For a set<Key> both the key_type and value_type are Key. Descriptions are provided here only for operations on set that are not described in one of these tables and for operations where there is additional semantic information.

namespace std {

    template<class Key, class Compare = less<Key>,
             class Allocator = allocator<Key>>
    class set {

        public:

        // types
        using key_type = Key;
        using key_compare = Compare;
        using value_type = Key;
        using value_compare = Compare;
        using allocator_type = Allocator;
        using pointer = typename allocator_traits<Allocator>::pointer;
        using const_pointer = typename allocator_traits<Allocator>::const_pointer;
        using reference = value_type&;
        using const_reference = const value_type&;
        using size_type = implementation-defined; // see 24.2
        using difference_type = implementation-defined; // see 24.2
        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
        using reverse_iterator = std::reverse_iterator<iterator>;
        using const_reverse_iterator = std::reverse_iterator<const_iterator>;
        using node_type = unspecified;
        using insert_return_type = insert-return-type<iterator, node_type>;

        // 24.4.6.2, construct/copy/destroy
        set() : set(Compare()) {} 
        explicit set(const Compare& comp, const Allocator& = Allocator());
        template<class InputIterator>
        set(InputIterator first, InputIterator last,
            const Compare& comp = Compare(), const Allocator& = Allocator());
        template<container-compatible-range<value_type> R>
        set(from_range_t, R&& rg, const Compare& comp = Compare(), const Allocator& = Allocator());
        set(const set& x);
        set(set&& x);
        explicit set(const Allocator&);
        set(const set&, const type_identity_t<Allocator>&);
        set(initializer_list<value_type>, const Compare& = Compare(),
            const Allocator& = Allocator());
        template<class InputIterator>
        set(InputIterator first, InputIterator last, const Allocator& a)
            : set(first, last, Compare(), a) {} 
        template<container-compatible-range<value_type> R>
        set(from_range_t, R&& rg, const Allocator& a))
            : set(from_range, std::forward<R>(rg), Compare(), a) {} 
        set(initializer_list<value_type> il, const Allocator& a)
            : set(il, Compare(), a) {} 
    } // class set

} // namespace std

§ 24.4.1
- `set();`
- `set& operator=(const set& x);`
- `set& operator=(set&& x) noexcept(algorithm_traits<Allocator>::is_always_equal::value && is_nothrow_move_assignable_v<Compare>);`
- `set& operator=(initializer_list<value_type>);`

// iterators
- `iterator begin() noexcept;`
- `const_iterator begin() const noexcept;`
- `iterator end() noexcept;`
- `const_iterator end() const noexcept;`
- `reverse_iterator rbegin() noexcept;`
- `const_reverse_iterator rbegin() const noexcept;`
- `reverse_iterator rend() noexcept;`
- `const_reverse_iterator rend() const noexcept;`
- `const_iterator cbegin() const noexcept;`
- `const_iterator cend() const noexcept;`
- `const_reverse_iterator crbegin() const noexcept;`
- `const_reverse_iterator crend() const noexcept;`

// capacity
- `[nodiscard] bool empty() const noexcept;`
- `size_type size() const noexcept;`
- `size_type max_size() const noexcept;`

// 24.4.6.4, modifiers
- `template<class... Args> pair<iterator, bool> emplace(Args&&... args);`
- `template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);`
- `pair<iterator,bool> insert(const value_type& x);`
- `pair<iterator,bool> insert(value_type&& x);`
- `template<class K> pair<iterator, bool> insert(K&& x);`
- `template<class K> iterator insert(const_iterator position, K&& x);`
- `template<class InputIterator> void insert(InputIterator first, InputIterator last);`
- `template<container-compatible-range<value_type> R> void insert_range(R&& rg);`
- `void insert(initializer_list<value_type>);`
- `node_type extract(const_iterator position);`
- `node_type extract(const key_type& x);`
- `template<class K> node_type extract(K&& x);`
- `insert_return_type insert(node_type&& nh);`
- `iterator insert(const_iterator hint, node_type&& nh);`
- `iterator erase(iterator position) requires (!same_as<iterator, const_iterator>);`
- `iterator erase(const_iterator position);`
- `size_type erase(const key_type& x);`
- `template<class K> size_type erase(K&& x);`
- `iterator erase(const_iterator first, const_iterator last);`
- `void swap(set&) noexcept(algorithm_traits<Allocator>::is_always_equal::value && is_nothrow_swappable_v<Compare>);`
- `void clear() noexcept;`

template<class C2>
void merge(set<Key, C2, Allocator>& source);
template<class C2>
    void merge(set<Key, C2, Allocator>&& source);
template<class C2>
    void merge(multiset<Key, C2, Allocator>& source);
template<class C2>
    void merge(multiset<Key, C2, Allocator>&& source);

// observers
    key_compare key_comp() const;
    value_compare value_comp() const;

// set operations
    iterator find(const key_type& x);
    const_iterator find(const key_type& x) const;
template<class K> iterator find(const K& x);
template<class K> const_iterator find(const K& x) const;
    size_type count(const key_type& x) const;
template<class K> size_type count(const K& x) const;
    bool contains(const key_type& x) const;
template<class K> bool contains(const K& x) const;
    iterator lower_bound(const key_type& x);
    const_iterator lower_bound(const key_type& x) const;
template<class K> iterator lower_bound(const K& x);
template<class K> const_iterator lower_bound(const K& x) const;
    iterator upper_bound(const key_type& x);
    const_iterator upper_bound(const key_type& x) const;
template<class K> iterator upper_bound(const K& x);
template<class K> const_iterator upper_bound(const K& x) const;
    pair<iterator, iterator> equal_range(const key_type& x);
    pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
template<class K> pair<iterator, iterator> equal_range(const K& x);
template<class K> pair<const_iterator, const_iterator> equal_range(const K& x) const;
};

template<class InputIterator, 
    class Compare = less<
        iter_value_type<
            InputIterator
        >>, 
    class Allocator = allocator<
        iter_value_type<
            InputIterator
        >>>
set(InputIterator, InputIterator, 
    Compare = Compare(), Allocator = Allocator())
-> set<
    iter_value_type<
        InputIterator
    >, Compare, Allocator>;

template<ranges::input_range R, class Compare = less<ranges::range_value_t<R>>, 
    class Allocator = allocator<ranges::range_value_t<R>>> 
set(from_range_t, R&&, 
    Compare = Compare(), Allocator = Allocator())
-> set<ranges::range_value_t<R>, Compare, Allocator>;

template<class Key, class Compare = less<Key>, class Allocator = allocator<Key>>
set(initializer_list<Key>, 
    Compare = Compare(), Allocator = Allocator())
-> set<Key, Compare, Allocator>;

template<class InputIterator, class Allocator>
set(InputIterator, 
    InputIterator, Allocator)
-> set<
    iter_value_type<
        InputIterator
    >, 
    less<
        iter_value_type<
            InputIterator
        >, Allocator>;

§ 24.4.6.1


```cpp
template<ranges::input_range R, class Allocator>
set(from_range_t, R&&, Allocator)
    -> set<ranges::range_value_t<R>, less<ranges::range_value_t<R>>, Allocator>;

template<class Key, class Allocator>
set(initializer_list<Key>, Allocator) -> set<Key, less<Key>, Allocator>;
```

## 24.4.6.2 Constructors, copy, and assignment

### [set.cons]

```cpp
explicit set(const Compare& comp, const Allocator& = Allocator());
```

**Effects:** Constructs an empty set using the specified comparison object and allocator.

**Complexity:** Constant.

### [set.cons]

```cpp
template<class InputIterator>
set(InputIterator first, InputIterator last,
    const Compare& comp = Compare(), const Allocator& = Allocator());
```

**Effects:** Constructs an empty set using the specified comparison object and allocator, and inserts elements from the range `[first, last)`.

**Complexity:** Linear in \( N \) if the range `[first, last)` is already sorted with respect to `comp` and otherwise \( N \log N \), where \( N \) is `last - first`.

### [set.cons]

```cpp
template<container-compatible-range<value_type> R>
set(from_range_t, R&& rg, const Compare& comp = Compare(), const Allocator& = Allocator());
```

**Effects:** Constructs an empty set using the specified comparison object and allocator, and inserts elements from the range `rg`.

**Complexity:** Linear in \( N \) if `rg` is already sorted with respect to `comp` and otherwise \( N \log N \), where \( N \) is `ranges::distance(rg)`.

## 24.4.6.3 Erasure

### [set.eraser]

```cpp
template<class Key, class Compare, class Allocator, class Predicate>
type name set<Key, Compare, Allocator>:::size_type
    erase_if(set<Key, Compare, Allocator>& c, Predicate pred);
```

**Effects:** Equivalent to:

```cpp
auto original_size = c.size();
for (auto i = c.begin(), last = c.end(); i != last; ) {
    if (pred(*i)) {
        i = c.erase(i);
    } else {
        ++i;
    }
} return original_size - c.size();
```

## 24.4.6.4 Modifiers

### [set.modifiers]

```cpp
template<class K> pair<iterator, bool> insert(K&& x);
```

**Constraints:** The qualified-id `Compare::is_transparent` is valid and denotes a type. For the second overload, `is_convertible_v<K&&, const_iterator>` and `is_convertible_v<K&&, iterator>` are both `false`.

**Preconditions:** `value_type` is `Cpp17EmplaceConstructible` into `set` from `std::forward<K>(x)`.

**Effects:** If the set already contains an element that is equivalent to `x`, there is no effect. Otherwise, let `r` be `equal_range(x)`. Constructs an object `u` of type `value_type` with `std::forward<K>(x)`. If `equal_range(u) == r` is `false`, the behavior is undefined. Inserts `u` into `*this`.

**Returns:** For the first overload, the `bool` component of the returned pair is `true` if and only if the insertion took place. The returned iterator points to the set element that is equivalent to `x`.

**Complexity:** Logarithmic.
A `multiset` is an associative container that supports equivalent keys (i.e., possibly contains multiple copies of the same key value) and provides for fast retrieval of the keys themselves. The `multiset` class supports bidirectional iterators.

`multiset` meets all of the requirements of a container (24.2.2.2), of a reversible container (24.2.2.3), of an allocator-aware container (24.2.2.5), of an associative container (24.2.7). `multiset` also provides most operations described in 24.2.7 for duplicate keys. This means that a `multiset` supports the `a_eq` operations in 24.2.7 but not the `a_uniq` operations. For a `multiset<Key>` both the `key_type` and `value_type` are `Key`.

Descriptions are provided here only for operations on `multiset` that are not described in one of these tables and for operations where there is additional semantic information.

```cpp
namespace std {
  template<class Key, class Compare = less<Key>,
           class Allocator = allocator<Key>>
  class multiset {
    public:
      // types
      using key_type = Key;
      using key_compare = Compare;
      using value_type = Key;
      using value_compare = Compare;
      using allocator_type = Allocator;
      using pointer = typename allocator_traits<Allocator>::pointer;
      using const_pointer = typename allocator_traits<Allocator>::const_pointer;
      using reference = value_type&;
      using const_reference = const value_type&;
      using size_type = implementation-defined; // see 24.2
      using difference_type = implementation-defined; // see 24.2
      using iterator = implementation-defined; // see 24.2
      using const_iterator = implementation-defined; // see 24.2
      using reverse_iterator = std::reverse_iterator<iterator>;
      using const_reverse_iterator = std::reverse_iterator<const_iterator>;
      using node_type = unspecified;

      // 24.4.7.2, construct/copy/destroy
      multiset() : multiset(Compare()) { }
      explicit multiset(const Compare& comp, const Allocator& = Allocator());
      template<class InputIterator>
      multiset(InputIterator first, InputIterator last,
                const Compare& comp = Compare(), const Allocator& = Allocator());
      template<container-compatible-range<value_type> R>
      multiset(from_range_t, R&& rg,
               const Compare& comp = Compare(), const Allocator& = Allocator());
      multiset(const multiset& x);
      multiset(multiset&& x);
      explicit multiset(const Allocator&);
      multiset(const multiset&, const type_identity_t<Allocator>&);
      multiset(multiset&&, const type_identity_t<Allocator>&);
      multiset(initializer_list<value_type>, const Compare& = Compare(),
               const Allocator& = Allocator());
      template<class InputIterator>
      multiset(InputIterator first, InputIterator last, const Allocator& a)
      : multiset(first, last, Compare(), a) { }
      template<container-compatible-range<value_type> R>
      multiset(from_range_t, R&& rg, const Allocator& a)
      : multiset(from_range, std::forward<R>(rg), Compare(), a) { }
      multiset(initializer_list<value_type> il, const Allocator& a)
      : multiset(il, Compare(), a) { }
    ~multiset();
    multiset& operator=(const multiset& x);
  }
}
```
multiset& operator=(multiset&& x)
    noexcept(allocator_traits<Allocator>::is_always_equal::value &&
              is_nothrow_move_assignable_v<Compare>);
multiset& operator=(initializer_list<value_type>);
allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;

const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// modifiers
template<class... Args> iterator emplace(Args&&... args);
template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
iterator insert(const value_type& x);
iterator insert(value_type&& x);
iterator insert(const_iterator position, const value_type& x);
iterator insert(const_iterator position, value_type&& x);
template<class InputIterator>
    void insert(InputIterator first, InputIterator last);
template<container-compatible-range<value_type> R>
    void insert_range(R&& rg);
    void insert(initializer_list<value_type>);
node_type extract(const_iterator position);
node_type extract(const key_type& x);
template<class K> node_type extract(K&& x);
iterator insert(node_type&& nh);
iterator insert(const_iterator hint, node_type&& nh);
iterator erase(iterator position)
    requires (!same_as<iterator, const_iterator>);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);
void swap(multiset&)
    noexcept(allocator_traits<Allocator>::is_always_equal::value &&
              is_nothrow_swappable_v<Compare>);
void clear() noexcept;

template<class C2>
    void merge(multiset<Key, C2, Allocator>& source);
template<class C2>
    void merge(multiset<Key, C2, Allocator>&& source);
template<class C2>
    void merge(set<Key, C2, Allocator>& source);

§ 24.4.7.1
template<class C2>
  void merge(set<Key, C2, Allocator>&& source);

// observers
key_compare key_comp() const;
value_compare value_comp() const;

// set operations
iterator find(const key_type& x);
const_iterator find(const key_type& x) const;
template<class K> iterator find(const K& x);
template<class K> const_iterator find(const K& x) const;

size_type count(const key_type& x) const;
template<class K> size_type count(const K& x) const;

bool contains(const key_type& x) const;
template<class K> bool contains(const K& x) const;

iterator lower_bound(const key_type& x);
const_iterator lower_bound(const key_type& x) const;
template<class K> iterator lower_bound(const K& x);
template<class K> const_iterator lower_bound(const K& x) const;

iterator upper_bound(const key_type& x);
const_iterator upper_bound(const key_type& x) const;
template<class K> iterator upper_bound(const K& x);
template<class K> const_iterator upper_bound(const K& x) const;
	pair<iterator, iterator> equal_range(const key_type& x);
	pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
template<class K> pair<iterator, iterator> equal_range(const K& x);
template<class K> pair<const_iterator, const_iterator> equal_range(const K& x) const;

§ 24.4.7.1
template<class Key, class Allocator>
    multiset(initializer_list<Key>, Allocator) -> multiset<Key, less<Key>, Allocator>;

24.4.7.2 Constructors

explicit multiset(const Compare& comp, const Allocator& = Allocator());

Effects: Constructs an empty multiset using the specified comparison object and allocator.

Complexity: Constant.

template<class InputIterator>
    multiset(InputIterator first, InputIterator last,
             const Compare& comp = Compare(), const Allocator& = Allocator());

Effects: Constructs an empty multiset using the specified comparison object and allocator, and inserts elements from the range [first, last).

Complexity: Linear in N if the range [first, last) is already sorted with respect to comp and otherwise N log N, where N is last - first.

template<container-compatible-range<value_type> R>
    multiset(from_range_t, R&& rg, const Compare& comp = Compare(), const Allocator& = Allocator());

Effects: Constructs an empty multiset using the specified comparison object and allocator, and inserts elements from the range rg.

Complexity: Linear in N if rg is already sorted with respect to comp and otherwise N log N, where N is ranges::distance(rg).

24.4.7.3 Erasure

template<class Key, class Compare, class Allocator, class Predicate>
    typename multiset<Key, Compare, Allocator>::size_type
    erase_if(multiset<Key, Compare, Allocator>& c, Predicate pred);

Effects: Equivalent to:

auto original_size = c.size();
for (auto i = c.begin(), last = c.end(); i != last; ) {
    if (pred(*i)) {
        i = c.erase(i);
    } else {
        ++i;
    }
}
return original_size - c.size();

24.5 Unordered associative containers

24.5.1 General

The header <unordered_map> defines the class templates unordered_map and unordered_multimap; the header <unordered_set> defines the class templates unordered_set and unordered_multiset.

The exposition-only alias templates iter-value-type, iter-key-type, iter-mapped-type, iter-to-alloc-type, range-key-type, range-mapped-type, and range-to-alloc-type defined in 24.4.1 may appear in deduction guides for unordered containers.

24.5.2 Header <unordered_map> synopsis

#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
    // 24.5.4, class template unordered_map
    template<class Key,
             class T,
             class Hash = hash<Key>,
             class Pred = equal_to<Key>,
             class Compare = equal_to<Key>,
             class Allocator = allocator<

§ 24.5.2 ©ISO/IEC 998
class Alloc = allocator<pair<const Key, T>>
class unordered_map;

// 24.5.5, class template unordered_multimap
template<class Key,
class T,
class Hash = hash<Key>,
class Pred = equal_to<Key>,
class Alloc = allocator<pair<const Key, T>>
class unordered_multimap;

template<class Key, class T, class Hash, class Pred, class Alloc>
bool operator==(const unordered_map<Key, T, Hash, Pred, Alloc>& a,
const unordered_map<Key, T, Hash, Pred, Alloc>& b);

template<class Key, class T, class Hash, class Pred, class Alloc>
bool operator==(const unordered_multimap<Key, T, Hash, Pred, Alloc>& a,
const unordered_multimap<Key, T, Hash, Pred, Alloc>& b);

template<class Key, class T, class Hash, class Pred, class Alloc>
void swap(unordered_map<Key, T, Hash, Pred, Alloc>& x,
unordered_map<Key, T, Hash, Pred, Alloc>& y)
noexcept(noexcept(x.swap(y)));

template<class Key, class T, class Hash, class Pred, class Alloc>
void swap(unordered_multimap<Key, T, Hash, Pred, Alloc>& x,
unordered_multimap<Key, T, Hash, Pred, Alloc>& y)
noexcept(noexcept(x.swap(y)));

// 24.5.4.5, erasure for unordered_map
template<class K, class T, class H, class P, class A, class Predicate>
typename unordered_map<K, T, H, P, A>::size_type
erase_if(unordered_map<K, T, H, P, A>& c, Predicate pred);

// 24.5.5.4, erasure for unordered_multimap
template<class K, class T, class H, class P, class A, class Predicate>
typename unordered_multimap<K, T, H, P, A>::size_type
erase_if(unordered_multimap<K, T, H, P, A>& c, Predicate pred);

namespace pmr {

template<class Key,
class T,
class Hash = hash<Key>,
class Pred = equal_to<Key>>
using unordered_map =
std::unordered_map<Key, T, Hash, Pred,
polymorphic_allocator<pair<const Key, T>>;

template<class Key,
class T,
class Hash = hash<Key>,
class Pred = equal_to<Key>>
using unordered_multimap =
std::unordered_multimap<Key, T, Hash, Pred,
polymorphic_allocator<pair<const Key, T>>;
}

24.5.3 Header <unordered_set> synopsis [unord.set.syn]
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

§ 24.5.3 ©ISO/IEC 999
namespace std {

    // 24.5.6, class template unordered_set
    template<class Key,
             class Hash = hash<Key>,
             class Pred = equal_to<Key>,
             class Alloc = allocator<Key>>
    class unordered_set;

    // 24.5.7, class template unordered_multiset
    template<class Key,
             class Hash = hash<Key>,
             class Pred = equal_to<Key>,
             class Alloc = allocator<Key>>
    class unordered_multiset;

template<class Key, class Hash, class Pred, class Alloc>
    bool operator==(const unordered_set<Key, Hash, Pred, Alloc>& a,
                    const unordered_set<Key, Hash, Pred, Alloc>& b);

template<class Key, class Hash, class Pred, class Alloc>
    bool operator==(const unordered_multiset<Key, Hash, Pred, Alloc>& a,
                    const unordered_multiset<Key, Hash, Pred, Alloc>& b);

template<class Key, class Hash, class Pred, class Alloc>
    void swap(unordered_set<Key, Hash, Pred, Alloc>& x,
              unordered_set<Key, Hash, Pred, Alloc>& y)
    noexcept(noexcept(x.swap(y)));

    template<class Key, class Hash, class Pred, class Alloc>
    void swap(unordered_multiset<Key, Hash, Pred, Alloc>& x,
              unordered_multiset<Key, Hash, Pred, Alloc>& y)
    noexcept(noexcept(x.swap(y)));

    // 24.5.6.3, erasure for unordered_set
    template<class K, class H, class P, class A, class Predicate>
    typename unordered_set<K, H, P, A>::size_type
    erase_if(unordered_set<K, H, P, A>& c, Predicate pred);

    // 24.5.7.3, erasure for unordered_multiset
    template<class K, class H, class P, class A, class Predicate>
    typename unordered_multiset<K, H, P, A>::size_type
    erase_if(unordered_multiset<K, H, P, A>& c, Predicate pred);

namespace pmr {
    template<class Key,
             class Hash = hash<Key>,
             class Pred = equal_to<Key>>
    using unordered_set = std::unordered_set<Key, Hash, Pred,
                                           polymorphic_allocator<Key>>;

    template<class Key,
             class Hash = hash<Key>,
             class Pred = equal_to<Key>>
    using unordered_multiset = std::unordered_multiset<Key, Hash, Pred,
                                             polymorphic_allocator<Key>>;
}

24.5.4 Class template unordered_map

24.5.4.1 Overview

An unordered_map is an unordered associative container that supports unique keys (an unordered_map contains at most one of each key value) and that associates values of another type mapped_type with the keys. The unordered_map class supports forward iterators.
An unordered_map meets all of the requirements of a container (24.2.2.2), of an allocator-aware container (24.2.2.5), and of an unordered associative container (24.2.8). It provides the operations described in the preceding requirements table for unique keys; that is, an unordered_map supports the a_uniq operations in that table, not the a_eq operations. For an unordered_map<Key, T> the key_type is Key, the mapped_type is T, and the value_type is pair<const Key, T>.

Subclause 24.5.4 only describes operations on unordered_map that are not described in one of the requirement tables, or for which there is additional semantic information.

```cpp
namespace std {
    template<class Key,
             class T,
             class Hash = hash<Key>,
             class Pred = equal_to<Key>,
             class Allocator = allocator<pair<const Key, T>>>
    class unordered_map {
    public:
        // types
        using key_type = Key;
        using mapped_type = T;
        using value_type = pair<const Key, T>;
        using hasher = Hash;
        using key_equal = Pred;
        using allocator_type = Allocator;
        using pointer = typename allocator_traits<Allocator>::pointer;
        using const_pointer = typename allocator_traits<Allocator>::const_pointer;
        using reference = value_type&;
        using const_reference = const value_type&;
        using size_type = implementation-defined; // see 24.2
        using difference_type = implementation-defined; // see 24.2
        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
        using local_iterator = implementation-defined; // see 24.2
        using const_local_iterator = implementation-defined; // see 24.2
        using node_type = unspecified;
        using insert_return_type = insert-return-type<iterator, node_type>;

        // 24.5.4.1, construct/copy/destroy
        unordered_map();
        explicit unordered_map(size_type n,
                                const hasher& hf = hasher(),
                                const key_equal& eql = key_equal(),
                                const allocator_type& a = allocator_type());
        template<class InputIterator>
        unordered_map(InputIterator f, InputIterator l,
                       size_type n = see below,
                       const hasher& hf = hasher(),
                       const key_equal& eql = key_equal(),
                       const allocator_type& a = allocator_type());
        template<container-compatible-range<value_type> R>
        unordered_map(from_range_t, R&& rg, size_type n = see below,
                       const hasher& hf = hasher(), const key_equal& eql = key_equal(),
                       const allocator_type& a = allocator_type());
        unordered_map(const unordered_map&);
        unordered_map(unordered_map&&);
        explicit unordered_map(const Allocator&);
        unordered_map(const unordered_map&, const type_identity_t<Allocator>&);
        unordered_map(unordered_map&&, const type_identity_t<Allocator>&);
        unordered_map(initializer_list<value_type> il,
                       size_type n = see below,
                       const hasher& hf = hasher(),
                       const key_equal& eql = key_equal(),
                       const allocator_type& a = allocator_type());
    } // unordered_map
}; // namespace std
```
const allocator_type& a = allocator_type();
unordered_map(size_type n, const allocator_type& a)
: unordered_map(n, hasher(), key_equal(), a) { }
unordered_map(size_type n, const hasher& hf, const allocator_type& a)
: unordered_map(n, hf, key_equal(), a) { }
template<class InputIterator>
unordered_map(InputIterator f, InputIterator l, size_type n, const allocator_type& a)
: unordered_map(f, l, n, hasher(), key_equal(), a) { }
template<class InputIterator>
unordered_map(InputIterator f, InputIterator l, size_type n, const hasher& hf,
const allocator_type& a, const allocator_type& a)
: unordered_map(f, l, n, hf, key_equal(), a) { }
template<container-compatible-range<value_type> R>
unordered_map(from_range_t, R&& rg, size_type n, const allocator_type& a)
: unordered_map(from_range, std::forward<R>(rg), n, hasher(), key_equal(), a) { }
template<container-compatible-range<value_type> R>
unordered_map(from_range_t, R&& rg, size_type n, const hasher& hf, const allocator_type& a)
: unordered_map(from_range, std::forward<R>(rg), n, hf, key_equal(), a) { }
unordered_map(initializer_list<value_type> il, size_type n, const allocator_type& a)
: unordered_map(il, n, hasher(), key_equal(), a) { }
unordered_map(initializer_list<value_type> il, size_type n, const hasher& hf,
const allocator_type& a)
: unordered_map(il, n, hf, key_equal(), a) { }
~unordered_map();
unordered_map& operator=(const unordered_map&);
unordered_map& operator=(unordered_map&&) noexcept(allocator_traits<Allocator>::is_always_equal::value &&
isnothrow_move_assignable_v<Hash> &&
isnothrow_move_assignable_v<Pred>);
allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.5.4.4, modifiers
template<class... Args> pair<iterator, bool> emplace(Args&&... args);
template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
pair<iterator, bool> insert(const value_type& obj);
pair<iterator, bool> insert(value_type&& obj);
template<class P> pair<iterator, bool> insert(P&& obj);
iterator insert(const_iterator hint, const value_type& obj);
iterator insert(const_iterator hint, value_type&& obj);
template<class P> iterator insert(const_iterator hint, P&& obj);
template<class InputIterator> void insert(InputIterator first, InputIterator last);
template<container-compatible-range<value_type> R>
void insert_range(R&& rg);
void insert(initializer_list<value_type>);
node_type extract(const_iterator position);
node_type extract(const key_type& x);
template<class K> node_type extract(K& x);
insert_return_type insert(node_type&& nh);
iterator insert(const_iterator hint, node_type&& nh);
template<class... Args>
  pair<iterator, bool> try_emplace(const key_type& k, Args&&... args);
template<class... Args>
  pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);
template<class K, class... Args>
  pair<iterator, bool> try_emplace(const_iterator hint, const key_type& k, Args&&... args);
template<class K, class... Args>
  pair<iterator, bool> try_emplace(const_iterator hint, key_type&& k, Args&&... args);
template<class K, class... Args>
  pair<iterator, bool> try_emplace(const_iterator hint, K&& k, Args&&... args);
template<class... Args>
  iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);
template<class... Args>
  iterator try_emplace(const_iterator hint, key_type&& k, Args&&... args);
template<class K, class... Args>
  iterator try_emplace(const_iterator hint, K&& k, Args&&... args);
template<class M>
  pair<iterator, bool> insert_or_assign(const key_type& k, M&& obj);  
template<class M>
  pair<iterator, bool> insert_or_assign(key_type&& k, M&& obj);  
template<class K, class M>
  pair<iterator, bool> insert_or_assign(const_iterator hint, const key_type& k, M&& obj);  
template<class K, class M>
  pair<iterator, bool> insert_or_assign(const_iterator hint, key_type&& k, M&& obj);  
template<class K, class M>
  pair<iterator, bool> insert_or_assign(const_iterator hint, K&& k, M&& obj);  

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& k);
size_type erase(const_iterator first, const_iterator last);
void swap(unordered_map&);

// observers
hasher hash_function() const;
key_equal key_eq() const;

// map operations
iterator find(const key_type& k);
const_iterator find(const key_type& k) const;
template<class K>
iterator find(const K& k);
template<class K>
const_iterator find(const K& k) const;
size_type count(const key_type& k) const;
size_type count(const_iterator first, const_iterator last) const;
bool contains(const key_type& k) const;
bool contains(const_iterator first, const_iterator last) const;
pair<iterator, iterator> equal_range(const key_type& k);  
pair<const_iterator, const_iterator> equal_range(const key_type& k) const;  
// 24.5.4.1
// 1003

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template<class K>
    pair<iterator, iterator> equal_range(const K& k);
template<class K>
    pair<const_iterator, const_iterator> equal_range(const K& k) const;

// 24.5.4.3, element access
mapped_type& operator[](const key_type& k);
mapped_type& operator[](key_type&& k);
template<class K> mapped_type& operator[](K&& k);
mapped_type& at(const key_type& k);
const mapped_type& at(const key_type& k) const;
template<class K> mapped_type& at(const K& k);
template<class K> const mapped_type& at(const K& k) const;

// bucket interface
size_type bucket_count() const noexcept;
size_type max_bucket_count() const noexcept;
size_type bucket_size(size_type n) const;
size_type bucket(const key_type& k) const;
template<class K> size_type bucket(const K& k) const;
local_iterator begin(size_type n);
const_local_iterator begin(size_type n) const;
local_iterator end(size_type n);
const_local_iterator end(size_type n) const;
const_local_iterator cbegin(size_type n) const;
const_local_iterator cend(size_type n) const;

// hash policy
float load_factor() const noexcept;
float max_load_factor() const noexcept;
void max_load_factor(float z);
void resize(size_type n);

};
template<class InputIterator, class Allocator>
unordered_map(InputIterator, InputIterator, Allocator)
  -> unordered_map<
    iter-key-type<InputIterator>,
    iter-mapped-type<InputIterator>,
    hash<iter-key-type<InputIterator>>,
    equal_to<iter-key-type<InputIterator>>,
    Allocator>;

template<class InputIterator, class Hash, class Allocator>
unordered_map(InputIterator, InputIterator, typename
  see below::size_type, Hash, Allocator)
  -> unordered_map<
    iter-key-type<InputIterator>,
    iter-mapped-type<InputIterator>,
    Hash,
    equal_to<iter-key-type<InputIterator>>,
    Allocator>;

template<ranges::input_range R, class Allocator>
unordered_map(from_range_t, R&&, typename
  see below::size_type, Allocator)
  -> unordered_map<
    range-key-type<R>,
    range-mapped-type<R>,
    hash<range-key-type<R>>,
    equal_to<range-key-type<R>>,
    Allocator>;

template<ranges::input_range R, class Allocator>
unordered_map(from_range_t, R&&, Allocator)
  -> unordered_map<
    range-key-type<R>,
    range-mapped-type<R>,
    hash<range-key-type<R>>,
    equal_to<range-key-type<R>>,
    Allocator>;

template<class Key, class T, class Allocator>
unordered_map(initializer_list<pair<Key, T>>, typename
  see below::size_type, Allocator)
  -> unordered_map<Key, T, hash<Key>, equal_to<Key>, Allocator>;

template<class Key, class T, class Allocator>
unordered_map(initializer_list<pair<Key, T>>, Allocator)
  -> unordered_map<Key, T, hash<Key>, equal_to<Key>, Allocator>;

A size_type parameter type in an unordered_map deduction guide refers to the size_type member type of the type deduced by the deduction guide.

24.5.4.2 Constructors

unordered_map() : unordered_map(size_type(see below)) { }
explicit unordered_map(size_type n,
  const hasher& hf = hasher(),
  const key_equal& eql = key_equal(),
  const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_map using the specified hash function, key equality predicate, and allocator, and using at least n buckets. For the default constructor, the number of buckets is implementation-defined. max_load_factor() returns 1.0.

Complexity: Constant.

template<class InputIterator>
unordered_map(InputIterator f, InputIterator l,
  size_type n = see below,
  const hasher& hf = hasher(),
  const key_equal& eql = key_equal(),
  const allocator_type& a = allocator_type());
template<container-compatible-range<value_type> R>
unordered_map(from_range_t, R&& rg,
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());
unordered_map(initializer_list<value_type> il,
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_map using the specified hash function, key equality predicate, and allocator, and using at least n buckets. If n is not provided, the number of buckets is implementation-defined. Then inserts elements from the range [f, l), rg, or il, respectively. max_load_factor() returns 1.0.

Complexity: Average case linear, worst case quadratic.

24.5.4.3 Element access

mapped_type& operator[](const key_type& k);

Effects: Equivalent to: return try_emplace(k).first->second;

mapped_type& operator[](key_type&& k);

Effects: Equivalent to: return try_emplace(std::move(k)).first->second;

template<class K> mapped_type& operator[](K&& k);

Effects: Equivalent to: return try_emplace(std::forward<K>(k)).first->second;

mapped_type& at(const key_type& k);
const mapped_type& at(const key_type& k) const;

Returns: A reference to x.second, where x is the (unique) element whose key is equivalent to k.

Throws: An exception object of type out_of_range if no such element is present.

template<class R> mapped_type& at(const K& k);
template<class R> const mapped_type& at(const K& k) const;

Constraints: The qualified-ids Hash::is_transparent and Pred::is_transparent are valid and denote types.

Preconditions: The expression find(k) is well-formed and has well-defined behavior.

Returns: A reference to find(k)->second.

Throws: An exception object of type out_of_range if find(k) == end() is true.

24.5.4.4 Modifiers

template<class P>
pair<iterator, bool> insert(P&& obj);

Constraints: is_constructible_v<value_type, P&&> is true.

Effects: Equivalent to: return emplace(std::forward<P>(obj));

template<class P>
iterator insert(const_iterator hint, P&& obj);

Constraints: is_constructible_v<value_type, P&&> is true.

Effects: Equivalent to: return emplace_hint(hint, std::forward<P>(obj));

template<class... Args>
pair<iterator, bool> try_emplace(const key_type& k, Args&&... args);
template<class... Args>
iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);

Preconditions: value_type is Cpp17EmplaceConstructible into unordered_map from piecewise_construct, forward_as_tuple(k), forward_as_tuple(std::forward<Args>(args)\ldots).

Effects: If the map already contains an element whose key is equivalent to k, there is no effect. Otherwise inserts an object of type value_type constructed with piecewise_construct, forward_as_tuple(k), forward_as_tuple(std::forward<Args>(args)\ldots).

Returns: In the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

Complexity: The same as emplace and emplace_hint, respectively.

template<class... Args>
pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);

Preconditions: value_type is Cpp17EmplaceConstructible into unordered_map from piecewise_construct, forward_as_tuple(std::move(k)), forward_as_tuple(std::forward<Args>(args)\ldots).

Effects: If the map already contains an element whose key is equivalent to k, there is no effect. Otherwise inserts an object of type value_type constructed with piecewise_construct, forward_as_tuple(std::move(k)), forward_as_tuple(std::forward<Args>(args)\ldots).

Returns: In the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

Complexity: The same as emplace and emplace_hint, respectively.

template<class K, class... Args>
pair<iterator, bool> try_emplace(K&& k, Args&&... args);

Preconditions: value_type is Cpp17EmplaceConstructible into unordered_map from piecewise_construct, forward_as_tuple(std::forward<K>(k)), forward_as_tuple(std::forward<Args>(args)\ldots).

Constraints: The qualified-ids Hash::is_transparent and Pred::is_transparent are valid and denote types. For the first overload, is_convertible_v<K&&, const_iterator> and is_convertible_v<K&&, iterator> are both false.

Effects: If the map already contains an element whose key is equivalent to k, there is no effect. Otherwise, let h be hash_function()(k). Constructs an object u of type value_type with piecewise_construct, forward_as_tuple(std::forward<K>(k)), forward_as_tuple(std::forward<Args>(args)\ldots). If hash_function()(u.first) != h || contains(u.first) is true, the behavior is undefined. Inserts u into *this.

Returns: For the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

Complexity: The same as emplace and emplace_hint, respectively.

template<class M>
pair<iterator, bool> insert_or_assign(const key_type& k, M&& obj);

template<class M>
iterator insert_or_assign(const_iterator hint, const key_type& k, M&& obj);

Mandates: is_assignable_v<mapped_type&, M&&> is true.

Preconditions: value_type is Cpp17EmplaceConstructible into unordered_map from k, std::forward<M>(obj).

Effects: If the map already contains an element e whose key is equivalent to k, assigns std::forward<M>(obj) to e.second. Otherwise inserts an object of type value_type constructed with k, std::forward<M>(obj).
Returns: In the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

Complexity: The same as emplace and emplace_hint, respectively.

```cpp
template<class M>
pair<iterator, bool> insert_or_assign(key_type&& k, M&& obj);
```

```cpp
template<class M>
iterator insert_or_assign(const_iterator hint, key_type&& k, M&& obj);
```

**Mandates:** is_assignable_v<mapped_type&, M&&> is true.

**Preconditions:** value_type is Cpp17EmplaceConstructible into unordered_map from std::move(k), std::forward<M>(obj).

**Effects:** If the map already contains an element e whose key is equivalent to k, assigns std::forward<M>(obj) to e.second. Otherwise inserts an object of type value_type constructed with std::move(k), std::forward<M>(obj).

**Returns:** In the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

**Complexity:** The same as emplace and emplace_hint, respectively.

```cpp
template<class K, class M>
pair<iterator, bool> insert_or_assign(K&& k, M&& obj);
```

```cpp
template<class K, class M>
iterator insert_or_assign(const_iterator hint, K&& k, M&& obj);
```

**Constraints:** The qualified-ids Hash::is_transparent and Pred::is_transparent are valid and denote types.

**Mandates:** is_assignable_v<mapped_type&, M&&> is true.

**Preconditions:** value_type is Cpp17EmplaceConstructible into unordered_map from std::forward<K>(k), std::forward<M>(obj).

**Effects:** If the map already contains an element e whose key is equivalent to k, assigns std::forward<M>(obj) to e.second. Otherwise, let h be hash_function()(k). Constructs an object u of type value_type with std::forward<K>(k), std::forward<M>(obj). If hash_function()(u.first) != h || contains(u.first) is true, the behavior is undefined. Inserts u into *this.

**Returns:** For the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

**Complexity:** The same as emplace and emplace_hint, respectively.

### 24.5.4.5 Erasure

```cpp
template<class K, class T, class H, class P, class A, class Predicate>
typename unordered_map<K, T, H, P, A>::size_type erase_if(unordered_map<K, T, H, P, A>& c, Predicate pred);
```

**Effects:** Equivalent to:

```cpp
auto original_size = c.size();
for (auto i = c.begin(), last = c.end(); i != last; ) {
    if (pred(*i)) {
        i = c.erase(i);
    } else {
        ++i;
    }
}
return original_size - c.size();
```

### 24.5.5 Class template unordered_multimap

#### Overview

An unordered_multimap is an unordered associative container that supports equivalent keys (an instance of unordered_multimap may contain multiple copies of each key value) and that associates values of another type mapped_type with the keys. The unordered_multimap class supports forward iterators.

§ 24.5.5.1 ©ISO/IEC 1008
An unordered_multimap meets all of the requirements of a container (24.2.2.2), of an allocator-aware container (24.2.2.5), and of an unordered associative container (24.2.8). It provides the operations described in the preceding requirements table for equivalent keys; that is, an unordered_multimap supports the a_eq operations in that table, not the a_uniq operations. For an unordered_multimap<Key, T> the key_type is Key, the mapped_type is T, and the value_type is pair<const Key, T>.

Subclause 24.5.5 only describes operations on unordered_multimap that are not described in one of the requirement tables, or for which there is additional semantic information.

```cpp
namespace std {
    template<class Key, 
             class T, 
             class Hash = hash<Key>,  
             class Pred = equal_to<Key>, 
             class Allocator = allocator<pair<const Key, T>>>
    class unordered_multimap {
        public:
            // types
            using key_type = Key;
            using mapped_type = T;
            using value_type = pair<const Key, T>;
            using hasher = Hash;
            using key_equal = Pred;
            using allocator_type = Allocator;
            using pointer = typename allocator_traits<Allocator>::pointer;
            using const_pointer = typename allocator_traits<Allocator>::const_pointer;
            using reference = value_type&;
            using const_reference = const value_type&;
            using size_type = implementation-defined; // see 24.2
            using difference_type = implementation-defined; // see 24.2
            using iterator = implementation-defined; // see 24.2
            using const_iterator = implementation-defined; // see 24.2
            using local_iterator = implementation-defined; // see 24.2
            using const_local_iterator = implementation-defined; // see 24.2
            using node_type = unspecified;

            // 24.5.5.2, construct/copy/destroy
            unordered_multimap();
            explicit unordered_multimap(size_type n,
                const hasher& hf = hasher(),
                const key_equal& eql = key_equal(),
                const allocator_type& a = allocator_type());
            template<class InputIterator>
            unordered_multimap(InputIterator f, InputIterator l,
                size_type n = see below,
                const hasher& hf = hasher(),
                const key_equal& eql = key_equal(),
                const allocator_type& a = allocator_type());
            template<container-compatible-range<value_type> R>
            unordered_multimap(from_range_t, R&& rg,
                size_type n = see below,
                const hasher& hf = hasher(),
                const key_equal& eql = key_equal(),
                const allocator_type& a = allocator_type());
            unordered_multimap(const unordered_multimap&);
            unordered_multimap(unordered_multimap&&);
            explicit unordered_multimap(const Allocator&);
            unordered_multimap(const unordered_multimap&, const type_identity_t<Allocator>&);
            unordered_multimap(unordered_multimap&, const type_identity_t<Allocator>&);
            unordered_multimap(initializer_list<value_type> il,
                size_type n = see below,
                const hasher& hf = hasher(),
                const key_equal& eql = key_equal(),
```
const allocator_type& a = allocator_type();
unordered_multimap(size_type n, const allocator_type& a)
    : unordered_multimap(n, hasher(), key_equal(), a) { }
unordered_multimap(size_type n, const hasher& hf, const allocator_type& a)
    : unordered_multimap(n, hf, key_equal(), a) { }
template<class InputIterator>
unordered_multimap(InputIterator f, InputIterator l, size_type n, const allocator_type& a)
    : unordered_multimap(f, l, n, hasher(), key_equal(), a) { }
unordered_multimap(InputIterator f, InputIterator l, size_type n, const hasher& hf,
    const allocator_type& a)
    : unordered_multimap(f, l, n, hf, key_equal(), a) { }

template<container-compatible-range<value_type> R>
unordered_multimap(from_range_t, R&& rg, size_type n, const allocator_type& a)
    : unordered_multimap(from_range, std::forward<R>(rg),
        n, hasher(), key_equal(), a) { }
unordered_multimap(from_range_t, R&& rg, size_type n, const hasher& hf,
    const allocator_type& a)
    : unordered_multimap(from_range, std::forward<R>(rg),
        n, hf, key_equal(), a) { }
unordered_multimap(initializer_list<value_type> il, size_type n, const allocator_type& a)
    : unordered_multimap(il, n, hasher(), key_equal(), a) { }
unordered_multimap(initializer_list<value_type> il, size_type n, const hasher& hf,
    const allocator_type& a)
    : unordered_multimap(il, n, hf, key_equal(), a) { }

~unordered_multimap();
unordered_multimap& operator=(const unordered_multimap&);
unordered_multimap& operator=(unordered_multimap&&)
    noexcept(allocator_traits<Allocator>::is_always_equal::value &&
        is_nothrow_move_assignable_v<Hash> &&
        is_nothrow_move_assignable_v<Pred>);
unordered_multimap& operator=(initializer_list<value_type>);
allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.5.5.3, modifiers
template<class... Args> iterator emplace(Args&&... args);
template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
iterator insert(const value_type& obj);
iterator insert(value_type&& obj);
template<class P> iterator insert(const_iterator hint, const value_type& obj);
iterator insert(const_iterator hint, value_type&& obj);
template<class P> iterator insert(const_iterator hint, const value_type& obj);
iterator insert(const_iterator hint, value_type&& obj);
template<container-compatible-range<value_type> R>
    void insert_range(R&& rg);
void insert(initializer_list<value_type>);
node_type extract(const_iterator position);
node_type extract(const key_type& x);
template<class K> node_type extract(K& x);

§ 24.5.5.1
iterator insert(node_type&& nh);
iterator insert(const_iterator hint, node_type&& nh);

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& k);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);
void swap(unordered_multimap&)
    noexcept(allocator_traits<Allocator>::is_always_equal::value &&
    is_nothrow_swappable_v<Hash> &&
    is_nothrow_swappable_v<Pred>);
void clear() noexcept;

template<class H2, class P2>
void merge(unordered_multimap<Key, T, H2, P2, Allocator>& source);
template<class H2, class P2>
void merge(unordered_multimap<Key, T, H2, P2, Allocator>&& source);
template<class H2, class P2>
void merge(unordered_map<Key, T, H2, P2, Allocator>& source);
template<class H2, class P2>
void merge(unordered_map<Key, T, H2, P2, Allocator>&& source);

// observers
hasher hash_function() const;
key_equal key_eq() const;

// map operations
iterator find(const key_type& k);
const_iterator find(const key_type& k) const;
template<class K>
iterator find(const K& k);
template<class K>
const_iterator find(const K& k) const;
size_type count(const key_type& k) const;
template<class K>
size_type count(const K& k) const;
bool contains(const key_type& k) const;
template<class K>
bool contains(const K& k) const;
pair<iterator, iterator> equal_range(const key_type& k);
pair<const_iterator, const_iterator> equal_range(const key_type& k) const;
template<class K>
pair<iterator, iterator> equal_range(const K& k);
template<class K>
pair<const_iterator, const_iterator> equal_range(const K& k) const;

// bucket interface
size_type bucket_count() const noexcept;
size_type max_bucket_count() const noexcept;
size_type bucket(size_type n) const;
size_type bucket(const key_type& k) const;
template<class K>
size_type bucket(const K& k) const;
local_iterator begin(size_type n);
local_iterator end(size_type n);
local_iterator cbegin(size_type n) const;
local_iterator cend(size_type n) const;

// hash policy
float load_factor() const noexcept;
float max_load_factor() const noexcept;
void max_load_factor(float z);
```cpp
void rehash(size_type n);
void reserve(size_type n);
}

template<class InputIterator,
class Hash = hash<
    iter-key-type
    <InputIterator>>,
class Pred = equal_to<
    iter-key-type
    <InputIterator>>,
class Allocator = allocator<
    iter-to-alloc-type
    <InputIterator>>>
unordered_multimap(InputIterator, InputIterator,
    typename see below::size_type = see below,
    Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_multimap<
    iter-key-type
    <InputIterator>, 
    iter-mapped-type
    <InputIterator>,
    Hash, Pred, Allocator>;

template<ranges::input_range R,
class Hash = hash<
    range-key-type
    <R>>,
class Pred = equal_to<
    range-key-type
    <R>>,
class Allocator = allocator<
    range-to-alloc-type
    <R>>>
unordered_multimap(from_range_t, R&&, typename see below::size_type = see below,
    Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_multimap<
    range-key-type
    <R>, 
    range-mapped-type
    <R>, Hash, Pred, Allocator>;
```
template<class Key, class T, class Allocator>
unordered_multimap(initializer_list<pair<Key, T>>, typename
see below::size_type,
Allocator)
-> unordered_multimap<Key, T, hash<Key>, equal_to<Key>, Allocator>;

template<class Key, class T, class Allocator>
unordered_multimap(initializer_list<pair<Key, T>>, Allocator)
-> unordered_multimap<Key, T, hash<Key>, equal_to<Key>, Allocator>;

template<class Key, class T, class Hash, class Allocator>
unordered_multimap(initializer_list<pair<Key, T>>, typename
see below::size_type,
Hash, Allocator)
-> unordered_multimap<Key, T, Hash, equal_to<Key>, Allocator>;

A size_type parameter type in an unordered_multimap deduction guide refers to the size_type member type of the type deduced by the deduction guide.

24.5.5.2 Constructors [unord.multimap.cnstr]

unordered_multimap() : unordered_multimap(size_type(see below)) { }
explicit unordered_multimap(size_type n,
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_multimap using the specified hash function, key equality predicate, and allocator, and using at least n buckets. For the default constructor, the number of buckets is implementation-defined. max_load_factor() returns 1.0.

Complexity: Constant.

template<class InputIterator>
unordered_multimap(InputIterator f, InputIterator l,
size_type n = see below,
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());
template<container-compatible-range<value_type> R>
unordered_multimap(from_range_t, R&& rg,
size_type n = see below,
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());
unordered_multimap(initializer_list<value_type> il,
size_type n = see below,
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_multimap using the specified hash function, key equality predicate, and allocator, and using at least n buckets. If n is not provided, the number of buckets is implementation-defined. Then inserts elements from the range [f,l), rg, or il, respectively. max_load_factor() returns 1.0.

Complexity: Average case linear, worst case quadratic.

24.5.5.3 Modifiers [unord.multimap.modifiers]

template<class P>
iterator insert(P&& obj);

Constraints: is_constructible_v<value_type, P&&> is true.

Effects: Equivalent to: return emplace(std::forward<P>(obj));
template<class P>
    iterator insert(const_iterator hint, P&& obj);

3 Constraints: is_constructible_v<value_type, P&&> is true.

4 Effects: Equivalent to: return emplace_hint(hint, std::forward<P>(obj));

24.5.5.4 Erasure

template<class K, class T, class H, class P, class A, class Predicate>
    typename unordered_multimap<K, T, H, P, A>::size_type
    erase_if(unordered_multimap<K, T, H, P, A>& c, Predicate pred);

1 Effects: Equivalent to:
    auto original_size = c.size();
    for (auto i = c.begin(), last = c.end(); i != last; ) {
        if (pred(*i)) {
            i = c.erase(i);
        } else {
            ++i;
        }
    }
    return original_size - c.size();

24.5.6 Class template unordered_set

24.5.6.1 Overview

1 An unordered_set is an unordered associative container that supports unique keys (an unordered_set contains at most one of each key value) and in which the elements’ keys are the elements themselves. The unordered_set class supports forward iterators.

2 An unordered_set meets all of the requirements of a container (24.2.2.2), of an allocator-aware container (24.2.2.5), of an unordered associative container (24.2.8). It provides the operations described in the preceding requirements table for unique keys; that is, an unordered_set supports the a_uniq operations in that table, not the a_eq operations. For an unordered_set<Key> the key_type and the value_type are both Key. The iterator and const_iterator types are both constant iterator types. It is unspecified whether they are the same type.

3 Subclause 24.5.6 only describes operations on unordered_set that are not described in one of the requirement tables, or for which there is additional semantic information.

namespace std {
    template<class Key, class Hash = hash<Key>,
             class Pred = equal_to<Key>,
             class Allocator = allocator<Key>>
    class unordered_set {
    public:
        // types
        using key_type = Key;
        using value_type = Key;
        using hasher = Hash;
        using key_equal = Pred;
        using allocator_type = Allocator;
        using pointer = typename allocator_traits<Allocator>::pointer;
        using const_pointer = typename allocator_traits<Allocator>::const_pointer;
        using reference = value_type&;
        using const_reference = const value_type&;
        using size_type = implementation-defined; // see 24.2
        using difference_type = implementation-defined; // see 24.2

        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
        using local_iterator = implementation-defined; // see 24.2
        using const_local_iterator = implementation-defined; // see 24.2
        using node_type = unspecified;
        using insert_return_type = insert_return_type<iterator, node_type>;
    }
// 24.5.6.2, construct/copy/destroy
unordered_set();
explicit unordered_set(size_type n,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());
template<class InputIterator>
unordered_set(InputIterator f, InputIterator l,
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());
template<container-compatible-range<value_type> R>
unordered_set(from_range_t, R&& rg,
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());
unordered_set(const unordered_set&);
unordered_set(unordered_set&&);
explicit unordered_set(const Allocator&);
unordered_set(const unordered_set&, const type_identity_t<Allocator>&);
unordered_set(unordered_set&&, const type_identity_t<Allocator>&);
unordered_set(initializer_list<value_type> il,
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());
unordered_set(size_type n, const allocator_type& a)
    : unordered_set(n, hasher(), key_equal(), a) { }
unordered_set(size_type n, const hasher& hf, const allocator_type& a)
    : unordered_set(n, hf, key_equal(), a) { }
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.5.6.4, modifiers
template<class... Args> pair<iterator, bool> emplace(Args&&... args);
template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
pair<iterator, bool> insert(const value_type& obj);
pair<iterator, bool> insert(value_type&& obj);
iterator insert(const_iterator hint, const value_type& obj);
iterator insert(const_iterator hint, value_type&& obj);
template<class K> pair<iterator, bool> insert(const_iterator hint, K& obj);
template<class K> iterator insert(const_iterator hint, K&& obj);
iterator insert(const_iterator hint, node_type&& nh);

// observers
hasher hash_function() const;
key_equal key_eq() const;

// set operations
iterator find(const key_type& k);
const_iterator find(const key_type& k) const;
template<class K> iterator find(const K& k);
template<class K> const_iterator find(const K& k) const;
size_type count(const key_type& k) const;
template<class K> size_type count(const K& k) const;
bool contains(const key_type& k) const;

§ 24.5.6.1
template<class K>
  bool contains(const K& k) const;
pair<iterator, iterator> equal_range(const key_type& k);
pair<const_iterator, const_iterator> equal_range(const key_type& k) const;

template<class K>
  pair<iterator, iterator> equal_range(const K& k);

// bucket interface
size_type bucket_count() const noexcept;
size_type max_bucket_count() const noexcept;
size_type bucket_size(size_type n) const;
size_type bucket(const key_type& k) const;
template<class K> size_type bucket(const K& k) const;
local_iterator begin(size_type n);
const_local_iterator begin(size_type n) const;
local_iterator end(size_type n);
const_local_iterator end(size_type n) const;
const_local_iterator cbegin(size_type n) const;
const_local_iterator cend(size_type n) const;

// hash policy
float load_factor() const noexcept;
float max_load_factor() const noexcept;
void max_load_factor(float z);
void rehash(size_type n);
void reserve(size_type n);

};
unordered_set<ranges::input_range R, class Allocator>
-> unordered_set<ranges::range_value_t<R>, hash<ranges::range_value_t<R>>,
equal_to<ranges::range_value_t<R>>, Allocator>;

unordered_set<ranges::input_range R, class Allocator>
-> unordered_set<ranges::range_value_t<R>, hash<ranges::range_value_t<R>>,
equal_to<ranges::range_value_t<R>>, Allocator>;

unordered_set<ranges::input_range R, class Hash, class Allocator>
-> unordered_set<ranges::range_value_t<R>, Hash,
equal_to<ranges::range_value_t<R>>, Allocator>;

unordered_set<ranges::input_range R, class Hash, class Allocator>
-> unordered_set<ranges::range_value_t<R>, Hash,
equal_to<ranges::range_value_t<R>>, Allocator>;

unordered_set(initializer_list<T>, typename
see below::size_type, Allocator)
-> unordered_set<T, hash<T>, equal_to<T>, Allocator>;

unordered_set(initializer_list<T>, typename
see below::size_type, Hash, Allocator)
-> unordered_set<T, Hash, equal_to<T>, Allocator>;

A size_type parameter type in an unordered_set deduction guide refers to the size_type member type of the type deduced by the deduction guide.

24.5.6.2 Constructors [unord.set.cnstr]

unordered_set() : unordered_set(size_type(see below)) { }
explicit unordered_set(size_type n,
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_set using the specified hash function, key equality predicate, and allocator, and using at least n buckets. For the default constructor, the number of buckets is implementation-defined. max_load_factor() returns 1.0.

Complexity: Constant.

template<class InputIterator>
unordered_set(InputIterator f, InputIterator l,
size_type n = see below,  
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());

template<container-compatible-range<value_type> R>
unordered_multiset(from_range_t, R&& rg,
size_type n = see below,  
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());

unordered_set(initializer_list<value_type> il,
size_type n = see below,  
const hasher& hf = hasher(),
const key_equal& eql = key_equal(),
const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_set using the specified hash function, key equality predicate, and allocator, and using at least n buckets. If n is not provided, the number of buckets is implementation-defined. Then inserts elements from the range [f,l), rg, or il, respectively. max_load_factor() returns 1.0.
Complexity: Average case linear, worst case quadratic.

24.5.6.3 Erasure

```cpp
template<class K, class H, class P, class A, class Predicate>
typename unordered_set<K, H, P, A>::size_type
erase_if(unordered_set<K, H, P, A>& c, Predicate pred);
```

**Effects:** Equivalent to:
```
auto original_size = c.size();
for (auto i = c.begin(), last = c.end(); i != last; ) {
  if (pred(*i)) {
    i = c.erase(i);
  } else {
    ++i;
  }
}
return original_size - c.size();
```

24.5.6.4 Modifiers

```cpp
template<class K> pair<iterator, bool> insert(K&& obj);
template<class K> iterator insert(const_iterator hint, K&& obj);
```

**Constraints:** The qualified-ids Hash::is_transparent and Pred::is_transparent are valid and denote types. For the second overload, is_convertible_v<K&&, const_iterator> and is_convertible_v<K&&, iterator> are both false.

** Preconditions:** value_type is Cpp17EmplaceConstructible into unordered_set from std::forward<K>(obj).

**Effects:** If the set already contains an element that is equivalent to obj, there is no effect. Otherwise, let h be hash_function()(obj). Constructs an object u of type value_type with std::forward<K>(obj). If hash_function()(u) != h || contains(u) is true, the behavior is undefined. Inserts u into *this.

**Returns:** For the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the set element that is equivalent to obj.

**Complexity:** Average case constant, worst case linear.

24.5.7 Class template unordered_multiset

24.5.7.1 Overview

An unordered_multiset is an unordered associative container that supports equivalent keys (an instance of unordered_multiset may contain multiple copies of the same key value) and in which each element’s key is the element itself. The unordered_multiset class supports forward iterators.

An unordered_multiset meets all of the requirements of a container (24.2.2.2), of an allocator-aware container (24.2.2.5), and of an unordered associative container (24.2.8). It provides the operations described in the preceding requirements table for equivalent keys; that is, an unordered_multiset supports the a_eq operations in that table, not the a uniq operations. For an unordered_multiset<Key> the key_type and the value_type are both Key. The iterator and const_iterator types are both constant iterator types. It is unspecified whether they are the same type.

Subclause 24.5.7 only describes operations on unordered_multiset that are not described in one of the requirement tables, or for which there is additional semantic information.

```cpp
namespace std {
  template<class Key,
    class Hash = hash<Key>,
    class Pred = equal_to<Key>,
    class Allocator = allocator<Key>>
  class unordered_multiset {
    public:
      // types
      using key_type = Key;
      using value_type = Key;
  }
}
```
using hasher = Hash;
using key_equal = Pred;
using allocator_type = Allocator;
using pointer = typename allocator_traits<Allocator>::pointer;
using const_pointer = typename allocator_traits<Allocator>::const_pointer;
using reference = value_type&;
using const_reference = const value_type&;
using size_type = implementation-defined; // see 24.2
using difference_type = implementation-defined; // see 24.2
using iterator = implementation-defined; // see 24.2
using const_iterator = implementation-defined; // see 24.2
using local_iterator = implementation-defined; // see 24.2
using const_local_iterator = implementation-defined; // see 24.2
using node_type = unspecified;

unordered_multiset();
explicit unordered_multiset(size_type n, 
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());

template<class InputIterator>
unordered_multiset(InputIterator f, InputIterator l, 
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());

template<container-compatible-range<value_type> R>
unordered_multiset(from_range_t, R&& rg, 
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());

unordered_multiset(const unordered_multiset&);
unordered_multiset(unordered_multiset&&);
explicit unordered_multiset(const Allocator&);
unordered_multiset(const unordered_multiset&, const type_identity_t<Allocator>&);
unordered_multiset(unordered_multiset&, const type_identity_t<Allocator>&);
unordered_multiset(initializer_list<value_type> il, 
    size_type n = see below,
    const hasher& hf = hasher(),
    const key_equal& eql = key_equal(),
    const allocator_type& a = allocator_type());

unordered_multiset(size_type n, const allocator_type& a)
    : unordered_multiset(n, hasher(), key_equal(), a) { }
unordered_multiset(size_type n, const hasher& hf, const allocator_type& a)
    : unordered_multiset(n, hf, key_equal(), a) { }

template<class InputIterator>
unordered_multiset(InputIterator f, InputIterator l, size_type n, const allocator_type& a)
    : unordered_multiset(f, l, n, hasher(), key_equal(), a) { }

template<class InputIterator>
unordered_multiset(InputIterator f, InputIterator l, size_type n, const hasher& hf, 
    const allocator_type& a)
    : unordered_multiset(f, l, n, hf, key_equal(), a) { }

template<container-compatible-range<value_type> R>
unordered_multiset(from_range_t, R&& rg, size_type n, const allocator_type& a)
    : unordered_multiset(from_range, std::forward<R>(rg), 
        n, hasher(), key_equal(), a) { }

template<container-compatible-range<value_type> R>
unordered_multiset(from_range_t, R&& rg, size_type n, const hasher& hf, 
    const allocator_type& a)
    : unordered_multiset(from_range, std::forward<R>(rg), n, hf, key_equal(), a) { }
unordered_multiset(initializer_list<value_type> il, size_type n, const allocator_type& a) :
  unordered_multiset(il, n, hashers(), key_equal(), a) { }
unordered_multiset(initializer_list<value_type> il, size_type n, const hasher& hf, const allocator_type& a) :
  unordered_multiset(il, n, hf, key_equal(), a) { }
-unordered_multiset();
unordered_multiset& operator=(const unordered_multiset&);
unordered_multiset& operator=(unordered_multiset&&) noexcept(allocator_traits<Allocator>::is_always_equal::value &&
  is_nothrow_move_assignable_v<Hash> &&
  is_nothrow_move_assignable_v<Pred>);
unordered_multiset& operator=(initializer_list<value_type>);
allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
const_iterator cbegin() const noexcept;
cend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// modifiers
template<class... Args> iterator emplace(Args&&... args);
template<class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
iterator insert(const value_type& obj);
iterator insert(value_type&& obj);
iterator insert(const_iterator hint, const value_type& obj);
iterator insert(const_iterator hint, value_type&& obj);
template<class InputIterator> void insert(InputIterator first, InputIterator last);
template<container-compatible-range<value_type> R> void insert_range(R&& rg);
void insert(initializer_list<value_type>);
node_type extract(const_iterator position);
node_type extract(const key_type& x);
template<class K> node_type extract(K&& x);
iterator insert(node_type&& nh);
iterator insert(const_iterator hint, node_type&& nh);

iterator erase(const_iterator position)
  requires (!same_as<iterator, const_iterator>);
iterator erase(const_iterator position);
size_type erase(const key_type& k);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);
void swap(unordered_multiset&)
  noexcept(allocator_traits<Allocator>::is_always_equal::value &&
    is_nothrow_swappable_v<Hash> &&
    is_nothrow_swappable_v<Pred>);
void clear() noexcept;

template<class H2, class P2>
void merge(unordered_multiset<Key, H2, P2, Allocator>& source);
template<class H2, class P2>
void merge(unordered_multiset<Key, H2, P2, Allocator>&& source);
template<class H2, class P2>
void merge(unordered_set<Key, H2, P2, Allocator>& source);
template<class H2, class P2>
  void merge(unordered_set<Key, H2, P2, Allocator>&& source);

// observers
hasher hash_function() const;
key_equal key_eq() const;

// set operations
iterator find(const key_type& k);
const_iterator find(const key_type& k) const;
template<class K>
  iterator find(const K& k);
template<class K>
  const_iterator find(const K& k) const;
size_type count(const key_type& k) const;
template<class K>
  size_type count(const K& k) const;
bool contains(const key_type& k) const;
template<class K>
  bool contains(const K& k) const;
pair<iterator, iterator> equal_range(const key_type& k);
pair<const_iterator, const_iterator> equal_range(const key_type& k) const;
template<class K>
  pair<iterator, iterator> equal_range(const K& k);
template<class K>
  pair<const_iterator, const_iterator> equal_range(const K& k) const;

// bucket interface
size_type bucket_count() const noexcept;
size_type max_bucket_count() const noexcept;
size_type bucket(size_type n) const;
local_iterator begin(size_type n);
const_local_iterator begin(size_type n) const;
local_iterator end(size_type n);
const_local_iterator end(size_type n) const;
const_local_iterator cbegin(size_type n) const;
const_local_iterator cend(size_type n) const;

// hash policy
float load_factor() const noexcept;
float max_load_factor() const noexcept;
void max_load_factor(float z);
void rehash(size_type n);
void reserve(size_type n);
};

template<
  class InputIterator,
  class Hash = hash<
    iter-value-type<InputIterator>>,
  class Pred = equal_to<
    iter-value-type<InputIterator>>,
  class Allocator = allocator<
    iter-value-type<InputIterator>>>
unordered_multiset(InputIterator, InputIterator,
  see below::size_type = see below,
  Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_multiset<
  iter-value-type<InputIterator>,
  Hash, Pred, Allocator>;

template<
  ranges::input_range R,
  class Hash = hash<
    ranges::range_value_t<R>>,
  class Pred = equal_to<
    ranges::range_value_t<R>>,
  class Allocator = allocator<
    ranges::range_value_t<R>>>
unordered_multiset(from_range_t, R&&,
  typename see below::size_type = see below,
  Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_multiset<
  ranges::range_value_t<R>, Hash, Pred, Allocator>;

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4 A size_type parameter type in an unordered_multiset deduction guide refers to the size_type member type of the type deduced by the deduction guide.

### 24.5.7.2 Constructors

 unordered_multiset() : unordered_multiset(size_type(see below)) { }
 explicit unordered_multiset(size_type n,  
   const hasher& hf = hasher(),  
   const key_equal& eql = key_equal(),  
   const allocator_type& a = allocator_type());

#### Effects

Constructs an empty unordered_multiset using the specified hash function, key equality predicate, and allocator, and using at least n buckets. For the default constructor, the number of buckets is implementation-defined. max_load_factor() returns 1.0.

#### Complexity

Constant.
const allocator_type& a = allocator_type();

unordered_multiset(from_range_t, R&& rg,
   size_type n = see below,
   const hasher& hf = hasher(),
   const key_equal& eql = key_equal(),
   const allocator_type& a = allocator_type());

unordered_multiset(initializer_list<value_type> il,
   size_type n = see below,
   const hasher& hf = hasher(),
   const key_equal& eql = key_equal(),
   const allocator_type& a = allocator_type());

Effects: Constructs an empty unordered_multiset using the specified hash function, key equality predicate, and allocator, and using at least n buckets. If n is not provided, the number of buckets is implementation-defined. Then inserts elements from the range [f,l), rg, or il, respectively. max_load_factor() returns 1.0.

Complexity: Average case linear, worst case quadratic.

24.5.7.3 Erasure

template<class K, class H, class P, class A, class Predicate>
typename unordered_multiset<K, H, P, A>::size_type
   erase_if(unordered_multiset<K, H, P, A>& c, Predicate pred);

Effects: Equivalent to:
   auto original_size = c.size();
   for (auto i = c.begin(), last = c.end(); i != last; ) {
      if (pred(*i)) {
         i = c.erase(i);
      } else {
         ++i;
      }
   }
   return original_size - c.size();

24.6 Container adaptors

24.6.1 General

The headers <queue>, <stack>, <flat_map>, and <flat_set> define the container adaptors queue and priority_queue, stack, flat_map and flat_multimap, and flat_set and flat_multiset, respectively.

Each container adaptor takes one or more template parameters named Container, KeyContainer, or MappedContainer that denote the types of containers that the container adaptor adapts. Each container adaptor has at least one constructor that takes a reference argument to one or more such template parameters. For each constructor reference argument to a container C, the constructor copies the container into the container adaptor. If C takes an allocator, then a compatible allocator may be passed in to the adaptor’s constructor. Otherwise, normal copy or move construction is used for the container argument. For the container adaptors that take a single container template parameter Container, the first template parameter T of the container adaptor shall denote the same type as Container::value_type.

For container adaptors, no swap function throws an exception unless that exception is thrown by the swap of the adaptor’s Container, KeyContainer, MappedContainer, or Compare object (if any).

A constructor template of a container adaptor shall not participate in overload resolution if it has an InputIterator template parameter and a type that does not qualify as an input iterator is deduced for that parameter.

For container adaptors that have them, the insert, emplace, and erase members affect the validity of iterators, references, and pointers to the adaptor’s container(s) in the same way that the containers’ respective insert, emplace, and erase members do.

[Example 1: A call to flat_map<Key, T>::insert can invalidate all iterators to the flat_map. — end example]
A deduction guide for a container adaptor shall not participate in overload resolution if any of the following are true:

1. It has an `InputIterator` template parameter and a type that does not qualify as an input iterator is deduced for that parameter.
2. It has a `Compare` template parameter and a type that qualifies as an allocator is deduced for that parameter.
3. It has a `Container`, `KeyContainer`, or `MappedContainer` template parameter and a type that qualifies as an allocator is deduced for that parameter.
4. It has an `Allocator` template parameter, and a type that does not qualify as an allocator is deduced for that parameter.
5. It has both `Container` and `Allocator` template parameters, and `uses_allocator_v<Container, Allocator>` is `false`.
6. It has both `KeyContainer` and `Allocator` template parameters, and `uses_allocator_v<KeyContainer, Allocator>` is `false`.
7. It has both `KeyType` and `Compare` template parameters, and `is_invocable_v<const Compare&, const typename KeyContainer::value_type&, const typename KeyContainer::value_type&>` is not a valid expression or is `false`.
8. It has both `MappedContainer` and `Allocator` template parameters, and `uses_allocator_v<MappedContainer, Allocator>` is `false`.

The exposition-only alias template `iter-value-type` defined in 24.3.1 and the exposition-only alias templates `iter-key-type`, `iter-mapped-type`, `range-key-type`, and `range-mapped-type` defined in 24.4.1 may appear in deduction guides for container adaptors.

The following exposition-only alias template may appear in deduction guides for container adaptors:

```cpp
template<class Allocator, class T>
using alloc_rebind = // exposition only
    typename allocator_traits<Allocator>::template rebind_alloc<T>;
```

### 24.6.2 Header `<queue>` synopsis

```c++
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 24.6.6, class template queue
template<class T, class Container = deque<T>> class queue;

template<class T, class Container>
    bool operator==(const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container>
    bool operator!=(const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container>
    bool operator< (const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container>
    bool operator> (const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container>
    bool operator<=(const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container>
    bool operator>=(const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container, class Alloc>
    compare_three_way_result_t<Container>
        operator<=>(const queue<T, Container>& x, const queue<T, Container>& y);

template<class T, class Container>
    void swap(queue<T, Container>& x, queue<T, Container>& y) noexcept(noexcept(x.swap(y)));

template<class T, class Container, class Alloc>
    struct uses_allocator<queue<T, Container>, Alloc>;

```
// 24.6.13, formatter specialization for queue
template<class charT, class T, formattable<charT> Container>
struct formatter<queue<T, Container>, charT>;

// 24.6.7, class template priority_queue
template<class T, class Container = vector<T>,
    class Compare = less<typename Container::value_type>>
class priority_queue;

template<class T, class Container, class Compare>
void swap(priority_queue<T, Container, Compare>& x,
    priority_queue<T, Container, Compare>& y) noexcept(noexcept(x.swap(y)));

template<class T, class Container, class Compare, class Alloc>
struct uses_allocator<priority_queue<T, Container, Compare>, Alloc>;

// 24.6.13, formatter specialization for priority_queue
template<class charT, class T, formattable<charT> Container, class Compare>
struct formatter<priority_queue<T, Container, Compare>, charT>;

} // end namespace std

24.6.3 Header <stack> synopsis

#include <compare>   // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {

    // 24.6.8, class template stack
    template<class T, class Container = deque<T>> class stack;

    template<class T, class Container>
    bool operator==<const stack<T, Container>& x, const stack<T, Container>& y>;

    template<class T, class Container>
    bool operator!=<const stack<T, Container>& x, const stack<T, Container>& y>;

    template<class T, class Container>
    bool operator<(const stack<T, Container>& x, const stack<T, Container>& y);

    template<class T, class Container>
    bool operator>(const stack<T, Container>& x, const stack<T, Container>& y);

    template<class T, class Container>
    bool operator<=(const stack<T, Container>& x, const stack<T, Container>& y);

    template<class T, class Container>
    bool operator>=(const stack<T, Container>& x, const stack<T, Container>& y);

    template<class T, class Container
    three_way_comparable Container>
    compare_three_way_result_t<Container>
    operator<=>(const stack<T, Container>& x, const stack<T, Container>& y);

    template<class T, class Container>
    void swap(stack<T, Container>& x, stack<T, Container>& y) noexcept(noexcept(x.swap(y)));

    template<class T, class Container, class Alloc>
    struct uses_allocator<stack<T, Container>, Alloc>;

    // 24.6.13, formatter specialization for stack
    template<class charT, class T, formattable<charT> Container, charT>
    struct formatter<stack<T, Container>, charT>;

} // end namespace std

24.6.4 Header <flat_map> synopsis

#include <compare>   // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {

    // 24.6.9, class template flat_map
    template<class Key, class T, class Compare = less<Key>,
        class KeyContainer = vector<Key>, class MappedContainer = vector<T>>
    class flat_map;;
struct sorted_unique_t { explicit sorted_unique_t() = default; 
inline constexpr sorted_unique_t sorted_unique{};

template<class Key, class T, class Compare, class KeyContainer, class MappedContainer,
class Allocator>
struct uses_allocator<flat_map<Key, T, Compare, KeyContainer, MappedContainer>,
Allocator>;

// 24.6.9.8, erasure for flat_map
template<class Key, class T, class Compare, class KeyContainer, class MappedContainer,
class Predicate>
typename flat_map<Key, T, Compare, KeyContainer, MappedContainer>::size_type
erase_if(flat_map<Key, T, Compare, KeyContainer, MappedContainer>& c, Predicate pred);

// 24.6.10, class template flat_multimap
template<class Key, class T, class Compare = less<Key>,
class KeyContainer = vector<Key>, class MappedContainer = vector<T>>
class flat_multimap;

struct sorted_equivalent_t { explicit sorted_equivalent_t() = default; 
inline constexpr sorted_equivalent_t sorted_equivalent{};

template<class Key, class T, class Compare, class KeyContainer, class MappedContainer,
class Allocator>
struct uses_allocator<flat_multimap<Key, T, Compare, KeyContainer, MappedContainer>,
Allocator>;

// 24.6.10.5, erasure for flat_multimap
template<class Key, class T, class Compare, class KeyContainer, class MappedContainer,
class Predicate>
typename flat_multimap<Key, T, Compare, KeyContainer, MappedContainer>::size_type
erase_if(flat_multimap<Key, T, Compare, KeyContainer, MappedContainer>& c, Predicate pred);

24.6.5 Header <flat_set> synopsis [flat.set.syn]
#include <compare>     // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {

// 24.6.11, class template flat_set
template<class Key, class Compare = less<Key>, class KeyContainer = vector<Key>>
class flat_set;

struct sorted_unique_t { explicit sorted_unique_t() = default; 
inline constexpr sorted_unique_t sorted_unique{};

template<class Key, class Compare, class KeyContainer, class Allocator>
struct uses_allocator<flat_set<Key, Compare, KeyContainer>, Allocator>;

// 24.6.11.6, erasure for flat_set
template<class Key, class Compare, class KeyContainer, class Predicate>
typename flat_set<Key, Compare, KeyContainer>::size_type
erase_if(flat_set<Key, Compare, KeyContainer>& c, Predicate pred);

// 24.6.12, class template flat_multiset
template<class Key, class Compare = less<Key>, class KeyContainer = vector<Key>>
class flat_multiset;

struct sorted_equivalent_t { explicit sorted_equivalent_t() = default; 
inline constexpr sorted_equivalent_t sorted_equivalent{};

template<class Key, class Compare, class KeyContainer, class Allocator>
struct uses_allocator<flat_multiset<Key, Compare, KeyContainer>, Allocator>;

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24.6.6 Class template queue

24.6.6.1 Definition

Any sequence container supporting operations \texttt{front()}, \texttt{back()}, \texttt{push\_back()} and \texttt{pop\_front()} can be used to instantiate \texttt{queue}. In particular, list (24.3.11) and deque (24.3.9) can be used.

```cpp
namespace std {
    template<class T, class Container = deque<T>>
    class queue {
        public:
            using value_type = typename Container::value_type;
            using reference = typename Container::reference;
            using const_reference = typename Container::const_reference;
            using size_type = typename Container::size_type;
            using container_type = Container;

            Container c;

        public:
            queue() : queue(Container()) {}
            explicit queue(const Container&);
            explicit queue(Container&&);
            template<class InputIterator> queue(InputIterator first, InputIterator last);
            template<container-compatible-range<T> R> queue(from_range_t, R&& rg);
            template<class Alloc> explicit queue(const Alloc&);
            template<class Alloc> queue(const Container&, const Alloc&);
            template<class Alloc> queue(Container&&, const Alloc&);
            template<class Alloc> queue(const queue&, const Alloc&);
            template<class Alloc> queue(queue&&, const Alloc&);
            template<class InputIterator, class Alloc>
            queue(InputIterator first, InputIterator last, const Alloc&);
            template<container-compatible-range<T> R, class Alloc>
            queue(from_range_t, R&& rg, const Alloc&);

            [[nodiscard]] bool empty() const { return c.empty(); }
            size_type size() const { return c.size(); }
            reference front() { return c.front(); }
            const_reference front() const { return c.front(); }
            reference back() { return c.back(); }
            const_reference back() const { return c.back(); }
            void push(const value_type& x) { c.push_back(x); }
            void push(value_type&& x) { c.push_back(std::move(x)); }
            template<container-compatible-range<T> R>
            void push_range(R&& rg);
            template<class... Args>
            decltype(auto) emplace(Args&&... args)
            { return c.emplace_back(std::forward<Args>(args)...); }
            void pop() { c.pop_front(); }
            void swap(queue& q) noexcept(is_nothrow_swappable_v<Container>)
            { using std::swap; swap(c, q.c); }
    };

    template<class Container>
    queue(Container) -> queue<typename Container::value_type, Container>;

    template<class InputIterator>
    queue(InputIterator, InputIterator) ->
    queue<iter-value-type<InputIterator>>;
```
template<ranges::input_range R>
queue(from_range_t, R&&) -> queue<ranges::range_value_t<R>>;

template<class Container, class Allocator>
queue(Container, Allocator) -> queue<typename Container::value_type, Container>;

template<class InputIterator, class Allocator>
queue(InputIterator, InputIterator, Allocator)
-> queue<iter-value-type<InputIterator>, deque<iter-value-type<InputIterator>,
Allocator>>;

template<ranges::input_range R, class Allocator>
queue(from_range_t, R&&, Allocator)
-> queue<ranges::range_value_t<R>, deque<ranges::range_value_t<R>, Allocator>>;

template<class T, class Container, class Alloc>
struct uses_allocator<queue<T, Container>, Alloc>
: uses_allocator<Container, Alloc>::type { };

24.6.6.2 Constructors

explicit queue(const Container& cont);
Effects: Initializes c with cont.

explicit queue(Container&& cont);
Effects: Initializes c with std::move(cont).

template<class InputIterator>
queue(InputIterator first, InputIterator last);
Effects: Initializes c with first as the first argument and last as the second argument.

template<container-compatible-range<T> R>
queue(from_range_t, R&& rg);
Effects: Initializes c with ranges::to<Container>(std::forward<R>(rg)).

24.6.6.3 Constructors with allocators

If uses_allocator_v<container_type, Alloc> is false the constructors in this subclause shall not participate in overload resolution.

template<class Alloc> explicit queue(const Alloc& a);
Effects: Initializes c with a.

template<class Alloc> queue(const container_type& cont, const Alloc& a);
Effects: Initializes c with cont as the first argument and a as the second argument.

template<class Alloc> queue(container_type& cont, const Alloc& a);
Effects: Initializes c with std::move(cont) as the first argument and a as the second argument.

template<class Alloc> queue(const queue& q, const Alloc& a);
Effects: Initializes c with q.c as the first argument and a as the second argument.

template<class Alloc> queue(queue&& q, const Alloc& a);
Effects: Initializes c with std::move(q.c) as the first argument and a as the second argument.

template<class InputIterator, class Alloc>
queue(InputIterator first, InputIterator last, const Alloc& alloc);
Effects: Initializes c with first as the first argument, last as the second argument, and alloc as the third argument.
template<container-compatible-range<T> R, class Alloc>
    queue(from_range_t, R&& rg, const Alloc& a);

Effects: Initializes c with ranges::to<Container>(std::forward<R>(rg), a).

24.6.6.4 Modifiers

template<container-compatible-range<T> R>
    void push_range(R&& rg);

Effects: Equivalent to c.append_range(std::forward<R>(rg)) if that is a valid expression, otherwise
ranges::copy(rg, back_inserter(c)).

24.6.6.5 Operators

template<class T, class Container>
bool operator==(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c == y.c.

template<class T, class Container>
bool operator!=(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c != y.c.

template<class T, class Container>
bool operator<(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c < y.c.

template<class T, class Container>
bool operator>(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c > y.c.

template<class T, class Container>
bool operator<=(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c <= y.c.

template<class T, class Container>
bool operator>=(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c >= y.c.

template<class T, three_way_comparable Container>
compare_three_way_result_t<Container>
    operator<=>(const queue<T, Container>& x, const queue<T, Container>& y);

Returns: x.c <=> y.c.

24.6.6.6 Specialized algorithms

template<class T, class Container>
    void swap(queue<T, Container>& x, queue<T, Container>& y) noexcept(noexcept(x.swap(y)));

Constraints: is_swappable_v<Container> is true.

Effects: As if by x.swap(y).

24.6.7 Class template priority_queue

24.6.7.1 Overview

Any sequence container with random access iterator and supporting operations front(), push_back() and
pop_back() can be used to instantiate priority_queue. In particular, vector (24.3.12) and deque (24.3.9)
can be used. Instantiating priority_queue also involves supplying a function or function object for
making priority comparisons; the library assumes that the function or function object defines a strict weak
ordering (27.8).
namespace std {

template<class T, class Container = vector<T>,
    class Compare = less<typename Container::value_type>>
class priority_queue {
    public:
        using value_type = typename Container::value_type;
        using reference = typename Container::reference;
        using const_reference = typename Container::const_reference;
        using size_type = typename Container::size_type;
        using container_type = Container;
        using value_compare = Compare;
    protected:
        Container c;
        Compare comp;

    public:
        priority_queue() : priority_queue(Compare()) {}  
        explicit priority_queue(const Compare& x) : priority_queue(x, Container()) {}
        priority_queue(const Compare& x, const Container&);
        priority_queue(const Compare& x, Container&&);
        template<class InputIterator>
            priority_queue(InputIterator first, InputIterator last, const Compare& x = Compare());
        template<class InputIterator>
            priority_queue(InputIterator first, InputIterator last, const Compare& x, 
                const Container&);
        template<class InputIterator>
            priority_queue(InputIterator first, InputIterator last, const Compare& x, 
                Container&&);
        template<container-compatible-range<T> R>
            priority_queue(from_range_t, R&& rg, const Compare& x = Compare());
        template<class Alloc>
            explicit priority_queue(const Alloc&);
        template<class Alloc>
            priority_queue(const Compare&, const Alloc&);
        template<class Alloc>
            priority_queue(const Compare&, const Container&, const Alloc&);
        template<class Alloc>
            priority_queue(const Compare&, Container&&, const Alloc&);
        template<class Alloc>
            priority_queue(const priority_queue&, const Alloc&);
        template<class Alloc>
            priority_queue(priority_queue&&, const Alloc&);
        template<class InputIterator, class Alloc>
            priority_queue(InputIterator, InputIterator, const Alloc&);
        template<class InputIterator, class Alloc>
            priority_queue(InputIterator, InputIterator, const Compare&, const Alloc&);
        template<class InputIterator, class Alloc>
            priority_queue(InputIterator, InputIterator, const Compare&, const Container&, 
                const Alloc&);
        template<container-compatible-range<T> R, class Alloc>
            priority_queue(from_range_t, R&& rg, const Compare&, const Alloc&);
        template<container-compatible-range<T> R, class Alloc>
            priority_queue(from_range_t, R&& rg, const Alloc&);

        [[nodiscard]] bool empty() const { return c.empty(); }  
        size_type size() const { return c.size(); }  
        const_reference top() const { return c.front(); }  
        void push(const value_type& x);
        void push(value_type&& x);
        template<container-compatible-range<T> R>
            void push_range(R&& rg);
        template<class... Args> void emplace(Args&&... args);
        void pop();
        void swap(priority_queue& q) noexcept(is_nothrow_swappable_v<Container> 
            && is_nothrow_swappable_v<Compare>)
            { using std::swap; swap(c, q.c); swap(comp, q.comp); }
    }
template<class Compare, class Container>
 priority_queue(Compare, Container)
 -> priority_queue<typename Container::value_type, Container, Compare>;

template<class InputIterator,
 class Compare = less<typename iter_value_type<InputIterator>>,
 class Container = vector<typename iter_value_type<InputIterator>>>
priority_queue(InputIterator, InputIterator, Compare = Compare(), Container = Container())
 -> priority_queue<typename iter_value_type<InputIterator>, Container, Compare>;

template<ranges::input_range R, class Compare = less<ranges::range_value_t<R>>,
 class Container = vector<ranges::range_value_t<R>>, Compare = Compare()>
priority_queue(from_range_t, R&&, Container = Container())
 -> priority_queue<ranges::range_value_t<R>, vector<ranges::range_value_t<R>>, Compare>;

template<class Compare, class Container, class Allocator>
priority_queue(Compare, Container, Allocator)
 -> priority_queue<typename Container::value_type, Container, Compare>;

template<class InputIterator, class Allocator>
priority_queue(InputIterator, InputIterator, Allocator)
 -> priority_queue<typename iter_value_type<InputIterator>,
 vector<typename iter_value_type<InputIterator>>, Allocator>,
 less<typename iter_value_type<InputIterator>>>;

template<class InputIterator, class Compare, class Allocator>
priority_queue(InputIterator, InputIterator, Compare, Allocator)
 -> priority_queue<typename iter_value_type<InputIterator>,
 vector<typename iter_value_type<InputIterator>>, Allocator>, Compare>;

template<class InputIterator, class Compare, class Container, class Allocator>
priority_queue(InputIterator, InputIterator, Compare, Container, Allocator)
 -> priority_queue<typename Container::value_type, Container, Compare>;

template<ranges::input_range R, class Compare, class Allocator>
priority_queue(from_range_t, R&&, Compare, Allocator)
 -> priority_queue<ranges::range_value_t<R>, vector<ranges::range_value_t<R>, Allocator>,
 Compare>;

template<ranges::input_range R, class Allocator>
priority_queue(from_range_t, R&&, Allocator)
 -> priority_queue<ranges::range_value_t<R>, vector<ranges::range_value_t<R>, Allocator>>;

§ 24.6.7.2 Constructors
[priqueue.cons]
priority_queue(const Compare& x, const Container& y);
 priority_queue(const Compare& x, Container&& y);
1  Preconditions: x defines a strict weak ordering (27.8).
2  Effects: Initializes comp with x and c with y (copy constructing or move constructing as appropriate);
 calls make_heap(c.begin(), c.end(), comp).

template<class InputIterator>
priority_queue(InputIterator first, InputIterator last, const Compare& x = Compare());
3  Preconditions: x defines a strict weak ordering (27.8).
4  Effects: Initializes c with first as the first argument and last as the second argument, and initializes
 comp with x; then calls make_heap(c.begin(), c.end(), comp).
template<class InputIterator>
priority_queue(InputIterator first, InputIterator last, const Compare& x, const Container& y);

5
Preconditions: x defines a strict weak ordering (27.8).
6
Effects: Initializes comp with x and c with y (copy constructing or move constructing as appropriate); calls c.insert(c.end(), first, last); and finally calls make_heap(c.begin(), c.end(), comp).

template<container-compatible-range<T> R>
priority_queue(from_range_t, R&& rg, const Compare& x = Compare());
7
Preconditions: x defines a strict weak ordering (27.8).
8
Effects: Initializes comp with x and with ranges::to<Container>(std::forward<R>(rg)) and finally calls make_heap(c.begin(), c.end(), comp).

24.6.7.3 Constructors with allocators [priqueue.cons.alloc]
1
If uses_allocator_v<container_type, Alloc> is false the constructors in this subclause shall not participate in overload resolution.

template<class Alloc> explicit priority_queue(const Alloc& a);
2
Effects: Initializes c with a and value-initializes comp.
3

template<class Alloc> priority_queue(const Compare& compare, const Alloc& a);
4
Effects: Initializes c with a and initializes comp with compare.
5

template<class Alloc>
priority_queue(const Compare& compare, const Container& cont, const Alloc& a);
6
Effects: Initializes c with cont as the first argument and a as the second argument, and initializes comp with compare; calls make_heap(c.begin(), c.end(), comp).
7

template<class Alloc>
priority_queue(const Compare& compare, Container&& cont, const Alloc& a);
8
Effects: Initializes c with std::move(cont) as the first argument and a as the second argument, and initializes comp with compare; calls make_heap(c.begin(), c.end(), comp).
9

template<class Alloc> priority_queue(const priority_queue& q, const Alloc& a);
10
Effects: Initializes c with q.c as the first argument and a as the second argument, and initializes comp with q.comp.
11

template<class Alloc> priority_queue(priority_queue&& q, const Alloc& a);
12
Effects: Initializes c with std::move(q.c) as the first argument and a as the second argument, and initializes comp with std::move(q.comp).
13

§ 24.6.7.3 © ISO/IEC 1033
template<class InputIterator, class Alloc>
priority_queue(InputIterator first, InputIterator last, const Compare& compare, Container&& cont,
const Alloc& a);
Effects: Initializes c with std::move(cont) as the first argument and a as the second argument,
and initializes comp with compare; calls c.insert(c.end(), first, last); and finally calls make_heap(c.begin(), c.end(), comp).

Effects: Initializes comp with compare and c with ranges::to<Container>(std::forward<R>(rg),
a); calls make_heap(c.begin(), c.end(), comp).

Effects: Initializes c with ranges::to<Container>(std::forward<R>(rg), a); calls make_heap(c.
begin(), c.end(), comp).

Effects: As if by:
c.push_back(x);
push_heap(c.begin(), c.end(), comp);

Effects: As if by:
c.push_back(std::move(x));
push_heap(c.begin(), c.end(), comp);

Effects: Inserts all elements of rg in c via c.append_range(std::forward<R>(rg)) if that is a valid
expression, or ranges::copy(rg, back_inserter(c)) otherwise. Then restores the heap property as
if by make_heap(c.begin(), c.end(), comp).
Postconditions: is_heap(c.begin(), c.end(), comp) is true.

Effects: As if by:
c.emplace_back(std::forward<Args>(args)...);
push_heap(c.begin(), c.end(), comp);

Effects: As if by:
pop_heap(c.begin(), c.end(), comp);
c.pop_back();

24.6.7.5 Specialized algorithms

template<class T, class Container, class Compare>
void swap(priority_queue<T, Container, Compare>& x,
priority_queue<T, Container, Compare>& y) noexcept(noexcept(x.swap(y)));
Constraints: is_swappable_v<Container> is true and is_swappable_v<Compare> is true.
Effects: As if by x.swap(y).

24.6.8 Class template stack

24.6.8.1 General

Any sequence container supporting operations back(), push_back() and pop_back() can be used to instantiate stack. In particular, vector (24.3.12), list (24.3.11) and deque (24.3.9) can be used.
24.6.8.2 Definition

```cpp
namespace std {
    template<class T, class Container = deque<T>>
    class stack {
    public:
        using value_type = typename Container::value_type;
        using reference = typename Container::reference;
        using const_reference = typename Container::const_reference;
        using size_type = typename Container::size_type;
        using container_type = Container;

    protected:
        Container c;

    public:
        stack() : stack(Container()) {}
        explicit stack(const Container&);
        explicit stack(Container&&);
        template<class InputIterator> stack(InputIterator first, InputIterator last);
        template<container-compatible-range<
            T> R> stack(from_range_t, R&& rg);
        template<class Alloc> explicit stack(const Alloc&);
        template<class Alloc> stack(const Container&, const Alloc&);
        template<class Alloc> stack(Container&&, const Alloc&);
        template<class Alloc> stack(const stack&, const Alloc&);
        template<class Alloc> stack(stack&&, const Alloc&);
        template<class InputIterator, class Alloc>
        stack(InputIterator first, InputIterator last, const Alloc&);
        template<container-compatible-range<
            T> R, class Alloc>
        stack(from_range_t, R&& rg, const Alloc&);
        [[nodiscard]] bool empty() const { return c.empty(); }
        size_type size() const { return c.size(); }
        reference top() { return c.back(); }
        const_reference top() const { return c.back(); }
        void push(const value_type& x) { c.push_back(x); }
        void push(value_type&& x) { c.push_back(std::move(x)); }
        template<container-compatible-range<
            T> R>
        void push_range(R&& rg);
        template<class... Args>
        decltype(auto) emplace(Args&&... args)
            { return c.emplace_back(std::forward<Args>(args)...); }
        void pop() { c.pop_back(); }
        void swap(stack& s) noexcept(is_nothrow_swappable_v<Container>)
            { using std::swap; swap(c, s.c); }
    };    
```

```
    template<class Container>
    stack(Container) -> stack<typename Container::value_type, Container>;
    template<class InputIterator>
    stack(InputIterator, InputIterator) -> stack<iter-value-type<InputIterator>>;
    template<ranges::input_range R>
    stack(from_range_t, R&&) -> stack<ranges::range_value_t<R>>;
    template<class Container, class Allocator>
    stack(Container, Allocator) -> stack<typename Container::value_type, Container>;
    template<class InputIterator, class Allocator>
    stack(InputIterator, InputIterator, Allocator)
        -> stack<iter-value-type<InputIterator>, deque<iter-value-type<InputIterator>,
            Allocator>>;
```
template<ranges::input_range R, class Allocator>
stack(from_range_t, R&&, Allocator)
- > stack<ranges::range_value_t<R>, deque<ranges::range_value_t<R>, Allocator>>;

template<class T, class Container, class Alloc>
struct uses_allocator<stack<T, Container>, Alloc>:
uses_allocator<Container, Alloc>::type { };

24.6.8.3 Constructors [stack.cons]

explicit stack(const Container& cont);
Effects: Initializes c with cont.
explicit stack(Container&& cont);
Effects: Initializes c with std::move(cont).

template<class InputIterator>
stack(InputIterator first, InputIterator last);
Effects: Initializes c with first as the first argument and last as the second argument.

template<container-compatible-range<T> R>
stack(from_range_t, R&& rg);
Effects: Initializes c with ranges::to<Container>(std::forward<R>(rg)).

24.6.8.4 Constructors with allocators [stack.cons.alloc]

1 If uses_allocator_v<container_type, Alloc> is false the constructors in this subclause shall not participate in overload resolution.

template<class Alloc> explicit stack(const Alloc& a);
Effects: Initializes c with a.

template<class Alloc> stack(const container_type& cont, const Alloc& a);
Effects: Initializes c with cont as the first argument and a as the second argument.

template<class Alloc> stack(container_type&& cont, const Alloc& a);
Effects: Initializes c with std::move(cont) as the first argument and a as the second argument.

template<class Alloc> stack(const stack& s, const Alloc& a);
Effects: Initializes c with s.c as the first argument and a as the second argument.

template<class Alloc> stack(stack&& s, const Alloc& a);
Effects: Initializes c with std::move(s.c) as the first argument and a as the second argument.

template<class InputIterator, class Alloc>
stack(InputIterator first, InputIterator last, const Alloc& alloc);
Effects: Initializes c with first as the first argument, last as the second argument, and alloc as the third argument.

template<container-compatible-range<T> R, class Alloc>
stack(from_range_t, R&& rg, const Alloc& alloc);
Effects: Initializes c with ranges::to<Container>(std::forward<R>(rg), a).

24.6.8.5 Modifiers [stack.mod]

template<container-compatible-range<T> R>
void push_range(R&& rg);
Effects: Equivalent to c.append_range(std::forward<R>(rg)) if that is a valid expression, otherwise ranges::copy(rg, back_inserter(c)).
24.6.8.6 Operators [stack.ops]

```
template<class T, class Container>
bool operator==(const stack<T, Container>& x, const stack<T, Container>& y);
```
1

Returns: x.c == y.c.

```
template<class T, class Container>
bool operator!=(const stack<T, Container>& x, const stack<T, Container>& y);
```
2

Returns: x.c != y.c.

```
template<class T, class Container>
bool operator<( const stack<T, Container>& x, const stack<T, Container>& y);
```
3

Returns: x.c < y.c.

```
template<class T, class Container>
bool operator> ( const stack<T, Container>& x, const stack<T, Container>& y);
```
4

Returns: x.c > y.c.

```
template<class T, class Container>
bool operator<=(const stack<T, Container>& x, const stack<T, Container>& y);
```
5

Returns: x.c <= y.c.

```
template<class T, class Container>
bool operator>=(const stack<T, Container>& x, const stack<T, Container>& y);
```
6

Returns: x.c >= y.c.

```
template<class T, three_way_comparable Container>
compare_three_way_result_t<Container>
operator<=>(const stack<T, Container>& x, const stack<T, Container>& y);
```
7

Returns: x.c <=> y.c.

24.6.8.7 Specialized algorithms [stack.special]

```
template<class T, class Container>
void swap(stack<T, Container>& x, stack<T, Container>& y) noexcept(noexcept(x.swap(y)));
```
1

Constraints: is_swappable_v<Container> is true.

Effects: As if by x.swap(y).

24.6.9 Class template flat_map [flat.map]

24.6.9.1 Overview [flat.map.overview]

A flat_map is a container adaptor that provides an associative container interface that supports unique keys (i.e., contains at most one of each key value) and provides for fast retrieval of values of another type T based on the keys. flat_map supports iterators that meet the Cpp17InputIterator requirements and model the random_access_iterator concept (25.3.4.13).

A flat_map meets all of the requirements of a container (24.2.2.2) and of a reversible container (24.2.2.3), plus the optional container requirements (24.2.2.4). flat_map meets the requirements of an associative container (24.2.7), except that:

1. it does not meet the requirements related to node handles (24.2.5),
2. it does not meet the requirements related to iterator invalidation, and
3. the time complexity of the operations that insert or erase a single element from the map is linear, including the ones that take an insertion position iterator.

[Note 1: A flat_map does not meet the additional requirements of an allocator-aware container (24.2.2.5). — end note]

A flat_map also provides most operations described in 24.2.7 for unique keys. This means that a flat_map supports the a_uniq operations in 24.2.7 but not the a_eq operations. For a flat_map<Key, T> the key_type is Key and the value_type is pair<Key, T>.
Descriptions are provided here only for operations on `flat_map` that are not described in one of those sets of requirements or for operations where there is additional semantic information.

A `flat_map` maintains the following invariants:

- it contains the same number of keys and values;
- the keys are sorted with respect to the comparison object; and
- the value at offset `off` within the value container is the value associated with the key at offset `off` within the key container.

If any member function in 24.6.9.2 exits via an exception the invariants are restored.

[Note 2: This can result in the `flat_map` being emptied. — end note]

Any type `C` that meets the sequence container requirements (24.2.4) can be used to instantiate `flat_map`, as long as `C::iterator` meets the `Cpp17RandomAccessIterator` requirements and invocations of member functions `C::size` and `C::max_size` do not exit via an exception. In particular, `vector` (24.3.12) and `deque` (24.3.9) can be used.

[Note 3: `vector<bool>` is not a sequence container. — end note]

The program is ill-formed if `Key` is not the same type as `KeyContainer::value_type` or `T` is not the same type as `MappedContainer::value_type`.

The effect of calling a constructor that takes both `key_container_type` and `mapped_container_type` arguments with containers of different sizes is undefined.

The effect of calling a constructor or member function that takes a `sorted_unique_t` argument with a container, containers, or range that is not sorted with respect to `key_comp()`, or that contains equal elements, is undefined.

### 24.6.9.2 Definition

```cpp
namespace std {
    template<class Key, class T, class Compare = less<Key>,
             class KeyContainer = vector<Key>, class MappedContainer = vector<T>>
    class flat_map {
        public:
            // types
            using key_type = Key;
            using mapped_type = T;
            using value_type = pair<key_type, mapped_type>;
            using key_compare = Compare;
            using reference = pair<const key_type&, mapped_type&>;
            using const_reference = pair<const key_type&, const mapped_type&>;
            using size_type = size_t;
            using difference_type = ptrdiff_t;
            using iterator = implementation-defined; // see 24.2
            using const_iterator = implementation-defined; // see 24.2
            using reverse_iterator = std::reverse_iterator<iterator>;
            using const_reverse_iterator = std::reverse_iterator<const_iterator>;
            using key_container_type = KeyContainer;
            using mapped_container_type = MappedContainer;

            class value_compare {
                private:
                    key_compare comp; // exposition only
                value_compare(key_compare c) : comp(c) {} // exposition only
            }

            public:
                bool operator()(const_reference x, const_reference y) const {
                    return comp(x.first, y.first);
                }
            }

        struct containers {
            key_container_type keys;
            mapped_container_type values;
        }
    }
}
```

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};

// 24.6.9.3, constructors
flat_map() : flat_map(key_compare()) { }

explicit flat_map(const key_compare& comp)
: c(), compare(comp) { }

flat_map(key_container_type key_cont, mapped_container_type mapped_cont,
const key_compare& comp = key_compare());

flat_map(sorted_unique_t, key_container_type key_cont, mapped_container_type mapped_cont,
const key_compare& comp = key_compare());

template<class InputIterator>
flat_map(InputIterator first, InputIterator last, const key_compare& comp = key_compare())
: c(), compare(comp) { insert(first, last); }

template<class InputIterator>
flat_map(sorted_unique_t s, InputIterator first, InputIterator last,
const key_compare& comp = key_compare())
: c(), compare(comp) { insert(s, first, last); }

template<container-compatible-range<value_type> R>
flat_map(from_range_t fr, R&& rg) :
flat_map(fr, std::forward<R>(rg), key_compare()) { }

template<container-compatible-range<value_type> R>
flat_map(from_range_t, R&& rg, const key_compare& comp)
: flat_map(comp) { insert_range(std::forward<R>(rg)); }

flat_map(initializer_list<value_type> il, const key_compare& comp = key_compare())
: flat_map(il.begin(), il.end(), comp) { }

flat_map(sorted_unique_t s, initializer_list<value_type> il,
const key_compare& comp = key_compare())
: flat_map(s, il.begin(), il.end(), comp) { }

// 24.6.9.4, constructors with allocators

template<class Alloc>
explicit flat_map(const Alloc& a);

template<class Alloc>
flat_map(const key_compare& comp, const Alloc& a);

template<class Alloc>
flat_map(const key_container_type& key_cont, const mapped_container_type& mapped_cont,
const Alloc& a);

template<class Alloc>
flat_map(const key_container_type& key_cont, const mapped_container_type& mapped_cont,
const key_compare& comp, const Alloc& a);

template<class Alloc>
flat_map(sorted_unique_t, const key_container_type& key_cont,
const mapped_container_type& mapped_cont, const Alloc& a);

template<class Alloc>
flat_map(sorted_unique_t, const key_container_type& key_cont,
const mapped_container_type& mapped_cont,
const key_compare& comp, const Alloc& a);

template<class Alloc>
flat_map(const flat_map&, const Alloc& a);

template<class Alloc>
flat_map(flat_map&&, const Alloc& a);

template<class InputIterator, class Alloc>
flat_map(InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
flat_map(InputIterator first, InputIterator last,
const key_compare& comp, const Alloc& a);

template<class InputIterator, class Alloc>
flat_map(sorted_unique_t, InputIterator first, InputIterator last,
const Alloc& a);

template<class InputIterator, class Alloc>
flat_map(sorted_unique_t, InputIterator first, InputIterator last,
const key_compare& comp, const Alloc& a);

template<container-compatible-range<value_type> R, class Alloc>
flat_map(from_range_t, R&& rg, const Alloc& a);

template<container-compatible-range<value_type> R, class Alloc>
flat_map(from_range_t, R&& rg, const key_compare& comp, const Alloc& a);

template<class Alloc>
flat_map(initializer_list<value_type> il, const Alloc& a);

template<class Alloc>
flat_map(initializer_list<value_type> il, const key_compare& comp, const Alloc& a);

template<class Alloc>
flat_map(sorted_unique_t, initializer_list<value_type> il, const Alloc& a);

template<class Alloc>
flat_map(sorted_unique_t, initializer_list<value_type> il,
const key_compare& comp, const Alloc& a);

flat_map& operator=(initializer_list<value_type>);

// iterators

iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;

const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// 24.6.9.5, capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.6.9.6, element access

mapped_type& operator[](const key_type& x);
mapped_type& operator[](key_type&& x);

template<class K> mapped_type& operator[](K&& x);
mapped_type& at(const key_type& x);
const mapped_type& at(const key_type& x) const;
const mapped_type& at(const key_type& x) const;

template<class K> mapped_type& at(const K& x);

template<class K> const mapped_type& at(const K& x) const;

// 24.6.9.7, modifiers

template<class... Args> pair<iterator, bool> emplace(Args&&... args);

pair<iterator, bool> insert(const value_type& x)
{ return emplace(x); }
pair<iterator, bool> insert(value_type&& x)
{ return emplace(std::move(x)); }
iterator insert(const_iterator position, const value_type& x)
    { return emplace_hint(position, x); }
iterator insert(const_iterator position, value_type&& x)
    { return emplace_hint(position, std::move(x)); }

template<class P> pair<iterator, bool> insert(P&& x);
template<class P>
    iterator insert(const_iterator position, P&& x);
template<class InputIterator>
    void insert(InputIterator first, InputIterator last);
template<class InputIterator>
    void insert(sorted_unique_t, InputIterator first, InputIterator last);
template<container-compatible-range<value_type> R>
    void insert_range(R&& rg);

void insert(initializer_list<value_type> il)
    { insert(il.begin(), il.end()); }
void insert(sorted_unique_t s, initializer_list<value_type> il)
    { insert(s, il.begin(), il.end()); }

containers extract() &&;
void replace(key_container_type&& key_cont, mapped_container_type&& mapped_cont);
template<class... Args>
    pair<iterator, bool> try_emplace(const key_type& k, Args&&... args);
template<class... Args>
    pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);
template<class K, class... Args>
    iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);
template<class K, class... Args>
    iterator try_emplace(const_iterator hint, key_type&& k, Args&&... args);
template<class M>
    iterator try_emplace(const_iterator hint, const key_type& k, M&& obj);
template<class M>
    iterator try_emplace(const_iterator hint, key_type&& k, M&& obj);
template<class M>
    iterator insert_or_assign(const_iterator hint, const key_type& k, M&& obj);
template<class M>
    iterator insert_or_assign(const_iterator hint, key_type&& k, M&& obj);
template<class M>
    iterator insert_or_assign(const_iterator hint, const key_type& k, M&& obj);
template<class M>
    iterator insert_or_assign(const_iterator hint, key_type&& k, M&& obj);

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);
void swap(flat_map& y) noexcept;
void clear() noexcept;

// observers
key_compare key_comp() const;
value_compare value_comp() const;

const key_container_type& keys() const noexcept { return c.keys; }
const mapped_container_type& values() const noexcept { return c.values; }
// map operations
iterator find(const key_type& x);
const_iterator find(const key_type& x) const;
template<class K> iterator find(const K& x);
template<class K> const_iterator find(const K& x) const;

size_type count(const key_type& x) const;
template<class K> size_type count(const K& x) const;

bool contains(const key_type& x) const;
template<class K> bool contains(const K& x) const;

iterator lower_bound(const key_type& x);
const_iterator lower_bound(const key_type& x) const;
template<class K> iterator lower_bound(const K& x);
template<class K> const_iterator lower_bound(const K& x) const;

iterator upper_bound(const key_type& x);
const_iterator upper_bound(const key_type& x) const;
template<class K> iterator upper_bound(const K& x);
template<class K> const_iterator upper_bound(const K& x) const;

class pair<iterator, iterator> equal_range(const key_type& x);
class pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
template<class K> class pair<iterator, iterator> equal_range(const K& x);
template<class K> class pair<const_iterator, const_iterator> equal_range(const K& x) const;

friend bool operator==(const flat_map& x, const flat_map& y);
friend
synth-three-way-result<value_type>
operator<=>(const flat_map& x, const flat_map& y);
friend void swap(flat_map& x, flat_map& y) noexcept
{ x.swap(y); }

private:
containers c;                 // exposition only
key_compare compare;         // exposition only

struct key_equiv {            // exposition only
  key_equiv(key_compare c) : comp(c) { }
  bool operator()(const_reference x, const_reference y) const {
    return !comp(x.first, y.first) && !comp(y.first, x.first);
  }
  key_compare comp;
};

template<class KeyContainer, class MappedContainer, class Compare = less<typename KeyContainer::value_type>>
flat_map(KeyContainer, MappedContainer, Compare = Compare())
  -> flat_map<typename KeyContainer::value_type, typename MappedContainer::value_type, Compare, KeyContainer, MappedContainer>;

template<class KeyContainer, class MappedContainer, class Allocator>
flat_map(KeyContainer, MappedContainer, Allocator)
  -> flat_map<typename KeyContainer::value_type, typename MappedContainer::value_type, less<typename KeyContainer::value_type>, KeyContainer, MappedContainer>;
template<class KeyContainer, class MappedContainer, class Compare, class Allocator>
flat_map(KeyContainer, MappedContainer, Compare, Allocator)
  -> flat_map<typename KeyContainer::value_type, typename MappedContainer::value_type, Compare, KeyContainer, MappedContainer>;
The member type containers has the data members and special members specified above. It has no base classes or members other than those specified.

24.6.9.3 Constructors

flat_map(key_container_type key_cont, mapped_container_type mapped_cont, const key_compare& comp = key_compare());

Effects: Initializes c.keys with std::move(key_cont), c.values with std::move(mapped_cont), and compare with comp; sorts the range [begin(), end()) with respect to value_comp(); and finally erases the duplicate elements as if by:

auto zv = views::zip(c.keys, c.values);
auto it = ranges::unique(zv, key_equiv(compare)).begin();
auto dist = distance(zv.begin(), it);
c.keys.erase(c.keys.begin() + dist, c.keys.end());
c.values.erase(c.values.begin() + dist, c.values.end());

Complexity: Linear in \( N \) if the container arguments are already sorted with respect to \( \text{value\_comp()} \) and otherwise \( N \log N \), where \( N \) is the value of \( \text{key\_cont.size()} \) before this call.

\[
\text{flat\_map}(\text{sorted\_unique\_t}, \text{key\_container\_type} \text{ key\_cont}, \text{mapped\_container\_type} \text{ mapped\_cont},
\text{const key\_compare& comp} = \text{key\_compare}());
\]

Effects: Initializes \( c\text{.keys} \) with \( \text{std\::move(key\_cont)} \), \( c\text{.values} \) with \( \text{std\::move(mapped\_cont)} \), and \( \text{compare with comp} \).

Complexity: Constant.

### 24.6.9.4 Constructors with allocators

The constructors in this subclause shall not participate in overload resolution unless \( \text{uses\_allocator\_v}<\text{key\_container\_type}, \text{Alloc}> \) is true and \( \text{uses\_allocator\_v}<\text{mapped\_container\_type}, \text{Alloc}> \) is true.

\[
\text{template<class Alloc>}
\text{flat\_map(const key\_container\_type& key\_cont, const mapped\_container\_type& mapped\_cont, const Alloc& a);}
\]

Effects: Equivalent to \( \text{flat\_map(key\_cont, mapped\_cont)} \) and \( \text{flat\_map(key\_cont, mapped\_cont, comp)} \), respectively, except that \( c\text{.keys} \) and \( c\text{.values} \) are constructed with uses-allocator construction (20.2.8.2).

Complexity: Same as \( \text{flat\_map(key\_cont, mapped\_cont)} \) and \( \text{flat\_map(key\_cont, mapped\_cont, comp)} \), respectively.

\[
\text{template<class Alloc>}
\text{flat\_map(sorted\_unique\_t s, const key\_container\_type& key\_cont, const mapped\_container\_type& mapped\_cont, const Alloc& a);}
\]

Effects: Equivalent to \( \text{flat\_map(s, key\_cont, mapped\_cont)} \) and \( \text{flat\_map(s, key\_cont, mapped\_cont, comp)} \), respectively, except that \( c\text{.keys} \) and \( c\text{.values} \) are constructed with uses-allocator construction (20.2.8.2).

Complexity: Linear.
template<class Alloc>
    flat_map(initializer_list<value_type> il, const Alloc& a);
-template<class Alloc>
    flat_map(initializer_list<value_type> il, const key_compare& comp, const Alloc& a);
-template<class Alloc>
    flat_map(sorted_unique_t, initializer_list<value_type> il, const Alloc& a);
-template<class Alloc>
    flat_map(sorted_unique_t, initializer_list<value_type> il, const key_compare& comp, const Alloc& a);

Effects: Equivalent to the corresponding non-allocator constructors except that c.keys and c.values are constructed with uses-allocator construction (20.2.8.2).

24.6.9.5 Capacity

    size_type size() const noexcept;

Returns: c.keys.size().

    size_type max_size() const noexcept;

Returns: min<size_type>(c.keys.max_size(), c.values.max_size()).

24.6.9.6 Access

    mapped_type& operator[](const key_type& x);

Effects: Equivalent to: return try_emplace(x).first->second;

    mapped_type& operator[](key_type&& x);

Effects: Equivalent to: return try_emplace(std::move(x)).first->second;

    template<class K> mapped_type& operator[](K&& x);

Constraints: The qualified-id Compare::is_transparent is valid and denotes a type.

Effects: Equivalent to: return try_emplace(std::forward<K>(x)).first->second;

    mapped_type& at(const key_type& x);

const mapped_type& at(const key_type& x) const;

Returns: A reference to the mapped_type corresponding to x in *this.

Throws: An exception object of type out_of_range if no such element is present.

Complexity: Logarithmic.

    template<class K> mapped_type& at(const K& x);

    template<class K> const mapped_type& at(const K& x) const;

Constraints: The qualified-id Compare::is_transparent is valid and denotes a type.

Preconditions: The expression find(x) is well-formed and has well-defined behavior.

Returns: A reference to the mapped_type corresponding to x in *this.

Throws: An exception object of type out_of_range if no such element is present.

Complexity: Logarithmic.

24.6.9.7 Modifiers

    template<class... Args> pair<iterator, bool> emplace(Args&&... args);

Constraints: is_constructible_v<pair<key_type, mapped_type>, Args...> is true.

Effects: Initializes an object t of type pair<key_type, mapped_type> with std::forward<Args>(args).... if the map already contains an element whose key is equivalent to t.first, *this is unchanged. Otherwise, equivalent to:

    auto key_it = ranges::upper_bound(c.keys, t.first, compare);
    auto value_it = c.values.begin() + distance(c.keys.begin(), key_it);
    c.keys.insert(key_it, std::move(t.first));
    c.values.insert(value_it, std::move(t.second));

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Returns: The bool component of the returned pair is true if and only if the insertion took place, and the iterator component of the pair points to the element with key equivalent to t.first.

\[
\text{template<class P> pair<iterator, bool> insert(P&& x);}\
\text{template<class P> iterator insert(const_iterator position, P&& x);}\
\text{Constraints: is_constructible_v<pair<key_type, mapped_type>, P> is true.}\
\text{Effects: The first form is equivalent to return emplace(std::forward<P>(x)); The second form is equivalent to return emplace_hint(position, std::forward<P>(x));}\
\]

template<class InputIterator>
\text{void insert(InputIterator first, InputIterator last);}\
\text{Effects: Adds elements to c as if by:}\
\text{for (; first != last; ++first) { value_type value = *first; c.keys.insert(c.keys.end(), std::move(value.first)); c.values.insert(c.values.end(), std::move(value.second)); }\
Then, sorts the range of newly inserted elements with respect to value_comp(); merges the resulting sorted range and the sorted range of pre-existing elements into a single sorted range; and finally erases the duplicate elements as if by:}\
\text{auto zv = views::zip(c.keys, c.values); auto it = ranges::unique(zv, key_equiv(compare)).begin(); auto dist = distance(zv.begin(), it); c.keys.erase(c.keys.begin() + dist, c.keys.end()); c.values.erase(c.values.begin() + dist, c.values.end());}\
\text{Complexity: } N + M \log M, \text{ where } N \text{ is size() before the operation and } M \text{ is distance(first, last).}\
\text{Remarks: Since this operation performs an in-place merge, it may allocate memory.}\

\text{template<class InputIterator>
void insert(sorted_unique_t, InputIterator first, InputIterator last);}\
\text{Effects: Adds elements to c as if by:}\
\text{for (; first != last; ++first) { value_type value = *first; c.keys.insert(c.keys.end(), std::move(value.first)); c.values.insert(c.values.end(), std::move(value.second)); }\
Then, merges the sorted range of newly added elements and the sorted range of pre-existing elements into a single sorted range; and finally erases the duplicate elements as if by:}\
\text{auto zv = views::zip(c.keys, c.values); auto it = ranges::unique(zv, key_equiv(compare)).begin(); auto dist = distance(zv.begin(), it); c.keys.erase(c.keys.begin() + dist, c.keys.end()); c.values.erase(c.values.begin() + dist, c.values.end());}\
\text{Complexity: Linear in } N, \text{ where } N \text{ is size() after the operation.}\
\text{Remarks: Since this operation performs an in-place merge, it may allocate memory.}\

\text{template<container-compatible-range<value_type> R>
void insert_range(R&& rg);}\
\text{Effects: Adds elements to c as if by:}\
\text{for (const auto& e : rg) { c.keys.insert(c.keys.end(), e.first); c.values.insert(c.values.end(), e.second); }
Then, sorts the range of newly inserted elements with respect to `value_comp()`; merges the resulting sorted range and the sorted range of pre-existing elements into a single sorted range; and finally erases the duplicate elements as if by:

```cpp
auto zv = views::zip(c.keys, c.values);
auto it = ranges::unique(zv, key_equiv(compare)).begin();
c.keys.erase(c.keys.begin() + dist, c.keys.end());
c.values.erase(c.values.begin() + dist, c.values.end());
```

**Complexity:** \( N + M \log M \), where \( N \) is `size()` before the operation and \( M \) is `ranges::distance(rg)`.

**Remarks:** Since this operation performs an in-place merge, it may allocate memory.

```cpp
template<class... Args>
pair<iterator, bool> try_emplace(const key_type& k, Args&&... args);
template<class... Args>
pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);
template<class... Args>
iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);
template<class... Args>
iterator try_emplace(const_iterator hint, key_type&& k, Args&&... args);
```

**Constraints:** `is_constructible_v<mapped_type, Args...>` is true.

**Effects:** If the map already contains an element whose key is equivalent to `k`, `*this` and `args...` are unchanged. Otherwise equivalent to:

```cpp
auto key_it = ranges::upper_bound(c.keys, k, compare);
c.keys.insert(key_it, std::forward<decltype(k)>(k));
c.values.emplace(value_it, std::forward<Args>(args)...);
```

**Returns:** In the first two overloads, the bool component of the returned pair is `true` if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to `k`.

**Complexity:** The same as `emplace` for the first two overloads, and the same as `emplace_hint` for the last two overloads.

```cpp
template<class K, class... Args>
pair<iterator, bool> try_emplace(K&& k, Args&&... args);
template<class K, class... Args>
iterator try_emplace(const_iterator hint, K&& k, Args&&... args);
```

**Constraints:**

1. The qualified-id `Compare::is_transparent` is valid and denotes a type.
2. `is_constructible_v<key_type, K>` is true.
3. `is_constructible_v<mapped_type, Args...>` is true.
4. For the first overload, `is_convertible_v<K&&, const_iterator>` and `is_convertible_v<K&&, iterator>` are both false.

**Preconditions:** The conversion from `k` into `key_type` constructs an object `u`, for which `find(k) == find(u)` is true.

**Effects:** If the map already contains an element whose key is equivalent to `k`, `*this` and `args...` are unchanged. Otherwise equivalent to:

```cpp
auto key_it = ranges::upper_bound(c.keys, k, compare);
c.keys.insert(key_it, std::forward<K>(k));
c.values.emplace(value_it, std::forward<Args>(args)...);
```

**Returns:** In the first overload, the bool component of the returned pair is `true` if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to `k`.

**Complexity:** The same as `emplace` and `emplace_hint`, respectively.

```cpp
template<class M>
pair<iterator, bool> insert_or_assign(const key_type& k, M&& obj);
```
template<class M>
    pair<iterator, bool> insert_or_assign(key_type&& k, M&& obj);

template<class M>
    iterator insert_or_assign(const_iterator hint, const key_type& k, M&& obj);

template<class M>
    iterator insert_or_assign(const_iterator hint, key_type&& k, M&& obj);

Constraints: is_assignable_v<mapped_type&, M> is true and is_constructible_v<mapped_type, M> is true.

Effects: If the map already contains an element e whose key is equivalent to k, assigns std::forward<M>(obj) to e.second. Otherwise, equivalent to

    try_emplace(std::forward<decltype(k)>(k), std::forward<M>(obj))

for the first two overloads or

    try_emplace(hint, std::forward<decltype(k)>(k), std::forward<M>(obj))

for the last two overloads.

Returns: In the first two overloads, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

Complexity: The same as emplace for the first two overloads and the same as emplace_hint for the last two overloads.

template<class K, class M>
    pair<iterator, bool> insert_or_assign(K&& k, M&& obj);

template<class K, class M>
    iterator insert_or_assign(const_iterator hint, K&& k, M&& obj);

Constraints:

    — The qualified-id Compare::is_transparent is valid and denotes a type.

    — is_constructible_v<key_type, K> is true.

    — is_assignable_v<mapped_type&, M> is true.

    — is_constructible_v<mapped_type, M> is true.

Preconditions: The conversion from k into key_type constructs an object u, for which find(k) == find(u) is true.

Effects: If the map already contains an element e whose key is equivalent to k, assigns std::forward<M>(obj) to e.second. Otherwise, equivalent to

    try_emplace(std::forward<K>(k), std::forward<M>(obj))

for the first overload or

    try_emplace(hint, std::forward<K>(k), std::forward<M>(obj))

for the second overload.

Returns: In the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the map element whose key is equivalent to k.

Complexity: The same as emplace and emplace_hint, respectively.

void swap(flat_map& y) noexcept;

Effects: Equivalent to:

    ranges::swap(compare, y.compare);
    ranges::swap(c.keys, y.c.keys);
    ranges::swap(c.values, y.c.values);

containers extract() &&;

Postconditions: *this is emptied, even if the function exits via an exception.

Returns: std::move(c). 

§ 24.6.9.7

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1048
void replace(key_container_type&& key_cont, mapped_container_type&& mapped_cont);

36 Preconditions: key_cont.size() == mapped_cont.size() is true, the elements of key_cont are sorted with respect to compare, and key_cont contains no equal elements.

37 Effects: Equivalent to:
   c.keys = std::move(key_cont);
   c.values = std::move(mapped_cont);

24.6.9.8 Erasure
   
   template<class Key, class T, class Compare, class KeyContainer, class MappedContainer,
    class Predicate>
   typename flat_map<Key, T, Compare, KeyContainer, MappedContainer>::size_type
   erase_if(flat_map<Key, T, Compare, KeyContainer, MappedContainer>& c, Predicate pred);

1 Preconditions: Key and T meet the Cpp17MoveAssignable requirements.
2 Effects: Let E be bool(pred(pair<const Key&, const T&>(e))). Erases all elements e in c for which E holds.
3 Returns: The number of elements erased.
4 Complexity: Exactly c.size() applications of the predicate.
5 Remarks: Stable (16.4.6.8). If an invocation of erase_if exits via an exception, c is in a valid but unspecified state (3.65).

[Note 1: c still meets its invariants, but can be empty. — end note]

24.6.10 Class template flat_multimap

24.6.10.1 Overview

1 A flat_multimap is a container adaptor that provides an associative container interface that supports equivalent keys (i.e., possibly containing multiple copies of the same key value) and provides for fast retrieval of values of another type T based on the keys. flat_multimap supports iterators that meet the Cpp17InputIterator requirements and model the random_access_iterator concept (25.3.4.13).

2 A flat_multimap meets all of the requirements for a container (24.2.2.2) and for a reversible container (24.2.2.3), plus the optional container requirements (24.2.2.4). flat_multimap meets the requirements of an associative container (24.2.7), except that:
   (2.1) — it does not meet the requirements related to node handles (24.2.5),
   (2.2) — it does not meet the requirements related to iterator invalidation, and
   (2.3) — the time complexity of the operations that insert or erase a single element from the map is linear, including the ones that take an insertion position iterator.

[Note 1: A flat_multimap does not meet the additional requirements of an allocator-aware container (24.2.2.5). — end note]

3 A flat_multimap also provides most operations described in 24.2.7 for equal keys. This means that a flat_multimap supports the a_eq operations in 24.2.7 but not the a_uniq operations. For a flat_multimap<Key, T> the key_type is Key and the value_type is pair<Key, T>.

4 Except as otherwise noted, operations on flat_multimap are equivalent to those of flat_map, except that flat_multimap operations do not remove or replace elements with equal keys. 

[Example 1: flat_multimap constructors and emplace do not erase non-unique elements after sorting them. — end example]

5 A flat_multimap maintains the following invariants:
   (5.1) — it contains the same number of keys and values;
   (5.2) — the keys are sorted with respect to the comparison object; and
   (5.3) — the value at offset off within the value container is the value associated with the key at offset off within the key container.

6 If any member function in 24.6.10.2 exits via an exception, the invariants are restored.

[Note 2: This can result in the flat_multimap being emptied. — end note]
Any type `C` that meets the sequence container requirements (24.2.4) can be used to instantiate `flat_multimap`, as long as `C::iterator` meets the `Cpp17RandomAccessIterator` requirements and invocations of member functions `C::size` and `C::max_size` do not exit via an exception. In particular, `vector` (24.3.12) and `deque` (24.3.9) can be used.

[Note 3: `vector<bool>` is not a sequence container. — end note]

The program is ill-formed if `Key` is not the same type as `KeyContainer::value_type` or `T` is not the same type as `MappedContainer::value_type`.

The effect of calling a constructor that takes both `key_container_type` and `mapped_container_type` arguments with containers of different sizes is undefined.

The effect of calling a constructor or member function that takes a `sorted_equivalent_t` argument with a container, containers, or range that are not sorted with respect to `key_comp()` is undefined.

24.6.10.2 Definition

```cpp
namespace std {
  template<class Key, class T, class Compare = less<Key>,
           class KeyContainer = vector<Key>, class MappedContainer = vector<T>>
  class flat_multimap {
    public:
      // types
      using key_type = Key;
      using mapped_type = T;
      using value_type = pair<key_type, mapped_type>;
      using key_compare = Compare;
      using reference = pair<const key_type&, mapped_type&>;
      using const_reference = pair<const key_type&, const mapped_type&>;
      using size_type = size_t;
      using difference_type = ptrdiff_t;
      using iterator = implementation-defined;   // see 24.2
      using const_iterator = implementation-defined;   // see 24.2
      using reverse_iterator = std::reverse_iterator<iterator>;
      using const_reverse_iterator = std::reverse_iterator<const_iterator>;
      using key_container_type = KeyContainer;
      using mapped_container_type = MappedContainer;

      class value_compare {
        private:
          key_compare comp;
          value_compare(key_compare c) : comp(c) {}  // exposition only
        public:
          bool operator()(const_reference x, const_reference y) const {
            return comp(x.first, y.first);
          }
      };

      struct containers {
        key_container_type keys;
        mapped_container_type values;
      };

      // 24.6.10.3, constructors
      flat_multimap() : flat_multimap(key_compare()) {}  // 24.6.10.2
      explicit flat_multimap(const key_compare& comp)
        : c(), compare(comp) {}  // 24.6.10.2
      flat_multimap(key_container_type key_cont, mapped_container_type mapped_cont,
                    const key_compare& comp = key_compare());  // 24.6.10.2
  };
}
```

§ 24.6.10.2
flat_multimap(sorted_equivalent_t,
    key_container_type key_cont, mapped_container_type mapped_cont,
    const key_compare& comp = key_compare());

template<class InputIterator>
flat_multimap(InputIterator first, InputIterator last,
    const key_compare& comp = key_compare())
    : c(), compare(comp) { insert(first, last); }

template<class InputIterator>
flat_multimap(sorted_equivalent_t s, InputIterator first, InputIterator last,
    const key_compare& comp = key_compare())
    : c(), compare(comp) { insert(s, first, last); }

template<container-compatible-range<value_type> R>
flat_multimap(from_range_t fr, R&& rg)
    : flat_multimap(fr, std::forward<R>(rg), key_compare()) { }
template<container-compatible-range<value_type> R>
flat_multimap(from_range_t, R&& rg, const key_compare& comp)
    : flat_multimap(comp) { insert_range(std::forward<R>(rg)); }

flat_multimap(initializer_list<value_type> il, const key_compare& comp = key_compare())
    : flat_multimap(il.begin(), il.end(), comp) { }

flat_multimap(sorted_equivalent_t s, initializer_list<value_type> il,
    const key_compare& comp = key_compare())
    : flat_multimap(s, il.begin(), il.end(), comp) { }

// 24.6.10.4, constructors with allocators

template<class Alloc>
    explicit flat_multimap(const Alloc& a);
template<class Alloc>
    flat_multimap(const key_compare& comp, const Alloc& a);
template<class Alloc>
    flat_multimap(const key_container_type& key_cont, const mapped_container_type& mapped_cont,
        const Alloc& a);
template<class Alloc>
    flat_multimap(const key_container_type& key_cont, const mapped_container_type& mapped_cont,
        const Alloc& a);
template<class Alloc>
    flat_multimap(sorted_equivalent_t, const key_container_type& key_cont,
        const mapped_container_type& mapped_cont, const Alloc& a);
template<class Alloc>
    flat_multimap(sorted_equivalent_t, const key_container_type& key_cont,
        const mapped_container_type& mapped_cont, const Alloc& a);
template<class Alloc>
    flat_multimap(const flat_multimap&, const Alloc& a);
template<class Alloc>
    flat_multimap(flat_multimap&, const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(InputIterator first, InputIterator last,
        const key_compare& comp, const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(sorted_equivalent_t, InputIterator first, InputIterator last,
        const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(sorted_equivalent_t, InputIterator first, InputIterator last,
        const key_compare& comp, const Alloc& a);
template<container-compatible-range<value_type> R, class Alloc>
    flat_multimap(from_range_t, R&& rg, const Alloc& a);
template<container-compatible-range<value_type> R, class Alloc>
    flat_multimap(from_range_t, R&& rg, const key_compare& comp, const Alloc& a);
template<Alloc>
    flat_multimap(initializer_list<value_type> il, const Alloc& a);
template<Alloc>
    flat_multimap(initializer_list<value_type> il, const key_compare& comp, const Alloc& a);
template<Alloc>
    flat_multimap(sorted_equivalent_t, initializer_list<value_type> il, const Alloc& a);
template<Alloc>
    flat_multimap(sorted_equivalent_t, initializer_list<value_type> il, const key_compare& comp, const Alloc& a);

flat_multimap& operator=(initializer_list<value_type>);

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// modifiers
template<class... Args> iterator emplace(Args&&... args);
template<class... Args>
    iterator emplace_hint(const_iterator position, Args&&... args);

iterator insert(const value_type& x)
    { return emplace(x); }
iterator insert(value_type&& x)
    { return emplace(std::move(x)); }
iterator insert(const_iterator position, const value_type& x)
    { return emplace_hint(position, x); }
iterator insert(const_iterator position, value_type&& x)
    { return emplace_hint(position, std::move(x)); }

template<class P> iterator insert(P&& x);
template<class P>
    iterator insert(const_iterator position, P&&);
template<class InputIterator>
    void insert(InputIterator first, InputIterator last);
template<class InputIterator>
    void insert(sorted_equivalent_t, InputIterator first, InputIterator last);
template<container-compatible-range<value_type> R>
    void insert_range(R&& rg);

void insert(initializer_list<value_type> il)
    { insert(il.begin(), il.end()); }
void insert(sorted_equivalent_t s, initializer_list<value_type> il)
    { insert(s, il.begin(), il.end()); }

containers extract() &&;
void replace(key_container_type&& key_cont, mapped_container_type&& mapped_cont);

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);

void swap(flat_multimap&) noexcept;
void clear() noexcept;

// observers
key_compare key_comp() const;
value_compare value_comp() const;

const key_container_type& keys() const noexcept { return c.keys; }
const mapped_container_type& values() const noexcept { return c.values; }

// map operations
iterator find(const key_type& x);
const_iterator find(const key_type& x) const;
template<class K> iterator find(const K& x);
template<class K> const_iterator find(const K& x) const;

size_type count(const key_type& x) const;
template<class K> size_type count(const K& x) const;

bool contains(const key_type& x) const;
template<class K> bool contains(const K& x) const;

iterator lower_bound(const key_type& x);
const_iterator lower_bound(const key_type& x) const;
template<class K> iterator lower_bound(const K& x);
template<class K> const_iterator lower_bound(const K& x) const;

iterator upper_bound(const key_type& x);
const_iterator upper_bound(const key_type& x) const;
template<class K> iterator upper_bound(const K& x);
template<class K> const_iterator upper_bound(const K& x) const;

pair<iterator, iterator> equal_range(const key_type& x);
pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
template<class K>
    pair<iterator, iterator> equal_range(const K& x);
template<class K>
    pair<const_iterator, const_iterator> equal_range(const K& x) const;

friend bool operator==(const flat_multimap& x, const flat_multimap& y);
friend synth-three-way-result<value_type>
    operator<=>(const flat_multimap& x, const flat_multimap& y);
friend void swap(flat_multimap& x, flat_multimap& y) noexcept
    { x.swap(y); }

private:
    containers c;                     // exposition only
    key_compare compare;             // exposition only
template<class KeyContainer, class MappedContainer, 
    class Compare = less<typename KeyContainer::value_type>>
flat_multimap(KeyContainer, MappedContainer, Compare = Compare())
-> flat_multimap<typename KeyContainer::value_type, typename MappedContainer::value_type, 
    Compare, KeyContainer, MappedContainer>;

template<class KeyContainer, class MappedContainer, class Allocator>
flat_multimap(KeyContainer, MappedContainer, Allocator)
-> flat_multimap<typename KeyContainer::value_type, typename MappedContainer::value_type, 
    less<typename KeyContainer::value_type>, KeyContainer, MappedContainer>;

template<class KeyContainer, class MappedContainer, class Compare, class Allocator>
flat_multimap(KeyContainer, MappedContainer, Compare, Allocator)
-> flat_multimap<typename KeyContainer::value_type, typename MappedContainer::value_type, 
    Compare, KeyContainer, MappedContainer>;

template<class KeyContainer, class MappedContainer, class Compare = less<typename KeyContainer::value_type>>
flat_multimap(sorted_equivalent_t, KeyContainer, MappedContainer, Compare = Compare())
-> flat_multimap<typename KeyContainer::value_type, typename MappedContainer::value_type, 
    Compare, KeyContainer, MappedContainer>;

template<class KeyContainer, class MappedContainer, class Allocator>
flat_multimap(sorted_equivalent_t, KeyContainer, MappedContainer, Allocator)
-> flat_multimap<typename KeyContainer::value_type, typename MappedContainer::value_type, 
    less<typename KeyContainer::value_type>, KeyContainer, MappedContainer>;

template<class KeyContainer, class MappedContainer, class Compare, class Allocator>
flat_multimap(sorted_equivalent_t, KeyContainer, MappedContainer, Compare, Allocator)
-> flat_multimap<typename KeyContainer::value_type, typename MappedContainer::value_type, 
    Compare, KeyContainer, MappedContainer>;

template<class InputIterator, class Compare = less<
    iter-key-type<InputIterator>>>>
flat_multimap(InputIterator, InputIterator, Compare = Compare())
-> flat_multimap<iter-key-type<InputIterator>, iter-mapped-type<InputIterator>, Compare>;

template<class InputIterator, class Compare = less<
    iter-key-type<InputIterator>>>>
flat_multimap(sorted_equivalent_t, InputIterator, InputIterator, Compare = Compare())
-> flat_multimap<iter-key-type<InputIterator>, iter-mapped-type<InputIterator>, Compare>;

template<ranges::input_range R, class Compare = less<
    range-key-type<R>>, class Allocator = allocator<byte>>
flat_multimap(from_range_t, R&&, Compare = Compare(), Allocator = Allocator())
-> flat_multimap<range-key-type<R>, range-mapped-type<R>, Compare, 
    vector<range-key-type<R>, 
    alloc-rebind<Allocator, range-key-type<R>>, 
    vector<range-mapped-type<R>, 
    alloc-rebind<Allocator, range-mapped-type<R>>>>;
template<class Key, class T, class Compare, class KeyContainer, class MappedContainer, class Allocator>
struct uses_allocator<flat_multimap<Key, T, Compare, KeyContainer, MappedContainer>, Allocator>
 : bool_constant<uses_allocator_v<KeyContainer, Allocator> &&
 uses_allocator_v<MappedContainer, Allocator>> { };

The member type containers has the data members and special members specified above. It has no base classes or members other than those specified.

24.6.10.3 Constructors

```cpp
flat_multimap(key_container_type key_cont, mapped_container_type mapped_cont,
 const key_compare& comp = key_compare());
```

Effects: Initializes c.keys with std::move(key_cont), c.values with std::move(mapped_cont), and compare with comp; sorts the range [begin(), end()) with respect to value_comp().

Complexity: Linear in N if the container arguments are already sorted with respect to value_comp() and otherwise N log N, where N is the value of key_cont.size() before this call.

```cpp
flat_multimap(sorted_equivalent_t s, key_container_type key_cont, mapped_container_type mapped_cont,
 const key_compare& comp = key_compare());
```

Effects: Initializes c.keys with std::move(key_cont), c.values with std::move(mapped_cont), and compare with comp.

Complexity: Constant.

24.6.10.4 Constructors with allocators

The constructors in this subclause shall not participate in overload resolution unless uses_allocator_v<key_container_type, Alloc> is true and uses_allocator_v<mapped_container_type, Alloc> is true.

```cpp
template<class Alloc>
flat_multimap(const key_container_type& key_cont, const mapped_container_type& mapped_cont,
 const Alloc& a);
```

Effects: Equivalent to flat_multimap(key_cont, mapped_cont) and flat_multimap(key_cont, mapped_cont, comp), respectively, except that c.keys and c.values are constructed with uses-allocator construction (20.2.8.2).

Complexity: Same as flat_multimap(key_cont, mapped_cont) and flat_multimap(key_cont, mapped_cont, comp), respectively.

```cpp
template<class Alloc>
flat_multimap(const sorted_equivalent_t s, const key_container_type& key_cont,
 const mapped_container_type& mapped_cont, const Alloc& a);
```

Effects: Equivalent to flat_multimap(s, key_cont, mapped_cont) and flat_multimap(s, key_cont, mapped_cont, comp), respectively, except that c.keys and c.values are constructed with uses-allocator construction (20.2.8.2).

Complexity: Linear.
template<class Alloc>
    flat_multimap(flat_multimap&&, const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(InputIterator first, InputIterator last, const key_compare& comp,
                   const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(sorted_equivalent_t, InputIterator first, InputIterator last,
                   const Alloc& a);
template<class InputIterator, class Alloc>
    flat_multimap(sorted_equivalent_t, InputIterator first, InputIterator last,
                   const key_compare& comp, const Alloc& a);
template<container-compatible-range<value_type> R, class Alloc>
    flat_multimap(from_range_t, R&& rg, const Alloc& a);
template<container-compatible-range<value_type> R, class Alloc>
    flat_multimap(from_range_t, R&& rg, const key_compare& comp, const Alloc& a);
template<class Alloc>
    flat_multimap(initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
    flat_multimap(initializer_list<value_type> il, const key_compare& comp, const Alloc& a);
template<class Alloc>
    flat_multimap(sorted_equivalent_t, initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
    flat_multimap(sorted_equivalent_t, initializer_list<value_type> il,
                   const key_compare& comp, const Alloc& a);

Effects: Equivalent to the corresponding non-allocator constructors except that c.keys and c.values are constructed with uses-allocator construction (20.2.8.2).

24.6.10.5 Erasure [flat.multimap.erase]

template<class Key, class T, class Compare, class KeyContainer, class MappedContainer,
         class Predicate>
    typename flat_multimap<Key, T, Compare, KeyContainer, MappedContainer>::size_type
        erase_if(flat_multimap<Key, T, Compare, KeyContainer, MappedContainer>& c, Predicate pred);

1 Preconditions: Key and T meet the Cpp17MoveAssignable requirements.
2 Effects: Let E be bool(pred(pair<const Key&, const T&>(e))). Erases all elements e in c for which E holds.
3 Returns: The number of elements erased.
4 Complexity: Exactly c.size() applications of the predicate.
5 Remarks: Stable (16.4.6.8). If an invocation of erase_if exits via an exception, c is in a valid but unspecified state (3.65).
   [Note 1: c still meets its invariants, but can be empty. — end note]

24.6.11 Class template flat_set [flat.set]

24.6.11.1 Overview [flat.set.overview]

1 A flat_set is a container adaptor that provides an associative container interface that supports unique keys (i.e., contains at most one of each key value) and provides for fast retrieval of the keys themselves. flat_set supports iterators that model the random_access_iterator concept (25.3.4.13).
2 A flat_set meets all of the requirements for a container (24.2.2.2) and for a reversible container (24.2.2.3), plus the optional container requirements (24.2.2.4). flat_set meets the requirements of an associative container (24.2.7), except that:

(2.1) it does not meet the requirements related to node handles (24.2.5.1),
(2.2) it does not meet the requirements related to iterator invalidation, and
(2.3) the time complexity of the operations that insert or erase a single element from the set is linear, including the ones that take an insertion position iterator.
A flat_set also provides most operations described in 24.2.7 for unique keys. This means that a flat_set supports the a_uniq operations in 24.2.7 but not the a_eq operations. For a flat_set<Key>, both the key_type and value_type are Key.

Descriptions are provided here only for operations on flat_set that are not described in one of those sets of requirements or for operations where there is additional semantic information.

A flat_set maintains the invariant that the keys are sorted with respect to the comparison object.

If any member function in 24.6.11.2 exits via an exception, the invariant is restored.

Any sequence container (24.2.4) supporting Cpp17RandomAccessIterator can be used to instantiate flat_set. In particular, vector (24.3.12) and deque (24.3.9) can be used.

The program is ill-formed if Key is not the same type as KeyContainer::value_type.

The effect of calling a constructor or member function that takes a sorted_unique_t argument with a range that is not sorted with respect to key_comp(), or that contains equal elements, is undefined.
template< container-compatible-range <value_type> R >
flat_set ( from_range_t fr, R&& rg )
    : flat_set ( fr, std::forward<R>(rg), key_compare() ) { }

template< container-compatible-range <value_type> R >
flat_set ( from_range_t, R&& rg, const key_compare& comp )
    : flat_set ( comp )
    { insert_range ( std::forward<R>(rg) ); } 

flat_set ( initializer_list < value_type > il, const key_compare& comp = key_compare() )
    : flat_set ( il.begin(), il.end(), comp ) { } 

flat_set ( sorted_unique_t s, initializer_list < value_type > il, 
    const key_compare& comp = key_compare() )
    : flat_set ( s, il.begin(), il.end(), comp ) { } 

// 24.6.11.4, constructors with allocators

template< class Alloc >
    explicit flat_set ( const Alloc& a );

template< class Alloc >
    flat_set ( const key_compare& comp, const Alloc& a );

template< class Alloc >
    flat_set ( const container_type& cont, const Alloc& a );

template< class Alloc >
    flat_set ( const container_type& cont, const key_compare& comp, const Alloc& a );

template< class Alloc >
    flat_set ( sorted_unique_t, const container_type& cont, const Alloc& a );

template< class Alloc >
    flat_set ( sorted_unique_t, const container_type& cont, 
        const key_compare& comp, const Alloc& a );

template< class Alloc >
    flat_set ( const flat_set&, const Alloc& a );

template< class Alloc >
    flat_set ( flat_set&&, const Alloc& a );

template< class Alloc >
    flat_set ( initial_list < value_type > il, const Alloc& a );

template< class Alloc >
    flat_set ( initial_list < value_type > il, const key_compare& comp, const Alloc& a );

template< class Alloc >
    flat_set ( sorted_unique_t, initial_list < value_type > il, const Alloc& a );

template< class Alloc >
    flat_set ( sorted_unique_t, initial_list < value_type > il, 
        const key_compare& comp, const Alloc& a );

flat_set& operator=( initializer_list < value_type > );

// iterators

iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;

reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;

const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.6.11.5, modifiers
template<class... Args> pair<iterator, bool> emplace(Args&&... args);
template<class... Args>
iterator emplace_hint(const_iterator position, Args&&... args);

pair<iterator, bool> insert(const value_type& x)
{ return emplace(x); }
pair<iterator, bool> insert(value_type&& x)
{ return emplace(std::move(x)); }

template<class K> pair<iterator, bool> insert(K&& x);
iterator insert(const_iterator position, const value_type& x)
{ return emplace_hint(position, x); }
iterator insert(const_iterator position, value_type&& x)
{ return emplace_hint(position, std::move(x)); }

template<class K> iterator insert(const_iterator hint, K&& x);
template<class InputIterator>
void insert(InputIterator first, InputIterator last);
template<class InputIterator>
void insert(sorted_unique_t, InputIterator first, InputIterator last);
template<container-compatible-range<value_type> R>
void insert_range(R&& rg);

void insert(initializer_list<value_type> il)
{ insert(il.begin(), il.end()); }
void insert(sorted_unique_t s, initializer_list<value_type> il)
{ insert(s, il.begin(), il.end()); }

container_type extract() &&;
void replace(container_type&&);

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);

void swap(flat_set& y) noexcept;
void clear() noexcept;

// observers
key_compare key_comp() const;
value_compare value_comp() const;

// set operations
iterator find(const key_type& x);
const_iterator find(const key_type& x) const;
template<class K> iterator find(const K& x);
template<class K> const_iterator find(const K& x) const;

size_type count(const key_type& x) const;
template<class K> size_type count(const K& x) const;

bool contains(const key_type& x) const;
template<class K> bool contains(const K& x) const;

iterator lower_bound(const key_type& x);
const_iterator lower_bound(const key_type& x) const;
template<class K> iterator lower_bound(const K& x);
template<class K> const_iterator lower_bound(const K& x) const;

iterator upper_bound(const key_type& x);
const_iterator upper_bound(const key_type& x) const;
template<class K> iterator upper_bound(const K& x);
template<class K> const_iterator upper_bound(const K& x) const;

pair<iterator, iterator> equal_range(const key_type& x);
pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
template<class K>
    pair<iterator, iterator> equal_range(const K& x);
template<class K>
    pair<const_iterator, const_iterator> equal_range(const K& x) const;

friend bool operator==(const flat_set& x, const flat_set& y);
friend// exposition only
    synth-three-way-result<value_type>
    operator<=>(const flat_set& x, const flat_set& y);

friend void swap(flat_set& x, flat_set& y) noexcept { x.swap(y); }

private:
    container_type c; // exposition only
    key_compare compare; // exposition only
};

template<class KeyContainer, class Compare = less<typename KeyContainer::value_type>>
    flat_set(KeyContainer, Compare = Compare())
    -> flat_set<typename KeyContainer::value_type, Compare, KeyContainer>;
template<class KeyContainer, class Allocator>
    flat_set(KeyContainer, Allocator)
    -> flat_set<typename KeyContainer::value_type,
        less<typename KeyContainer::value_type>, KeyContainer>;
template<class KeyContainer, class Compare, class Allocator>
    flat_set(KeyContainer, Compare, Allocator)
    -> flat_set<typename KeyContainer::value_type, Compare, KeyContainer>;

template<class KeyContainer, class Compare = less<typename KeyContainer::value_type>>
    flat_set(sorted_unique_t, KeyContainer, Compare = Compare())
    -> flat_set<typename KeyContainer::value_type, Compare, KeyContainer>;
template<class KeyContainer, class Allocator>
    flat_set(sorted_unique_t, KeyContainer, Allocator)
    -> flat_set<typename KeyContainer::value_type,
        less<typename KeyContainer::value_type>, KeyContainer>;
template<class KeyContainer, class Compare, class Allocator>
    flat_set(sorted_unique_t, KeyContainer, Compare, Allocator)
    -> flat_set<typename KeyContainer::value_type, Compare, KeyContainer>;

template<class InputIterator, class Compare = less<typename InputIterator::value_type>>
    flat_set(InputIterator, InputIterator, Compare = Compare())
    -> flat_set<typename InputIterator::value_type, Compare>;
template<class InputIterator, class Compare = less<iter-value-type<InputIterator>>>  
  flat_set(sorted_unique_t, InputIterator, InputIterator, Compare = Compare())  
  -> flat_set<iter-value-type<InputIterator>, Compare>();

template<ranges::input_range R, class Compare = less<ranges::range_value_t<R>>,  
  class Allocator = allocator<ranges::range_value_t<R>>>  
  flat_set(from_range_t, R&, Compare = Compare(), Allocator = Allocator())  
  -> flat_set<ranges::range_value_t<R>, Compare,  
      vector<ranges::range_value_t<R>,  
      alloc-rebind<Allocator, ranges::range_value_t<R>>>();

template<ranges::input_range R, class Allocator>  
  flat_set(from_range_t, R&, Allocator)  
  -> flat_set<ranges::range_value_t<R>, less<ranges::range_value_t<R>>,  
       vector<ranges::range_value_t<R>,  
       alloc-rebind<Allocator, ranges::range_value_t<R>>>();

template<class Key, class Compare = less<Key>>  
  flat_set(initializer_list<Key>, Compare = Compare())  
  -> flat_set<Key, Compare>();

template<class Key, class Compare = less<Key>>  
  flat_set(sorted_unique_t, initializer_list<Key>, Compare = Compare())  
  -> flat_set<Key, Compare>();

template<class Key, class Compare, class KeyContainer, class Allocator>  
  struct uses_allocator<flat_set<Key, Compare, KeyContainer>, Allocator>  
  : bool_constant<uses_allocator_v<KeyContainer, Allocator>> { };
template<class Alloc>
  explicit flat_set(const Alloc& a);
template<class Alloc>
  flat_set(const key_compare& comp, const Alloc& a);
template<class Alloc>
  flat_set(const flat_set&, const Alloc& a);
template<class Alloc>
  flat_set(flat_set&&, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_set(InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_set(InputIterator first, InputIterator last, const key_compare& comp, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_set(sorted_unique_t, InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_set(sorted_unique_t, InputIterator first, InputIterator last, const key_compare& comp, const Alloc& a);
template<container-compatible-range<value_type> R, class Alloc>
  flat_set(from_range_t, R&& rg, const Alloc& a);
template<container-compatible-range<value_type> R, class Alloc>
  flat_set(from_range_t, R&& rg, const key_compare& comp, const Alloc& a);
template<class Alloc>
  flat_set(initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
  flat_set(initializer_list<value_type> il, const key_compare& comp, const Alloc& a);
template<class Alloc>
  flat_set(sorted_unique_t, initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
  flat_set(sorted_unique_t, initializer_list<value_type> il,
        const key_compare& comp, const Alloc& a);

Effects: Equivalent to the corresponding non-allocator constructors except that c is constructed with uses-allocator construction (20.2.8.2).

24.6.11.5 Modifiers [flat.set.modifiers]

template<class K> pair<iterator, bool> insert(K&& x);
template<class K> iterator insert(const_iterator hint, K&& x);

Constraints: The qualified-id Compare::is_transparent is valid and denotes a type. is_constructible_v<value_type, K> is true.

Preconditions: The conversion from x into value_type constructs an object u, for which find(x) == find(u) is true.

Effects: If the set already contains an element equivalent to x, *this and x are unchanged. Otherwise, inserts a new element as if by emplace(std::forward<K>(x)).

Returns: In the first overload, the bool component of the returned pair is true if and only if the insertion took place. The returned iterator points to the element whose key is equivalent to x.

Effects: Adds elements to c as if by:
  c.insert(c.end(), first, last);
Then, sorts the range of newly inserted elements with respect to compare; merges the resulting sorted range and the sorted range of pre-existing elements into a single sorted range; and finally erases all but the first element from each group of consecutive equivalent elements.

Complexity: N + M \log M, where N is size() before the operation and M is distance(first, last).

Remarks: Since this operation performs an in-place merge, it may allocate memory.
template<class InputIterator>
void insert(sorted_unique_t, InputIterator first, InputIterator last);

Effects: Equivalent to insert(first, last).

Complexity: Linear.

template<container-compatible-range<value_type> R>
void insert_range(R&& rg);

Effects: Adds elements to c as if by:
for (const auto& e : rg) {  
c.insert(c.end(), e);
}

Then, sorts the range of newly inserted elements with respect to compare; merges the resulting sorted range and the sorted range of pre-existing elements into a single sorted range; and finally erases all but the first element from each group of consecutive equivalent elements.

Complexity: \( N + M \log M \), where \( N \) is size() before the operation and \( M \) is ranges::distance(rg).

Remarks: Since this operation performs an in-place merge, it may allocate memory.

void swap(flat_set& y) noexcept;

Effects: Equivalent to:
ranges::swap(compare, y.compare);
ranges::swap(c, y.c);

Effects: Equivalent to:
container_type extract() &;&

Postconditions: *this is emptied, even if the function exits via an exception.
Returns: std::move(c).

void replace(container_type&& cont);

Preconditions: The elements of cont are sorted with respect to compare, and cont contains no equal elements.

Effects: Equivalent to: c = std::move(cont);

24.6.11.6 Erasure [flat.set.ereasure]

template<class Key, class Compare, class KeyContainer, class Predicate>
typename flat_set<Key, Compare, KeyContainer>::size_type
erase_if(flat_set<Key, Compare, KeyContainer>& c, Predicate pred);

Preconditions: Key meets the Cpp17MoveAssignable requirements.

Effects: Let \( E \) be bool(pred(as_const(e))). Erases all elements \( e \) in \( c \) for which \( E \) holds.

Returns: The number of elements erased.

Complexity: Exactly \( c.size() \) applications of the predicate.

Remarks: Stable (16.4.6.8). If an invocation of erase_if exits via an exception, \( c \) is in a valid but unspecified state (3.65).

[Note 1: \( c \) still meets its invariants, but can be empty. — end note]

24.6.12 Class template flat_multiset [flat.multiset]

24.6.12.1 Overview [flat.multiset.overview]

A flat_multiset is a container adaptor that provides an associative container interface that supports equivalent keys (i.e., possibly containing multiple copies of the same key value) and provides for fast retrieval of the keys themselves. flat_multiset supports iterators that model the random_access_iterator concept (25.3.4.13).

A flat_multiset meets all of the requirements for a container (24.2.2.2) and for a reversible container (24.2.2.3), plus the optional container requirements (24.2.2.4). flat_multiset meets the requirements of an associative container (24.2.7), except that:

it does not meet the requirements related to node handles (24.2.5.1),
— it does not meet the requirements related to iterator invalidation, and
— the time complexity of the operations that insert or erase a single element from the set is linear,
  including the ones that take an insertion position iterator.

[Note 1: A flat_multiset does not meet the additional requirements of an allocator-aware container, as described in 24.2.2.5. — end note]

3 A flat_multiset also provides most operations described in 24.2.7 for equal keys. This means that a flat_multiset supports the a_eq operations in 24.2.7 but not the a_uniq operations. For a flat_multiset<Key>, both the key_type and value_type are Key.

4 Descriptions are provided here only for operations on flat_multiset that are not described in one of the general sections or for operations where there is additional semantic information.

5 A flat_multiset maintains the invariant that the keys are sorted with respect to the comparison object.

6 If any member function in 24.6.12.2 exits via an exception, the invariant is restored.

[Note 2: This can result in the flat_multiset’s being emptied. — end note]

7 Any sequence container (24.2.4) supporting Cpp17RandomAccessIterator can be used to instantiate flat_multiset. In particular, vector (24.3.12) and deque (24.3.9) can be used.

[Note 3: vector<bool> is not a sequence container. — end note]

8 The program is ill-formed if Key is not the same type as KeyContainer::value_type.

9 The effect of calling a constructor or member function that takes a sorted_equivalent_t argument with a range that is not sorted with respect to key_comp() is undefined.

24.6.12.2 Definition [flat_multiset.defn]

namespace std {
    template<class Key, class Compare = less<Key>, class KeyContainer = vector<Key>>
    class flat_multiset {
    public:
        // types
        using key_type = Key;
        using value_type = Key;
        using key_compare = Compare;
        using value_compare = Compare;
        using reference = value_type&;
        using const_reference = const value_type&;
        using size_type = typename KeyContainer::size_type;
        using difference_type = typename KeyContainer::difference_type;
        using iterator = implementation-defined; // see 24.2
        using const_iterator = implementation-defined; // see 24.2
        using reverse_iterator = std::reverse_iterator<iterator>;
        using const_reverse_iterator = std::reverse_iterator<const_iterator>;
        using container_type = KeyContainer;

        // 24.6.12.3, constructors
        flat_multiset() : flat_multiset(key_compare()) {}

        explicit flat_multiset(const key_compare& comp)
            : c(), compare(comp) {}

        explicit flat_multiset(container_type cont, const key_compare& comp = key_compare());

        flat_multiset(sorted_equivalent_t, container_type cont,
            const key_compare& comp = key_compare())
            : c(std::move(cont)), compare(comp) {}

        template<class InputIterator>
        flat_multiset(InputIterator first, InputIterator last,
            const key_compare& comp = key_compare())
            : c(), compare(comp)
            { insert(first, last); }

        § 24.6.12.2 © ISO/IEC 1064
template<class InputIterator>
flat_multiset(sorted_equivalent_t, InputIterator first, InputIterator last,
    const key_compare& comp = key_compare())
    : c(first, last), compare(comp) { }

template<container-compatible-range<value_type> R>
flat_multiset(from_range_t fr, R&& rg)
    : flat_multiset(fr, std::forward<R>(rg), key_compare()) { }

template<container-compatible-range<value_type> R>
flat_multiset(from_range_t, R&& rg, const key_compare& comp)
    : flat_multiset(comp)
    { insert_range(std::forward<R>(rg)); }

flat_multiset(initializer_list<value_type> il, const key_compare& comp = key_compare())
    : flat_multiset(il.begin(), il.end(), comp) { }

flat_multiset(sorted_equivalent_t s, initializer_list<value_type> il,
    const key_compare& comp = key_compare())
    : flat_multiset(s, il.begin(), il.end(), comp) { }

// § 24.6.12.4, constructors with allocators

template<class Alloc>
explicit flat_multiset(const Alloc& a);
template<class Alloc>
flat_multiset(const key_compare& comp, const Alloc& a);
template<class Alloc>
flat_multiset(const container_type& cont, const Alloc& a);
template<class Alloc>
flat_multiset(const container_type& cont, const key_compare& comp, const Alloc& a);
template<class Alloc>
flat_multiset(sorted_equivalent_t, const container_type& cont, const Alloc& a);
template<class Alloc>
flat_multiset(sorted_equivalent_t, const container_type& cont,
    const key_compare& comp, const Alloc& a);
template<class Alloc>
flat_multiset(const flat_multiset&, const Alloc& a);
template<class Alloc>
flat_multiset(flat_multiset&&, const Alloc& a);
template<class InputIterator, class Alloc>
flat_multiset(InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
flat_multiset(InputIterator first, InputIterator last,
    const key_compare& comp, const Alloc& a);
template<class InputIterator, class Alloc>
flat_multiset(sorted_equivalent_t, InputIterator first, InputIterator last,
    const Alloc& a);
template<class InputIterator, class Alloc>
flat_multiset(sorted_equivalent_t, InputIterator first, InputIterator last,
    const key_compare& comp, const Alloc& a);
template<class container-compatible-range<value_type> R, class Alloc>
flat_multiset(from_range_t, R&& rg, const Alloc& a);
template<class container-compatible-range<value_type> R, class Alloc>
flat_multiset(from_range_t, R&& rg, const key_compare& comp, const Alloc& a);
template<class Alloc>
flat_multiset(initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
flat_multiset(initializer_list<value_type> il, const key_compare& comp,
    const Alloc& a);
template<class Alloc>
flat_multiset(sorted_equivalent_t, initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
flat_multiset(sorted_equivalent_t, initializer_list<value_type> il,
    const key_compare& comp, const Alloc& a);
flat_multiset& operator=(initializer_list<value_type>);

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;
reverse_iterator rbegin() noexcept;
const_reverse_iterator rbegin() const noexcept;
reverse_iterator rend() noexcept;
const_reverse_iterator rend() const noexcept;
const_iterator cbegin() const noexcept;
const_iterator cend() const noexcept;
const_reverse_iterator crbegin() const noexcept;
const_reverse_iterator crend() const noexcept;

// capacity
[[nodiscard]] bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 24.6.12.5. modifiers
template<class... Args> iterator emplace(Args&&... args);

iterator insert(const value_type& x)
{ return emplace(x); }
iterator insert(value_type&& x)
{ return emplace(std::move(x)); }
iterator insert(const_iterator position, const value_type& x)
{ return emplace_hint(position, x); }
iterator insert(const_iterator position, value_type&& x)
{ return emplace_hint(position, std::move(x)); }

template<class InputIterator>
void insert(InputIterator first, InputIterator last);

template<class InputIterator>
void insert(sorted_equivalent_t, InputIterator first, InputIterator last);

template<container-compatible-range<value_type> R>
void insert_range(R&& rg);

void insert(initializer_list<value_type> il)
{ insert(il.begin(), il.end()); }
void insert(sorted_equivalent_t s, initializer_list<value_type> il)
{ insert(s, il.begin(), il.end()); }

container_type extract() &&;
void replace(container_type&&);

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
template<class K> size_type erase(K&& x);
iterator erase(const_iterator first, const_iterator last);

void swap(flat_multiset& y) noexcept;
void clear() noexcept;

// observers
key_compare key_comp() const;
value_compare value_comp() const;
// set operations
iterator find(const key_type& x);
const_iterator find(const key_type& x) const;
template<class K> iterator find(const K& x);
template<class K> const_iterator find(const K& x) const;

template<class K> size_type count(const K& x) const;
size_type count(const key_type& x) const;

bool contains(const key_type& x) const;
template<class K> bool contains(const K& x) const;

iterator lower_bound(const key_type& x);
const_iterator lower_bound(const key_type& x) const;
template<class K> iterator lower_bound(const K& x);
template<class K> const_iterator lower_bound(const K& x) const;

iterator upper_bound(const key_type& x);
const_iterator upper_bound(const key_type& x) const;
template<class K> iterator upper_bound(const K& x);
template<class K> const_iterator upper_bound(const K& x) const;

pair<iterator, iterator> equal_range(const key_type& x);
pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
template<class K> pair<iterator, iterator> equal_range(const K& x);
template<class K> pair<const_iterator, const_iterator> equal_range(const K& x) const;

friend bool operator==(const flat_multiset& x, const flat_multiset& y);
fresh comparative<value_type>(const flat_multiset& x, const flat_multiset& y);
template<class InputIterator, class Compare = less<typename InputIterator::value_type>>
    flat_multiset(InputIterator, InputIterator, Compare = Compare())
    -> flat_multiset<typename InputIterator::value_type, Compare>;

template<class InputIterator, class Compare = less<typename InputIterator::value_type>>
    flat_multiset(sorted_equivalent_t, InputIterator, InputIterator, Compare = Compare())
    -> flat_multiset<typename InputIterator::value_type, Compare>;

template<class InputIterator, class Compare = less<typename InputIterator::value_type>>
    flat_multiset(sorted_equivalent_t, InputIterator, InputIterator, Compare = Compare())
    -> flat_multiset<typename InputIterator::value_type, Compare>;

template<class Key, class Compare = less<Key>>
    flat_multiset(initializer_list<Key>, Compare = Compare())
    -> flat_multiset<Key, Compare>;

24.6.12.4 Constructors with allocators [flat.multiset.cons.alloc]

1 The constructors in this subclause shall not participate in overload resolution unless uses_allocator_v<
2 container_type, Alloc> is true.

    template<class Alloc>
        flat_multiset(const container_type& cont, const Alloc& a);
    template<class Alloc>
        flat_multiset(const container_type& cont, const Alloc& a);

2 Effects: Equivalent to flat_multiset(cont) and flat_multiset(cont, comp), respectively, except that
3 c is constructed with uses-allocator construction (20.2.8.2).

    template<class Alloc>
        flat_multiset(sorted_equivalent_t s, const container_type& cont, const Alloc& a);
    template<class Alloc>
        flat_multiset(sorted_equivalent_t s, const container_type& cont,
3 const key_compare& comp, const Alloc& a);

4 Effects: Equivalent to flat_multiset(s, cont) and flat_multiset(s, cont, comp), respectively,
5 except that c is constructed with uses-allocator construction (20.2.8.2).
template<class Alloc>
  explicit flat_multiset(const Alloc& a);
template<class Alloc>
  flat_multiset(const key_compare& comp, const Alloc& a);
template<class Alloc>
  flat_multiset(const flat_multiset&, const Alloc& a);
template<class Alloc>
  flat_multiset(flat_multiset&, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_multiset(InputIterator first, InputIterator last, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_multiset(InputIterator first, InputIterator last,
               const key_compare& comp, const Alloc& a);
template<class InputIterator, class Alloc>
  flat_multiset(sorted_equivalent_t, InputIterator first, InputIterator last,
               const Alloc& a);
template<class InputIterator, class Alloc>
  flat_multiset(sorted_equivalent_t, InputIterator first, InputIterator last,
               const key_compare& comp, const Alloc& a);
template<class Alloc>
  flat_multiset(initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
  flat_multiset(initializer_list<value_type> il, const key_compare& comp, const Alloc& a);
template<class Alloc>
  flat_multiset(sorted_equivalent_t, initializer_list<value_type> il, const Alloc& a);
template<class Alloc>
  flat_multiset(sorted_equivalent_t, initializer_list<value_type> il,
               const key_compare& comp, const Alloc& a);

Effects: Equivalent to the corresponding non-allocator constructors except that \( c \) is constructed with uses-allocator construction (20.2.8.2).

§ 24.6.12.5 Modifiers

```
template<class... Args> iterator emplace(Args&&... args);
```

Constraints: \( \text{is\_constructible\_v<value\_type, Args...> is \text{true}.} \)

Effects: First, initializes an object \( t \) of type \( \text{value\_type} \) with \( \text{std::forward<Args>(args)...} \), then inserts \( t \) as if by:

\[
\text{auto \, it = ranges::upper\_bound(c, t, compare);} \\
\text{c.insert(it, std::move(t))};
\]

Returns: An iterator that points to the inserted element.

```
template<class InputIterator>
  void insert(InputIterator first, InputIterator last);
```

Effects: Adds elements to \( c \) as if by:

\[
\text{c.insert(c.end(), first, last)};
\]

Then, sorts the range of newly inserted elements with respect to \( \text{compare} \), and merges the resulting sorted range and the sorted range of pre-existing elements into a single sorted range.

Complexity: \( N + M \log M \), where \( N \) is \( \text{size()} \) before the operation and \( M \) is \( \text{distance(first, last)} \).

Remarks: Since this operation performs an in-place merge, it may allocate memory.

```
template<class InputIterator>
  void insert(sorted_equivalent_t, InputIterator first, InputIterator last);
```

Effects: Equivalent to \( \text{insert(first, last)} \).
Complexity: Linear.

```cpp
void swap(flat_multiset& y) noexcept;
```

Effects: Equivalent to:
- \(\text{ranges::swap(compare, y.compare)}\);
- \(\text{ranges::swap(c, y.c)}\);

```cpp
container_type extract() &&;
```

Postconditions: *This* is emptied, even if the function exits via an exception.

Returns: `std::move(c)`.

```cpp
void replace(container_type&& cont);
```

Preconditions: The elements of `cont` are sorted with respect to `compare`.

Effects: Equivalent to: `c = std::move(cont);`

24.6.12.6 Erasure

```cpp
template<class Key, class Compare, class KeyContainer, class Predicate>
type name flat_multiset<Key, Compare, KeyContainer>::size_type
erase_if(flat_multiset<Key, Compare, KeyContainer>& c, Predicate pred);
```

Preconditions: `Key` meets the \texttt{Cpp17MoveAssignable} requirements.

Effects: Let \(E\) be `bool(pred(as\_const(e)))`. Erases all elements `e` in `c` for which \(E\) holds.

Returns: The number of elements erased.

Complexity: Exactly `c.size()` applications of the predicate.

Remarks: Stable (16.4.6.8). If an invocation of `erase_if` exits via an exception, `c` is in a valid but unspecified state (3.65).

[Note 1: `c` still meets its invariants, but can be empty. — end note]

24.6.13 Container adaptors formatting

```cpp
namespace std {
    template<class charT, class T, formattable<charT> Container, class... U>
    struct formatter<adaptor-type<T, Container, U...>, charT> {
        private:
        // exposition only
        using maybe-const-container = fmt-maybe-const<Container, charT>;
        using maybe-const-adaptor = maybe-const<is\_const_v<maybe-const-container>, adaptor-type<T, Container, U...>>;
        formatter<ranges::ref\_view<maybe-const-container>, charT> underlying_;
        // exposition only

        public:
        template<class ParseContext>
        constexpr typename ParseContext::iterator
        parse(ParseContext& ctx);

        template<class FormatContext>
        typename FormatContext::iterator
        format(maybe-const-adaptor& r, FormatContext& ctx) const;
    };
}
```

```cpp
template<class ParseContext>
constexpr typename ParseContext::iterator
parse(ParseContext& ctx);
```

Effects: Equivalent to: `return underlying_.parse(ctx);`
template<class FormatContext>
    typename FormatContext::iterator
    format(maybe-const-adaptor& r, FormatContext& ctx) const;

Effects: Equivalent to: return underlying_.format(r.c, ctx);

24.7 Views

24.7.1 General

The header <span> defines the view span. The header <mdspan> defines the class template mdspan and other facilities for interacting with these multidimensional views.

24.7.2 Contiguous access

24.7.2.1 Header <span> synopsis

#include <initializer_list> // see 17.10.2

// mostly freestanding

namespace std {

// constants

inline constexpr size_t dynamic_extent = numeric_limits<size_t>::max();

// exposition only

template<class T>
    concept integral-constant-like = // exposition only
        is_integral_v<decltype(T::value)> &&
        !is_same_v<bool, remove_const_t<decltype(T::value)>> &&
        convertible_to<T, decltype(T::value)> &&
        equality_comparable_with<T, decltype(T::value)> &&
        bool_constant<T() == T::value>::value &&
        bool_constant<static_cast<decltype(T::value)>(T()) == T::value>::value;

// exposition only

template<class T>
    constexpr size_t maybe-static-ext = dynamic_extent;

// exposition only

template<integral-constant-like T>
    constexpr size_t maybe-static-ext<T> = {T::value};

// 24.7.2.2, class template span

template<class ElementType, size_t Extent = dynamic_extent>
    class span;

// partially freestanding

template<class ElementType, size_t Extent>
    constexpr bool ranges::enable_view<span<ElementType, Extent>> = true;

template<class ElementType, size_t Extent>
    constexpr bool ranges::enable_borrowed_range<span<ElementType, Extent>> = true;

// 24.7.2.3, views of object representation

template<class ElementType, size_t Extent>
    span<const byte, Extent == dynamic_extent ? dynamic_extent : sizeof(ElementType) * Extent>
    as_bytes(span<ElementType, Extent> s) noexcept;

template<class ElementType, size_t Extent>
    span<byte, Extent == dynamic_extent ? dynamic_extent : sizeof(ElementType) * Extent>
    as_writable_bytes(span<ElementType, Extent> s) noexcept;

}
namespace std {
    template<class ElementType, size_t Extent = dynamic_extent>
    class span {
    public:
        // constants and types
        using element_type = ElementType;
        using value_type = remove_cv_t<ElementType>;
        using size_type = size_t;
        using difference_type = ptrdiff_t;
        using pointer = element_type*;
        using const_pointer = const element_type*;
        using reference = element_type&;
        using const_reference = const element_type&;
        using iterator = implementation-defined; // see 24.7.2.2.7
        using const_iterator = std::const_iterator<iterator>;
        using reverse_iterator = std::reverse_iterator<iterator>;
        using const_reverse_iterator = std::const_iterator<reverse_iterator>;
        static constexpr size_type extent = Extent;

        // 24.7.2.2.2, constructors, copy, and assignment
        constexpr span() noexcept;
        template<class It>
            constexpr explicit(extent != dynamic_extent) span(It first, size_type count);
        template<class It, class End>
            constexpr explicit(extent != dynamic_extent) span(It first, End last);
        template<size_t N>
            constexpr span(type_identity_t<element_type> (&arr)[N]) noexcept;
        template<class T, size_t N>
            constexpr span(array<T, N>& arr) noexcept;
        template<class T, size_t N>
            constexpr span(const array<T, N>& arr) noexcept;
        template<class R>
            constexpr explicit(extent != dynamic_extent) span(R&& r);
        constexpr explicit(extent != dynamic_extent) span(std::initializer_list<value_type> il);
        template<class OtherElementType, size_t OtherExtent>
            constexpr explicit(see below) span(const span<OtherElementType, OtherExtent>& s) noexcept;
        constexpr span<element_type, dynamic_extent> first(size_type count) const;
        constexpr span<element_type, dynamic_extent> last(size_type count) const;
        constexpr span<element_type, dynamic_extent> subspan(size_type offset, size_type count = dynamic_extent) const;

        // 24.7.2.2.4, subviews
        template<size_t Count>
            constexpr span<element_type, Count> first() const;
        template<size_t Count>
            constexpr span<element_type, Count> last() const;
        template<size_t Offset, size_type Count = dynamic_extent>
            constexpr span<element_type, see below> subspan() const;

        // 24.7.2.2.5, observers
        constexpr size_type size() const noexcept;
        constexpr size_type size_bytes() const noexcept;
        [[nodiscard]] constexpr bool empty() const noexcept;

        // 24.7.2.2.6, element access
        constexpr reference operator[] (size_type idx) const;
        constexpr reference at(size_type idx) const;
        constexpr reference front() const;
        constexpr reference back() const;
        constexpr pointer data() const noexcept;
    } // template<>
} // namespace std
// 24.7.2.2.7, iterator support
constexpr iterator begin() const noexcept;
constexpr iterator end() const noexcept;
constexpr const_iterator cbegin() const noexcept { return begin(); }
constexpr const_iterator cend() const noexcept { return end(); }
constexpr reverse_iterator rbegin() const noexcept;
constexpr reverse_iterator rend() const noexcept;
constexpr const_reverse_iterator crbegin() const noexcept { return rbegin(); }
constexpr const_reverse_iterator crend() const noexcept { return rend(); }

private:
    pointer data_; // exposition only
    size_type size_; // exposition only
};

template<class It, class EndOrSize>
span(It, EndOrSize) -> span<remove_reference_t<iter_reference_t<It>>, maybe-static-ext<EndOrSize>>;

template<class T, size_t N>
span(T (&)[N]) -> span<T, N>;

3 span<ElementType, Extent> is a trivially copyable type (6.8.1).

4 ElementType is required to be a complete object type that is not an abstract class type.

5 For a span s, any operation that invalidates a pointer in the range [s.data(), s.data() + s.size())
invalidates pointers, iterators, and references to elements of s.

24.7.2.2.2 Constructors, copy, and assignment [span.cons]

constexpr span() noexcept;

1 Constraints: Extent == dynamic_extent || Extent == 0 is true.

2 Postconditions: size() == 0 && data() == nullptr.

template<class It>
constexpr explicit(extent != dynamic_extent) span(It first, size_type count);

3 Constraints: Let U be remove_reference_t<iter_reference_t<It>>.

(3.1) It satisfies contiguous_iterator.

(3.2) is_convertible_v<U(*[]), element_type(*[])> is true.

[Note 1: The intent is to allow only qualification conversions of the iterator reference type to element_type.

— end note]

4 Preconditions:

(4.1) [first.first + count) is a valid range.

(4.2) It models contiguous_iterator.

(4.3) If extent is not equal to dynamic_extent, then count is equal to extent.

5 Effects: Initializes data_ with to_address(first) and size_ with count.

6 Throws: Nothing.

template<class It, class End>
constexpr explicit(extent != dynamic_extent) span(It first, End last);

7 Constraints: Let U be remove_reference_t<iter_reference_t<It>>.

(7.1) is_convertible_v<U(*[]), element_type(*[])> is true.
Note 2: The intent is to allow only qualification conversions of the iterator reference type to `element_type`.  
— end note

(7.2) It satisfies `contiguous_iterator`.
(7.3) End satisfies `sized_sentinel_for<It>`.
(7.4) `is_convertible_v<End, size_t>` is false.

Preconditions:
(8.1) If `extent` is not equal to `dynamic_extent`, then `last - first` is equal to `extent`.
(8.2) `[first, last)` is a valid range.
(8.3) It models `contiguous_iterator`.
(8.4) End models `sized_sentinel_for<It>`.

Effects: Initializes `data_` with `to_address(first)` and `size_` with `last - first`.

Throws: When and what `last - first` throws.

```cpp
template<size_t N> constexpr span(type_identity_t<element_type> (&arr)[N]) noexcept;
template<class T, size_t N> constexpr span(array<T, N>& arr) noexcept;
template<class T, size_t N> constexpr span(const array<T, N>& arr) noexcept;
```

Note 3: The intent is to allow only qualification conversions of the array element type to `element_type`.  
— end note

(11) Constraints: Let `U` be `remove_pointer_t<decltype(std::data(arr))>>`.
(11.1) `extent == dynamic_extent || N == extent` is true, and
(11.2) `is_convertible_v<U(*)[], element_type(*)[]>` is true.

Note 4: `type_identity_t` affects class template argument deduction.  
— end note

Postconditions: `size() == N && data() == std::data(arr)` is true.

```cpp
template<class R> constexpr explicit(extent != dynamic_extent) span(R&& r);
```

(14.1) `R` satisfies `ranges::contiguous_range` and `ranges::sized_range`.
(14.2) Either `R` satisfies `ranges::borrowed_range` or `is_const_v<element_type>` is true.
(14.3) `remove_cvref_t<R>` is not a specialization of `span`.
(14.4) `remove_cvref_t<R>` is not a specialization of `array`.
(14.5) `is_array_v<remove_cvref_t<R>>` is false.
(14.6) `is_convertible_v<U(*)[], element_type(*)[]>` is true.

Note 5: The intent is to allow only qualification conversions of the range reference type to `element_type`.  
— end note

Preconditions:
(15.1) If `extent` is not equal to `dynamic_extent`, then `ranges::size(r)` is equal to `extent`.
(15.2) `R` models `ranges::contiguous_range` and `ranges::sized_range`.
(15.3) If `is_const_v<element_type>` is false, `R` models `ranges::borrowed_range`.

Effects: Initializes `data_` with `ranges::data(r)` and `size_` with `ranges::size(r)`.

Throws: What and when `ranges::data(r)` and `ranges::size(r)` throw.

```cpp
constexpr explicit(extent != dynamic_extent) span(std::initializer_list<value_type> il);
```

Constraints: `is_const_v<element_type>` is true.

Preconditions: If `extent` is not equal to `dynamic_extent`, then `il.size()` is equal to `extent`.

Effects: Initializes `data_` with `il.begin()` and `size_` with `il.size()`.
constexpr span(const span& other) noexcept = default;

Postconditions: other.size() == size() && other.data() == data().

template<class OtherElementType, size_t OtherExtent>
constexpr explicit(see below) span(const span<OtherElementType, OtherExtent>& s) noexcept;

Constraints:
1. extent == dynamic_extent || OtherExtent == dynamic_extent || extent == OtherExtent
   is true, and
2. is_convertible_v<OtherElementType(*)[], element_type(*)[]> is true.
   [Note 6: The intent is to allow only qualification conversions of the OtherElementType to element_type. — end note]

Preconditions: If extent is not equal to dynamic_extent, then s.size() is equal to extent.

Effects: Constructs a span that is a view over the range [s.data(), s.data() + s.size()).

Postconditions: size() == s.size() && data() == s.data().

Remarks: The expression inside explicit is equivalent to:
extent != dynamic_extent && OtherExtent == dynamic_extent

constexpr span& operator=(const span& other) noexcept = default;

Postconditions: size() == other.size() && data() == other.data().

24.7.2.2.3 Deduction guides

template<class It, class EndOrSize>
span(It, EndOrSize) -> span<remove_reference_t<iter_reference_t<It>>, maybe-static-ext<EndOrSize>>;

Constraints: It satisfies contiguous_iterator.

template<class R>
span(R&&) -> span<remove_reference_t<ranges::range_reference_t<R>>>;

Constraints: R satisfies ranges::contiguous_range.

24.7.2.2.4 Subviews

template<size_t Count> constexpr span<element_type, Count> first() const;

Mandates: Count <= Extent is true.

Preconditions: Count <= size() is true.

Effects: Equivalent to: return R{data(), Count}; where R is the return type.

template<size_t Count> constexpr span<element_type, Count> last() const;

Mandates: Count <= Extent is true.

Preconditions: Count <= size() is true.

Effects: Equivalent to: return R{data() + (size() - Count), Count}; where R is the return type.

template<size_t Offset, size_t Count = dynamic_extent>
constexpr span<element_type, see below> subspan() const;

Mandates:
Offset <= Extent && (Count == dynamic_extent || Count <= Extent - Offset)
is true.

Preconditions:
Offset <= size() && (Count == dynamic_extent || Count <= size() - Offset)
is true.

Effects: Equivalent to:
return span<ElementType, see below>(
    data() + Offset, Count != dynamic_extent ? Count : size() - Offset);

Remarks: The second template argument of the returned span type is:
    Count != dynamic_extent ? Count
    : (Extent != dynamic_extent ? Extent - Offset
    : dynamic_extent)

constexpr span<element_type, dynamic_extent> first(size_type count) const;

Preconditions: count <= size() is true.

Effects: Equivalent to: return {data(), count};

constexpr span<element_type, dynamic_extent> last(size_type count) const;

Preconditions: count <= size() is true.

Effects: Equivalent to: return {data() + (size() - count), count};

constexpr span<element_type, dynamic_extent> subspan(
    size_type offset, size_type count = dynamic_extent) const;

Preconditions:
    offset <= size() && (count == dynamic_extent || count <= size() - offset)
    is true.

Effects: Equivalent to:
    return {data() + offset, count == dynamic_extent ? size() - offset : count};

24.7.2.2.5 Observers [span.obs]

constexpr size_type size() const noexcept;

Effects: Equivalent to: return size_;

constexpr size_type size_bytes() const noexcept;

Effects: Equivalent to: return size() * sizeof(element_type);

[[nodiscard]] constexpr bool empty() const noexcept;

Effects: Equivalent to: return size() == 0;

24.7.2.2.6 Element access [span.elem]

constexpr reference operator[](size_type idx) const;

Preconditions: idx < size() is true.

Returns: *(data() + idx).

Throws: Nothing.

constexpr reference at(size_type idx) const;

Returns: *(data() + idx).

Throws: out_of_range if idx >= size() is true.

constexpr reference front() const;

Preconditions: empty() is false.

Returns: *data().

Throws: Nothing.

constexpr reference back() const;

Preconditions: empty() is false.

Returns: *(data() + (size() - 1)).

Throws: Nothing.
constexpr pointer data() const noexcept;

Returns: data_.

### 24.7.2.2.7 Iterator support

using iterator = implementation-defined;

1. The type models contiguous_iterator (25.3.4.14), meets the Cpp17RandomAccessIterator requirements (25.3.5.7), and meets the requirements for constexpr iterators (25.3.1), whose value type is value_type and whose reference type is reference.

2. All requirements on container iterators (24.2.2.2) apply to span::iterator as well.

constexpr iterator begin() const noexcept;

3. Returns: An iterator referring to the first element in the span. If empty() is true, then it returns the same value as end().

constexpr iterator end() const noexcept;

4. Returns: An iterator which is the past-the-end value.

constexpr reverse_iterator rbegin() const noexcept;

5. Effects: Equivalent to: return reverse_iterator(end());

constexpr reverse_iterator rend() const noexcept;

6. Effects: Equivalent to: return reverse_iterator(begin());

### 24.7.2.3 Views of object representation

```cpp
template<class ElementType, size_t Extent>
span<const byte, Extent == dynamic_extent ? dynamic_extent : sizeof(ElementType) * Extent> as_bytes(span<ElementType, Extent> s) noexcept;
```

1. Effects: Equivalent to: return R{reinterpret_cast<const byte*>(s.data()), s.size_bytes()}; where R is the return type.

```cpp
template<class ElementType, size_t Extent>
span<byte, Extent == dynamic_extent ? dynamic_extent : sizeof(ElementType) * Extent> as_writable_bytes(span<ElementType, Extent> s) noexcept;
```

1. Constraints: is_const_v<ElementType> is false.

2. Effects: Equivalent to: return R{reinterpret_cast<byte*>(s.data()), s.size_bytes()}; where R is the return type.

### 24.7.3 Multidimensional access

#### 24.7.3.1 Overview

A multidimensional index space is a Cartesian product of integer intervals. Each interval can be represented by a half-open range \([L_i, U_i]\), where \(L_i\) and \(U_i\) are the lower and upper bounds of the \(i^{th}\) dimension. The rank of a multidimensional index space is the number of intervals it represents. The size of a multidimensional index space is the product of \(U_i - L_i\) for each dimension \(i\) if its rank is greater than 0, and 1 otherwise.

An integer \(r\) is a rank index of an index space \(S\) if \(r\) is in the range \([0, \text{rank of } S)\).

A pack of integers \(idx\) is a multidimensional index in a multidimensional index space \(S\) (or representation thereof) if both of the following are true:

(3.1) \(\text{sizeof}(\ldots(idx))\) is equal to the rank of \(S\), and

(3.2) for every rank index \(i\) of \(S\), the \(i^{th}\) value of \(idx\) is an integer in the interval \([L_i, U_i)\) of \(S\).

#### 24.7.3.2 Header <mdspan> synopsis

```cpp
namespace std {
    // 24.7.3.3, class template extents
    template<class IndexType, size_t... Extents>
    class extents;
}
```
// 24.7.3.3.6, alias template dextents
template<class IndexType, size_t Rank>
  using dextents = see below;

// 24.7.3.3.7, alias templatedims
template<size_t Rank, class IndexType = size_t>
  using dims = see below;

// 24.7.3.4, layout mapping
struct layout_left;
struct layout_right;
struct layout_stride;
template<size_t PaddingValue = dynamic_extent>
  struct layout_left_padded;
template<size_t PaddingValue = dynamic_extent>
  struct layout_right_padded;

// 24.7.3.5.3, class template default_accessor
template<class ElementType>
  class default_accessor;

// 24.7.3.6, class template mdspan
template<class ElementType, class Extents, class LayoutPolicy = layout_right, class AccessorPolicy = default_accessor<ElementType>>
  class mdspan;

// 24.7.3.7, submdspan creation
template<class OffsetType, class LengthType, class StrideType>
  struct strided_slice;
template<class LayoutMapping>
  struct submdspan_mapping_result;

struct full_extent_t { explicit full_extent_t() = default; };
inline constexpr full_extent_t full_extent{};
template<class IndexType, class... Extents, class... SliceSpecifiers>
  constexpr auto submdspan_extents(const extents<IndexType, Extents...>&, SliceSpecifiers...);

// 24.7.3.7.7, submdspan function template
template<class ElementType, class Extents, class LayoutPolicy, class AccessorPolicy, class... SliceSpecifiers>
  constexpr auto submdspan(
    const mdspan<ElementType, Extents, LayoutPolicy, AccessorPolicy>& src,
    SliceSpecifiers... slices) -> see below;

template<class T, class IndexType>
  concept index-pair-like =
    pair-like<T> &&
    convertible_to<tuple_element_t<0, T>, IndexType> &&
    convertible_to<tuple_element_t<1, T>, IndexType>;

24.7.3.3 Class template extents

24.7.3.3.1 Overview

The class template extents represents a multidimensional index space of rank equal to sizeof...(Extents).
In (24.7), extents is used synonymously with multidimensional index space.

namespace std {
  template<class IndexType, size_t... Extents>
    class extents {
      public:
        using index_type = IndexType;
        using size_type = make_unsigned_t<index_type>;
    }
}
using rank_type = size_t;

// 24.7.3.3.4, observers of the multidimensional index space
static constexpr rank_type rank() noexcept { return sizeof...(Extents); }
static constexpr rank_type rank_dynamic() noexcept { return dynamic_index(rank()); }
static constexpr size_t static_extent(rank_type) noexcept;
constexpr index_type extent(rank_type) const noexcept;

// 24.7.3.3.3, constructors
constexpr extents() noexcept = default;

// 24.7.3.3.3, constructors
template<class OtherIndexType, size_t... OtherExtents>
constexpr explicit(OtherIndexType&&) noexcept;

// 24.7.3.3.5, comparison operators
friend constexpr bool operator==(const extents&, const extents<OtherIndexType, OtherExtents...>&) noexcept;

// 24.7.3.3.2, exposition-only helpers
static constexpr rank_type dynamic_index(rank_type) noexcept;
static constexpr rank_type dynamic_index_inv(rank_type) noexcept;
array<index_type, rank_dynamic()> dynamic_extents{};

private:
static constexpr rank_type dynamic_index(rank_type i) noexcept; // exposition only
static constexpr rank_type dynamic_index_inv(rank_type i) noexcept; // exposition only

};

template<class... Integrals>
explicit extents(Integrals...) -> see below;

1 Mandates:
(1.1) — IndexType is a signed or unsigned integer type, and
(1.2) — each element of Extents is either equal to dynamic_extent, or is representable as a value of type IndexType.

Each specialization of extents models regular and is trivially copyable.

2 Let \(E_r\) be the \(r^{th}\) element of Extents. \(E_r\) is a dynamic extent if it is equal to dynamic_extent, otherwise \(E_r\) is a static extent. Let \(D_r\) be the value of \(\text{dynamic-extents}[\text{dynamic-index}(r)]\) if \(E_r\) is a dynamic extent, otherwise \(E_r\).

4 The \(r^{th}\) interval of the multidimensional index space represented by an extents object is \([0, D_r)\).

24.7.3.3.2 Exposition-only helpers

static constexpr rank_type dynamic_index(rank_type i) noexcept;

1 Preconditions: \(i \leq \text{rank()}\) is true.
2 Returns: The number of \(E_r\) with \(r < i\) for which \(E_r\) is a dynamic extent.
N4986

static constexpr rank_type dynamic-index-inv(rank_type i) noexcept;

Preconditions: i < rank_dynamic() is true.

Returns: The minimum value of r such that dynamic-index(r + 1) == i + 1 is true.

constexpr size_t fwd-prod-of-extents(rank_type i) const noexcept;

Preconditions: i <= rank() is true.

Returns: If i > 0 is true, the product of extent(k) for all k in the range [0, i), otherwise 1.

constexpr size_t rev-prod-of-extents(rank_type i) const noexcept;

Preconditions: i < rank() is true.

Returns: If i + 1 < rank() is true, the product of extent(k) for all k in the range [i + 1, rank()), otherwise 1.

template<class OtherIndexType>
static constexpr auto index-cast(OtherIndexType&& i) noexcept;

Effects:

(9.1) If OtherIndexType is an integral type other than bool, then equivalent to return i;
(9.2) otherwise, equivalent to return static_cast<index_type>(i);

[Note 1: This function will always return an integral type other than bool. Since this function’s call sites are constrained on convertibility of OtherIndexType to index_type, integer-class types can use the static_cast branch without loss of precision. —end note]

24.7.3.3.3 Constructors

template<class OtherIndexType, size_t... OtherExtents>
constexpr explicit(see below)
extents(const extents<OtherIndexType, OtherExtents...>& other) noexcept;

Constraints:

(1.1) sizeof...(OtherExtents) == rank() is true.
(1.2) ((OtherExtents == dynamic_extent || Extents == dynamic_extent || OtherExtents == Extents) && ...) is true.

Preconditions:

(2.1) other.extent(r) equals Er for each r for which Er is a static extent, and
(2.2) either
(2.2.1) sizeof...(OtherExtents) is zero, or
(2.2.2) other.extent(r) is representable as a value of type index_type for every rank index r of other.

Postconditions: *this == other is true.

Remarks: The expression inside explicit is equivalent to:

((Extents != dynamic_extent) && (OtherExtents == dynamic_extent)) || ...
|| (numeric_limits<index_type>::max() < numeric_limits<OtherIndexType>::max())

template<class... OtherIndexTypes>
constexpr explicit extents(OtherIndexTypes... exts) noexcept;

Let N be sizeof...(OtherIndexTypes), and let exts_arr be array<index_type, N>{static_cast<index_type>(std::move(exts))...}.

Constraints:

(6.1) (is_convertible_v<OtherIndexTypes, index_type> && ...) is true,
(6.2) (is_nothrow_constructible_v<index_type, OtherIndexTypes> && ...) is true, and
(6.3) N == rank_dynamic() || N == rank() is true.

[Note 1: One can construct extents from just dynamic extents, which are all the values getting stored, or from all the extents with a precondition. —end note]
Preconditions:

(7.1) If \( N \neq \text{rank\_dynamic()} \) is true, \( \text{exts\_arr}[r] \) equals \( E_r \) for each \( r \) for which \( E_r \) is a static extent, and

(7.2) either

(7.2.1) \( \text{sizeof...(\text{exts})} = 0 \) is true, or

(7.2.2) each element of \( \text{exts} \) is representable as a nonnegative value of type \( \text{index\_type} \).

Postconditions: \( \text{*this == extents(\text{exts\_arr})} \) is true.

template<class OtherIndexType, size_t N>
constexpr explicit(N != rank\_dynamic())
 extents(span<OtherIndexType, N> exts) noexcept;

template<class OtherIndexType, size_t N>
constexpr explicit(N != rank\_dynamic())
 extents(const array<OtherIndexType, N>& exts) noexcept;

Constraints:

(9.1) \( \text{is\_convertible\_v<const OtherIndexType\&, index\_type>} \) is true,

(9.2) \( \text{is\_nothrow\_constructible\_v<index\_type, const OtherIndexType\&>} \) is true, and

(9.3) \( N == \text{rank\_dynamic()} \) \( || \) \( N == \text{rank()} \) is true.

Preconditions:

(10.1) If \( N \neq \text{rank\_dynamic()} \) is true, \( \text{exts}[r] \) equals \( E_r \) for each \( r \) for which \( E_r \) is a static extent, and

(10.2) either

(10.2.1) \( N \) is zero, or

(10.2.2) \( \text{exts}[r] \) is representable as a nonnegative value of type \( \text{index\_type} \) for every rank index \( r \).

Effects:

(11.1) If \( N \) equals \( \text{rank\_dynamic()} \), for all \( d \) in the range \( [0, \text{rank\_dynamic()}) \), direct-non-list-initializes \( \text{dynamic\_extents}[d] \) with \( \text{as\_const(\text{exts}[d])} \).

(11.2) Otherwise, for all \( d \) in the range \( [0, \text{rank\_dynamic()}) \), direct-non-list-initializes \( \text{dynamic\_extents}[d] \) with \( \text{as\_const(\text{exts}[\text{dynamic\_index\_inv}(d)])} \).

Constraints: \( \text{(is\_convertible\_v<Integrals, size_t \& \& \ldots)} \) is true.

Remarks: The deduced type is \( \text{extents<size_t, maybe\_static\_ext<Integrals>\ldots>} \).

24.7.3.3.4 Observers of the multidimensional index space [mdspan.extents.obs]

static constexpr size_t static\_extent(rank\_type i) noexcept;

Preconditions: \( i < \text{rank()} \) is true.

Returns: \( E_i \).

constexpr index\_type extent(rank\_type i) const noexcept;

Preconditions: \( i < \text{rank()} \) is true.

Returns: \( D_i \).

24.7.3.3.5 Comparison operators [mdspan.extents.cmp]

template<class OtherIndexType, size_t\ldots OtherExtents>
friend constexpr bool operator==(const extents& lhs, const extents<OtherIndexType, OtherExtents\ldots>& rhs) noexcept;

Returns: true if \( \text{lhs.rank()} \) equals \( \text{rhs.rank()} \) and if \( \text{lhs.extent}(r) \) equals \( \text{rhs.extent}(r) \) for every rank index \( r \) of \( \text{rhs} \), otherwise false.
24.7.3.3.6 Alias template dextents

```plaintext
template<class IndexType, size_t Rank>
using dextents = see below;
```

1 Result: A type E that is a specialization of `extents` such that `E::rank() == Rank` if `E::rank() == E::rank_dynamic()` is true, and `E::index_type` denotes `IndexType`.

24.7.3.3.7 Alias template dims

```plaintext
template<size_t Rank, class IndexType = size_t>
using dims = see below;
```

1 Result: A type E that is a specialization of `extents` such that `E::rank() == Rank` if `E::rank() == E::rank_dynamic()` is true, and `E::index_type` denotes `IndexType`.

24.7.3.4 Layout mapping

24.7.3.4.1 General

1 In 24.7.3.4.2 and 24.7.3.4.3:

(1.1) — M denotes a layout mapping class.

(1.2) — m denotes a (possibly const) value of type M.

(1.3) — i and j are packs of (possibly const) integers that are multidimensional indices in m.extents() (24.7.3.1).

[Note 1: The type of each element of the packs can be a different integer type. — end note]

(1.4) — r is a (possibly const) rank index of typename M::extents_type.

(1.5) — d_r is a pack of (possibly const) integers for which sizeof...(d_r) == M::extents_type::rank() is true, the r\_th element is equal to 1, and all other elements are equal to 0.

2 In 24.7.3.4.2 through 24.7.3.4.7:

(2.1) — Let `is-mapping-of` be the exposition-only variable template defined as follows:

```plaintext
template<class Layout, class Mapping>
constexpr bool is-mapping-of = // exposition only
    is_same_v<typename Layout::template mapping<typename Mapping::extents_type>, Mapping>;
```

(2.2) — Let `is-layout-left-padded-mapping-of` be the exposition-only variable template defined as follows:

```plaintext
template<class Mapping>
constexpr bool is-layout-left-padded-mapping-of = see below; // exposition only
```

where `is-layout-left-padded-mapping-of<Mapping>` is true if and only if Mapping denotes a specialization of layout_left_padded<S>::mapping for some value S of type size_t.

(2.3) — Let `is-layout-right-padded-mapping-of` be the exposition-only variable template defined as follows:

```plaintext
template<class Mapping>
constexpr bool is-layout-right-padded-mapping-of = see below; // exposition only
```

where `is-layout-right-padded-mapping-of<Mapping>` is true if and only if Mapping denotes a specialization of layout_right_padded<S>::mapping for some value S of type size_t.

(2.4) — For nonnegative integers x and y, let LEAST-MULTIPLE-AT-LEAST(x, y) denote

(2.4.1) — y if x is zero,

(2.4.2) — otherwise, the least multiple of x that is greater than or equal to y.

24.7.3.4.2 Requirements

1 A type M meets the layout mapping requirements if

(1.1) — M models copyable and equality_comparable,

(1.2) — is_nothrow_move_constructible_v<M> is true,

(1.3) — is_nothrow_moveAssignable_v<M> is true,

(1.4) — is_nothrow_swappable_v<M> is true, and

(1.5) — the following types and expressions are well-formed and have the specified semantics.
typename M::extents_type
   Result: A type that is a specialization of extents.

typename M::index_type
   Result: typename M::extents_type::index_type.

typename M::rank_type
   Result: typename M::extents_type::rank_type.

typename M::layout_type
   Result: A type MP that meets the layout mapping policy requirements (24.7.3.4.3) and for which
   is-mapping-of<MP, M> is true.

m.extents()
   Result: const typename M::extents_type&

m(i...)
   Result: typename M::index_type
   Returns: A nonnegative integer less than numeric_limits<typename M::index_type>::max() and
   less than or equal to numeric_limits<size_t>::max().

m(i...) == m(static_cast<typename M::index_type>(i)...) 
   Result: bool
   Returns: true

m.required_span_size()
   Result: typename M::index_type
   Returns: If the size of the multidimensional index space m.extents() is 0, then 0, else 1 plus the
   maximum value of m(i...) for all i.

m.is_unique()
   Result: bool
   Returns: true only if for every i and j where (i != j || ...) is true, m(i...) != m(j...) is true.
   [Note 1: A mapping can return false even if the condition is met. For certain layouts, it is possibly not feasible
to determine efficiently whether the layout is unique. — end note]

m.is_exhaustive()
   Result: bool
   Returns: true only if for all k in the range [0,m.required_span_size()) there exists an i such that
   m(i...) equals k.
   [Note 2: A mapping can return false even if the condition is met. For certain layouts, it is possibly not feasible
to determine efficiently whether the layout is exhaustive. — end note]

m.is_strided()
   Result: bool
   Returns: true only if for every rank index r of m.extents() there exists an integer s_r such that, for all
   i where (i + d_r) is a multidimensional index in m.extents() (24.7.3.1), m((i + d_r)...) - m(i...) equals s_r.
   [Note 3: This implies that for a strided layout m(i_0,...,i_k) = m(0,...,0) + i_0 * s_0 + ... + i_k * s_k. — end note]
   [Note 4: A mapping can return false even if the condition is met. For certain layouts, it is possibly not feasible
to determine efficiently whether the layout is strided. — end note]

m.stride(r)
   Preconditions: m.is_strided() is true.
   Result: typename M::index_type
Returns: \( s_r \) as defined in `m.is_strided()` above.

\[
\text{M::is_always_unique()}
\]

Result: A constant expression (7.7) of type `bool`.

Returns: `true` only if `m.is_unique()` is `true` for all possible objects `m` of type `M`.

[Note 5: A mapping can return `false` even if the above condition is met. For certain layout mappings, it is possibly not feasible to determine whether every instance is unique. — end note]

\[
\text{M::is_always_exhaustive()}
\]

Result: A constant expression (7.7) of type `bool`.

Returns: `true` only if `m.is_exhaustive()` is `true` for all possible objects `m` of type `M`.

[Note 6: A mapping can return `false` even if the above condition is met. For certain layout mappings, it is possibly not feasible to determine whether every instance is exhaustive. — end note]

\[
\text{M::is_always_strided()}
\]

Result: A constant expression (7.7) of type `bool`.

Returns: `true` only if `m.is_strided()` is `true` for all possible objects `m` of type `M`.

[Note 7: A mapping can return `false` even if the above condition is met. For certain layout mappings, it is possibly not feasible to determine whether every instance is strided. — end note]

24.7.3.4.3 Layout mapping policy requirements

A type `MP` meets the layout mapping policy requirements if for a type `E` that is a specialization of `extents`, `MP::mapping<E>` is valid and denotes a type `X` that meets the layout mapping requirements (24.7.3.4.2), and for which the qualified-id `X::layout_type` is valid and denotes the type `MP` and the qualified-id `X::extents_type` denotes `E`.

24.7.3.4.4 Layout mapping policies

```
namespace std {
    struct layout_left {
        template<class Extents>
            class mapping;
    };
    struct layout_right {
        template<class Extents>
            class mapping;
    };
    struct layout_stride {
        template<class Extents>
            class mapping;
    };

    template<
        size_t PaddingValue>
    struct layout_left_padded {
        template<class Extents>
            class mapping;
    };
    template<
        size_t PaddingValue>
    struct layout_right_padded {
        template<class Extents>
            class mapping;
    };
}
```

1 Each of `layout_left`, `layout_right`, and `layout_stride` meets the layout mapping policy requirements and is a trivial type.

2 Each specialization of `layout_left_padded` and `layout_right_padded` meets the layout mapping policy requirements and is a trivial type.
24.7.3.4.5 Class template layout_left::mapping

24.7.3.4.5.1 Overview

layout_left provides a layout mapping where the leftmost extent has stride 1, and strides increase left-to-right as the product of extents.

```cpp
namespace std {
  template<class Extents>
  class layout_left::mapping {
    public:
      using extents_type = Extents;
      using index_type = typename extents_type::index_type;
      using size_type = typename extents_type::size_type;
      using rank_type = typename extents_type::rank_type;
      using layout_type = layout_left;

      // 24.7.3.4.5.2, constructors
      constexpr mapping() noexcept = default;
      constexpr mapping(const mapping&) noexcept = default;
      constexpr mapping(const extents_type&) noexcept;
      template<class OtherExtents>
      constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
      mapping(const mapping<OtherExtents>&) noexcept;
      template<class OtherExtents>
      constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
      mapping(const layout_right::mapping<OtherExtents>&) noexcept;
      template<class LayoutLeftPaddedMapping>
      constexpr explicit(!is_convertible_v<typename LayoutLeftPaddedMapping::extents_type,
                                           extents_type>)
      mapping(const LayoutLeftPaddedMapping&) noexcept;
      template<class OtherExtents>
      constexpr explicit(rank_type > 0)
      mapping(const layout_stride::mapping<OtherExtents>&);

      constexpr mapping& operator=(const mapping&) noexcept = default;

      // 24.7.3.4.5.3, observers
      constexpr const extents_type& extents() const noexcept { return extents_; }
      constexpr index_type required_span_size() const noexcept;
      template<class... Indices>
      constexpr index_type operator()(Indices...) const noexcept;
      static constexpr bool is_always_unique() noexcept { return true; }
      static constexpr bool is_always_exhaustive() noexcept { return true; }
      static constexpr bool is_always_strided() noexcept { return true; }
      static constexpr bool is_unique() noexcept { return true; }
      static constexpr bool is_exhaustive() noexcept { return true; }
      static constexpr bool is_strided() noexcept { return true; }

      constexpr index_type stride(rank_type) const noexcept;
      template<class OtherExtents>
      friend constexpr bool operator==(const mapping&, const mapping<OtherExtents>&) noexcept;

    private:
      extents_type extents_{};
      // exposition only

    // 24.7.3.4.5.6, submdspan mapping specialization
    template<class... SliceSpecifiers>
    constexpr auto submdspan-mapping-impl(SliceSpecifiers...) const
    -> see below;
  }
}
```

§ 24.7.3.4.5 © ISO/IEC 1085
template<class... SliceSpecifiers>
friend constexpr auto submdspan_mapping(
    const mapping& src, SliceSpecifiers... slices) {
    return src.submdspan_mapping-impl(slices...);
};

If Extents is not a specialization of extents, then the program is ill-formed.

layout_left::mapping<E> is a trivially copyable type that models regular for each E.

Mandates: If Extents::rank_dynamic() == 0 is true, then the size of the multidimensional index space Extents() is representable as a value of type typename Extents::index_type.

24.7.3.4.5.2 Constructors

constexpr mapping(const extents_type& e) noexcept;

Preconditions: The size of the multidimensional index space e is representable as a value of type index_type (6.8.2).

Effects: Direct-non-list-initializes extents_ with e.

template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
mapping(const mapping<OtherExtents>& other) noexcept;

Constraints: is_constructible_v<extents_type, OtherExtents> is true.

Preconditions: other.required_span_size() is representable as a value of type index_type (6.8.2).

Effects: Direct-non-list-initializes extents_ with other.extents().

template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
mapping(const layout_right::mapping<OtherExtents>& other) noexcept;

Constraints:
(6.1) extents_type::rank() <= 1 is true, and
(6.2) is_constructible_v<extents_type, OtherExtents> is true.

Preconditions: other.required_span_size() is representable as a value of type index_type (6.8.2).

Effects: Direct-non-list-initializes extents_ with other.extents().

template<class LayoutLeftPaddedMapping>
constexpr explicit(!is_convertible_v<typename LayoutLeftPaddedMapping::extents_type, extents_type>)
mapping(const LayoutLeftPaddedMapping& other) noexcept;

Constraints:
(9.1) is-layout-left-padded-mapping-of<LayoutLeftPaddedMapping> is true.
(9.2) is_constructible_v<extents_type, typename LayoutLeftPaddedMapping::extents_type> is true.

Mandates: If
(10.1) Extents::rank() is greater than one,
(10.2) Extents::static_extent(0) does not equal dynamic_extent, and
(10.3) LayoutLeftPaddedMapping::static-padding-stride does not equal dynamic_extent,
then Extents::static_extent(0) equals LayoutLeftPaddedMapping::static-padding-stride.

Preconditions:
(11.1) If extents_type::rank() > 1 is true, then other.stride(1) equals other.extents(0).
(11.2) other.required_span_size() is representable as a value of type index_type.

Effects: Effects: Direct-non-list-initializes extents_ with other.extents().
template<class OtherExtents>
constexpr explicit(extents_type::rank() > 0)
(mapping(const layout_stride::mapping<OtherExtents>& other);

Constraints: is_constructible_v<extents_type, OtherExtents> is true.

Preconditions:
(14.1) — If extents_type::rank() > 0 is true, then for all r in the range [0, extents_type::rank()),
other.stride(r) equals other.extents().fwd-prod-of-extents(r), and
(14.2) — other.required_span_size() is representable as a value of type index_type (6.8.2).

Effects: Direct-non-list-initializes extents_ with other.extents().

24.7.3.4.5.3 Observers

constexpr index_type required_span_size() const noexcept;

Returns: extents().fwd-prod-of-extents(extents_type::rank()).

template<class... Indices>
constexpr index_type operator()(Indices... i) const noexcept;

Constraints:
(2.1) — sizeof...(Indices) == extents_type::rank() is true,
(2.2) — (is_convertible_v<Indices, index_type> && ...) is true, and
(2.3) — (is_nothrow_constructible_v<index_type, Indices> && ...) is true.

Preconditions: extents_type::index-cast(i) is a multidimensional index in extents_ (24.7.3.1).

Effects: Let P be a parameter pack such that
is_same_v<index_sequence_for<Indices...>, index_sequence<P...>> is true. Equivalent to:
return ((static_cast<index_type>(i) * stride(P)) + ... + 0);

constexpr index_type stride(rank_type i) const;

Constraints: extents_type::rank() > 0 is true.

Preconditions: i < extents_type::rank() is true.

Returns: extents().fwd-prod-of-extents(i).

template<class OtherExtents>
friend constexpr bool operator==(const mapping& x, const mapping<OtherExtents>& y) noexcept;

Constraints: extents_type::rank() == OtherExtents::rank() is true.

Effects: Equivalent to: return x.extents() == y.extents();

24.7.3.4.6 Class template layout_right::mapping

24.7.3.4.6.1 Overview

layout_right provides a layout mapping where the rightmost extent is stride 1, and strides increase
right-to-left as the product of extents.

namespace std {
    template<class Extents>
    class layout_right::mapping {
        public:
            using extents_type = Extents;
            using index_type = typename extents_type::index_type;
            using size_type = typename extents_type::size_type;
            using rank_type = typename extents_type::rank_type;
            using layout_type = layout_right;

            // 24.7.3.4.6.2, constructors
            constexpr mapping() noexcept = default;
            constexpr mapping(const mapping&) noexcept = default;

    };
constexpr mapping(const extents_type&) noexcept;

template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
    mapping(const mapping<OtherExtents>&) noexcept;

template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
    mapping(const layout_left::mapping<OtherExtents>&) noexcept;

template<class OtherExtents>
constexpr explicit(!is_convertible_v<typename LayoutRightPaddedMapping::extents_type,
    extents_type>)
    mapping(const LayoutRightPaddedMapping&) noexcept;

template<class OtherExtents>
constexpr explicit(extents_type::rank() > 0)
    mapping(const layout_stride::mapping<OtherExtents>&) noexcept;

constexpr mapping& operator=(const mapping&) noexcept = default;

// 24.7.3.4.6.3, observers
constexpr const extents_type& extents() const noexcept { return extents_; }

constexpr index_type required_span_size() const noexcept;

template<class... Indices>
constexpr index_type operator()(Indices...) const noexcept;

static constexpr bool is_always_unique() noexcept { return true; }
static constexpr bool is_always_exhaustive() noexcept { return true; }
static constexpr bool is_always_strided() noexcept { return true; }

static constexpr bool is_unique() noexcept { return true; }
static constexpr bool is_exhaustive() noexcept { return true; }
static constexpr bool is_strided() noexcept { return true; }

constexpr index_type stride(rank_type) const noexcept;

template<class OtherExtents>
friend constexpr bool operator==(const mapping&, const mapping<OtherExtents>&) noexcept;

private:

    extents_type extents_;   // exposition only

    // 24.7.3.7.6, submdspan mapping specialization
    template<class... SliceSpecifiers>
        constexpr auto submdspan_mapping_impl(SliceSpecifiers...) const
            -> see below;

    template<class... SliceSpecifiers>
        friend constexpr auto submdspan_mapping(
            const mapping& src, SliceSpecifiers... slices) {
            return src.submdspan_mapping_impl(slices...);
        }
    
};

2 If Extents is not a specialization of extents, then the program is ill-formed.

3 layout_right::mapping<E> is a trivially copyable type that models regular for each E.

4 Mandates: If Extents::rank_dynamic() == 0 is true, then the size of the multidimensional index space Extents() is representable as a value of type typename Extents::index_type.
constexpr mapping(const extents_type& e) noexcept;

**Preconditions:** The size of the multidimensional index space \( e \) is representable as a value of type `index_type` (6.8.2).

**Effects:** Direct-non-list-initializes `extents_` with \( e \).

```cpp
template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
mapping(const mapping<OtherExtents>& other) noexcept;
```

**Constraints:**
- `is_constructible_v<extents_type, OtherExtents>` is true.
- `other.required_span_size()` is representable as a value of type `index_type` (6.8.2).

**Effects:** Direct-non-list-initializes `extents_` with `other.extents()`.

```cpp
template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
mapping(const layout_left::mapping<OtherExtents>& other) noexcept;
```

**Constraints:**
- `is_constructible_v<extents_type, OtherExtents>` is true.
- `other.required_span_size()` is representable as a value of type `index_type` (6.8.2).

**Effects:** Direct-non-list-initializes `extents_` with `other.extents()`.

```cpp
template<class OtherExtents>
constexpr explicit(!is_convertible_v<typename LayoutRightPaddedMapping::extents_type, extents_type>)
mapping(const LayoutRightPaddedMapping&) noexcept;
```

**Constraints:**
- `is-layout-right-padded-mapping-of<LayoutRightPaddedMapping>` is true.
- `is_constructible_v<extents_type, typename LayoutRightPaddedMapping::extents_type>` is true.

**Mandates:** If
- `extents_type::rank()` is greater than one,
- `extents_type::static_extent(Extents::rank() - 1)` does not equal `dynamic_extent`, and
- `LayoutRightPaddedMapping::static-padding-stride` does not equal `dynamic_extent`,

then `Extents::static_extent(Extents::rank() - 1)` equals `LayoutRightPaddedMapping::static-padding-stride`.

**Preconditions:**
- If `extents_type::rank() > 1` is true, then `other.stride(extents_type::rank() - 2)` equals `other.extents().extent(extents_type::rank() - 1)`.
- `other.required_span_size()` is representable as a value of type `index_type`.

**Effects:** Direct-non-list-initializes `extents_` with `other.extents()`.

```cpp
template<class OtherExtents>
constexpr explicit(extents_type::rank() > 0)
mapping(const layout_stride::mapping<OtherExtents>& other) noexcept;
```

**Constraints:**
- `is_constructible_v<extents_type, OtherExtents>` is true.

**Preconditions:**
- If `extents_type::rank() > 0` is true, then for all \( r \) in the range \([0, extents_type::rank())\),
  `other.stride(r)` equals `other.extents().rev-prod-of-extents(r)`.
- `other.required_span_size()` is representable as a value of type `index_type` (6.8.2).

**Effects:** Direct-non-list-initializes `extents_` with `other.extents()`.
24.7.3.4.6.3 Observers

index_type required_span_size() const noexcept;

Returns: extents().fwd-prod-of-extents(extents_type::rank()).

template<class... Indices>
constexpr index_type operator()(Indices... i) const noexcept;

Constraints:

(2.1) sizeof...(Indices) == extents_type::rank() is true,
(2.2) (is_convertible_v<Indices, index_type> && ...) is true, and
(2.3) (is_nothrow_constructible_v<index_type, Indices> && ...) is true.

Preconditions: extents_type::index-cast(i) is a multidimensional index in extents_ (24.7.3.1).

Effects: Let P be a parameter pack such that
is_same_v<index_sequence_for<Indices...>, index_sequence<P...>>
is true. Equivalent to:

return ((static_cast<index_type>(i) * stride(P)) + ... + 0);

constexpr index_type stride(rank_type i) const noexcept;

Constraints: extents_type::rank() > 0 is true.

Preconditions: i < extents_type::rank() is true.

Returns: extents().rev-prod-of-extents(i).

template<class OtherExtents>
friend constexpr bool operator==(const mapping& x, const mapping<OtherExtents>& y) noexcept;

Constraints: extents_type::rank() == OtherExtents::rank() is true.

Effects: Equivalent to: return x.extents() == y.extents();

24.7.3.4.7 Class template layout_stride::mapping

24.7.3.4.7.1 Overview

layout_stride provides a layout mapping where the strides are user-defined.

namespace std {
    template<class Extents>
    class layout_stride::mapping {
        public:
            using extents_type = Extents;
            using index_type = typename extents_type::index_type;
            using size_type = typename extents_type::size_type;
            using rank_type = typename extents_type::rank_type;
            using layout_type = layout_stride;

            private:
                static constexpr rank_type rank_ = extents_type::rank();  // exposition only

        public:
            // 24.7.3.4.7.3, constructors
            constexpr mapping() noexcept;
            constexpr mapping(const mapping&) noexcept = default;
            template<class OtherIndexType>
                constexpr mapping(const OtherIndexType& x, const OtherIndexType& y) noexcept;
            template<class OtherIndexType>
                constexpr mapping(const OtherIndexType& x, span<OtherIndexType, rank_> y) noexcept;
            template<class OtherIndexType>
                constexpr mapping(const OtherIndexType& x, const array<OtherIndexType, rank_>& y) noexcept;
            template<class StridedLayoutMapping>
                constexpr explicit(see below) mapping(const StridedLayoutMapping& x) noexcept;

            constexpr mapping& operator=(const mapping&) noexcept = default;
        }
    }

§ 24.7.3.4.7
// 24.7.3.4.7.4, observers
constexpr const extents_type& extents() const noexcept { return extents_; }
constexpr array<index_type, rank_> strides() const noexcept { return strides_; }
constexpr index_type required_span_size() const noexcept;

template<class... Indices>
constexpr index_type operator()(Indices...) const noexcept;
static constexpr bool is_always_unique() noexcept { return true; }
static constexpr bool is_always_exhaustive() noexcept { return false; }
static constexpr bool is_always_strided() noexcept { return true; }
static constexpr bool is_unique() noexcept { return true; }
constexpr bool is_exhaustive() const noexcept;
static constexpr bool is_strided() noexcept { return true; }
constexpr index_type stride(rank_type i) const noexcept { return strides_[i]; }

template<class OtherMapping>
friend constexpr bool operator==(const mapping&, const OtherMapping&) noexcept;

private:
  extents_type extents_{}; // exposition only
  array<index_type, rank_> strides_{}; // exposition only

// 24.7.3.7.6, submdspan mapping specialization

template<class... SliceSpecifiers>
constexpr auto submdspan-mapping-impl(SliceSpecifiers...) const // exposition only
  -> see below;

template<class... SliceSpecifiers>
friend constexpr auto submdspan_mapping(const mapping& src, SliceSpecifiers... slices) {
  return src.submdspan-mapping-impl(slices...);
}

2 If Extents is not a specialization of extents, then the program is ill-formed.
3 layout_stride::mapping<E> is a trivially copyable type that models regular for each E.
4 Mandates: If Extents::rank_dynamic() == 0 is true, then the size of the multidimensional index space
   Extents() is representable as a value of type typename Extents::index_type.

24.7.3.4.7.2 Exposition-only helpers [mdspan.layout.stride.expo]

1 Let REQUIRED-SPAN-SIZE(e, strides) be:

(1.1) — 1, if e.rank() == 0 is true,
(1.2) — otherwise 0, if the size of the multidimensional index space e is 0,
(1.3) — otherwise 1 plus the sum of products of (e.extent(r) - 1) and
   extents_type::index-cast(strides[r])
   for all r in the range [0, e.rank()).

2 Let OFFSET(m) be:

(2.1) — m(), if e.rank() == 0 is true,
(2.2) — otherwise 0, if the size of the multidimensional index space e is 0,
(2.3) — otherwise m(z...) for a pack of integers z that is a multidimensional index in m.extents() and each
   element of z equals 0.

3 Let is-extents be the exposition-only variable template defined as follows:
Let \( \text{layout-mapping-alike} \) be the exposition-only concept defined as follows:

\[
\begin{align*}
\text{template<class M> concept layout-mapping-alike} &= \text{requires } \{ \\
\text{requires } \text{is-extents}<\text{typename M::extents_type}>; \\
\text{requires } \text{M::is_always_strided}(); \to \text{same_as<bool>}; \\
\text{requires } \text{M::is_always_exhaustive}(); \to \text{same_as<bool>}; \\
\text{requires } \text{M::is_always_unique}(); \to \text{same_as<bool>}; \\
\text{bool_constant}<\text{M::is_always_strided}>::\text{value}; \\
\text{bool_constant}<\text{M::is_always_exhaustive}>::\text{value}; \\
\text{bool_constant}<\text{M::is_always_unique}>::\text{value}; \\
\};
\end{align*}
\]

[Note 1: This concept checks that the functions \( \text{M::is_always_strided}(), \text{M::is_always_exhaustive}(), \) and \( \text{M::is_always_unique}() \) exist, are constant expressions, and have a return type of \( \text{bool} \). — end note]

### 24.7.3.4.7.3 Constructors

\[
\begin{align*}
\text{constexpr mapping()} \ &\text{noexcept;}
\end{align*}
\]

**Preconditions:** \( \text{layout_right::mapping}<\text{extents_type}>().\text{required_span_size}() \) is representable as a value of type \( \text{index_type} \) (6.8.2).

**Effects:** Direct-non-list-initializes \( \text{extents}_\) with \( \text{extents_type}() \), and for all \( d \) in the range \( [0, \text{rank}_) \), direct-non-list-initializes \( \text{strides}_\[d\] \) with \( \text{layout_right::mapping}<\text{extents_type}>().\text{stride}(d) \).

\[
\begin{align*}
\text{template<class OtherIndexType> concept mapping(const extents_type& e, span<OtherIndexType, \text{rank}_> s) noexcept;}
\end{align*}
\]

**Constraints:**

(3.1) \( \text{is_convertible_v<const OtherIndexType&, index_type> is true, and} \)

(3.2) \( \text{is_nothrow_constructible_v<index_type, const OtherIndexType&> is true.} \)

**Preconditions:**

(4.1) \( \text{The result of converting } s[i] \text{ to } \text{index_type} \text{ is greater than 0 for all } i \text{ in the range } [0, \text{rank}_).} \)

(4.2) \( \text{REQUIRED-SPAN-SIZE}(e, s) \) is representable as a value of type \( \text{index_type} \) (6.8.2).

(4.3) \( \text{If } \text{rank}_ \text{ is greater than 0, then there exists a permutation } P \text{ of the integers in the range } [0, \text{rank}_), \) such that \( s[p_i] \geq s[p_{i-1}] \ast e.\text{extent}(p_{i-1}) \) is \( \text{true} \) for all \( i \) in the range \( [1, \text{rank}_) \), where \( p_i \) is the \( i \)-th element of \( P \).

[Note 1: For \( \text{layout_stride} \), this condition is necessary and sufficient for \( \text{is_unique}() \) to be \( \text{true} \). — end note]

**Effects:** Direct-non-list-initializes \( \text{extents}_\) with \( e \), and for all \( d \) in the range \( [0, \text{rank}_) \), direct-non-list-initializes \( \text{strides}_\[d\] \) with \( \text{as_const}(s[d]) \).

\[
\begin{align*}
\text{template<class StridedLayoutMapping> concept explicit(see below) mapping(const StridedLayoutMapping& other) noexcept;}
\end{align*}
\]

**Constraints:**

(6.1) \( \text{layout-mapping-alike<StridedLayoutMapping> is satisfied.} \)

(6.2) \( \text{is_constructible_v<extents_type, typename StridedLayoutMapping::extents_type> is true.} \)

(6.3) \( \text{StridedLayoutMapping::is_always_unique()} \text{ is true.} \)

(6.4) \( \text{StridedLayoutMapping::is_always_strided()} \text{ is true.} \)
Preconditions:

(7.1) StridedLayoutMapping meets the layout mapping requirements (24.7.3.4.2),

(7.2) other.stride(r) > 0 is true for every rank index r of extents(),

(7.3) other.required_span_size() is representable as a value of type index_type (6.8.2), and

(7.4) OFFSET(other) == 0 is true.

Effects: Direct-non-list-initializes extents_ with other.extents(), and for all d in the range [0, rank_),
direct-non-list-initializes strides_[d] with other.stride(d).

Remarks: The expression inside explicit is equivalent to:

\![\text{is_convertible_v<
\text{typename StridedLayoutMapping::extents_type, extents_type> } \&\& \\
\text{is-mapping-of<layout_left, StridedLayoutMapping> } || \\
\text{is-mapping-of<layout_right, StridedLayoutMapping> } || \\
\text{is-layout-left-padded-mapping-of<StridedLayoutMapping> } || \\
\text{is-layout-right-padded-mapping-of<StridedLayoutMapping> } || \\
\text{is-mapping-of<layout_stride, StridedLayoutMapping>}}\)]

24.7.3.4.7.4 Observers

constexpr index_type required_span_size() const noexcept;

template<class... Indices>
constexpr index_type operator()(Indices... i) const noexcept;

Constraints:

(2.1) sizeof...(Indices) == rank_ is true,

(2.2) (is_convertible_v<Indices, index_type> && ...) is true, and

(2.3) (is_nothrow_constructible_v<index_type, Indices> && ...) is true.

Preconditions: extents_type::index-cast(i) is a multidimensional index in extents_ (24.7.3.1).

Effects: Let P be a parameter pack such that

\![\text{is_same_v<index_sequence_for<Indices...>, index_sequence<P...>>}]\)

is true. Equivalent to:

\[ \text{return } ((\text{static_cast<index_type>(i)} * \text{stride}(P)) + ... + 0); \]

constexpr bool is_exhaustive() const noexcept;

Returns:

(5.1) true if rank_ is 0.

(5.2) Otherwise, true if there is a permutation P of the integers in the range [0, rank_) such that

\[ \text{stride}(p_0) \text{ equals } 1, \text{ and } \text{stride}(p_i) \text{ equals } \text{stride}(p_{i-1}) \text{ * extents().extent}(p_{i-1}) \text{ for } i \text{ in the range } [1, \text{rank_}], \]

where \( p_i \) is the \( i \)th element of \( P \).

(5.3) Otherwise, false.

Constraints:

(6.1) layout-mapping-alike<OtherMapping> is satisfied.

(6.2) rank_ == OtherMapping::extents_type::rank() is true.

(6.3) OtherMapping::is_always_strided() is true.

Preconditions: OtherMapping meets the layout mapping requirements (24.7.3.4.3).

Returns: true if x.extents() == y.extents() is true, OFFSET(y) == 0 is true, and each of
x.stride(r) == y.stride(r) is true for r in the range [0, x.extents().rank()). Otherwise, false.
24.7.3.4.8 Class template layout_left_padded::mapping

24.7.3.4.8.1 Overview

layout_left_padded provides a layout mapping that behaves like layout_left::mapping, except that the padding stride \( \text{stride}(1) \) can be greater than or equal to \( \text{extent}(0) \).

namespace std {
  template<size_t PaddingValue>
  template<class Extents>
  class layout_left_padded<PaddingValue>::mapping {
    public:
      static constexpr size_t padding_value = PaddingValue;

      using extents_type = Extents;
      using index_type = typename extents_type::index_type;
      using size_type = typename extents_type::size_type;
      using rank_type = typename extents_type::rank_type;
      using layout_type = layout_left_padded<PaddingValue>;

    private:
      static constexpr size_t rank_ = extents_type::rank(); // exposition only
      static constexpr size_t first-static-extent =
        extents_type::static_extent(0); // exposition only

      // 24.7.3.4.8.2, exposition-only members
      static constexpr size_t static-padding-stride = see below; // exposition only

    public:
      // 24.7.3.4.8.3, constructors
      constexpr mapping() noexcept : mapping(extents_type{}) {}
      constexpr mapping(const mapping&) noexcept = default;
      constexpr mapping(const extents_type&);
      template<class OtherIndexType>
        constexpr mapping(const extents_type&, OtherIndexType);
      template<class OtherExtents>
        constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
          mapping(const layout_left::mapping<OtherExtents>&);
      template<class OtherExtents>
        constexpr explicit(extends_type::rank() > 0)
          mapping(const layout_stride::mapping<OtherExtents>&);
      template<class LayoutLeftPaddedMapping>
        constexpr explicit(see below)
          mapping(const LayoutLeftPaddedMapping&);
      template<class LayoutRightPaddedMapping>
        constexpr explicit(see below)
          mapping(const LayoutRightPaddedMapping& noexcept);

      constexpr mapping& operator=(const mapping&) noexcept = default;

      // 24.7.3.4.8.4, observers
      constexpr const extents_type& extents() const noexcept { return extents_; }
      constexpr array<index_type, rank_> strides() const noexcept;
      constexpr index_type required_span_size() const noexcept;
      template<class... Indices>
        constexpr index_type operator()(Indices...) const noexcept;
      static constexpr bool is_always_unique() noexcept { return true; }
      static constexpr bool is_always_exhaustive() noexcept;
      static constexpr bool is_always_strided() noexcept { return true; }

      static constexpr bool is_unique() const noexcept { return true; }
      static constexpr bool is_strided() noexcept { return true; }
  }
}
constexpr index_type stride(rank_type) const noexcept;

template<class LayoutLeftPaddedMapping>
friend constexpr bool operator==(const mapping&, const LayoutLeftPaddedMapping&) noexcept;

private:
// 24.7.3.4.8.2, exposition-only members
index_type stride-1 = static-padding-stride; // exposition only
extents_type extents_{}; // exposition only

// 24.7.3.7.6, submdspan mapping specialization
template<class... SliceSpecifiers>
constexpr auto submdspan-mapping-impl(SliceSpecifiers...) const // exposition only
-> see below;

template<class... SliceSpecifiers>
friend constexpr auto submdspan_mapping(const mapping& src, SliceSpecifiers... slices) {
    return src.submdspan-mapping-impl(slices...);
}

2 If Extents is not a specialization of extents, then the program is ill-formed.
3 layout_left_padded::mapping<E> is a trivially copyable type that models regular for each E.
4 Throughout 24.7.3.4.8, let P_rank be the following size rank_ parameter pack of size_t values:
   (4.1) — the empty parameter pack, if rank_ equals zero;
   (4.2) — otherwise, 0zu, if rank_ equals one;
   (4.3) — otherwise, the parameter pack 0zu, 1zu, ..., rank_-1.

Mandates:
(5.1) — If rank_dynamic() == 0 is true, then the size of the multidimensional index space Extents() is representable as a value of type index_type.
(5.2) — padding_value is representable as a value of type index_type.
(5.3) — If
   (5.3.1) — rank_ is greater than one,
   (5.3.2) — padding_value does not equal dynamic_extent, and
   (5.3.3) — first-static-extent does not equal dynamic_extent,
   then LEAST-MULTIPLE-AT-LEAST(padding_value, first-static-extent) is representable as a value of type size_t, and is representable as a value of type index_type.
(5.4) — If
   (5.4.1) — rank_ is greater than one,
   (5.4.2) — padding_value does not equal dynamic_extent, and
   (5.4.3) — extents_type::static_extent(k) does not equal dynamic_extent for all k in the range [0, extents_type::rank()),
   then the product of LEAST-MULTIPLE-AT-LEAST(padding_value, ext.static_extent(0)) and all values ext.static_extent(k) with k in the range [1, rank_) is representable as a value of type size_t, and is representable as a value of type index_type.

24.7.3.4.8.2 Exposition-only members

static constexpr size_t static-padding-stride = see below;

1 The value is
   (1.1) — 0, if rank_ equals zero or one;
   (1.2) — otherwise, dynamic_extent, if padding_value or first-static-extent equals dynamic_extent;
   (1.3) — otherwise, the size_t value which is LEAST-MULTIPLE-AT-LEAST(padding_value, first-static-extent).
index_type stride-1 = static-padding-stride;

Recommended practice: Implementations should not store this value if static-padding-stride is not dynamic_extent.

[Note 1: Using extents<index_type, static-padding-stride> instead of index_type as the type of stride-1 would achieve this. — end note]

24.7.3.4.8.3 Constructors

constexpr mapping(const extents_type& ext);

1 Preconditions:

(1.1) The size of the multidimensional index space ext is representable as a value of type index_type.
(1.2) If rank_ is greater than one and padding_value does not equal dynamic_extent, then LEAST-MULTIPLE-AT-LEAST(padding_value, ext.extent(0)) is representable as a value of type index_type.
(1.3) If rank_ is greater than one and padding_value does not equal dynamic_extent, then the product of LEAST-MULTIPLE-AT-LEAST(padding_value, ext.extent(0)) and all values ext.extent(k) with k in the range of [1, rank_) is representable as a value of type index_type.

2 Effects:

(2.1) Direct-non-list-initializes extents_ with ext; and
(2.2) if rank_ is greater than one, direct-non-list-initializes stride-1
(2.2.1) with ext.extent(0) if padding_value is dynamic_extent,
(2.2.2) otherwise with LEAST-MULTIPLE-AT-LEAST(padding_value, ext.extent(0)).

template<class OtherIndexType>
constexpr mapping(const extents_type& ext, OtherIndexType pad);

3 Constraints:

(3.1) is_convertible_v<OtherIndexType, index_type> is true.
(3.2) is_nothrow_convertible_v<index_type, OtherIndexType> is true.

4 Preconditions:

(4.1) pad is representable as a value of type index_type.
(4.2) extents_type::index-cast(pad) is greater than zero.
(4.3) If rank_ is greater than one, then LEAST-MULTIPLE-AT-LEAST(pad, ext.extent(0)) is representable as a value of type index_type.
(4.4) If rank_ is greater than one, then the product of LEAST-MULTIPLE-AT-LEAST(pad, ext.extent(0)) and all values ext.extent(k) with k in the range of [1, rank_) is representable as a value of type index_type.
(4.5) If padding_value is not equal to dynamic_extent, padding_value equals extents_type::index-cast(pad).

5 Effects: Direct-non-list-initializes extents_ with ext, and if rank_ is greater than one, direct-non-list-initializes stride-1 with LEAST-MULTIPLE-AT-LEAST(pad, ext.extent(0)).

template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
mapping(const layout_left::mapping<OtherExtents>& other);

6 Constraints: is_convertible_v<extents_type, OtherExtents> is true.

7 Mandates: If OtherExtents::rank() is greater than 1, then

( static-padding-stride == dynamic_extent ) ||
( OtherExtents::static_extent(0) == dynamic_extent ) ||
( static-padding-stride == OtherExtents::static_extent(0) )

is true.

8 Preconditions:
If `extents_type::rank() > 1` is true and `padding_value == dynamic_extent` is false, then `other.stride(1)` equals 

\[ \text{LEAST-MULTIPLE-AT-LEAST}(padding_value, \text{extents_type::index-cast}(other.extents().extent(0))) \]

and

- `other.required_span_size()` is representable as a value of type `index_type`.

**Effects:** Equivalent to `mapping(other.extents())`.

```cpp
template<class OtherExtents>
constexpr explicit(rank_ > 0)
mapping(const layout_stride::mapping<OtherExtents>& other);
```

**Constraints:**
- `is_constructible_v<extents_type, OtherExtents>` is true.

**Preconditions:**
1. If `rank_` is greater than 1 and `padding_value` does not equal `dynamic_extent`, then `other.stride(1)` equals 
   \[ \text{LEAST-MULTIPLE-AT-LEAST}(padding_value, \text{extents_type::index-cast}(other.extents().extent(0))) \]
2. If `rank_` is greater than 0, then `other.stride(0)` equals 1.
3. If `rank_` is greater than 2, then for all `r` in the range \([2, \text{rank_}]\), `other.stride(r)` equals 
   \[ \text{other.extents().prod-of-extents(r)} / \text{other.extents().extent(0)} \times \text{other.stride(1)} \]
4. `other.required_span_size()` is representable as a value of type `index_type`.

**Effects:**
- Direct-non-list-initializes `extents_` with `other.extents()` and
- if `rank_` is greater than one, direct-non-list-initializes `stride-1` with `other.stride(1)`. 

```cpp
template<class LayoutLeftPaddedMapping>
constexpr explicit(see below)
mapping(const LayoutLeftPaddedMapping& other);
```

**Constraints:**
- `is-layout-left-padded-mapping-of<LayoutLeftPaddedMapping>` is true.
- `is_constructible_v<extents_type, typename LayoutLeftPaddedMapping::extents_type>` is true.

**Mandates:** If `rank_` is greater than 1, then
- `padding_value == dynamic_extent || LayoutLeftPaddedMapping::padding_value == dynamic_extent || padding_value == LayoutLeftPaddedMapping::padding_value` is true.

1. If `rank_` is greater than 1 and `padding_value` does not equal `dynamic_extent`, then `other.stride(1)` equals 
   \[ \text{LEAST-MULTIPLE-AT-LEAST}(padding_value, \text{extents_type::index-cast}(other.extent(0))) \]
2. `other.required_span_size()` is representable as a value of type `index_type`.

**Effects:**
- Direct-non-list-initializes `extents_` with `other.extents()` and
- if `rank_` is greater than one, direct-non-list-initializes `stride-1` with `other.stride(1)`. 

**Remarks:** The expression inside `explicit` is equivalent to:

```cpp
rank_ > 1 &&
(padding_value != dynamic_extent ||
 LayoutLeftPaddedMapping::padding_value == dynamic_extent)
```
template<class LayoutRightPaddedMapping>
constexpr explicit(
    see below)
mapping(const LayoutRightPaddedMapping& other) noexcept;

Constraints:

(17.1) is-layout-right-padded-mapping-of<LayoutRightPaddedMapping> is true or
is-mapping-of<layout_right, LayoutRightPaddedMapping> is true.

(17.2) rank_ equals zero or one.

(17.3) is_constructible_v<extents_type, typename LayoutRightPaddedMapping::extents_-type> is true.

Preconditions: other.required_span_size() is representable as a value of type index_type.

Effects: Direct-non-list-initializes extents_ with other.extents().

Remarks: The expression inside explicit is equivalent to:

!is_convertible_v<typename LayoutRightPaddedMapping::extents_type, extents_type>

[Note 1: Neither the input mapping nor the mapping to be constructed uses the padding stride in the rank-0 or
rank-1 case, so the padding stride does not affect either the constraints or the preconditions. — end note]

24.7.3.4.8.4 Observers

constexpr array<index_type, rank_> strides() const noexcept;

Returns: array<index_type, rank_>({stride(P_rank)...}).

constexpr index_type required_span_size() const noexcept;

Returns:

(2.1) 0 if the multidimensional index space extents_ is empty;

(2.2) otherwise, this((extents_(P_rank) - index_type(1))...) + 1.

template<class... Indices>
constexpr size_t operator()(Indices... idxs) const noexcept;

Constraints:

(3.1) sizeof...(Indices) == rank_ is true.

(3.2) (is_convertible_v<Indices, index_type> && ...) is true.

(3.3) (is_nothrow_constructible_v<index_type, Indices> && ...) is true.

Preconditions: extents_type::index-cast(idxs) is a multidimensional index in extents() (24.7.3.1).

Returns: ((static_cast<index_type>(idxs) * stride(P_rank)) + ... + 0).

static constexpr bool is_always_exhaustive() noexcept;

Returns:

(6.1) If rank_ equals zero or one, then true;

(6.2) otherwise, if neither static-padding-stride nor first-static-extent equal dynamic_extent,
then static-padding-stride == first-static-extent;

(6.3) otherwise, false.

constexpr bool is_exhaustive() const noexcept;

Returns: true if rank_ equals zero or one; otherwise, extents_.extent(0) == stride(1).

constexpr index_type stride(rank_type r) const noexcept;

Preconditions: r is smaller than rank_.

Returns:

(9.1) If r equals zero: 1;

(9.2) otherwise, if r equals one: stride-1;

(9.3) otherwise, the product of stride-1 and all values extents_.extent(k) with k in the range [1, r).
template<class LayoutLeftPaddedMapping>
friend constexpr bool operator==(const mapping& x, const LayoutLeftPaddedMapping& y) noexcept;

Constraints:
— \text{is-layout-left-padded-mapping-of}<\text{LayoutLeftPaddedMapping}> is true.
— \text{LayoutLeftPaddedMapping}.\text{extents_type}.\text{rank}() == \text{rank}_ is true.

Returns: true if \text{x}.\text{extents}() == \text{y}.\text{extents}() is true and \text{rank}_ < 2 || \text{x}.\text{stride}(1) == \text{y}.\text{stride}(1) is true. Otherwise, false.

24.7.3.4.9 Class template layout_right_padded::mapping [mdspan.layout.rightpad]

24.7.3.4.9.1 Overview [mdspan.layout.rightpad.overview]

\text{layout_right_padded} provides a layout mapping that behaves like \text{layout_right::mapping}, except that the padding stride \text{stride}(\text{extents_type}.\text{rank}() - 2) can be greater than or equal to \text{extents_type}.\text{extent}(\text{extents_type}.\text{rank}() - 1).

namespace std {
    template<size_t PaddingValue>
    template<class Extents>
    class layout_right_padded<PaddingValue>::mapping {
        public:
            static constexpr size_t padding_value = PaddingValue;
            using extents_type = Extents;
            using index_type = typename extents_type::index_type;
            using size_type = typename extents_type::size_type;
            using rank_type = typename extents_type::rank_type;
            using layout_type = layout_right_padded<PaddingValue>;

        private:
            static constexpr size_t rank_ = extents_type::rank(); // exposition only
            static constexpr size_t last-static-extent = extents_type::static_extent(rank_ - 1); // exposition only

            static constexpr size_t static-padding-stride = see below; // exposition only

        public:
            // 24.7.3.4.9.3, constructors
            constexpr mapping() noexcept : mapping(extents_type{}) {} // exposition only
            constexpr mapping(const mapping&) noexcept = default;
            constexpr mapping(const extents_type&);
            template<class OtherIndexType>
                constexpr mapping(const extents_type&, OtherIndexType);
            template<class OtherExtents>
                constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
                    mapping(const layout_right::mapping<OtherExtents>&);
            template<class OtherExtents>
                constexpr explicit(rank_ > 0)
                    mapping(const layout_stride::mapping<OtherExtents>&);
            template<class LayoutRightPaddedMapping>
                constexpr explicit(see below)
                    mapping(const LayoutRightPaddedMapping&);
            template<class LayoutLeftPaddedMapping>
                constexpr explicit(see below)
                    mapping(const LayoutLeftPaddedMapping&)
                        noexcept;
                constexpr mapping& operator=(const mapping&) noexcept = default;

            // 24.7.3.4.9.4, observers
            constexpr const extents_type& extents() const noexcept { return extents_; }
            constexpr array<index_type, rank_> strides() const noexcept;
constexpr index_type required_span_size() const noexcept;

template<class... Indices>
constexpr index_type operator()(Indices...) const noexcept;

static constexpr bool is_always_unique() noexcept { return true; }
static constexpr bool is_always_exhaustive() noexcept;
static constexpr bool is_always_strided() noexcept { return true; }

static constexpr bool is_unique() noexcept { return true; }
constexpr bool is_exhaustive() const noexcept;
static constexpr bool is_strided() noexcept { return true; }

constexpr index_type stride(rank_type) const noexcept;

template<class LayoutRightPaddedMapping>
friend constexpr bool operator==(const mapping&, const LayoutRightPaddedMapping&) noexcept;

private:
  // 24.7.3.4.9.2, exposition-only members
  index_type stride_rm2_{ static-padding-stride_ };
  extents_type extents_{ }; // exposition only

  // 24.7.3.7.6, submdspan mapping specialization
  template<class... SliceSpecifiers>
  constexpr auto submdspan_mapping_impl(SliceSpecifiers...) const
    -> see below;

  template<class... SliceSpecifiers>
  friend constexpr auto submdspan_mapping(const mapping& src, SliceSpecifiers... slices) {
    return src.submdspan_mapping_impl(slices...);
  }
};

2 If Extents is not a specialization of extents, then the program is ill-formed.
3 layout_right_padded::mapping<E> is a trivially copyable type that models regular for each E.
4 Throughout 24.7.3.4.9, let P_rank be the following size rank_ parameter pack of size_t values:
   (4.1) the empty parameter pack, if rank_ equals zero;
   (4.2) otherwise, 0zu, if rank_ equals one;
   (4.3) otherwise, the parameter pack 0zu, 1zu, ..., rank_- 1.
5 Mandates:
   (5.1) If rank_dynamic() == 0 is true, then the size of the multidimensional index space Extents() is
        representable as a value of type index_type.
   (5.2) padding_value is representable as a value of type index_type.
   (5.3) If
       (5.3.1) rank_ is greater than one,
       (5.3.2) padding_value does not equal dynamic_extent, and
       (5.3.3) last-static-extent does not equal dynamic_extent,
       then LEAST-MULTIPLE-AT-LEAST(padding_value, last-static-extent) is representable as a value
        of type size_t, and is representable as a value of type index_type.
   (5.4) If
       (5.4.1) rank_ is greater than one,
       (5.4.2) padding_value does not equal dynamic_extent, and
       (5.4.3) extents_type::static_extent(k) does not equal dynamic_extent for all k in the range [0, rank_).
then the product of \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{padding_value}, \text{ext.static.extent}(\text{rank}_- 1))\) and all values \(\text{ext.static.extent}(k)\) with \(k\) in the range of \([0, \text{rank}_- 1)\) is representable as a value of type size_t, and is representable as a value of type index_type.

24.7.3.4.9.2 Exposition-only members

```cpp
static constexpr size_t static-padding-stride = see below;
```

1

The value is

1.1 — 0, if \(\text{rank}_-\) equals zero or one;
1.2 — otherwise, dynamic_extent, if \(\text{padding_value}\) or \(\text{last-static-extent}\) equals dynamic_extent;
1.3 — otherwise, the size_t value which is \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{padding_value}, \text{last-static-extent})\).

```cpp
index_type stride-rm2 = static-padding-stride;
```

2

Recommended practice: Implementations should not store this value if \(\text{static-padding-stride}\) is not dynamic_extent.

[Note 1: Using extents<index_type, static-padding-stride> instead of index_type as the type of stride- \(\text{rm2}\) would achieve this. — end note]

24.7.3.4.9.3 Constructors

```cpp
constexpr mapping(const extents_type& ext);
```

1

Preconditions:

1.1 — The size of the multidimensional index space \(\text{ext}\) is representable as a value of type index_type.
1.2 — If \(\text{rank}_-\) is greater than one and \(\text{padding_value}\) does not equal dynamic_extent, then \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{padding_value}, \text{ext.extent}(\text{rank}_- 1))\) is representable as a value of type index_type.
1.3 — If \(\text{rank}_-\) is greater than one and \(\text{padding_value}\) does not equal dynamic_extent, then the product of \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{padding_value}, \text{ext.extent}(\text{rank}_- 1))\) and all values \(\text{ext.extent}(k)\) with \(k\) in the range of \([0, \text{rank}_- 1)\) is representable as a value of type index_type.

2

Effects:

2.1 — Direct-non-list-initializes \(\text{extents}_-\) with \(\text{ext}\); and
2.2 — if \(\text{rank}_-\) is greater than one, direct-non-list-initializes \(\text{stride-rm2}\)
2.2.1 — with \(\text{ext.extent}(\text{rank}_- 1)\) if \(\text{padding_value}\) is dynamic_extent,
2.2.2 — otherwise with \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{padding_value}, \text{ext.extent}(\text{rank}_- 1))\).

```cpp
template<class OtherIndexType>
constexpr mapping(const extents_type& ext, OtherIndexType pad);
```

3

Constraints:

3.1 — is_convertible_v<OtherIndexType, index_type> is true.
3.2 — is_nothrow_constructible_v<index_type, OtherIndexType> is true.

4

Preconditions:

4.1 — \(\text{pad}\) is representable as a value of type index_type.
4.2 — \(\text{extents_type::index-cast}(\text{pad})\) is greater than zero.
4.3 — If \(\text{rank}_-\) is greater than one, then \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{pad}, \text{ext.extent}(\text{rank}_- 1))\) is representable as a value of type index_type.
4.4 — If \(\text{rank}_-\) is greater than one, then the product of \(\text{LEAST-MULTIPLE-AT-LEAST}(\text{pad}, \text{ext.extent}(\text{rank}_- 1))\) and all values \(\text{ext.extent}(k)\) with \(k\) in the range of \([0, \text{rank}_- 1)\) is representable as a value of type index_type.
4.5 — If \(\text{padding_value}\) is not equal to dynamic_extent, \(\text{padding_value}\) equals \(\text{extents_type::index-cast}(\text{pad})\).
Effects: Direct-non-list-initializes extents_ with ext, and if rank_ is greater than one, direct-non-list-initializes stride-rm2 with LEAST-MULTIPLE-AT-LEAST(pad, ext.extent(rank_ - 1)).

```cpp
template<class OtherExtents>
constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
mapping(const layout_right::mapping<OtherExtents>& other);
```

Constraints: is_convertible_v<extents_type, OtherExtents> is true.

Mandates: If OtherExtents::rank() is greater than 1, then

- (static-padding-stride == dynamic_extent) ||
- (OtherExtents::static_extent(rank_ - 1) == dynamic_extent) ||
- (static-padding-stride == OtherExtents::static_extent(rank_ - 1))

is true.

Preconditions:

(8.1)  
- If rank_ > 1 is true and padding_value == dynamic_extent is false, then other.stride(rank_ - 2) equals LEAST-MULTIPLE-AT-LEAST(padding_value, extents_type::index-cast(other.extents().extent(rank_ - 1)))

and

(8.2)  
- other.required_span_size() is representable as a value of type index_type.

Effects: Equivalent to mapping(other.extents()).

```cpp
template<class OtherExtents>
constexpr explicit(rank_ > 0)
mapping(const layout_stride::mapping<OtherExtents>& other);
```

Constraints: is_convertible_v<extents_type, OtherExtents> is true.

Preconditions:

(11.1)  
- If rank_ is greater than 1 and padding_value does not equal dynamic_extent, then other.stride(rank_ - 2) equals LEAST-MULTIPLE-AT-LEAST(padding_value, extents_type::index-cast(other.extents().extent(rank_ - 1)))

(11.2)  
- If rank_ is greater than 0, then other.stride(rank_ - 1) equals 1.

(11.3)  
- If rank_ is greater than 2, then for all r in the range [0, rank_ - 2), other.stride(r) equals (other.extents().rev-prod-of-extents(r) / other.extents().extent(rank_ - 1)) * other.stride(rank_ - 2)

(11.4)  
- other.required_span_size() is representable as a value of type index_type.

Effects:

(12.1)  
- Direct-non-list-initializes extents_ with other.extents(); and

(12.2)  
- if rank_ is greater than one, direct-non-list-initializes stride-rm2 with other.stride(rank_ - 2).

```cpp
template<class LayoutRightPaddedMapping>
constexpr explicit(see below)
mapping(const LayoutRightPaddedMapping& other);
```

Constraints:

(13.1)  
- is-layout-right-padded-mapping-of<LayoutRightPaddedMapping> is true.

(13.2)  
- is_convertible_v<extents_type, typename LayoutRightPaddedMapping::extents_type> is true.

Mandates: If rank_ is greater than 1, then

- padding_value == dynamic_extent ||
- LayoutRightPaddedMapping::padding_value == dynamic_extent ||
- padding_value == LayoutRightPaddedMapping::padding_value

§ 24.7.3.4.9
is true.

**Preconditions:**

- If \( \text{rank} \) is greater than 1 and \( \text{padding\_value} \) does not equal \( \text{dynamic\_extent} \), then \( \text{other}.\text{stride}(\text{rank} - 2) \) equals
  
  \[
  \text{LEAST-MULTIPLE-AT-LEAST}(\text{padding\_value},
  \text{extents\_type::index-cast}(\text{other.extent}(\text{rank} - 1)))
  \]

- \( \text{other}.\text{required\_span\_size()} \) is representable as a value of type \text{index\_type}.

**Effects:**

- Direct-non-list-initializes \( \text{extents\_} \) with \( \text{other}.\text{extents()} \); and
- if \( \text{rank} \) is greater than one, direct-non-list-initializes \( \text{stride\_rm2} \) with \( \text{other}.\text{stride}(	ext{rank} - 2) \).

**Remarks:** The expression inside \text{explicit} is equivalent to:

\[
\text{rank} > 1 \&\&
(\text{padding\_value} \neq \text{dynamic\_extent} \mid\mid 
\text{LayoutRightPaddedMapping::padding\_value} == \text{dynamic\_extent})
\]

```cpp
template<class LayoutLeftPaddedMapping>
constexpr explicit(see below)
mapping(const LayoutLeftPaddedMapping& other) noexcept;
```

**Constraints:**

- \( \text{is\_layout\_left\_padded\_mapping\_of<LayoutLeftPaddedMapping> is true or}
\( \text{is\_mapping\_of<layout\_left, LayoutLeftPaddedMapping> is true.}
\)

- \( \text{rank} \) equals zero or one.

- \( \text{is\_constructible\_v<extents\_type, typename LayoutLeftPaddedMapping::extents\_type>}
\) is true.

**Preconditions:** \( \text{other}.\text{required\_span\_size()} \) is representable as a value of type \text{index\_type}.

**Effects:** Direct-non-list-initializes \( \text{extents\_} \) with \( \text{other}.\text{extents()} \).

**Remarks:** The expression inside \text{explicit} is equivalent to:

\[
\text{!is\_convertible\_v<extents\_type, typename LayoutLeftPaddedMapping::extents\_type>}
\]

[Note 1: Neither the input mapping nor the mapping to be constructed uses the padding stride in the rank-0 or rank-1 case, so the padding stride affects neither the constraints nor the preconditions. —end note]

### 24.7.3.4.9.4 Observers [mdspan.layout.rightpad.obs]

```cpp
constexpr array<index_type, rank, > strides() const noexcept;
```

**Returns:** \( \text{array<index\_type, rank, >}(\text{stride(P\_rank)\ldots}) \).

```cpp
constexpr index_type required_span_size() const noexcept;
```

**Returns:** 0 if the multidimensional index space \( \text{extents\_} \) is empty, otherwise \( \text{*this}(((\text{extents\_}(\text{P\_rank}) - \text{index\_type}(1)))\ldots)) + 1 \).

```cpp
template<class... Indices>
constexpr size_t operator()(Indices... idxs) const noexcept;
```

**Constraints:**

- \( \text{sizeof...(Indices)} == \text{rank} \) is true.

- \( \text{(is\_convertible\_v<Indices, index\_type> \&\& \ldots) is true.}
\)

- \( \text{(is\_nothrow\_constructible\_v<index\_type, Indices> \&\& \ldots) is true.}
\)

**Preconditions:** \( \text{extents\_type::index\_cast(idxs) is a multidimensional index in extents()} \) (24.7.3.1).

**Returns:** \( (((\text{static\_cast<index\_type>(idxs) \* stride(P\_rank)}) + \ldots + 0)\).

```cpp
static constexpr bool is_always_exhaustive() noexcept;
```

**Returns:**
If \( \text{rank}_e \) equals zero or one, then \( \text{true} \);

otherwise, if neither \( \text{static-padding-stride} \) nor \( \text{last-static-extent} \) equal \( \text{dynamic_extent} \), then \( \text{static-padding-stride} = \text{last-static-extent} \);

otherwise, \( \text{false} \).

```cpp
constexpr bool is_exhaustive() const noexcept;
```

Returns: \( \text{true} \) if \( \text{rank}_e \) equals zero or one; otherwise,

\[
\text{extents}_e\text{.extent}(\text{rank}_e - 1) = \text{stride}(\text{rank}_e - 2)
\]

```cpp
constexpr index_type stride(rank_type r) const noexcept;
```

Preconditions: \( r \) is smaller than \( \text{rank}_e \).

Returns:

- If \( r \) equals \( \text{rank}_e - 1 \): 1;
- otherwise, if \( r \) equals \( \text{rank}_e - 2 \): \( \text{stride}-\text{rm2} \);
- otherwise, the product of \( \text{stride}-\text{rm2} \) and all values \( \text{extents}_e\text{.extent}(k) \) with \( k \) in the range of \( [r + 1, \text{rank}_e - 1] \).

```cpp
template<class LayoutRightPaddedMapping>
friend constexpr bool operator==(const mapping& x, const LayoutRightPaddedMapping& y) noexcept;
```

Constraints:

- \( \text{is-layout-right-padded-mapping-of}<\text{LayoutRightPaddedMapping}> \) is true.
- \( \text{LayoutRightPaddedMapping}::\text{extents_type}::\text{rank}() = \text{rank}_e \) is true.

Returns: \( \text{true} \) if \( x\text{.extents}() = y\text{.extents}() \) is true and \( \text{rank}_e < 2 \) or \( x\text{.stride}(\text{rank}_e - 2) = y\text{.stride}(\text{rank}_e - 2) \) is true. Otherwise, \( \text{false} \).

### 24.7.3.5 Accessor policy

An accessor policy defines types and operations by which a reference to a single object is created from an abstract data handle to a number of such objects and an index.

A range of indices \( [0, N) \) is an accessible range of a given data handle and an accessor if, for each \( i \) in the range, the accessor policy’s \( \text{access} \) function produces a valid reference to an object.

In 24.7.3.5.2,

- A denotes an accessor policy.
- \( a \) denotes a value of type \( A \) or \( \text{const} \ A \).
- \( p \) denotes a value of type \( A::\text{data_handle_type} \) or \( \text{const} A::\text{data_handle_type} \).

[Note 1: The type \( A::\text{data_handle_type} \) need not be dereferenceable. — end note]

- \( n, i, \) and \( j \) each denote values of type \( \text{size_t} \).

### 24.7.3.5.2 Requirements

A type \( A \) meets the accessor policy requirements if

- \( A \) models \textit{copyable},
- \( \text{is_nothrow\_move\_constructible\_v}<A> \) is true,
- \( \text{is_nothrow\_move\_assignable\_v}<A> \) is true,
- \( \text{is_nothrow\_swappable\_v}<A> \) is true, and
- the following types and expressions are well-formed and have the specified semantics.

\[
\text{typename } A::\text{element_type}
\]

Result: A complete object type that is not an abstract class type.
typename A::data_handle_type

Result: A type that models copyable, and for which is_nothrow_move_constructible_v<A::data_handle_type> is true, is_nothrow_moveAssignable_v<A::data_handle_type> is true, and is_nothrow_swappable_v<A::data_handle_type> is true.

[Note 1: The type of data_handle_type need not be element_type*. — end note]

typename A::reference

Result: A type that models common_reference_with<A::reference&&, A::element_type&>.

[Note 2: The type of reference need not be element_type&. — end note]

typename A::offset_policy

Result: A type OP such that:

(5.1) OP meets the accessor policy requirements,
(5.2) constructible_from<OP, const A&> is modeled, and
(5.3) is_same_v<typename OP::element_type, typename A::element_type> is true.

a.access(p, i)

Result: A::reference

Remarks: The expression is equality preserving.

[Note 3: Concrete accessor policies can impose preconditions for their access function. However, they might not. For example, an accessor where p is span<A::element_type, dynamic_extent> and access(p, i) returns p[i % p.size()] does not need to impose a precondition on i. — end note]

a.offset(p, i)

Result: A::offset_policy::data_handle_type

Returns: q such that for b being A::offset_policy(a), and any integer n for which [0, n) is an accessible range of p and a:

(10.1) [0, n − i) is an accessible range of q and b; and
(10.2) b.access(q, j) provides access to the same element as a.access(p, i + j), for every j in the range [0, n − i).

Remarks: The expression is equality-preserving.

24.7.3.5.3 Class template default_accessor

namespace std {
    template<class ElementType>
    struct default_accessor {
        using offset_policy = default_accessor;
        using element_type = ElementType;
        using reference = ElementType&;
        using data_handle_type = ElementType*;

        constexpr default_accessor() noexcept = default;
        template<class OtherElementType>
        constexpr default_accessor(default_accessor<OtherElementType>) noexcept;
        constexpr reference access(data_handle_type p, size_t i) const noexcept;
        constexpr data_handle_type offset(data_handle_type p, size_t i) const noexcept;
    };
}

1 default_accessor meets the accessor policy requirements.

2 ElementType is required to be a complete object type that is neither an abstract class type nor an array type.

3 Each specialization of default_accessor is a trivially copyable type that models semiregular.

4 [0, n) is an accessible range for an object p of type data_handle_type and an object of type default_accessor if and only if [p, p + n) is a valid range.

§ 24.7.3.5.3 © ISO/IEC 1105
24.7.3.5.3.2 Members

template<class OtherElementType>
constexpr default_accessor(default_accessor<OtherElementType>) noexcept {}

Constraints: is_convertible_v<OtherElementType(*)[], element_type(*)[]> is true.

constexpr reference access(data_handle_type p, size_t i) const noexcept;

Effects: Equivalent to: return p[i];

constexpr data_handle_type offset(data_handle_type p, size_t i) const noexcept;

Effects: Equivalent to: return p + i;

24.7.3.6 Class template mdspan

24.7.3.6.1 Overview

mdspan is a view of a multidimensional array of elements.

namespace std {
    template<class ElementType, class Extents, class LayoutPolicy = layout_right,
             class AccessorPolicy = default_accessor<ElementType>>
    class mdspan {
        public:
            using extents_type = Extents;
            using layout_type = LayoutPolicy;
            using accessor_type = AccessorPolicy;
            using mapping_type = typename layout_type::template mapping<extents_type>;
            using element_type = ElementType;
            using value_type = remove_cv_t<element_type>;
            using index_type = typename extents_type::index_type;
            using size_type = typename extents_type::size_type;
            using rank_type = typename extents_type::rank_type;
            using data_handle_type = typename accessor_type::data_handle_type;
            using reference = typename accessor_type::reference;

            static constexpr rank_type rank() noexcept { return extents_type::rank(); }
            static constexpr rank_type rank_dynamic() noexcept { return extents_type::rank_dynamic(); }
            static constexpr size_t static_extent(rank_type r) noexcept { return extents_type::static_extent(r); }
            constexpr index_type extent(rank_type r) const noexcept { return extents().extent(r); }

            // 24.7.3.6.2, constructors
            constexpr mdspan();
            constexpr mdspan(const mdspan& rhs) = default;
            constexpr mdspan(mdspan&& rhs) = default;

            template<class... OtherIndexTypes>
            constexpr explicit mdspan(data_handle_type ptr, OtherIndexTypes... exts);
            template<class OtherIndexType, size_t N>
            constexpr explicit(N != rank_dynamic())
                mdspan(data_handle_type p, span<OtherIndexType, N> exts);
            template<class OtherIndexType, size_t N>
            constexpr explicit(N != rank_dynamic())
                mdspan(data_handle_type p, const array<OtherIndexType, N>& exts);
            constexpr mdspan(data_handle_type p, const extents_type& ext);
            constexpr mdspan(data_handle_type p, const mapping_type& m);
            constexpr mdspan(data_handle_type p, const mapping_type& m, const accessor_type& a);

            template<class OtherElementType, class OtherExtents,
                     class OtherLayoutPolicy, class OtherAccessorPolicy>
            constexpr explicit(see below)
                mdspan(const mdspan<OtherElementType, OtherExtents,
                         OtherLayoutPolicy, OtherAccessorPolicy>& other);
constexpr mdspan& operator=(const mdspan& rhs) = default;
constexpr mdspan& operator=(mdspan&& rhs) = default;

// 24.7.3.6.3, members
template<class... OtherIndexTypes>
constexpr reference operator[](OtherIndexTypes... indices) const;
template<class OtherIndexType>
constexpr reference operator[](span<OtherIndexType, rank()> indices) const;
template<class OtherIndexType>
constexpr reference operator[](const array<OtherIndexType, rank()>& indices) const;

constexpr size_type size() const noexcept;
[[nodiscard]] constexpr bool empty() const noexcept;

friend constexpr void swap(mdspan& x, mdspan& y) noexcept;

constexpr const extents_type& extents() const noexcept { return map_.extents(); }
constexpr const data_handle_type& data_handle() const noexcept { return ptr_; }
constexpr const mapping_type& mapping() const noexcept { return map_; }
constexpr const accessor_type& accessor() const noexcept { return acc_; }

static constexpr bool is_always_unique()
  { return mapping_type::is_always_unique(); }
static constexpr bool is_always_exhaustive()
  { return mapping_type::is_always_exhaustive(); }
static constexpr bool is_always_strided()
  { return mapping_type::is_always_strided(); }

constexpr bool is_unique() const
  { return map_.is_unique(); }
constexpr bool is_exhaustive() const
  { return map_.is_exhaustive(); }
constexpr bool is_strided() const
  { return map_.is_strided(); }

constexpr index_type stride(rank_type r) const
  { return map_.stride(r); }

private:
  accessor_type acc_; // exposition only
  mapping_type map_; // exposition only
  data_handle_type ptr_; // exposition only
};

template<class CArray>
requires (is_array_v<CArray> && rank_v<CArray> == 1)
mdspan(CArray&)
  -> mdspan<remove_all_extents_t<CArray>, extents<size_t, extent_v<CArray, 0>>);

template<class Pointer>
requires (is_pointer_v<remove_reference_t<Pointer>>)
mdspan(Pointer&&)
  -> mdspan<remove_pointer_t<remove_reference_t<Pointer>>, extents<size_t>>;

template<class ElementType, class... Integrals>
requires ((is_convertible_v<Integrals, size_t> && ...) && sizeof...(Integrals) > 0)
exlicit mdspan(ElementType*, Integrals...)
  -> mdspan<ElementType, extents<size_t, maybe-static-ext<Integrals>...>>;

template<class ElementType, class OtherIndexType, size_t N>
mdspan(ElementType*, span<OtherIndexType, N>)
  -> mdspan<ElementType, dextents<size_t, N>>;
template<class ElementType, class OtherIndexType, size_t N>
mdspan(ElementType*, const array<OtherIndexType, N>&)
-> mdspan<ElementType, dextents<size_t, N>>;

template<class ElementType, class IndexType, size_t... ExtentsPack>
mdspan(ElementType*, const extents<IndexType, ExtentsPack...>&)
-> mdspan<ElementType, extents<IndexType, ExtentsPack...>>;

template<class ElementType, class MappingType>
mdspan(ElementType*, const MappingType&)
-> mdspan<ElementType, typename MappingType::extents_type,
typename MappingType::layout_type>;

template<class MappingType, class AccessorType>
mdspan(const typename AccessorType::data_handle_type&, const MappingType&,
const AccessorType&)
-> mdspan<typename AccessorType::element_type, typename MappingType::extents_type,
typename MappingType::layout_type, AccessorType>;

Mandates:

— ElementType is a complete object type that is neither an abstract class type nor an array type,
— Extents is a specialization of extents, and
— is_same_v<ElementType, typename AccessorPolicy::element_type> is true.

LayoutPolicy shall meet the layout mapping policy requirements (24.7.3.4.3), and AccessorPolicy shall
meet the accessor policy requirements (24.7.3.5.2).

Each specialization MDS of mdspan models copyable and
— is_nothrow_move_constructible_v<MDS> is true,
— is_nothrow_move_assignable_v<MDS> is true, and
— is_nothrow_swappable_v<MDS> is true.

A specialization of mdspan is a trivially copyable type if its accessor_type, mapping_type, and data_-
handle_type are trivially copyable types.

24.7.3.6.2 Constructors

constexpr mdspan();

Constraints:

— rank_dynamic() > 0 is true.
— is_default_constructible_v<data_handle_type> is true.
— is_default_constructible_v<mapping_type> is true.
— is_default_constructible_v<accessor_type> is true.

Preconditions: [0, map_.required_span_size()) is an accessible range of ptr_ and acc_ for the values
of map_ and acc_ after the invocation of this constructor.

Effects: Value-initializes ptr_, map_, and acc_.

template<class... OtherIndexTypes>
constexpr explicit mdspan(data_handle_type p, OtherIndexTypes... exts);

Let N be sizeof...(OtherIndexTypes).

Constraints:

— (is_convertible_v<OtherIndexTypes, index_type> && ...) is true,
— (is_nothrow_constructible<index_type, OtherIndexTypes> && ...) is true,
— N == rank() || N == rank_dynamic() is true,
— is_constructible_v<mapping_type, extents_type> is true, and
— is_default_constructible_v<accessor_type> is true.
Preconditions: \([0, \text{map\_}.\text{required\_span\_size()}]) is an accessible range of \(p\) and \(\text{acc\_}\) for the values of \(\text{map\_}\) and \(\text{acc\_}\) after the invocation of this constructor.

Effects:

7.1 — Direct-non-list-initializes \(\text{ptr\_}\) with \(\text{std\::move}(p)\),
7.2 — direct-non-list-initializes \(\text{map\_}\) with \(\text{extents\_type}(\text{static\_cast<index\_type>}(\text{std\::move(/exts }))...)\), and
7.3 — value-initializes \(\text{acc\_}\).

### 8 Constraints:

8.1 — \text{is\_convertible\_v<\text{const OtherIndexType\&, index\_type}}\) is true,
8.2 — \text{is\_nothrow\_constructible\_v<index\_type, const OtherIndexType&>>} is true,
8.3 — \(N == \text{rank()} || N == \text{rank\_dynamic()}\) is true,
8.4 — \text{is\_constructible\_v<\text{mapping\_type, extents\_type}}\) is true, and
8.5 — \text{is\_default\_constructible\_v<\text{accessor\_type}}\) is true.

Preconditions: \([0, \text{map\_}.\text{required\_span\_size()}]) is an accessible range of \(p\) and \(\text{acc\_}\) for the values of \(\text{map\_}\) and \(\text{acc\_}\) after the invocation of this constructor.

Effects:

10.1 — Direct-non-list-initializes \(\text{ptr\_}\) with \(\text{std\::move}(p)\),
10.2 — direct-non-list-initializes \(\text{map\_}\) with \(\text{exts}\), and
10.3 — value-initializes \(\text{acc\_}\).

### 11 Constraints:

11.1 — \text{is\_constructible\_v<\text{mapping\_type, const extents\_type&}\>\) is true, and
11.2 — \text{is\_default\_constructible\_v<\text{accessor\_type}\>\} is true.

Preconditions: \([0, \text{map\_}.\text{required\_span\_size()}]) is an accessible range of \(p\) and \(\text{acc\_}\) for the values of \(\text{map\_}\) and \(\text{acc\_}\) after the invocation of this constructor.

Effects:

13.1 — Direct-non-list-initializes \(\text{ptr\_}\) with \(\text{std\::move}(p)\),
13.2 — direct-non-list-initializes \(\text{map\_}\) with \(\text{ext}\), and
13.3 — value-initializes \(\text{acc\_}\).

### 14 Constraints:

\text{is\_default\_constructible\_v<\text{accessor\_type}\>\) is true.

Preconditions: \([0, \text{m\_.required\_span\_size()}]) is an accessible range of \(p\) and \(\text{acc\_}\) for the value of \(\text{acc\_}\) after the invocation of this constructor.

Effects:

16.1 — Direct-non-list-initializes \(\text{ptr\_}\) with \(\text{std\::move}(p)\),
16.2 — direct-non-list-initializes \(\text{map\_}\) with \(\text{m}\), and
16.3 — value-initializes \(\text{acc\_}\).

### 17 Constraints:

\text{is\_default\_constructible\_v<\text{accessor\_type}\>\) is true.

Preconditions: \([0, \text{m\_.required\_span\_size()}]) is an accessible range of \(p\) and \(\text{a}\).
Effects:
— Direct-non-list-initializes \( p_r \) with std::move(\( p \)),
— direct-non-list-initializes \( m a p \) with \( m \), and
— direct-non-list-initializes \( a c c \) with \( a \).

```cpp
template<class OtherElementType, class OtherExtents, 
class OtherLayoutPolicy, class OtherAccessor>
constexpr explicit(see below)
mdspan(const mdspan<OtherElementType, OtherExtents, 
OtherLayoutPolicy, OtherAccessor>& other);
```

Constraints:
— is_constructible_v<mapping_type, const OtherLayoutPolicy::template mapping<OtherExtents>&> is true, and
— is_constructible_v<accessor_type, const OtherAccessor&> is true.

Mandates:
— is_constructible_v<data_handle_type, const OtherAccessor::data_handle_type&> is true, and
— is_constructible_v<extents_type, OtherExtents> is true.

Preconditions:
— For each rank index \( r \) of extents_type, static_extent(\( r \)) == dynamic_extent || static_extent(\( r \)) == other.extent(\( r \)) is true.
— \([0, map_.required_span_size())\) is an accessible range of \( p_r \) and \( a c c \) for values of \( p_r \), \( m a p \), and \( a c c \) after the invocation of this constructor.

Effects:
— Direct-non-list-initializes \( p_r \) with other.\( p_r \),
— direct-non-list-initializes \( m a p \) with other.\( m a p \), and
— direct-non-list-initializes \( a c c \) with other.\( a c c \).

Remarks: The expression inside explicit is equivalent to:
```
!is_convertible_v<const OtherLayoutPolicy::template mapping<OtherExtents>&, mapping_type>
|| !is_convertible_v<const OtherAccessor&, accessor_type>
```

24.7.3.6.3 Members

```
template<class... OtherIndexTypes>
constexpr reference operator[](OtherIndexTypes... indices) const;
```

Constraints:
— (is_convertible_v<OtherIndexTypes, index_type> && ...) is true,
— (is_nothrow_constructible_v<index_type, OtherIndexTypes> && ...) is true, and
— sizeof...(OtherIndexTypes) == rank() is true.

Let \( I \) be `extents_type::index-cast(std::move(indices))`.

Preconditions: \( I \) is a multidimensional index in `extents()`.  
[Note 1: This implies that \( map_.(I) < map_.required_span_size() \) is true. — end note]

Effects: Equivalent to:
```
return acc_.access(ptr_, map_(static_cast<index_type>(std::move(indices))...));
```

```cpp
template<class OtherIndexType>
constexpr reference operator[](span<OtherIndexType, rank()> indices) const;
template<class OtherIndexType>
constexpr reference operator[](const array<OtherIndexType, rank()>& indices) const;
```

Constraints:
— is_convertible_v<const OtherIndexType&, index_type> is true, and
— `is_nothrow_constructible_v<index_type, const OtherIndexType&>` is true.

**Effects:** Let \( P \) be a parameter pack such that

\[
\text{is_same_v<make_index_sequence<rank()>, index_sequence<P...>>}
\]

is true. Equivalent to:

```cpp
constexpr size_type size() const noexcept;
```

**Preconditions:** The size of the multidimensional index space `extents()` is representable as a value of type `size_type` (6.8.2).

**Returns:** `extents().fwd-prod-of-extents(rank())`.

```cpp
[[nodiscard]] constexpr bool empty() const noexcept;
```

Returns: `true` if the size of the multidimensional index space `extents()` is 0, otherwise `false`.

```cpp
friend constexpr void swap(mdspan& x, mdspan& y) noexcept;
```

**Effects:** Equivalent to:

```cpp
swap(x.ptr_, y.ptr_);
swap(x.map_, y.map_);
swap(x.acc_, y.acc_);
```

### 24.7.3.7 `submdspan`  [mdspan.sub]

#### 24.7.3.7.1 Overview  [mdspan.sub.overview]

The `submdspan` facilities create a new `mdspan` viewing a subset of elements of an existing input `mdspan`. The subset viewed by the created `mdspan` is determined by the `SliceSpecifier` arguments.

For each function defined in 24.7.3.7 that takes a parameter pack named `slices` as an argument:

- **index_type** be
  - `M::index_type` if the function is a member of a class `M`,
  - otherwise, `remove_reference_t<decltype(src)>::index_type` if the function has a parameter named `src`,
  - otherwise, the same type as the function’s template argument `IndexType`;

- **rank** be the number of elements in `slices`;

- **sk** be the \( k \)th element of `slices`;

- **S_k** be the type of `S_k`; and

- **map-rank** be an `array<size_t, rank>` such that for each \( k \) in the range \([0, \text{rank})\), \( \text{map-rank}[k] \) equals:
  - `dynamic_extent` if \( S_k \) models `convertible_to<index_type>`,
  - otherwise, the number of types \( S_j \) with \( j < k \) that do not model `convertible_to<index_type>`.

#### 24.7.3.7.2 `strided_slice`  [mdspan.sub.strided.slice]

`strided_slice` represents a set of `extent` regularly spaced integer indices. The indices start at `offset`, and increase by increments of `stride`.

```cpp
namespace std {
    template<class OffsetType, class ExtentType, class StrideType>
    struct strided_slice {
        using offset_type = OffsetType;
        using extent_type = ExtentType;
        using stride_type = StrideType;

        [[no_unique_address]] offset_type offset{};
        [[no_unique_address]] extent_type extent{};
        [[no_unique_address]] stride_type stride{};
    };
}
```
strided_slice has the data members and special members specified above. It has no base classes or members other than those specified.

Mandates: OffsetType, ExtentType, and StrideType are signed or unsigned integer types, or model integral-constant-like.

[Note 1: strided_slice(.offset = 1, .extent = 10, .stride = 3) indicates the indices 1, 4, 7, and 10. Indices are selected from the half-open interval [1, 1 + 10). — end note]

24.7.3.7.3 submdspan_mapping_result [mdspan.sub.map.result]

Specializations of submdspan_mapping_result are returned by overloads of submdspan_mapping.

namespace std {
  template<class LayoutMapping>
  struct submdspan_mapping_result {
    [[no_unique_address]] LayoutMapping mapping = LayoutMapping();
    size_t offset();
  };
}

submdspan_mapping_result has the data members and special members specified above. It has no base classes or members other than those specified.

LayoutMapping shall meet the layout mapping requirements (24.7.3.4.3).

24.7.3.7.4 Exposition-only helpers [mdspan.sub.helpers]

template<class T>
constexpr T de-ice(T val) { return val; }

template<integral-constant-like T>
constexpr auto de-ice(T) { return T::value; }

template<class IndexType, size_t k, class... SliceSpecifiers>
constexpr IndexType first_(SliceSpecifiers... slices);

Mandates: IndexType is a signed or unsigned integer type.

Let $\phi_k$ denote the following value:

(2.1) $s_k$ if $S_k$ models convertible_to<IndexType>;
(2.2) get<0>(s_k) if $S_k$ models index-pair-like<IndexType>;
(2.3) otherwise, de-ice(s_k.offset) if $S_k$ is a specialization of strided_slice;
(2.4) otherwise, 0.

Preconditions: $\phi_k$ is representable as a value of type IndexType.

Returns: extents<IndexType>::index-cast($\phi_k$).

template<size_t k, class Extents, class... SliceSpecifiers>
constexpr auto last_(const Extents& src, SliceSpecifiers... slices);

Mandates: Extents is a specialization of extents.

Let index_type be typename Extents::index_type.

Let $\lambda_k$ denote the following value:

(7.1) de-ice($s_k$) + 1 if $S_k$ models convertible_to<index_type>; otherwise
(7.2) get<1>(s_k) if $S_k$ models index-pair-like<index_type>; otherwise
(7.3) de-ice($s_k$.offset) + de-ice($s_k$.extent) if $S_k$ is a specialization of strided_slice; otherwise
(7.4) src.extent(k).

Preconditions: $\lambda_k$ is representable as a value of type index_type.

Returns: Extents::index-cast($\lambda_k$).
template<class IndexType, size_t N, class... SliceSpecifiers>
constexpr array<IndexType, sizeof...(SliceSpecifiers)>
src-indices(const array<IndexType, N>& indices, SliceSpecifiers... slices);

Mandates: IndexType is a signed or unsigned integer type.

Returns: An array<IndexType, sizeof...(SliceSpecifiers)> src_idx such that for each k in the
range [0, sizeof...(SliceSpecifiers)), src_idx[k] equals
- first_<IndexType, k>(slices...) for each k where map-rank[k] equals dynamic_extent,
- otherwise, first_<IndexType, k>(slices...) + indices[map-rank[k]].

24.7.3.7.5 submdspan_extents function

template<class IndexType, class... Extents, class... SliceSpecifiers>
constexpr auto submdspan_extents(const extents<IndexType, Extents...>& src,
SliceSpecifiers... slices);

Constraints: sizeof...(slices) equals Extents::rank().

Mandates: For each rank index k of src-extents(), exactly one of the following is true:
- S_k models convertible_to<IndexType>,
- S_k models index-pair-like<IndexType>,
- is_convertible_v<S_k, full_extent_t> is true, or
- S_k is a specialization of strided_slice.

Preconditions: For each rank index k of src-extents(), all of the following are true:
- if S_k is a specialization of strided_slice
- s_k.extent == 0, or
- s_k.stride > 0
- 0 ≤ first_<IndexType, k>(slices...) ≤ last_<k>(src, slices...) ≤ src.extent(k)

Let SubExtents be a specialization of extents such that:
- SubExtents::rank() equals the number of k such that S_k does not model convertible_to<IndexType>;
- for each rank index k of Extents such that map-rank[k] != dynamic_extent is true, SubExtents::static_extent(map-rank[k]) equals:
  - Extents::static_extent(k) if is_convertible_v<S_k, full_extent_t> is true; otherwise
  - de-ice(tuple_element_t<0, S_k>()) / de-ice(S_k::extent_type()) - 1 / de-ice(S_k::stride_type()), if S_k is a specialization of strided_slice whose extent_type and stride_type model integral-constant-like;
  - otherwise, dynamic_extent.

Returns: A value ext of type SubExtents such that for each k for which map-rank[k] != dynamic_extent
is true, ext.extent(map-rank[k]) equals:
- s_k.extent == 0 ? 0 : 1 + (de-ice(s_k.extent) - 1) / de-ice(s_k.stride) if S_k is a specialization of strided_slice,
- otherwise, last_<k>(src, slices...) - first_<IndexType, k>(slices...).

24.7.3.7.6 Specializations of submdspan_mapping

24.7.3.7.6.1 Common

The following elements apply to all functions in 24.7.3.7.6.
Constraints: sizeof...(slices) equals extents_type::rank().

Mandates: For each rank index \( k \) of extents(), exactly one of the following is true:

(3.1) \( S_k \) models convertible_to<index_type>,
(3.2) \( S_k \) models index-pair-like<index_type>,
(3.3) \( \text{is_convertible_v}<S_k, \text{full_extent_t}> \) is true, or
(3.4) \( S_k \) is a specialization of strided_slice.

Preconditions: For each rank index \( k \) of extents(), all of the following are true:

(4.1) if \( S_k \) is a specialization of strided_slice, \( s_k.extent \) is equal to zero or \( s_k.stride \) is greater than zero; and
(4.2) \( 0 \leq \text{first}_k<s_k.extent>(slices...) \leq \text{last}_k<s_k.extent>(extents(), slices...) \leq \text{extents}.extent(k) \)

Let \( \text{sub_ext} \) be the result of submdspan_extents(extents(), slices...) and let SubExtents be decl-type(sub_ext).

Let \( \text{sub_strides} \) be an array<SubExtents::index_type, SubExtents::rank()> such that for each rank index \( k \) of extents() for which map_rank[k] is not dynamic_extent, sub_strides[map_rank[k]] equals:

(6.1) \( \text{stride}(k) \ast \text{de-ice}(s_k.stride) \) if \( S_k \) is a specialization of strided_slice and \( s_k.stride < s_k.extent \) is true;
(6.2) otherwise, \( \text{stride}(k) \).

Let \( P \) be a parameter pack such that is_same_v<make_index_sequence<rank()>, index_sequence<P...>> is true.

If \( \text{first}_k<s_k.extent>(slices...) \) equals extents().extent(k) for any rank index \( k \) of extents(), then let \( \text{offset} \) be a value of type size_t equal to (*this).required_span_size(). Otherwise, let \( \text{offset} \) be a value of type size_t equal to (*this)(first_k<s_k.extent>(P<slices...>)...).

24.7.3.7.6.2 layout_left specialization of submdspan_mapping

```
template<class Extents>
template<class... SliceSpecifiers>
constexpr auto layout_left::mapping<Extents>::submdspan-mapping-impl(
    SliceSpecifiers... slices) const -> see below;
```

Returns:

(1.1) \( \text{submdspan_mapping_result}(*\text{this}, 0) \), if Extents::rank() == 0 is true;
(1.2) otherwise, \( \text{submdspan_mapping_result}(\text{layout_left::mapping}(\text{sub_ext}), \text{offset}) \), if SubExtents::rank() == 0 is true;
(1.3) otherwise, \( \text{submdspan_mapping_result}(\text{layout_left::mapping}(\text{sub_ext}), \text{offset}) \), if
(1.3.1) for each \( k \) in the range \([0,\text{SubExtents::rank() - 1})\), is_convertible_v<S_k, full_extent_t> is true; and
(1.3.2) for \( k \) equal to \( \text{SubExtents::rank() - 1} \), \( S_k \) models index-pair-like<index_type> or is_convertible_v<S_k, full_extent_t> is true;
[Note 1: If the above conditions are true, all \( S_k \) with \( k \) larger than \( \text{SubExtents::rank() - 1} \) are convertible to index_type. — end note]
(1.4) otherwise,
    \( \text{submdspan_mapping_result}(\text{layout_left_padded<S_static>::mapping}(\text{sub_ext}, \text{stride}(u + 1)), \text{offset}) \)
    if for a value \( u \) for which \( u + 1 \) is the smallest value \( p \) larger than zero for which \( S_p \) models index-pair-like<index_type> or is_convertible_v<S_p, full_extent_t> is true, the following conditions are met:
(1.4.1) \( S_0 \) models index-pair-like<index_type> or is_convertible_v<S_0, full_extent_t> is true; and
— for each \( k \) in the range \([u + 1, u + \text{SubExtents::rank() - 1}]\), \( \text{is_convertible_v}<S_k, \text{full_extent_t}> \) is true; and

— for \( k \) equal to \( u + \text{SubExtents::rank()} - 1 \), \( S_k \) models \( \text{index-pair-like}<\text{index_type}> \) or \( \text{is_convertible_v}<S_k, \text{full_extent_t}> \) is true;

and where \( S_{\text{static}} \) is:

— \( \text{dynamic_extent} \), if \( \text{static_extent}(k) \) is \( \text{dynamic_extent} \) for any \( k \) in the range \([0, u + 1)\),

— otherwise, the product of all values \( \text{static_extent}(k) \) for \( k \) in the range \([0, u + 1)\);

\[ \text{Note 1: If the above conditions are true, all } S_k \text{ with } k < \text{rank} - \text{SubExtents::rank()} \text{ are convertible to } \text{index_type}. \text{—end note} \]

— otherwise,

\[ \text{submdspan_mapping_result}{\text{layout_right_padded}<S_{\text{static}}>::\text{mapping}(\text{sub_ext}, \text{stride}(\text{rank} - u - 2)), \text{offset}} \]

if for a value \( u \) for which \( \text{rank} - u - 2 \) is the largest value \( p \) smaller than \( \text{rank} - 1 \) for which \( S_p \) models \( \text{index-pair-like}<\text{index_type}> \) or \( \text{is_convertible_v}<S_p, \text{full_extent_t}> \) is true, the following conditions are met:

— for \( k \) equal to \( \text{rank} - 1 \), \( S_k \) models \( \text{index-pair-like}<\text{index_type}> \) or \( \text{is_convertible_v}<S_k, \text{full_extent_t}> \) is true; and

— for each \( k \) in the range \([\text{rank} - \text{SubExtents::rank()} - u + 1, \text{rank} - u - 1)\), \( \text{is_convertible_v}<S_k, \text{full_extent_t}> \) is true; and

— for \( k \) equal to \( \text{rank} - \text{SubExtents::rank()} - u, S_k \) models \( \text{index-pair-like}<\text{index_type}> \) or \( \text{is_convertible_v}<S_k, \text{full_extent_t}> \) is true;

and where \( S_{\text{static}} \) is:

— \( \text{dynamic_extent} \), if \( \text{static_extent}(k) \) is \( \text{dynamic_extent} \) for any \( k \) in the range \([\text{rank} - u - 1, \text{rank}]\),

— otherwise, the product of all values \( \text{static_extent}(k) \) for \( k \) in the range \([\text{rank} - u - 1, \text{rank}]\);

— otherwise,

\[ \text{submdspan_mapping_result}{\text{layout_stride::mapping}(\text{sub_ext}, \text{sub_strides}), \text{offset}} \]
template<class Extents>
    template<class... SliceSpecifiers>
    constexpr auto layout_stride::mapping<Extents>::
        submdspan-mapping-impl(SliceSpecifiers... slices) const -> see below;

Returns:
(1.1) — submdspan_mapping_result(*this, 0), if Extents::rank() == 0 is true;
(1.2) — otherwise, submdspan_mapping_result(layout_stride::mapping(sub_ext, sub_strides), offset)

24.7.3.7.6.5 layout_left_padded specialization of submdspan_mapping

template<class Extents>
    template<class... SliceSpecifiers>
    constexpr auto layout_left_padded::mapping<Extents>::
        submdspan-mapping-impl(SliceSpecifiers... slices) const -> see below;

Returns:
(1.1) — submdspan_mapping_result(*this, 0), if Extents::rank() == 0 is true;
(1.2) — otherwise, submdspan_mapping_result(layout_left::mapping(sub_ext), offset), if rank_== 1 is true or SubExtents::rank() == 0 is true;
(1.3) — otherwise, submdspan_mapping_result(layout_left::mapping(sub_ext), offset), if
(1.3.1) — SubExtents::rank() == 1 is true and
(1.3.2) — S0 models index-pair-like<index_type> or is_convertible_v<S0, full_extent_t> is true;
(1.4) — otherwise,
        submdspan_mapping_result(layout_left_padded<S_static>::mapping(sub_ext, stride(u + 1)), offset)
        if for a value u for which u + 1 is the smallest value p larger than zero for which S_p models
        index-pair-like<index_type> or is_convertible_v<S_p, full_extent_t> is true, the following conditions are met:
        (1.4.1) — S0 models index-pair-like<index_type> or is_convertible_v<S0, full_extent_t> is true; and
        (1.4.2) — for each k in the range [u + 1, u + SubExtents::rank() - 1), is_convertible_v<S_k, full_extent_t> is true; and
        (1.4.3) — for k equal to u + SubExtents::rank() - 1, S_k models index-pair-like<index_type>
        or is_convertible_v<S_k, full_extent_t> is true;
        where S_static is:
        (1.4.4) — dynamic_extent, if static-padding-stride is dynamic_extent or static_extent(k) is
dynamic_extent for any k in the range [1, u + 1),
        (1.4.5) — otherwise, the product of static-padding-stride and all values static_extent(k) for k
        in the range [1, u + 1);
        (1.5) — otherwise,
        submdspan_mapping_result(layout_left::mapping(sub_ext, stride), offset)

24.7.3.7.6.6 layout_right_padded specialization of submdspan_mapping

template<class Extents>
    template<class... SliceSpecifiers>
    constexpr auto layout_right_padded::mapping<Extents>::
        submdspan-mapping-impl(SliceSpecifiers... slices) const -> see below;

Returns:
(1.1) — submdspan_mapping_result(*this, 0), if rank_ == 0 is true;
— otherwise, \( \text{submdspan\_mapping\_result} \{ \text{layout\_right}::\text{mapping}(\text{sub\_ext}), \text{offset} \} \),
if \( \text{rank\_} = 1 \) is true or \( \text{SubExtents::rank()} = 0 \) is true;
(1.3)
— otherwise, \( \text{submdspan\_mapping\_result} \{ \text{layout\_right}::\text{mapping}(\text{sub\_ext}), \text{offset} \} \),
if
(1.3.1)
— \( \text{SubExtents::rank()} = 1 \) is true and
(1.3.2)
— for \( k \) equal to \( \text{rank\_} - 1 \), \( S_k \) models \text{index-pair-like} <\text{index\_type}> or \text{is\_convertible\_v}\(<S_k>, \text{full\_extent\_t}) \) is true;
(1.4)
— otherwise,
\( \text{submdspan\_mapping\_result} \{ \text{layout\_right\_padded}<\text{S\_static}>::\text{mapping}(\text{sub\_ext}, \text{stride}(\text{rank\_} - u - 2)), \text{offset} \}
if for a value \( u \) for which \( \text{rank\_} - u - 2 \) is the largest value \( p \) smaller than \( \text{rank\_} - 1 \) for which \( S_p \) models \text{index-pair-like} <\text{index\_type}> or \text{is\_convertible\_v}<\text{S}_p>, \text{full\_extent\_t} \) is true,
the following conditions are met:
(1.4.1)
— for \( k \) equal to \( \text{rank\_} - 1 \), \( S_k \) models \text{index-pair-like} <\text{index\_type}> or \text{is\_convertible\_v}<\text{S}_k>, \text{full\_extent\_t} \) is true; and
(1.4.2)
— for each \( k \) in the range \( [\text{rank\_} - \text{SubExtents::rank()} - u + 1, \text{rank\_} - u - 1] \), \text{is\_convertible\_v}<\text{S}_k>, \text{full\_extent\_t} \) is true; and
(1.4.3)
— for \( k \) equal to \( \text{rank\_} - \text{SubExtents::rank()} - u \), \( S_k \) models \text{index-pair-like} <\text{index\_type}> or \text{is\_convertible\_v}<\text{S}_k>, \text{full\_extent\_t} \) is true;
and where \( \text{S\_static} \) is:
(1.4.4)
— \text{dynamic\_extent} if \text{static\_padding\_stride} is \text{dynamic\_extent} or for any \( k \) in the range \( [\text{rank\_} - u - 1, \text{rank\_} - 1] \) \text{static\_extent}(k) is \text{dynamic\_extent},
(1.4.5)
— otherwise, the product of \text{static\_padding\_stride} and all values \text{static\_extent}(k) with \( k \) in the range \( [\text{rank\_} - u - 1, \text{rank\_} - 1] \);
(1.5)
— otherwise,
\( \text{submdspan\_mapping\_result} \{ \text{layout\_stride}::\text{mapping}(\text{sub\_ext, sub\_strides}), \text{offset} \}
24.7.3.7.7 submdspan function template

\[
\text{template<class ElementType, class Extents, class LayoutPolicy, class AccessorPolicy, class... SliceSpecifiers>}
\text{constexpr auto submdspan(}
\text{const mdspan<ElementType, Extents, LayoutPolicy, AccessorPolicy>& src,}
\text{SliceSpecifiers... slices) } \Rightarrow \text{see below;}
1
\text{Let } \text{index\_type} \text{ be typename } \text{Extents::index\_type}. \text{
2
Let } \text{sub\_map\_offset} \text{ be the result of } \text{submdspan\_mapping}(\text{src.mapping()}, \text{slices}...). \text{
[Note 1: This invocation of submdspan\_mapping selects a function call via overload resolution on a candidate set that includes the lookup set found by argument-dependent lookup (6.5.4). — end note]}
3
\text{Constraints:}
(3.1)
— sizeof...(slices) equals Extents::rank(), and
(3.2)
— the expression submdspan\_mapping(src.mapping(), slices...) is well-formed when treated as an unevaluated operand.
4
\text{Mandates:}
(4.1)
— decltype(submdspan\_mapping(src.mapping(), slices...)) is a specialization of submdspan\_mapping\_result.
(4.2)
— is\_same\_v<remove\_cvref\_t<decltype(sub\_map\_offset.mapping.extents())>, decltype(submdspan\_extents(src.mapping(), slices...))> is true.
(4.3)
— For each rank index \( k \) of src\.extents(), exactly one of the following is true:
(4.3.1)
— \( S_k \) models convertible\_to<index\_type>,
(4.3.2)
— \( S_k \) models index\_pair\_like<index\_type>,
(4.3.3)
— is\_convertible\_v<\text{S}_k>, \text{full\_extent\_t} \) is true, or

§ 24.7.3.7.7 ©ISO/IEC 1117
— $S_k$ is a specialization of strided_slice.

Preconditions:

For each rank index $k$ of src.extents(), all of the following are true:

— if $S_k$ is a specialization of strided_slice

— $s_k$.extent = 0, or

— $s_k$.stride > 0

— $0 \leq \text{first}_{<\text{index_type},k>(\text{slices})} \leq \text{last}_{<\text{index_type},k>(\text{src.extents}(), \text{slices})} \leq \text{src.extent}(k)$

— sub_map_offset.mapping.extents() == submdspan_extents(src.mapping(), slices...) is true; and

— for each integer pack $I$ which is a multidimensional index in sub_map_offset.mapping.extents(),

\[
\text{sub_map_offset.mapping}(I...) + \text{sub_map_offset.offset} = \\
\text{src.mapping()}(\text{src-indices(array}[I...], \text{slices})\ldots)
\]

is true.

[Note 2: These conditions ensure that the mapping returned by submdspan_mapping matches the algorithmically expected index-mapping given the slice specifications. — end note]

Effects: Equivalent to:

\[
\text{auto sub_map_result} = \text{submdspan_mapping(src.mapping(), slices...); return mdspan(src.accessor().offset(src.data(), sub_map_result.offset),}
\]

\[
\text{sub_map_result.mapping,}
\]

\[
\text{AccessorPolicy::offset_policy(src.accessor()));}
\]

[Example 1: Given a rank-3 mdspan grid3d representing a three-dimensional grid of regularly spaced points in a rectangular prism, the function zero_surface sets all elements on the surface of the 3-dimensional shape to zero. It does so by reusing a function zero_2d that takes a rank-2 mdspan.

// zero out all elements in an mdspan
template<class T, class E, class L, class A>
void zero_2d(mdspan<T, E, L, A> a) {
    static_assert(a.rank() == 2);
    for (int i = 0; i < a.extent(0); i++)
        for (int j = 0; j < a.extent(1); j++)
            a[i, j] = 0;
}

// zero out just the surface
template<class T, class E, class L, class A>
void zero_surface(mdspan<T, E, L, A> grid3d) {
    static_assert(grid3d.rank() == 3);
    zero_2d(submdspan(grid3d, 0, full_extent, full_extent));
    zero_2d(submdspan(grid3d, full_extent, 0, full_extent));
    zero_2d(submdspan(grid3d, full_extent, full_extent, 0));
    zero_2d(submdspan(grid3d, grid3d.extent(0) - 1, full_extent, full_extent));
    zero_2d(submdspan(grid3d, full_extent, grid3d.extent(1) - 1, full_extent));
    zero_2d(submdspan(grid3d, full_extent, full_extent, grid3d.extent(2) - 1));
}]

— end example]
25 Iterators library [iterators]

25.1 General [iterators.general]

1 This Clause describes components that C++ programs may use to perform iterations over containers (Clause 24), streams (31.7), stream buffers (31.6), and other ranges (Clause 26).

2 The following subclauses describe iterator requirements, and components for iterator primitives, predefined iterators, and stream iterators, as summarized in Table 87.

Table 87 — Iterators library summary [tab:iterators.summary]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.3</td>
<td>Iterator requirements &lt;iterator&gt;</td>
</tr>
<tr>
<td>25.4</td>
<td>Iterator primitives</td>
</tr>
<tr>
<td>25.5</td>
<td>Iterator adaptors</td>
</tr>
<tr>
<td>25.6</td>
<td>Stream iterators</td>
</tr>
<tr>
<td>25.7</td>
<td>Range access</td>
</tr>
</tbody>
</table>

25.2 Header <iterator> synopsis [iterator.synopsis]

```cpp
#include <compare> // see 17.11.1
#include <concepts> // see 18.3

namespace std {
    template<class T> using with_reference = T&; // exposition only
    template<class T> concept can_reference = requires { typename with_reference<T>; };
    template<class T> concept dereferenceable = requires(T& t) {
        { *t } -> can-reference; // not required to be equality-preserving
    };

    // 25.3.2, associated types
    // 25.3.2.1, incrementable traits
    template<class> struct incrementable_traits; // freestanding
    template<class T>
        using iter_difference_t = see below; // freestanding

    // 25.3.2.2, indirectly readable traits
    template<class> struct indirectly_readable_traits; // freestanding
    template<class T>
        using iter_value_t = see below; // freestanding

    // 25.3.2.3, iterator traits
    template<class I> struct iterator_traits;
    template<class T> requires is_object_v<T> struct iterator_traits<T*>;

    template<dereferenceable T>
        using iter_reference_t = decltype(*declval<T&>()) ; // freestanding

    namespace ranges {
        // 25.3.3, customization point objects
        inline namespace unspecified {
            // 25.3.3.1, ranges::iter_move
            inline constexpr unspecified iter_move = unspecified;
        }
    }
}
```

§ 25.2 © ISO/IEC 1119
// 25.3.3.2, ranges::iter_swap
inline constexpr unspecified iter_swap = unspecified; // freestanding
}

template<dereferenceable T>
requires requires(T& t) {
   { ranges::iter_move(t) } -> can-reference;
}
using iter_rvalue_reference_t // freestanding
   = decltype(ranges::iter_move(declval<T&>()));

// 25.3.4, iterator concepts
// 25.3.4.2, concept indirectly_readable
template<class In>
concept indirectly_readable = see below; // freestanding

template<indirectly_readable T>
using indirect_value_t = see below; // exposition only

using iter_common_reference_t = // freestanding
   common_reference_t<iter_reference_t<T>, indirect_value_t<T>>;

// 25.3.4.3, concept indirectly_writable
template<class Out, class T>
concept indirectly_writable = see below; // freestanding

// 25.3.4.4, concept weakly_incrementable
template<class I>
concept weakly_incrementable = see below; // freestanding

// 25.3.4.5, concept incrementable
template<class I>
concept incrementable = see below; // freestanding

// 25.3.4.6, concept input_or_output_iterator
template<class I>
concept input_or_output_iterator = see below; // freestanding

// 25.3.4.7, concept sentinel_for
template<class S, class I>
concept sentinel_for = see below; // freestanding

// 25.3.4.8, concept sized_sentinel_for
template<class S, class I>
constexpr bool disable_sized_sentinel_for = false; // freestanding

template<class S, class I>
concept sized_sentinel_for = see below; // freestanding

// 25.3.4.9, concept input_iterator
template<class I>
concept input_iterator = see below; // freestanding

// 25.3.4.10, concept output_iterator
template<class I, class T>
concept output_iterator = see below; // freestanding

// 25.3.4.11, concept forward_iterator
template<class I>
concept forward_iterator = see below; // freestanding

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// 25.3.4.12, concept bidirectional_iterator
template<class I>
concept bidirectional_iterator = see below;  // freestanding

// 25.3.4.13, concept random_access_iterator
template<class I>
concept random_access_iterator = see below;  // freestanding

// 25.3.4.14, concept contiguous_iterator
template<class I>
concept contiguous_iterator = see below;  // freestanding

// 25.3.6, indirect callable requirements
// 25.3.6.3, indirect callables
template<class F, class I>
concept indirectly_unary_invocable = see below;  // freestanding

template<class F, class I>
concept indirectly_regular_unary_invocable = see below;  // freestanding

template<class F, class I>
concept indirect_unary_predicate = see below;  // freestanding

template<class F, class I1, class I2>
concept indirect_binary_predicate = see below;  // freestanding

template<class F, class I1, class I2 = I1>
concept indirect_equivalence_relation = see below;  // freestanding

template<class F, class I1, class I2 = I1>
concept indirect_strict_weak_order = see below;  // freestanding

template<class F, class... Is>
requires (indirectly_readable<Is> && ...) && invocable<F, iter_reference_t<Is>...>
using indirect_result_t = invoke_result_t<F, iter_reference_t<Is>...>;  // freestanding

// 25.3.6.4, projected
template<indirectly_readable I, indirectly_regular_unary_invocable<I> Proj>
struct projected;  // freestanding

template<weakly_incrementable I, class Proj>
struct incrementable_traits<projected<I, Proj>>;  // freestanding

template<indirectly_readable I, indirectly_regular_unary_invocable<I> Proj>
using projected_value_t = remove_cvref_t<invoke_result_t<Proj&, iter_value_t<I>&>>;  // freestanding

// 25.3.7, common algorithm requirements
// 25.3.7.2, concept indirectly_movable
template<class In, class Out>
concept indirectly_movable = see below;  // freestanding

template<class In, class Out>
concept indirectly_movable_storable = see below;  // freestanding

// 25.3.7.3, concept indirectly_copyable
template<class In, class Out>
concept indirectly_copyable = see below;  // freestanding

template<class In, class Out>
concept indirectly_copyable_storable = see below;  // freestanding
// 25.3.7.4, concept indirectly_swappable
template<class I1, class I2 = I1>
concept indirectly_swappable = see below; // freestanding

// 25.3.7.5, concept indirectly_comparable
template<class I1, class I2 = I1, class R, class P1 = identity, class P2 = identity>
concept indirectly_comparable = see below; // freestanding

// 25.3.7.6, concept permutable
template<class I>
concept permutable = see below; // freestanding

// 25.3.7.7, concept mergeable
template<class I1, class I2, class Out, class R = ranges::less, class P1 = identity, class P2 = identity>
concept mergeable = see below; // freestanding

// 25.3.7.8, concept sortable
template<class I, class R = ranges::less, class P = identity>
concept sortable = see below; // freestanding

// 25.4, primitives
// 25.4.2, iterator tags
struct input_iterator_tag { }; // freestanding
struct output_iterator_tag { }; // freestanding
struct forward_iterator_tag: public input_iterator_tag { }; // freestanding
struct bidirectional_iterator_tag: public forward_iterator_tag { }; // freestanding
struct random_access_iterator_tag: public bidirectional_iterator_tag { }; // freestanding
struct contiguous_iterator_tag: public random_access_iterator_tag { }; // freestanding

// 25.4.3, iterator operations
template<class InputIterator, class Distance>
constexpr void advance(InputIterator& i, Distance n); // freestanding
template<class InputIterator>
constexpr typename iterator_traits<InputIterator>::difference_type distance(InputIterator first, InputIterator last); // freestanding

template<class InputIterator>
constexpr InputIterator next(InputIterator x,
    typename iterator_traits<InputIterator>::difference_type n = 1); // freestanding

template<class BidirectionalIterator>
constexpr BidirectionalIterator prev(BidirectionalIterator x,
    typename iterator_traits<BidirectionalIterator>::difference_type n = 1); // freestanding

// 25.4.4, range iterator operations
namespace ranges { // freestanding
    // 25.4.4.2, ranges::advance
    template<input_or_output_iterator I>
    constexpr void advance(I& i, iter_difference_t<I> n); // freestanding

    template<input_or_output_iterator I, sentinel_for<I> S>
    constexpr void advance(I& i, S bound); // freestanding

    template<input_or_output_iterator I, sentinel_for<I> S>
    constexpr iter_difference_t<I> advance(I& i, iter_difference_t<I> n, S bound); // freestanding

    // 25.4.4.3, ranges::distance
    template<class I, sentinel_for<I> S>
    requires (!sized_sentinel_for<S, I>)
    constexpr iter_difference_t<I> distance(I first, S last); // freestanding

    template<class I, sized_sentinel_for<decay_t<I>> S>
    constexpr iter_difference_t<decay_t<I>> distance(I& first, S last); // freestanding

    template<class I, sized_sentinel_for<decay_t<I>> S>
    constexpr iter_difference_t<decay_t<I>> distance(I first, S last); // freestanding

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template<range R>
    constexpr range_difference_t<R> distance(R&& r); // freestanding

// 25.4.4.4, ranges::next
template<input_or_output_iterator I>
    constexpr I next(I x); // freestanding
    
    template<input_or_output_iterator I>
        constexpr I next(I x, iter_difference_t<I> n); // freestanding
    template<input_or_output_iterator I, sentinel_for<I> S>
        constexpr I next(I x, S bound); // freestanding
    template<input_or_output_iterator I, sentinel_for<I> S>
        constexpr I next(I x, iter_difference_t<I> n, S bound); // freestanding

// 25.4.4.5, ranges::prev
    template<bidirectional_iterator I>
        constexpr I prev(I x); // freestanding
    template<bidirectional_iterator I>
        constexpr I prev(I x, iter_difference_t<I> n); // freestanding
    template<bidirectional_iterator I>
        constexpr I prev(I x, iter_difference_t<I> n, I bound); // freestanding

// 25.5, predefined iterators and sentinels
// 25.5.1, reverse iterators
    template<class Iterator> class reverse_iterator; // freestanding

    template<class Iterator1, class Iterator2>
        constexpr bool operator==(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding
    template<class Iterator1, class Iterator2>
        constexpr bool operator!=(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding
    template<class Iterator1, class Iterator2>
        constexpr bool operator<(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding
    template<class Iterator1, class Iterator2>
        constexpr bool operator>(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding
    template<class Iterator1, class Iterator2>
        constexpr bool operator<=(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding
    template<class Iterator1, class Iterator2>
        constexpr bool operator>=(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding
    template<class Iterator1, three_way_comparable_with<Iterator1> Iterator2>
        constexpr compare_three_way_result_t<Iterator1, Iterator2> operator<=>(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y); // freestanding

    template<class Iterator1, class Iterator2>
        constexpr auto operator-(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y) -> decltype(y.base() - x.base()); // freestanding
    template<class Iterator>
        constexpr reverse_iterator<Iterator> operator+(iter_difference_t<Iterator> n, const reverse_iterator<Iterator>& x); // freestanding

§ 25.2
template<class Iterator>
constexpr reverse_iterator<Iterator> make_reverse_iterator(Iterator i); // freestanding

template<class Iterator1, class Iterator2>
    requires (!sized_sentinel_for<Iterator1, Iterator2>)
    constexpr bool disable_sized_sentinel_for<reverse_iterator<Iterator1>, reverse_iterator<Iterator2>> = true;

// 25.5.2, insert iterators
template<class Container> class back_insert_iterator; // freestanding
template<class Container>
    constexpr back_insert_iterator<Container> back_inserter(Container& x); // freestanding

// 25.5.3, constant iterators and sentinels
// 25.5.3.2, alias templates
template<indirectly_readable I>
using iter_const_reference_t = see below; // freestanding
template<class Iterator>
    concept constant_iterator = see below; // exposition only
template<input_iterator I>
using const_iterator = see below; // freestanding
template<semiregular S>
using const_sentinel = see below; // freestanding

// 25.5.3.3, class template basic_const_iterator
template<input_iterator Iterator>
    class basic_const_iterator; // freestanding
template<class T, common_with<T> U>
    requires input_iterator<common_type_t<T, U>>
    struct common_type<basic_const_iterator<T>, U> { // freestanding
        using type = basic_const_iterator<common_type_t<T, U>>;
    };
template<class T, common_with<T> U>
    requires input_iterator<common_type_t<T, U>>
    struct common_type<U, basic_const_iterator<T>> { // freestanding
        using type = basic_const_iterator<common_type_t<T, U>>;
    };
template<class T, common_with<T> U>
    requires input_iterator<common_type_t<T, U>>
    struct common_type<basic_const_iterator<T>, basic_const_iterator<U>> { // freestanding
        using type = basic_const_iterator<common_type_t<T, U>>;
    };

template<input_iterator I>
    constexpr const_iterator<I> make_const_iterator(I it) { return it; } // freestanding

template<semiregular S>
    constexpr const_sentinel<S> make_const_sentinel(S s) { return s; } // freestanding

// 25.5.4, move iterators and sentinels
template<class Iterator> class move_iterator; // freestanding
template<class Iterator1, class Iterator2>
constexpr bool operator==(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);  // freestanding

template<class Iterator1, class Iterator2>
constexpr bool operator<(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);  // freestanding

template<class Iterator1, class Iterator2>
constexpr bool operator>(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);  // freestanding

template<class Iterator1, class Iterator2>
constexpr bool operator<=(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);  // freestanding

template<class Iterator1, class Iterator2>
constexpr bool operator>=(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);  // freestanding

template<class Iterator1, three_way_comparable_with<Iterator1> Iterator2>
constexpr compare_three_way_result_t<Iterator1, Iterator2>
operator<=>(const move_iterator<Iterator1>& x, // freestanding
            const move_iterator<Iterator2>& y);

template<class Iterator1, class Iterator2>
constexpr auto operator-(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y)
-> decltype(x.base() - y.base());  // freestanding

template<class Iterator1, class Iterator2>
constexpr move_iterator<Iterator1>
operator+(iter_difference_t<Iterator1> n, const move_iterator<Iterator1>& x);  // freestanding

template<class Iterator>
constexpr move_iterator<Iterator>
operator+(iter_difference_t<Iterator> n, const move_iterator<Iterator>& x);

// 25.2, common iterators

// 25.5.5, common iterators
template<input_or_output_iterator I, sentinel_for<I> S>
requires (!same_as<I, S> && copyable<I>)
class common_iterator;  // freestanding

template<class I, class S>
struct incrementable_traits<common_iterator<I, S>>;  // freestanding

template<input_iterator I, class S>
requires see below
struct iterator_traits<counted_iterator<I, S>>;  // freestanding

// 25.5.6, default sentinel
struct default_sentinel_t;
inline constexpr default_sentinel_t default_sentinel{};  // freestanding

// 25.5.7, counted iterators

// 25.5.8, unreachable sentinel
struct unreachable_sentinel_t;
inline constexpr unreachable_sentinel_t unreachable_sentinel{};  // freestanding

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// 25.6, stream iterators

template<class T, class charT = char, class traits = char_traits<charT>,
         class Distance = ptrdiff_t>
class istream_iterator;

template<class T, class charT, class traits, class Distance>
bool operator==(const istream_iterator<T,charT,traits,Distance>& x,
               const istream_iterator<T,charT,traits,Distance>& y);

template<class T, class charT = char, class traits = char_traits<charT>>
class ostream_iterator;

template<class charT, class traits = char_traits<charT>>
class istreambuf_iterator;

template<class charT, class traits>
bool operator==(const istreambuf_iterator<charT,traits>& a,
               const istreambuf_iterator<charT,traits>& b);

template<class charT, class traits = char_traits<charT>>
class ostreambuf_iterator;

// 25.7, range access

template<class C> constexpr auto begin(C& c) -> decltype(c.begin());   // freestanding

template<class C> constexpr auto begin(const C& c) -> decltype(c.begin()); // freestanding

template<class C> constexpr auto end(C& c) -> decltype(c.end());         // freestanding

template<class C> constexpr auto end(const C& c) -> decltype(c.end());     // freestanding

template<class T, size_t N> constexpr T* begin(T (&array)[N]) noexcept;    // freestanding

template<class T, size_t N> constexpr T* end(T (&array)[N]) noexcept;       // freestanding

template<class C> constexpr auto cbegin(const C& c) noexcept(noexcept(std::begin(c))) -> decltype(std::begin(c));   // freestanding

template<class C> constexpr auto cend(const C& c) noexcept(noexcept(std::end(c))) -> decltype(std::end(c));     // freestanding

template<class C> constexpr auto rbegin(C& c) -> decltype(c.rbegin());     // freestanding

template<class C> constexpr auto rbegin(const C& c) -> decltype(c.rbegin()); // freestanding

template<class C> constexpr auto rend(C& c) -> decltype(c.rend());          // freestanding

template<class C> constexpr auto rend(const C& c) -> decltype(c.rend());     // freestanding

template<class T, size_t N> constexpr reverse_iterator<T*> rbegin(T (&array)[N]) noexcept;    // freestanding

template<class T, size_t N> constexpr reverse_iterator<T*> rend(T (&array)[N]);       // freestanding

template<class E> constexpr reverse_iterator<const E*>
rbegin(initializer_list<E> il);          // freestanding

template<class E> constexpr reverse_iterator<const E*>
rend(initializer_list<E> il);            // freestanding

template<class C> constexpr auto cbegin(const C& c) noexcept(std::begin(c));     // freestanding

template<class C> constexpr auto cend(const C& c) noexcept(std::end(c));         // freestanding

template<class C> constexpr size_t size(const C& c) noexcept;                   // freestanding

template<class T, size_t N> constexpr size_t size(const T (&array)[N]) noexcept;  // freestanding

template<class C> [[nodiscard]] constexpr auto empty(const C& c) -> decltype(c.empty());   // freestanding

template<class T, size_t N> [[nodiscard]] constexpr bool empty(const T (&array)[N]) noexcept; // freestanding

template<class E> [[nodiscard]] constexpr bool empty(initializer_list<E> il) noexcept;    // freestanding

§ 25.2
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1126
template<class C> constexpr auto data(C& c) -> decltype(c.data()); // freestanding
template<class C> constexpr auto data(const C& c) -> decltype(c.data()); // freestanding
template<class T, size_t N> constexpr T* data(T (&array)[N]) noexcept; // freestanding
template<class E> constexpr const E* data(initializer_list<E> il) noexcept; // freestanding

25.3 Iterator requirements
25.3.1 General

Iterators are a generalization of pointers that allow a C++ program to work with different data structures (for example, containers and ranges) in a uniform manner. To be able to construct template algorithms that work correctly and efficiently on different types of data structures, the library formalizes not just the interfaces but also the semantics and complexity assumptions of iterators. An input iterator \( i \) supports the expression \(*i\), resulting in a value of some object type \( T \), called the value type of the iterator. An output iterator \( i \) has a non-empty set of types that are indirectly writable to the iterator; for each such type \( T \), the expression \(*i = o\) is valid where \( o \) is a value of type \( T \). For every iterator type \( X \), there is a corresponding signed integer-like type (25.3.4.4) called the difference type of the iterator.

Since iterators are an abstraction of pointers, their semantics are a generalization of most of the semantics of pointers in C++. This ensures that every function template that takes iterators works as well with regular pointers. This document defines six categories of iterators, according to the operations defined on them: input iterators, output iterators, forward iterators, bidirectional iterators, random access iterators, and contiguous iterators, as shown in Table 88.

Table 88 — Relations among iterator categories

<table>
<thead>
<tr>
<th>Contiguous</th>
<th>Random Access</th>
<th>Bidirectional</th>
<th>Forward</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
</table>

The six categories of iterators correspond to the iterator concepts

1. input_iterator (25.3.4.9),
2. output_iterator (25.3.4.10),
3. forward_iterator (25.3.4.11),
4. bidirectional_iterator (25.3.4.12),
5. random_access_iterator (25.3.4.13), and
6. contiguous_iterator (25.3.4.14),

respectively. The generic term iterator refers to any type that models the input_or_output_iterator concept (25.3.4.6).

Forward iterators meet all the requirements of input iterators and can be used whenever an input iterator is specified; Bidirectional iterators also meet all the requirements of forward iterators and can be used whenever a forward iterator is specified; Random access iterators also meet all the requirements of bidirectional iterators and can be used whenever a bidirectional iterator is specified; Contiguous iterators also meet all the requirements of random access iterators and can be used whenever a random access iterator is specified.

Iterators that further meet the requirements of output iterators are called mutable iterators. Nonmutable iterators are referred to as constant iterators.

In addition to the requirements in this subclause, the nested typedef-names specified in 25.3.2.3 shall be provided for the iterator type.

[Note 1: Either the iterator type must provide the typedef-names directly (in which case iterator_traits pick them up automatically), or an iterator_traits specialization must provide them. — end note]

Just as a regular pointer to an array guarantees that there is a pointer value pointing past the last element of the array, so for any iterator type there is an iterator value that points past the last element of a corresponding sequence. Such a value is called a past-the-end value. Values of an iterator \( i \) for which the expression \(*i\) is defined are called dereferenceable. The library never assumes that past-the-end values are dereferenceable. Iterators can also have singular values that are not associated with any sequence. Results of most expressions are undefined for singular values; the only exceptions are destroying an iterator that holds a singular value,
the assignment of a non-singular value to an iterator that holds a singular value, and, for iterators that meet the Cpp17DefaultConstructible requirements, using a value-initialized iterator as the source of a copy or move operation.

[Note 2: This guarantee is not offered for default-initialization, although the distinction only matters for types with trivial default constructors such as pointers or aggregates holding pointers. — end note]

In these cases the singular value is overwritten the same way as any other value. Dereferenceable values are always non-singular.

Most of the library’s algorithmic templates that operate on data structures have interfaces that use ranges. A range is an iterator and a sentinel that designate the beginning and end of the computation, or an iterator and a count that designate the beginning and the number of elements to which the computation is to be applied.\[207\]

An iterator and a sentinel denoting a range are comparable. A range \([i, s)\) is empty if \(i == s\); otherwise, \([i, s)\) refers to the elements in the data structure starting with the element pointed to by \(i\) and up to but not including the element, if any, pointed to by the first iterator \(j\) such that \(j == s\).

A sentinel \(s\) is called reachable from an iterator \(i\) if and only if there is a finite sequence of applications of the expression \(++i\) that makes \(i == s\). If \(s\) is reachable from \(i\), \([i, s)\) denotes a valid range.

A counted range \(i + [0, n)\) is empty if \(n == 0\); otherwise, \(i + [0, n)\) refers to the \(n\) elements in the data structure starting with the element pointed to by \(i\) and up to but not including the element, if any, pointed to by the result of \(n\) applications of \(++i\). A counted range \(i + [0, n)\) is valid if and only if \(n == 0\); or \(n\) is positive, \(i\) is dereferenceable, and \(++i + [0, --n)\) is valid.

The result of the application of library functions to invalid ranges is undefined.

All the categories of iterators require only those functions that are realizable for a given category in constant time (amortized). Therefore, requirement tables and concept definitions for the iterators do not specify complexity.

Destruction of an iterator may invalidate pointers and references previously obtained from that iterator if its type does not meet the Cpp17ForwardIterator requirements and does not model forward_iterator.

An invalid iterator is an iterator that may be singular.\[208\]

Iterators meet the constexpr iterator requirements if all operations provided to meet iterator category requirements are constexpr functions.

[Note 3: For example, the types “pointer to int” and reverse_iterator<int*> meet the constexpr iterator requirements. — end note]

25.3.2 Associated types

25.3.2.1 Incrementable traits

To implement algorithms only in terms of incrementable types, it is often necessary to determine the difference type that corresponds to a particular incrementable type. Accordingly, it is required that if \(\text{WI}\) is the name of a type that models the weakly_incrementable concept (25.3.4.4), the type

\[
\text{iter_difference_t}(<\text{WI}>)
\]

be defined as the incrementable type’s difference type.

```
namespace std {
    template<class> struct incrementable_traits { };

    template<class T>
    requires is_object_v<T>
    struct incrementable_traits<T> {
        using difference_type = ptrdiff_t;
    };
```

\[207\] The sentinel denoting the end of a range can have the same type as the iterator denoting the beginning of the range, or a different type.

\[208\] This definition applies to pointers, since pointers are iterators. The effect of dereferencing an iterator that has been invalidated is undefined.
template<class I>
struct incrementable_traits<const I>
    : incrementable_traits<I> { }
;

template<class T>
requires requires { typename T::difference_type; }
struct incrementable_traits<T> { 
    using difference_type = typename T::difference_type;
};

template<class T>
requires (!requires { typename T::difference_type; } &&
    requires(const T& a, const T& b) { { a - b } -> integral; })
struct incrementable_traits<T> { 
    using difference_type = make_signed_t<decltype(declval<T>() - declval<T>())>;
};

template<class T>
using iter_difference_t = see below
;

Let \( R_I \) be `remove_cvref_t<I>`. The type `iter_difference_t<I>` denotes

(2.1) — `incrementable_traits<\( R_I \)>::difference_type` if `iterator_traits<\( R_I \)>` names a specialization generated from the primary template, and

(2.2) — `iterator_traits<\( R_I \)>::difference_type` otherwise.

Users may specialize `incrementable_traits` on program-defined types.

**25.3.2.2 Indirectly readable traits**

To implement algorithms only in terms of indirectly readable types, it is often necessary to determine the value type that corresponds to a particular indirectly readable type. Accordingly, it is required that if \( R \) is the name of a type that models the `indirectly_readable` concept (25.3.4.2), the type

\[
\text{iter_value_t}<R>
\]

be defined as the indirectly readable type's value type.

`cond-value-type` template<class> struct cond-value-type { }; // exposition only

`cond-value-type` template<class T>
    requires is_object_v<T>
struct cond-value-type<T> { 
    using value_type = remove_cv_t<T>;
};

`has-member-value-type` template<class T>
    concept has-member-value-type = requires { typename T::value_type; }; // exposition only

`has-member-element-type` template<class T>
    concept has-member-element-type = requires { typename T::element_type; }; // exposition only

`indirectly_readable_traits` template<class> struct indirectly_readable_traits { };

`indirectly_readable_traits` template<class T>
struct indirectly_readable_traits<T*> 
    : cond-value-type<T> { }
;

`indirectly_readable_traits` template<class I>
requires is_array_v<I>
struct indirectly_readable_traits<I> { 
    using value_type = remove_cv_t<remove_extent_t<I>>;
};

`indirectly_readable_traits` template<class I>
struct indirectly_readable_traits<const I> 
    : indirectly_readable_traits<I> { };
template<has-member-value-type T>
 struct indirectly_readable_traits<T>
  : cond-value-type<typename T::value_type> { };  

template<has-member-element-type T>
 struct indirectly_readable_traits<T>
  : cond-value-type<typename T::element_type> { };  

template<has-member-value-type T>
 requires has-member-element-type<T>
 struct indirectly_readable_traits<T> { };  

template<has-member-value-type T>
 requires has-member-element-type<T> &&
 same_as<remove_cv_t<typename T::element_type>, remove_cv_t<typename T::value_type>>
 struct indirectly_readable_traits<T>
  : cond-value-type<typename T::value_type> { };  

template<class T> using iter_value_t = see below;  

Let $R_I$ be remove_cvref_t$I$. The type iter_value_t$I$ denotes

- indirectly_readable_traits$<R_I>::value_type$ if iterator_traits$<R_I>$ names a specialization
generated from the primary template, and

- iterator_traits$<R_I>::value_type$ otherwise.

Class template indirectly_readable_traits may be specialized on program-defined types.

[Note 1: Some legacy output iterators define a nested type named value_type that is an alias for void. These types
are not indirectly_readable and have no associated value types. —end note]  

[Note 2: Smart pointers like shared_ptr<int> are indirectly_readable and have an associated value type, but a
smart pointer like shared_ptr<void> is not indirectly_readable and has no associated value type. —end note]

### 25.3.2.3 Iterator traits  

To implement algorithms only in terms of iterators, it is sometimes necessary to determine the iterator
category that corresponds to a particular iterator type. Accordingly, it is required that if I is the type of an
iterator, the type

```cpp
template<class I>  
concept cpp17-iterator = 
 requires(I i) {
  { *i } -> can-reference;  
  { ++i } -> same_as<I&>;  
  { *i++ } -> can-reference;  
} & & copyable<I>;  
```  

may be defined as void.

The definitions in this subclause make use of the following exposition-only concepts:
template<class I>
concept cpp17-input-iterator =
cpp17-iterator<I> && equality_comparable<I> && requires(I i) {
  typename incrementable_traits<I>::difference_type;
  typename indirectly_readable_traits<I>::value_type;
  typename common_reference_t<iter_reference_t<I>&&,
    typename indirectly_readable_traits<I>::value_type&>;
  typename common_reference_t<decltype(*i++)&&,
    typename indirectly_readable_traits<I>::value_type&>;
  requires signed_integral<typename incrementable_traits<I>::difference_type>;
};

template<class I>
concept cpp17-forward-iterator =
cpp17-input-iterator<I> && constructible_from<I> &&
is_reference_v<iter_reference_t<I>> &&
same_as<remove_cvref_t<iter_reference_t<I>>,
  typename indirectly_readable_traits<I>::value_type> &&
requires(I i) {
  i++ } -> convertible_to<const I&>;
  {*i++ } -> same_as<iter_reference_t<I>>;
};

template<class I>
concept cpp17-bidirectional-iterator =
cpp17-forward-iterator<I> && requires(I i) {
  { --i } -> same_as<I&>;
  { i-- } -> convertible_to<const I&>;
  {*i-- } -> same_as<iter_reference_t<I>>;
};

template<class I>
concept cpp17-random-access-iterator =
cpp17-bidirectional-iterator<I> && totally_ordered<I> &&
requires(I i, typename incrementable_traits<I>::difference_type n) {
  { i += n } -> same_as<I&>;
  { i -= n } -> same_as<I&>;
  { i + n } -> same_as<I>;
  { i - n } -> same_as<I>;
  { i - i } -> same_as<decltype(n)>;
  { i[n] } -> convertible_to<iter_reference_t<I>>;
};

3 The members of a specialization iterator_traits<I> generated from the iterator_traits primary template are computed as follows:

(3.1) If I has valid (13.10.3) member types difference_type, value_type, reference, and iterator_category, then iterator_traits<I> has the following publicly accessible members:

using iterator_category = typename I::iterator_category;
using value_type = typename I::value_type;
using difference_type = typename I::difference_type;
using pointer = see below;
using reference = see below;

If the qualified-id I::pointer is valid and denotes a type, then iterator_traits<I>::pointer names that type; otherwise, it names void.

(3.2) Otherwise, if I satisfies the exposition-only concept cpp17-input-iterator, iterator_traits<I> has the following publicly accessible members:

using iterator_category = see below;
using value_type = typename indirectly_readable_traits<I>::value_type;
using difference_type = typename incrementable_traits<I>::difference_type;
using pointer = see below;
using reference = see below;
If the qualified-id `I::pointer` is valid and denotes a type, `pointer` names that type. Otherwise, `pointer` names void.

If the qualified-id `I::reference` is valid and denotes a type, `reference` names that type. Otherwise, `reference` names `iter_reference_t<I>`.

If the qualified-id `I::iterator_category` is valid and denotes a type, `iterator_category` names that type. Otherwise, `iterator_category` names:

- `random_access_iterator_tag` if `I` satisfies `cpp17-random-access-iterator`, or otherwise
- `bidirectional_iterator_tag` if `I` satisfies `cpp17-bidirectional-iterator`, or otherwise
- `forward_iterator_tag` if `I` satisfies `cpp17-forward-iterator`, or otherwise
- `input_iterator_tag`.

Otherwise, if `I` satisfies the exposition-only concept `cpp17-iterator`, then `iterator_traits<I>` has the following publicly accessible members:

```cpp
using iterator_category = output_iterator_tag;
using value_type = void;
using difference_type = see below;
using pointer = void;
using reference = void;
```

If the qualified-id `incrementable_traits<I>::difference_type` is valid and denotes a type, then `difference_type` names that type; otherwise, it names void.

Otherwise, `iterator_traits<I>` has no members by any of the above names.

Explicit or partial specializations of `iterator_traits` may have a member type `iterator_concept` that is used to indicate conformance to the iterator concepts (25.3.4).

[Example 1: To indicate conformance to the `input_iterator` concept but a lack of conformance to the `Cpp17InputIterator` requirements (25.3.5.3), an `iterator_traits` specialization might have `iterator_concept` denote `input_iterator_tag` but not define `iterator_category`. — end example]

`iterator_traits` is specialized for pointers as

```cpp
namespace std {
  template<class T>
  requires is_object_v<T>
  struct iterator_traits<T*> {
    using iterator_concept = contiguous_iterator_tag;
    using iterator_category = random_access_iterator_tag;
    using value_type = remove_cv_t<T>;
    using difference_type = ptrdiff_t;
    using pointer = T*;
    using reference = T&;
  };
}
```

[Example 2: To implement a generic `reverse` function, a C++ program can do the following:

```cpp
template<class BI>
void reverse(BI first, BI last) {
  typename iterator_traits<BI>::difference_type n =
    distance(first, last);
  --n;
  while(n > 0) {
    typename iterator_traits<BI>::value_type tmp = *first;
    *first++ = *--last;
    *last = tmp;
    n -= 2;
  }
}
```
— end example]
(1.1) — `iter_move(E)`, if `E` has class or enumeration type and `iter_move(E)` is a well-formed expression when treated as an unevaluated operand, where the meaning of `iter_move` is established as-if by performing argument-dependent lookup only (6.5.4).

(1.2) — Otherwise, if the expression `*E` is well-formed:

   (1.2.1) — if `*E` is an lvalue, `std::move(*E)`;

   (1.2.2) — otherwise, `*E`.

(1.3) — Otherwise, `ranges::iter_move(E)` is ill-formed.

[Note 1: This case can result in substitution failure when `ranges::iter_move(E)` appears in the immediate context of a template instantiation. — end note]

2 If `ranges::iter_move(E)` is not equal to `*E`, the program is ill-formed, no diagnostic required.

25.3.3.2 `ranges::iter_swap` 

1 The name `ranges::iter_swap` denotes a customization point object (16.3.3.5) that exchanges the values (18.4.9) denoted by its arguments.

2 Let `iter-exchange-move` be the exposition-only function template:

```cpp
template<class X, class Y>
constexpr iter_value_t<X> iter-exchange-move(X&& x, Y&& y)
    noexcept(noexcept(iter_value_t<X>(iter_move(x))) &&
              noexcept(*x = iter_move(y)));
```

3 Effects: Equivalent to:

   ```cpp
   iter_value_t<X> old_value(iter_move(x));
   *x = iter_move(y);
   return old_value;
   ```

4 The expression `ranges::iter_swap(E1, E2)` for subexpressions `E1` and `E2` is expression-equivalent to:

   (4.1) — `(void)iter_swap(E1, E2)`, if either `E1` or `E2` has class or enumeration type and `iter_swap(E1, E2)` is a well-formed expression with overload resolution performed in a context that includes the declaration

   ```cpp
   template<class I1, class I2>
   void iter_swap(I1, I2) = delete;
   ```

   and does not include a declaration of `ranges::iter_swap`. If the function selected by overload resolution does not exchange the values denoted by `E1` and `E2`, the program is ill-formed, no diagnostic required.

   [Note 1: This precludes calling unconstrained `std::iter_swap`. When the deleted overload is viable, program-defined overloads need to be more specialized (13.7.7.3) to be selected. — end note]

   (4.2) — Otherwise, if the types of `E1` and `E2` each model `indirectly_readable`, and if the reference types of `E1` and `E2` model `swappable_with` (18.4.9), then `ranges::swap(*E1, *E2)`.

   (4.3) — Otherwise, if the types `T1` and `T2` of `E1` and `E2` model `indirectly_movable_storable<T1, T2>` and `indirectly_movable_storable<T2, T1>`, then `(void)(*E1 = iter-exchange-move(E2, E1))`, except that `E1` is evaluated only once.

   (4.4) — Otherwise, `ranges::iter_swap(E1, E2)` is ill-formed.

   [Note 2: This case can result in substitution failure when `ranges::iter_swap(E1, E2)` appears in the immediate context of a template instantiation. — end note]

25.3.4 Iterator concepts 

25.3.4.1 General 

1 For a type `I`, let `ITER_TRAITS(I)` denote the type `I` if `iterator_traits<I>` names a specialization generated from the primary template. Otherwise, `ITER_TRAITS(I)` denotes `iterator_traits<I>`.

(1.1) — If the qualified-id `ITER_TRAITS(I)::iterator_concept` is valid and names a type, then `ITER_CONCEPT(I)` denotes that type.
— Otherwise, if the qualified-id `ITER_TRAITS(I)::iterator_category` is valid and names a type, then `ITER_CONCEPT(I)` denotes that type.

— Otherwise, if `iterator_traits<I>` names a specialization generated from the primary template, then `ITER_CONCEPT(I)` denotes `random_access_iterator_tag`.

— Otherwise, `ITER_CONCEPT(I)` does not denote a type.

2 [Note 1: `ITER_TRAITS` enables independent syntactic determination of an iterator’s category and concept. — end note]

[Example 1:

```cpp
struct I {
    using value_type = int;
    using difference_type = int;

    int operator*() const;
    I& operator++();
    I operator++(int);
    I& operator--();
    I operator--(int);

    bool operator==(I) const;
};
```

`iterator_traits<I>::iterator_category` denotes `input_iterator_tag`, and `ITER_CONCEPT(I)` denotes `random_access_iterator_tag`. — end example]

25.3.4.2 Concept indirectly_readable

Types that are indirectly readable by applying `operator*` model the indirectly_readable concept, including pointers, smart pointers, and iterators.

```cpp
template<class In>
concept indirectly-readable-impl =
    // exposition only
    requires(const In in) {
        typename iter_value_t<In>;
        typename iter_reference_t<In>;
        typename iter_rvalue_reference_t<In>;
        { *in } -> same_as<iter_reference_t<In>>;
        { ranges::iter_move(in) } -> same_as<iter_rvalue_reference_t<In>>;
    } &&
    common_reference_with<iter_reference_t<In>&&, iter_value_t<In>&> &&
    common_reference_with<iter_reference_t<In>&&, iter_rvalue_reference_t<In>&>&
    common_reference_with<iter_rvalue_reference_t<In>&&, const iter_value_t<In>&>;

template<class In>
concept indirectly_readable =
    indirectly-readable-impl<remove_cvref_t<In>>;
```

2 Given a value `i` of type `I`, `I` models indirectly_readable only if the expression `*i` is equality-preserving.

25.3.4.3 Concept indirectly_writable

The indirectly_writable concept specifies the requirements for writing a value into an iterator’s referenced object.

```cpp
template<class Out, class T>
concept indirectly_writable =
    requires(Out&& o, T&& t) {
        *std::forward<Out>(o) = std::forward<T>(t); // not required to be equality-preserving
        const_cast<const iter_reference_t<Out>&&>(*o) =
            std::forward<T>(t); // not required to be equality-preserving
        const_cast<const iter_reference_t<Out>&&>(*std::forward<Out>(o)) =
            std::forward<T>(t); // not required to be equality-preserving
    };
```

2 Let `E` be an expression such that `decltype((E))` is `T`, and let `o` be a dereferenceable object of type `Out`. `Out` and `T` model indirectly_writable<Out, T> only if:
For every integral type $I$ other than $cv$ bool is integral-like if it models integral$I$ or if it is an integral-class type. An integral-like type $I$ is signed-integral-like if it models signed_integral$I$ or if it is a signed-integral-class type. An integral-like type $I$ is unsigned-integral-like if it models unsigned_integral$I$ or if it is an unsigned-integral-class type.

For every integral-class type $I$, let $B(I)$ be a unique hypothetical extended integer type of the same signedness with the same width (6.8.2) as $I$.

Expressions of integer-class type are explicitly convertible to any integer-like type, and implicitly convertible to any integer-class type of equal or greater width and the same signedness. Expressions of integral type are both implicitly and explicitly convertible to any integer-class type. Conversions between integral and integer-class types and between two integer-class types do not exit via an exception. The result of such a conversion is the unique value of the destination type that is congruent to the source modulo $2^N$, where $N$ is the width of the destination type.

Let $a$ be an object of integer-class type $I$, let $b$ be an object of integer-like type $I2$ such that the expression $b$ is implicitly convertible to $I$, let $x$ and $y$ be, respectively, objects of type $B(I)$ and $B(I2)$ as described above that represent the same values as $a$ and $b$, and let $c$ be an lvalue of any integral type.
The expressions `a++` and `a--` shall be prvalues of type `I` whose values are equal to that of `a` prior to the evaluation of the expressions. The expression `a++` shall modify the value of `a` by adding 1 to it. The expression `a--` shall modify the value of `a` by subtracting 1 from it.

The expressions `++a`, `--a`, and `&a` shall be expression-equivalent to `a += 1`, `a -= 1`, and `addressof(a)`, respectively.

For every unary-operator `@` other than `&` for which the expression `@x` is well-formed, `@a` shall also be well-formed and shall have the same value, effects, and value category as `@x`. If `@x` has type `bool`, so too does `@a`; if `@x` has type `B(I)`, then `@a` has type `I`.

For every assignment operator `@=` for which `c @= x` is well-formed, `c @= a` shall also be well-formed and shall have the same value and effects as `c ` @= ` x`. The expression `c @= a` shall be an lvalue referring to `c`.

For every assignment operator `@=` for which `x ` @= ` y` is well-formed, `a ` @= ` b` shall also be well-formed and shall have the same effects as `x ` @= ` y`, except that the value that would be stored into `x` is stored into `a`. The expression `a ` @= ` b` shall be an lvalue referring to `a`.

For every non-assignment binary operator `@` for which `x ` @ ` y` and `y ` @ ` x` are well-formed, `a ` @ ` b` and `b ` @ ` a` shall also be well-formed and shall have the same value, effects, and value category as `x ` @ ` y` and `y ` @ ` x`, respectively. If `x ` @ ` y` or `y ` @ ` x` has type `B(I1)`, then `a ` @ ` b` or `b ` @ ` a`, respectively, has type `I`; if `x ` @ ` y` or `y ` @ ` x` has type `B(I2)`, then `a ` @ ` b` or `b ` @ ` a`, respectively, has type `I2`; if `x ` @ ` y` or `y ` @ ` x` has any other type, then `a ` @ ` b` or `b ` @ ` a`, respectively, has that type.

An expression `E` of integer-class type `I` is contextually convertible to `bool` as if by `bool(E != I(0))`.

All integer-class types model `regular` (18.6) and `three_way_comparable<strong_ordering>` (17.11.4).

A value-initialized object of integer-class type has value 0.

For every (possibly cv-qualified) integer-class type `I`, `numeric_limits<I>` is specialized such that each static data member `m` has the same value as `numeric_limits<B(I)>::m`, and each static member function `f` returns `I(numeric_limits<B(I)>::f())`.

For any two integer-like types `I1` and `I2`, at least one of which is an integer-class type, `common_type_t<I1, I2>` denotes an integer-class type whose width is not less than that of `I1` or `I2`. If both `I1` and `I2` are signed-integer-like types, then `common_type_t<I1, I2>` is also a signed-integer-like type.

`is_integer-like<I>` is `true` if and only if `I` is an integer-like type. `is_signed_integer-like<I>` is `true` if and only if `I` is a signed-integer-like type.

Let `i` be an object of type `I`. When `i` is in the domain of both pre- and post-increment, `i` is said to be `incrementable`. `i` models `weakly_incrementable<I>` only if:

- The expressions `++i` and `i++` have the same domain.
- If `i` is incrementable, then both `++i` and `i++` advance `i` to the next element.
- If `i` is incrementable, then `addressof(++i)` is equal to `addressof(i)`.

Recommended practice: The implementation of an algorithm on a weakly incrementable type should never attempt to pass through the same incrementable value twice; such an algorithm should be a single-pass algorithm.

[Note 3: For `weakly_incrementable` types, `a` equals `b` does not imply that `++a` equals `++b`. (Equality does not guarantee the substitution property or referential transparency.) Such algorithms can be used with istreams as the source of the input data through the `istream_iterator` class template. — end note]

25.3.4.5 Concept `incrementable` [iterator.concept.inc]

The `incrementable` concept specifies requirements on types that can be incremented with the pre- and post-increment operators. The increment operations are required to be equality-preserving, and the type is required to be `equality_comparable`.

[Note 1: This supersedes the annotations on the increment expressions in the definition of `weakly_incrementable`. — end note]

```cpp
template<class I>
concept incrementable =
    regular<I> &&
    weakly_incrementable<I> &&
    requires(I i) {
```
Let \( a \) and \( b \) be incrementable objects of type \( I \). \( I \) models \texttt{incrementable} only if:

1. If \( \text{bool}(a == b) \) then \( \text{bool}(a++ == b) \).
2. If \( \text{bool}(a == b) \) then \( \text{bool}((\text{void})a++, a) == ++b \).

[Note 2: The requirement that \( a \) equals \( b \) implies \( a++ \) equals \( ++b \) (which is not true for weakly incrementable types) allows the use of multi-pass one-directional algorithms with types that model \texttt{incrementable}. — end note]

25.3.4.6 Concept \texttt{input\_or\_output\_iterator} \[iterator.concept.iterator\]

The \texttt{input\_or\_output\_iterator} concept forms the basis of the iterator concept taxonomy; every iterator models \texttt{input\_or\_output\_iterator}. This concept specifies operations for dereferencing and incrementing an iterator. Most algorithms will require additional operations to compare iterators with sentinels (25.3.4.7), to read (25.3.4.9) or write (25.3.4.10) values, or to provide a richer set of iterator movements (25.3.4.11, 25.3.4.12, 25.3.4.13).

```cpp
template<class I>
concept input_or_output_iterator =
requires(I i) {
    { *i } -> can-reference;
} &&
weakly_incrementable<I>;
```

[Note 1: Unlike the \texttt{Cpp17Iterator} requirements, the \texttt{input\_or\_output\_iterator} concept does not require copyability. — end note]

25.3.4.7 Concept \texttt{sentinel\_for} \[iterator.concept.sentinel\]

The \texttt{sentinel\_for} concept specifies the relationship between an \texttt{input\_or\_output\_iterator} type and a \texttt{semiregular} type whose values denote a range.

```cpp
template<class S, class I>
concept sentinel_for =
    semiregular<S> &&
    input_or_output_iterator<I> &&
    weakly-equality-comparable-with<S, I>;
```

Let \( s \) and \( i \) be values of type \( S \) and \( I \) such that \([i, s)\) denotes a range. Types \( S \) and \( I \) model \texttt{sentinel\_for<S, I>} only if:

1. \( i == s \) is well-defined.
2. If \( \text{bool}(i != s) \) then \( i \) is dereferenceable and \([++i, s)\) denotes a range.
3. \( \text{assignable\_from<I&, S>} \) is either modeled or not satisfied.

The domain of \( == \) is not static. Given an iterator \( i \) and sentinel \( s \) such that \([i, s)\) denotes a range and \( i != s \), \( i \) and \( s \) are not required to continue to denote a range after incrementing any other iterator equal to \( i \). Consequently, \( i == s \) is no longer required to be well-defined.

25.3.4.8 Concept \texttt{sized\_sentinel\_for} \[iterator.concept.sizedsentinel\]

The \texttt{sized\_sentinel\_for} concept specifies requirements on an \texttt{input\_or\_output\_iterator} type \( I \) and a corresponding \texttt{sentinel\_for<I>} that allow the use of the \( - \) operator to compute the distance between them in constant time.

```cpp
template<class S, class I>
concept sized_sentinel_for =
sentinel_for<S, I> &&
!disable_sized_sentinel_for<remove_cv_t<S>, remove_cv_t<I>> &&
requires(const I& i, const S& s) {
    { s - i } -> same_as<iter_difference_t<I>>;
    { i - s } -> same_as<iter_difference_t<I>>;
};
```

Let \( i \) be an iterator of type \( I \), and \( s \) a sentinel of type \( S \) such that \([i, s)\) denotes a range. Let \( N \) be the smallest number of applications of \( ++i \) necessary to make \( \text{bool}(i == s) \) be \texttt{true}. \( S \) and \( I \) model \texttt{sized\_sentinel\_for<S, I>} only if:
— If \( N \) is representable by `iter_difference_t<\text{I}>`, then \( s - i \) is well-defined and equals \( N \).

— If \( -N \) is representable by `iter_difference_t<\text{I}>`, then \( i - s \) is well-defined and equals \( -N \).

```cpp
template<class \text{S}, class \text{I}>
constexpr bool disable_sized_sentinel_for = false;
```

### Remarks

Pursuant to 16.4.5.2.1, users may specialize `disable_sized_sentinel_for` for cv-unqualified non-array object types \( \text{S} \) and \( \text{I} \) if \( \text{S} \) and/or \( \text{I} \) is a program-defined type. Such specializations shall be usable in constant expressions (7.7) and have type `const bool`.

[Note 1: `disable_sized_sentinel_for` allows use of sentinels and iterators with the library that satisfy but do not in fact model `sized_sentinel_for`. — end note]

[Example 1: The `sized_sentinel_for` concept is modeled by pairs of `random_access_iterators` (25.3.4.13) and by counted iterators and their sentinels (25.5.7.1). — end example]

#### 25.3.4.9 Concept `input_iterator`

The `input_iterator` concept defines requirements for a type whose referenced values can be read (from the requirement for `indirectly_readable` (25.3.4.2)) and which can be both pre- and post-incremented.

[Note 1: Unlike the `Cpp17InputIterator` requirements (25.3.5.3), the `input_iterator` concept does not need equality comparison since iterators are typically compared to sentinels. — end note]

```cpp
template<class \text{I}>
concept input_iterator =
    input_or_output_iterator<\text{I}> &&
    indirectly_readable<\text{I}> &&
    requires { typename \text{ITER_CONCEPT}(\text{I}); } &&
    derived_from<\text{ITER_CONCEPT}(\text{I}), input_iterator_tag>;
```

#### 25.3.4.10 Concept `output_iterator`

The `output_iterator` concept defines requirements for a type that can be used to write values (from the requirement for `indirectly_writable` (25.3.4.3)) and which can be both pre- and post-incremented.

[Note 1: Output iterators are not required to model `equality_comparable`. — end note]

```cpp
template<class \text{I}, class \text{T}>
concept output_iterator =
    input_or_output_iterator<\text{I}> &&
    indirectly_writable<\text{I}, \text{T}> &&
    requires(I i, T&& t) {
        *i++ = std::forward<T>(t);  // not required to be equality-preserving
    };
```

Let \( E \) be an expression such that `decltype((E))` is \( \text{T} \), and let \( i \) be a dereferenceable object of type \( \text{I} \). \( \text{I} \) and \( \text{T} \) model `output_iterator<\text{I}, \text{T}>` only if \( *i++ = E; \) has effects equivalent to:

\[
\begin{align*}
*\text{i} & = \text{E}; \\
++\text{i};
\end{align*}
\]

**Recommended practice:** The implementation of an algorithm on output iterators should never attempt to pass through the same iterator twice; such an algorithm should be a single-pass algorithm.

#### 25.3.4.11 Concept `forward_iterator`

The `forward_iterator` concept adds copyability, equality comparison, and the multi-pass guarantee, specified below.

```cpp
template<class \text{I}>
concept forward_iterator =
    input_iterator<\text{I}> &&
    derived_from<\text{ITER_CONCEPT}(\text{I}), forward_iterator_tag> &&
    incrementable<\text{I}> &&
    sentinel_for<\text{I}, \text{I}>;
```

The domain of `==` for forward iterators is that of iterators over the same underlying sequence. However, value-initialized iterators of the same type may be compared and shall compare equal to other value-initialized iterators of the same type.

[Note 1: Value-initialized iterators behave as if they refer past the end of the same empty sequence. — end note]
Pointers and references obtained from a forward iterator into a range \([i, s)\) shall remain valid while \([i, s)\) continues to denote a range.

Two dereferenceable iterators \(a\) and \(b\) of type \(X\) offer the **multi-pass guarantee** if

\[(4.1) \quad a == b \implies ++a == ++b \quad \text{and} \quad (4.2) \quad \text{the expression } ((\text{void})[](X x)\{++x\};(a), *a) \text{ is equivalent to the expression } *a.\]

[Note 2: The requirement that \(a == b\) implies \(++a == ++b\) and the removal of the restrictions on the number of assignments through a mutable iterator (which applies to output iterators) allow the use of multi-pass one-directional algorithms with forward iterators. — end note]

**25.3.4.12 Concept bidirectional_iterator** [iterator.concept.bidir]

The **bidirectional_iterator** concept adds the ability to move an iterator backward as well as forward.

```c++
template<class I>
concept bidirectional_iterator =
    forward_iterator<I> &&
    derived_from<ITER_CONCEPT(I), bidirectional_iterator_tag> &&
    requires(I i) {
        { --i } -> same_as<I&>;
        { i-- } -> same_as<I>;
    };
```

A bidirectional iterator \(r\) is decrementable if and only if there exists some \(q\) such that \(++q == r\). Decrementable iterators \(r\) shall be in the domain of the expressions \(--r\) and \(r--\).

Let \(a\) and \(b\) be equal objects of type \(I\). \(I\) models **bidirectional_iterator** only if:

\[(3.1) \quad \text{If } a \text{ and } b \text{ are decrementable, then all of the following are true:}\n\[(3.1.1) \quad \text{addressof}(--a) == \text{addressof}(a)\]
\[(3.1.2) \quad \text{bool}(a-- == b)\]
\[(3.1.3) \quad \text{after evaluating both } a-- \text{ and } --b, \text{ bool}(a == b) \text{ is still true}\]
\[(3.1.4) \quad \text{bool}(++(--a) == b)\]
\[(3.2) \quad \text{If } a \text{ and } b \text{ are incrementable, then } \text{bool}(--(++a) == b).\]

**25.3.4.13 Concept random_access_iterator** [iterator.concept.random.access]

The **random_access_iterator** concept adds support for constant-time advancement with \(+=\), \(+\), \(-=\), and \(-\), as well as the computation of distance in constant time with \(-\). Random access iterators also support array notation via subscripting.

```c++
template<class I>
concept random_access_iterator =
    bidirectional_iterator<I> &&
    derived_from<ITER_CONCEPT(I), random_access_iterator_tag> &&
    totally_ordered<I> &&
    sized_sentinel_for<I, I> &&
    requires(I i, const I j, const iter_difference_t<I> n) {
        { i += n } -> same_as<I&>;
        { j + n } -> same_as<I>;
        { n + j } -> same_as<I>;
        { i -= n } -> same_as<I&>;
        { j - n } -> same_as<I>;
        { j[n] } -> same_as<iter_reference_t<I>>;
    };
```

Let \(a\) and \(b\) be valid iterators of type \(I\) such that \(b\) is reachable from \(a\) after \(n\) applications of \(++a\), let \(D\) be \(iter_difference_t<I>\), and let \(n\) denote a value of type \(D\). \(I\) models **random_access_iterator** only if:

\[(2.1) \quad (a += n) \text{ is equal to } b.\]
\[(2.2) \quad \text{addressof}(a += n) \text{ is equal to } \text{addressof}(a).\]
\[(2.3) \quad (a + n) \text{ is equal to } (a += n).\]
\[(2.4) \quad \text{For any two positive values } x \text{ and } y \text{ of type } D, \text{ if } (a + D(x + y)) \text{ is valid, then } (a + D(x + y)) \text{ is equal to } ((a + x) + y).\]

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(2.5) \((a + D(0))\) is equal to \(a\).

(2.6) If \((a + D(n - 1))\) is valid, then \((a + n)\) is equal to \(a\).

(2.7) \((b += D(-n))\) is equal to \(b\).

(2.8) \((b -= n)\) is equal to \(b\).

(2.9) \(\text{addressof}(b -= n)\) is equal to \(\text{addressof}(b)\).

(2.10) \((b - n)\) is equal to \(b - n\).

(2.11) If \(b\) is dereferenceable, then \(a[n]\) is valid and is equal to \(*b\).

(2.12) \(\text{bool}(a <= b)\) is true.

25.3.4.14 Concept contiguous_iterator

The `contiguous_iterator` concept provides a guarantee that the denoted elements are stored contiguously in memory.

```
template<class I>
concept contiguous_iterator =
    random_access_iterator<I> &&
    derived_from<ITER_CONCEPT(I), contiguous_iterator_tag> &&
    is_lvalue_reference_v<iter_reference_t<I>> &&
    requires(const I& i) {
        { to_address(i) } -> same_as<add_pointer_t<iter_reference_t<I>>>;
    };
```

Let \(a\) and \(b\) be dereferenceable iterators and \(c\) be a non-dereferenceable iterator of type \(I\) such that \(b\) is reachable from \(a\) and \(c\) is reachable from \(b\), and let \(D\) be \(\text{iter_difference_t}\langle I\rangle\). The type \(I\) models `contiguous_iterator` only if

(2.1) \(\text{to_address}(a) == \text{addressof}(\*a)\),

(2.2) \(\text{to_address}(b) == \text{to_address}(a) + D(b - a)\),

(2.3) \(\text{to_address}(c) == \text{to_address}(a) + D(c - a)\),

(2.4) \(\text{ranges::iter_move}(a)\) has the same type, value category, and effects as \(\text{std}\::\text{move}(\*a)\), and

(2.5) if \(\text{ranges::iter_swap}(a, b)\) is well-formed, it has effects equivalent to \(\text{ranges::swap}(\*a, \*b)\).

25.3.5 C++17 iterator requirements

25.3.5.1 General

In the following sections, \(a\) and \(b\) denote values of type \(X\) or const \(X\), `difference_type` and `reference` refer to the types `iterator_traits<X>::difference_type` and `iterator_traits<X>::reference`, respectively, \(n\) denotes a value of `difference_type`, \(u\), \(tmp\), and \(m\) denote identifiers, \(r\) denotes a value of value type \(T\), \(o\) denotes a value of some type that is writable to the output iterator.

[Note 1: For an iterator type \(X\) there must be an instantiation of `iterator_traits<X>` (25.3.2.3). — end note]

25.3.5.2 Cpp17Iterator

The `Cpp17Iterator` requirements form the basis of the iterator taxonomy; every iterator meets the `Cpp17Iterator` requirements. This set of requirements specifies operations for dereferencing and incrementing an iterator. Most algorithms will require additional operations to read (25.3.5.3) or write (25.3.5.4) values, or to provide a richer set of iterator movements (25.3.5.5, 25.3.5.6, 25.3.5.7).

2 A type \(X\) meets the `Cpp17Iterator` requirements if

(2.1) \(X\) meets the `Cpp17CopyConstructible`, `Cpp17CopyAssignable`, `Cpp17Swappable`, and `Cpp17Destructible` requirements (16.4.4.2, 16.4.4.3), and

(2.2) `iterator_traits<X>::difference_type` is a signed integer type or void, and

(2.3) the expressions in Table 89 are valid and have the indicated semantics.
Table 89 — Cpp17Iterator requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note pre-/post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>*r</td>
<td>unspecified</td>
<td>Preconditions: r is dereferenceable.</td>
<td></td>
</tr>
<tr>
<td>++r</td>
<td>X&amp;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

25.3.5.3 Input iterators

1 A class or pointer type X meets the requirements of an input iterator for the value type T if X meets the Cpp17Iterator (25.3.5.2) and Cpp17EqualityComparable (Table 28) requirements and the expressions in Table 90 are valid and have the indicated semantics.

2 In Table 90, the term the domain of == is used in the ordinary mathematical sense to denote the set of values over which == is (required to be) defined. This set can change over time. Each algorithm places additional requirements on the domain of == for the iterator values it uses. These requirements can be inferred from the uses that algorithm makes of == and !=.

[Example 1: The call find(a,b,x) is defined only if the value of a has the property p defined as follows: b has property p and a value i has property p if (*i==x) or if (*i!=x and ++i has property p). — end example]

Table 90 — Cpp17InputIterator requirements (in addition to Cpp17Iterator)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note pre-/post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a != b</td>
<td>decltype(a != b) model of boolean-testable</td>
<td>Preconditions: (a,b) is in the domain of ==.</td>
<td></td>
</tr>
<tr>
<td>*a</td>
<td>reference, convertible to T</td>
<td>Preconditions: a is dereferenceable. The expression (void)*a, *a is equivalent to *a. If a == b and (a,b) is in the domain of == then *a is equivalent to *b.</td>
<td></td>
</tr>
<tr>
<td>a-&gt;m</td>
<td>(*a).m</td>
<td>Preconditions: a is dereferenceable.</td>
<td></td>
</tr>
<tr>
<td>++r</td>
<td>X&amp;</td>
<td>Preconditions: r is dereferenceable. Postconditions: r is dereferenceable or r is past-the-end; any copies of the previous value of r are no longer required to be dereferenceable nor to be in the domain of ==.</td>
<td></td>
</tr>
<tr>
<td>(void)r++</td>
<td>equivalent to (void)++r</td>
<td></td>
<td></td>
</tr>
<tr>
<td>++r++</td>
<td>convertible to T { T tmp = ++r; ++r; return tmp; }</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 Recommended practice: The implementation of an algorithm on input iterators should never attempt to pass through the same iterator twice; such an algorithm should be a single pass algorithm.
For input iterators, \( a == b \) does not imply \( ++a == ++b \). (Equality does not guarantee the substitution property or referential transparency.) Value type \( T \) is not required to be a \( \text{Cpp17CopyAssignable} \) type (Table 34). Such an algorithm can be used with istreams as the source of the input data through the \text{istream::iterator} class template. — end note

### 25.3.5.4 Output iterators

A class or pointer type \( X \) meets the requirements of an output iterator if \( X \) meets the \( \text{Cpp17Iterator} \) requirements (25.3.5.2) and the expressions in Table 91 are valid and have the indicated semantics.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td>(*r = o)</td>
<td>result is not used</td>
<td>Remarks: After this operation ( r ) is not required to be dereferenceable. Postconditions: ( r ) is incrementable.</td>
<td></td>
</tr>
<tr>
<td>++(r)</td>
<td>(X&amp;)</td>
<td>addressof((r)) == addressof(;++(r)). Remarks: After this operation ( r ) is not required to be dereferenceable. Postconditions: ( r ) is incrementable.</td>
<td></td>
</tr>
<tr>
<td>(r++)</td>
<td>convertible to (\text{const }X&amp;) { (X) tmp = (r); ++(r); return tmp; }</td>
<td>Remarks: After this operation ( r ) is not required to be dereferenceable. Postconditions: ( r ) is incrementable.</td>
<td></td>
</tr>
<tr>
<td>(*r++ = o)</td>
<td>result is not used</td>
<td>Remarks: After this operation ( r ) is not required to be dereferenceable. Postconditions: ( r ) is incrementable.</td>
<td></td>
</tr>
</tbody>
</table>

Recommended practice: The implementation of an algorithm on output iterators should never attempt to pass through the same iterator twice; such an algorithm should be a single-pass algorithm.

[Note 1: The only valid use of an \text{operator*} is on the left side of the assignment statement. Assignment through the same value of the iterator happens only once. Equality and inequality are not necessarily defined. — end note]

### 25.3.5.5 Forward iterators

A class or pointer type \( X \) meets the \( \text{Cpp17ForwardIterator} \) requirements if

- \( X \) meets the \( \text{Cpp17InputIterator} \) requirements (25.3.5.3),
- \( X \) meets the \( \text{Cpp17DefaultConstructible} \) requirements (16.4.4.2),
- if \( X \) is a mutable iterator, \text{reference} is a reference to \( T \); if \( X \) is a constant iterator, \text{reference} is a reference to \( \text{const } T \),
- the expressions in Table 92 are valid and have the indicated semantics, and
- objects of type \( X \) offer the multi-pass guarantee, described below.

The domain of \( == \) for forward iterators is that of iterators over the same underlying sequence. However, value-initialized iterators may be compared and shall compare equal to other value-initialized iterators of the same type.

[Note 1: Value-initialized iterators behave as if they refer past the end of the same empty sequence. — end note]
Two dereferenceable iterators \( a \) and \( b \) of type \( X \) offer the multi-pass guarantee if

\[
(3.1) \quad a == b \text{ implies } \++a == ++b \text{ and }
\]

\[
(3.2) \quad X \text{ is a pointer type or the expression } (\text{void})++X(a), \ast a \text{ is equivalent to the expression } \ast a.
\]

[Note 2: The requirement that \( a == b \) implies \( \++a == ++b \) (which is not true for input and output iterators) and the removal of the restrictions on the number of the assignments through a mutable iterator (which applies to output iterators) allows the use of multi-pass one-directional algorithms with forward iterators. — end note]

Table 92 — \textit{Cpp17ForwardIterator} requirements (in addition to \textit{Cpp17InputIterator})

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td>++r++</td>
<td>convertible to ( const X&amp; )</td>
<td>{ ( X ) tmp = r; +r; return tmp; }</td>
<td></td>
</tr>
<tr>
<td>*r++</td>
<td>reference</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If \( a \) and \( b \) are equal, then either \( a \) and \( b \) are both dereferenceable or else neither is dereferenceable.

If \( a \) and \( b \) are both dereferenceable, then \( a == b \) if and only if \( \ast a \) and \( \ast b \) are bound to the same object.

25.3.5.6 Bidirectional iterators

A class or pointer type \( X \) meets the requirements of a bidirectional iterator if, in addition to meeting the \textit{Cpp17ForwardIterator} requirements, the following expressions are valid as shown in Table 93.

Table 93 — \textit{Cpp17BidirectionalIterator} requirements (in addition to \textit{Cpp17ForwardIterator})

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td>--r</td>
<td>( X&amp; )</td>
<td>Preconditions: there exists ( s ) such that ( r == ++s ). Postconditions: ( r ) is dereferenceable. ( --(++r) == r ). ( --r == --s ) implies ( r == s ). ( \text{addressof}(r) == \text{addressof}(--r) ).</td>
<td></td>
</tr>
<tr>
<td>r--</td>
<td>convertible to ( const X&amp; )</td>
<td>{ ( X ) tmp = r; --r; return tmp; }</td>
<td></td>
</tr>
<tr>
<td>*r--</td>
<td>reference</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Note 1: Bidirectional iterators allow algorithms to move iterators backward as well as forward. — end note]

25.3.5.7 Random access iterators

A class or pointer type \( X \) meets the requirements of a random access iterator if, in addition to meeting the \textit{Cpp17BidirectionalIterator} requirements, the following expressions are valid as shown in Table 94.
Table 94 — Cpp17RandomAccessIterator requirements (in addition to Cpp17BidirectionalIterator) [tab:randomaccessiterator]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td>r += n</td>
<td>X &amp;</td>
<td><code>{ difference_type m = n; if (m &gt;= 0) while (m--) ++r; else while (m++) --r; return r; }</code></td>
<td></td>
</tr>
<tr>
<td>a + n</td>
<td>X</td>
<td><code>{ X tmp = a; return tmp += n; }</code></td>
<td>a + n == n + a.</td>
</tr>
<tr>
<td>n + a</td>
<td>X</td>
<td><code>{ X tmp = a; return tmp += n; }</code></td>
<td></td>
</tr>
<tr>
<td>r -= n</td>
<td>X &amp;</td>
<td>return r += -n;</td>
<td>Precondition: the absolute value of n is in the range of representable values of difference_type.</td>
</tr>
<tr>
<td>a - n</td>
<td>X</td>
<td><code>{ X tmp = a; return tmp -= n; }</code></td>
<td></td>
</tr>
</tbody>
</table>
| b - a      | difference_-
             | type                  | return n; Precondition: there exists a value n of type difference_type such that a + n == b. b == a + (b - a). |
| a[n]       | convertible to reference | *(a + n) | |
| a < b      | decltype(a < b) models boolean-test-
             | able        | Effects: Equivalent to: return b - a > 0; |
| a > b      | decltype(a > b) models boolean-test-
             | able        | b < a > is a total ordering relation opposite to <. |
| a >= b     | decltype(a >= b) models boolean-test-
             | able        | !(a < b) > is a total ordering relation opposite to <. |
| a <= b     | decltype(a <= b) models boolean-test-
             | able        | !(a > b) |

25.3.6 Indirect callable requirements [indirectcallable]

25.3.6.1 General [indirectcallable.general]

1 There are several concepts that group requirements of algorithms that take callable objects (22.10.3) as arguments.

25.3.6.2 Indirect callable traits [indirectcallable.traits]

1 To implement algorithms taking projections, it is necessary to determine the projected type of an iterator’s value type. For the exposition-only alias template indirect-value-t, indirect-value-t<T> denotes invoke_result_t<Proj&>, indirect-value-t<T>& if T names projected<I, Proj>, and iter_value_t<T>& otherwise.

§ 25.3.6.2 ©ISO/IEC 1144
25.3.6.3 Indirect callables

The indirect callable concepts are used to constrain those algorithms that accept callable objects (22.10.3) as arguments.

```cpp
namespace std {
    template<class F, class I>
    concept indirectly_callable =
        indirectly_readable<I> &&
        copy_constructible<F> &&
        invocable<F, indirect-value-t<I>> &&
        invocable<F, iter_reference_t<I>> &&
        common_reference_with<
            invoke_result_t<F, indirect-value-t<I>>,
            invoke_result_t<F, iter_reference_t<I>>>
        ;

template<class F, class I>
    concept indirectly_regular_callable =
        indirectly_readable<I> &&
        copy_constructible<F> &&
        regular_invocable<F, indirect-value-t<I>> &&
        regular_invocable<F, iter_reference_t<I>> &&
        common_reference_with<
            invoke_result_t<F, indirect-value-t<I>>,
            invoke_result_t<F, iter_reference_t<I>>>
        ;

template<class F, class I1, class I2>
    concept indirectly_binary_predicate =
        indirectly_readable<I1> && indirectly_readable<I2> &&
        copy_constructible<F> &&
        predicate<F, indirect-value-t<I1>, indirect-value-t<I2>> &&
        predicate<F, indirect-value-t<I1>, iter_reference_t<I2>> &&
        predicate<F, iter_reference_t<I1>, indirect-value-t<I2>> &&
        predicate<F, iter_reference_t<I1>, iter_reference_t<I2>>;

template<class F, class I1, class I2 = I1>
    concept indirectly_equivalence_relation =
        indirectly_readable<I1> && indirectly_readable<I2> &&
        copy_constructible<F> &&
        equivalence_relation<F, indirect-value-t<I1>, indirect-value-t<I2>> &&
        equivalence_relation<F, indirect-value-t<I1>, iter_reference_t<I2>> &&
        equivalence_relation<F, iter_reference_t<I1>, indirect-value-t<I2>> &&
        equivalence_relation<F, iter_reference_t<I1>, iter_reference_t<I2>>;

template<class F, class I1, class I2 = I1>
    concept indirectly_strict_weak_order =
        indirectly_readable<I1> && indirectly_readable<I2> &&
        copy_constructible<F> &&
        strict_weak_order<F, indirect-value-t<I1>, indirect-value-t<I2>> &&
        strict_weak_order<F, indirect-value-t<I1>, iter_reference_t<I2>> &&
        strict_weak_order<F, iter_reference_t<I1>, indirect-value-t<I2>> &&
        strict_weak_order<F, iter_reference_t<I1>, iter_reference_t<I2>>;
}
```

25.3.6.4 Class template projected

Class template `projected` is used to constrain algorithms that accept callable objects and projections (3.43). It combines an `indirectly_readable` type `I` and a callable object type `Proj` into a new `indirectly_readable` type whose `reference` type is the result of applying `Proj` to the `iter_reference_t` of `I`. 

[projected]
namespace std {
    template<class I, class Proj>
    struct projected_impl { // exposition only
        struct type { // exposition only
            using value_type = remove_cvref_t<indirect_result_t<Proj&, I>>; // present only if I models weakly_incrementable
            using difference_type = iter_difference_t<I>; // not defined
            indirect_result_t<Proj&, I> operator*(.) const;
        };
    };
}

25.3.7 Common algorithm requirements [alg.req]
25.3.7.1 General [alg.req.general]

1 There are several additional iterator concepts that are commonly applied to families of algorithms. These
group together iterator requirements of algorithm families. There are three relational concepts that specify how
element values are transferred between indirectly_readable and indirectly_writable types: indirectly_movable, indirectly_copyable, and indirectly_swappable. There are three relational concepts for rearrangements: permutable, mergeable, and sortable. There is one relational concept for comparing values from different sequences: indirectly_comparable.

2 [Note 1: The ranges::less function object type used in the concepts below imposes constraints on the concepts’
arguments in addition to those that appear in the concepts’ bodies (22.10.9). —end note]

25.3.7.2 Concept indirectly_movable [alg.req.ind.move]

1 The indirectly_movable concept specifies the relationship between an indirectly_readable type and an
indirectly_writable type between which values may be moved.

    template<class In, class Out>
    concept indirectly_movable = indirectly_readable<In> && indirectly_writable<Out, iter_rvalue_reference_t<In>>;

2 The indirectly_movable_storable concept augments indirectly_movable with additional requirements
enabling the transfer to be performed through an intermediate object of the indirectly_readable type’s
value type.

    template<class In, class Out>
    concept indirectly_movable_storable = indirectly_movable<In, Out> && indirectly_writable<Out, iter_value_t<In>> && movable<iter_value_t<In>> && constructible_from<iter_value_t<In>, iter_rvalue_reference_t<In>> && assignable_from<iter_value_t<In>&, iter_rvalue_reference_t<In>>;

3 Let i be a dereferenceable value of type In. In and Out model indirectly_movable_storable<In, Out> only if after the initialization of the object obj in

    iter_value_t<In> obj(ranges::iter_move(i));

obj is equal to the value previously denoted by *i. If iter_rvalue_reference_t<In> is an rvalue reference
type, the resulting state of the value denoted by *i is valid but unspecified (16.4.6.15).

25.3.7.3 Concept indirectly_copyable [alg.req.ind.copy]

1 The indirectly_copyable concept specifies the relationship between an indirectly_readable type and an
indirectly_writable type between which values may be copied.

    template<class In, class Out>
    concept indirectly_copyable = indirectly_readable<In> && indirectly_writable<Out, iter_reference_t<In>>;

§ 25.3.7.3 © ISO/IEC 1146
The `indirectly_copyable_storable` concept augments `indirectly_copyable` with additional requirements enabling the transfer to be performed through an intermediate object of the `indirectly_readable` type’s value type. It also requires the capability to make copies of values.

```cpp
template<class In, class Out>
concept indirectly_copyable_storable =
    indirectly_copyable<In, Out> &&
    indirectly_writable<Out, iter_value_t<In>&> &&
    indirectly_writable<Out, const iter_value_t<In>&> &&
    indirectly_writable<Out, iter_value_t<In>&&> &&
    indirectly_writable<Out, const iter_value_t<In>&&> &&
    copyable<iter_value_t<In>> &&
    constructible_from<iter_value_t<In>>, iter_reference_t<In>> &&
    assignable_from<iter_value_t<In>&, iter_reference_t<In>>;
```

Let `i` be a dereferenceable value of type `In`. `In` and `Out` model `indirectly_copyable_storable<In, Out>` only if after the initialization of the object `obj` in

```cpp
iter_value_t<In> obj(*i);
```

`obj` is equal to the value previously denoted by `*i`. If `iter_reference_t<In>` is an rvalue reference type, the resulting state of the value denoted by `*i` is valid but unspecified (16.4.6.15).

### 25.3.7.4 Concept indirectly_swappable

The `indirectly_swappable` concept specifies a swappable relationship between the values referenced by two `indirectly_readable` types.

```cpp
template<class I1, class I2 = I1>
concept indirectly_swappable =
    indirectly_readable<I1> && indirectly_readable<I2> &&
    requires(const I1 i1, const I2 i2) {
        ranges::iter_swap(i1, i1);
        ranges::iter_swap(i2, i2);
        ranges::iter_swap(i1, i2);
        ranges::iter_swap(i2, i1);
    };
```

### 25.3.7.5 Concept indirectly_comparable

The `indirectly_comparable` concept specifies the common requirements of algorithms that compare values from two different sequences.

```cpp
template<class I1, class I2, class R, class P1 = identity,
    class P2 = identity>
concept indirectly_comparable =
    indirect_binary_predicate<R, projected<I1, P1>, projected<I2, P2>>;
```

### 25.3.7.6 Concept permutable

The `permutable` concept specifies the common requirements of algorithms that reorder elements in place by moving or swapping them.

```cpp
template<class I>
concept permutable =
    forward_iterator<I> &&
    indirectly_movable_storable<I, I> &&
    indirectly_swappable<I, I>;
```

### 25.3.7.7 Concept mergeable

The `mergeable` concept specifies the requirements of algorithms that merge sorted sequences into an output sequence by copying elements.

```cpp
template<class I1, class I2, class Out, class R = ranges::less,
    class P1 = identity, class P2 = identity>
concept mergeable =
    input_iterator<I1> &&
    input_iterator<I2> &&
    weakly_incrementable<Out> &&
    indirectly_copyable<Out, Out> &&
```
25.3.7.8 Concept sortable

The sortable concept specifies the common requirements of algorithms that permute sequences into ordered sequences (e.g., sort).

```cpp
template<class I, class R = ranges::less, class P = identity>
concept sortable =
    permutable<I> &&
    indirect_strict_weak_order<R, projected<I, P>>;
```

25.4 Iterator primitives

25.4.1 General

To simplify the use of iterators, the library provides several classes and functions.

25.4.2 Standard iterator tags

It is often desirable for a function template specialization to find out what is the most specific category of its iterator argument, so that the function can select the most efficient algorithm at compile time. To facilitate this, the library introduces category tag classes which are used as compile time tags for algorithm selection. They are: output_iterator_tag, input_iterator_tag, forward_iterator_tag, bidirectional_iterator_tag, random_access_iterator_tag, and contiguous_iterator_tag. For every iterator of type I, iterator_traits<I>::iterator_category shall be defined to be a category tag that describes the iterator's behavior. Additionally, iterator_traits<I>::iterator_concept may be used to indicate conformance to the iterator concepts (25.3.4).

```cpp
namespace std {
    struct output_iterator_tag { };  
    struct input_iterator_tag { };    
    struct forward_iterator_tag: public input_iterator_tag { }; 
    struct bidirectional_iterator_tag: public forward_iterator_tag { };  
    struct random_access_iterator_tag: public bidirectional_iterator_tag { }; 
    struct contiguous_iterator_tag: public random_access_iterator_tag { }; 
}
```

- Example 1: A program-defined iterator BinaryTreeIterator can be included into the bidirectional iterator category by specializing the iterator_traits template:

```cpp
template<class T> struct iterator_traits<BinaryTreeIterator<T>> {
    using iterator_category = bidirectional_iterator_tag;
    using difference_type = ptrdiff_t;
    using value_type = T;
    using pointer = T*;
    using reference = T&;
};
```

- Example 2: If evolve() is well-defined for bidirectional iterators, but can be implemented more efficiently for random access iterators, then the implementation is as follows:

```cpp
template<class BidirectionalIterator>
inline void 
evolve(BidirectionalIterator first, BidirectionalIterator last) {
    evolve(first, last,
          typename iterator_traits<BidirectionalIterator>::iterator_category());
}
```

```cpp
template<class BidirectionalIterator>
void evolve(BidirectionalIterator first, BidirectionalIterator last,
            bidirectional_iterator_tag) {
    // more generic, but less efficient algorithm
}
```
template<class RandomAccessIterator>
void evolve(RandomAccessIterator first, RandomAccessIterator last,
    random_access_iterator_tag) {
    // more efficient, but less generic algorithm
}
—end example

25.4.3 Iterator operations

Since only random access iterators provide + and - operators, the library provides two function templates advance and distance. These function templates use + and - for random access iterators (and are, therefore, constant time for them); for input, forward and bidirectional iterators they use ++ to provide linear time implementations.

template<class InputIterator, class Distance>
constexpr void advance(InputIterator& i, Distance n);

Preconditions: n is negative only for bidirectional iterators.

Effects: Increments i by n if n is non-negative, and decrements i by -n otherwise.

template<class InputIterator>
constexpr typename iterator_traits<InputIterator>::difference_type
    distance(InputIterator first, InputIterator last);

Preconditions: last is reachable from first, or InputIterator meets the Cpp17RandomAccessIterator requirements and first is reachable from last.

Effects: If InputIterator meets the Cpp17RandomAccessIterator requirements, returns (last - first); otherwise, increments first until last is reached and returns the number of increments.

template<class InputIterator>
constexpr InputIterator next(InputIterator x,
    typename iterator_traits<InputIterator>::difference_type n = 1);

Effects: Equivalent to: advance(x, n); return x;

template<class BidirectionalIterator>
constexpr BidirectionalIterator prev(BidirectionalIterator x,
    typename iterator_traits<BidirectionalIterator>::difference_type n = 1);

Effects: Equivalent to: advance(x, -n); return x;

25.4.4 Range iterator operations

25.4.4.1 General

The library includes the function templates ranges::advance, ranges::distance, ranges::next, and ranges::prev to manipulate iterators. These operations adapt to the set of operators provided by each iterator category to provide the most efficient implementation possible for a concrete iterator type.

[Example 1: ranges::advance uses the + operator to move a random_access_iterator forward n steps in constant time. For an iterator type that does not model random_access_iterator, ranges::advance instead performs n individual increments with the ++ operator. —end example]

The function templates defined in 25.4.4 are not found by argument-dependent name lookup (6.5.4). When found by unqualified (6.5.3) name lookup for the postfix-expression in a function call (7.6.1.3), they inhibit argument-dependent name lookup.

[Example 2:

void foo() {
    using namespace std::ranges;
    std::vector<int> vec{1,2,3};
    distance(begin(vec), end(vec)); // #1
}
}

The function call expression at #1 invokes std::ranges::distance, not std::distance, despite that (a) the iterator type returned from begin(vec) and end(vec) may be associated with namespace std and (b) std::distance is more specialized (13.7.7.3) than std::ranges::distance since the former requires its first two parameters to have the same type. —end example]
The number and order of deducible template parameters for the function templates defined in 25.4.4 is unspecified, except where explicitly stated otherwise.

25.4.4.2 ranges::advance

template<input_or_output_iterator I>
constexpr void ranges::advance(I& i, iter_difference_t<I> n);

1 Preconditions: If I does not model bidirectional_iterator, n is not negative.

2 Effects:
   (2.1) — If I models random_access_iterator, equivalent to i += n.
   (2.2) — Otherwise, if n is non-negative, increments i by n.
   (2.3) — Otherwise, decrements i by -n.

template<input_or_output_iterator I, sentinel_for<I> S>
constexpr void ranges::advance(I& i, S bound);

3 Preconditions: Either assignable_from<I&, S> || sized_sentinel_for<S, I> is modeled, or [i, bound) denotes a range.

4 Effects:
   (4.1) — If I and S model assignable_from<I&, S>, equivalent to i = std::move(bound).
   (4.2) — Otherwise, if S and I model sized_sentinel_for<S, I>, equivalent to ranges::advance(i, bound - i).
   (4.3) — Otherwise, while bool(i != bound) is true, increments i.

template<input_or_output_iterator I, sentinel_for<I> S>
constexpr iter_difference_t<I> ranges::advance(I& i, iter_difference_t<I> n, S bound);

5 Preconditions: If n > 0, [i, bound) denotes a range. If n == 0, [i, bound) or [bound, i) denotes a range. If n < 0, [bound, i) denotes a range, I models bidirectional_iterator, and I and S model same_as<I, S>.

6 Effects:
   (6.1) — If I and S model sized_sentinel_for<S, I>:
      (6.1.1) — If |n| ≥ |bound - i|, equivalent to ranges::advance(i, bound).
      (6.1.2) — Otherwise, equivalent to ranges::advance(i, n).
   (6.2) — Otherwise,
      (6.2.1) — if n is non-negative, while bool(i != bound) is true, increments i but at most n times.
      (6.2.2) — Otherwise, while bool(i != bound) is true, decrements i but at most -n times.

Returns: n - M, where M is the difference between the ending and starting positions of i.

25.4.4.3 ranges::distance

template<class I, sentinel_for<I> S>
requires (!sized_sentinel_for<S, I>)
constexpr iter_difference_t<I> ranges::distance(I first, S last);

1 Preconditions: [first, last) denotes a range.

2 Effects: Increments first until last is reached and returns the number of increments.

template<class I, sized_sentinel_for<decay_t<I>> S>
constexpr iter_difference_t<decay_t<I>> ranges::distance(I&& first, S last);

3 Effects: Equivalent to: return last - static_cast<const decay_t<I>&>(first);

template<range R>
constexpr range_difference_t<R> ranges::distance(R&& r);

4 Effects: If R models sized_range, equivalent to:
return static_cast<range_difference_t<R>>(ranges::size(r)); // 26.3.10
Otherwise, equivalent to:

```cpp
return ranges::distance(ranges::begin(r), ranges::end(r)); // 26.3
```

### 25.4.4.4 `ranges::next`

```cpp
template<input_or_output_iterator I>
constexpr I ranges::next(I x);
```

**Effects**: Equivalent to: `++x; return x;`

```cpp
template<input_or_output_iterator I>
constexpr I ranges::next(I x, iter_difference_t<I> n);
```

**Effects**: Equivalent to: `ranges::advance(x, n); return x;`

```cpp
template<input_or_output_iterator I, sentinel_for<I> S>
constexpr I ranges::next(I x, S bound);
```

**Effects**: Equivalent to: `ranges::advance(x, bound); return x;`

```cpp
template<input_or_output_iterator I, sentinel_for<I> S>
constexpr I ranges::next(I x, iter_difference_t<I> n, S bound);
```

**Effects**: Equivalent to: `ranges::advance(x, n, bound); return x;`

### 25.4.4.5 `ranges::prev`

```cpp
template<bidirectional_iterator I>
constexpr I ranges::prev(I x);
```

**Effects**: Equivalent to: `--x; return x;`

```cpp
template<bidirectional_iterator I>
constexpr I ranges::prev(I x, iter_difference_t<I> n);
```

**Effects**: Equivalent to: `ranges::advance(x, -n); return x;`

```cpp
template<bidirectional_iterator I>
constexpr I ranges::prev(I x, iter_difference_t<I> n, I bound);
```

**Effects**: Equivalent to: `ranges::advance(x, -n, bound); return x;`

### 25.5 Iterator adaptors

#### 25.5.1 Reverse iterators

##### 25.5.1.1 General

Class template `reverse_iterator` is an iterator adaptor that iterates from the end of the sequence defined by its underlying iterator to the beginning of that sequence.

#### 25.5.1.2 Class template `reverse_iterator`

```cpp
namespace std {
    template<class Iterator>
    class reverse_iterator {
        public:
            using iterator_type = Iterator;
            using iterator_concept = see below;
            using iterator_category = see below;
            using value_type = iter_value_t<Iterator>;
            using difference_type = iter_difference_t<Iterator>;
            using pointer = typename iterator_traits<Iterator>::pointer;
            using reference = iter_reference_t<Iterator>;

            constexpr reverse_iterator();
            constexpr explicit reverse_iterator(Iterator x);
            template<class U> constexpr reverse_iterator(const reverse_iterator<U>& u);
            template<class U> constexpr reverse_iterator& operator=(const reverse_iterator<U>& u);
```
constexpr Iterator base() const;
constexpr reference operator*() const;
constexpr pointer operator->() const requires see below;

constexpr reverse_iterator& operator++();
constexpr reverse_iterator operator++(int);
constexpr reverse_iterator& operator--();
constexpr reverse_iterator operator--(int);

constexpr reverse_iterator operator+ (difference_type n) const;
constexpr reverse_iterator& operator+=(difference_type n);
constexpr reverse_iterator operator- (difference_type n) const;
constexpr reverse_iterator& operator-=(difference_type n);
constexpr unspecified operator[](difference_type n) const;

friend constexpr iter_rvalue_reference_t<Iterator> iter_move(const reverse_iterator& i) noexcept(see below);

template<indirectly_swappable<Iterator> Iterator2>
friend constexpr void iter_swap(const reverse_iterator& x,
 const reverse_iterator<Iterator2>& y) noexcept(see below);

protected:
Iterator current;
};

1 The member typedef-name iterator_concept denotes
(1.1) — random_access_iterator_tag if Iterator models random_access_iterator, and
(1.2) — bidirectional_iterator_tag otherwise.

2 The member typedef-name iterator_category denotes
(2.1) — random_access_iterator_tag if the type iterator_traits<Iterator>::iterator_category mod-
els derived_from<random_access_iterator_tag>, and
(2.2) — iterator_traits<Iterator>::iterator_category otherwise.

25.5.1.3 Requirements  [reverse.iter.requirements]

1 The template parameter Iterator shall either meet the requirements of a Cpp17BidirectionalIterator (25.3.5.6) or model bidirectional_iterator (25.3.4.12).

2 Additionally, Iterator shall either meet the requirements of a Cpp17RandomAccessIterator (25.3.5.7) or model random_access_iterator (25.3.4.13) if the definitions of any of the members
(2.1) — operator+, operator-, operator=, operator==(25.5.1.7), or
(2.2) — operator[] (25.5.1.6),
or the non-member operators (25.5.1.8)
(2.3) — operator<, operator>, operator<=, operator>=, operator-, or operator+ (25.5.1.9)

are instantiated (13.9.2).

25.5.1.4 Construction and assignment  [reverse.iter.cons]

constexpr reverse_iterator();

1 Effects: Value-initializes current. Iterator operations applied to the resulting iterator have defined behavior if and only if the corresponding operations are defined on a value-initialized iterator of type Iterator.

constexpr explicit reverse_iterator(Iterator x);

2 Effects: Initializes current with x.
template<class U> constexpr reverse_iterator(const reverse_iterator<U>& u);

Constraints: is_same_v<
, Iterator> is false and const U& models convertible_to<Iterator>
.

Effects: Initializes current with u.current.

template<class U>
constexpr reverse_iterator& operator=(const reverse_iterator<U>& u);

Constraints: is_same_v<
, Iterator> is false, const U& models convertible_to<Iterator>, and assignable_from<Iterator&, const U&> is modeled.

Effects: Assigns u.current to current.

Returns: *this.

25.5.1.5 Conversion [reverse.iter.conv]

constexpr Iterator base() const;

Returns: current.

25.5.1.6 Element access [reverse.iter.elem]

constexpr reference operator*() const;

Effects: As if by:

Iterator tmp = current;
return *--tmp;

constexpr pointer operator->() const
requires (is_pointer_v<Iterator> ||
requires(const Iterator i) { i.operator->(); });

Effects:

(2.1) — If Iterator is a pointer type, equivalent to: return prev(current);
(2.2) — Otherwise, equivalent to: return prev(current).operator->();

constexpr unspecified operator[](difference_type n) const;

Returns: current[-n-1].

25.5.1.7 Navigation [reverse.iter.nav]

constexpr reverse_iterator operator+(difference_type n) const;

Returns: reverse_iterator(current-n).

constexpr reverse_iterator operator-(difference_type n) const;

Returns: reverse_iterator(current+n).

constexpr reverse_iterator& operator++();

Effects: As if by: --current;

Returns: *this.

constexpr reverse_iterator& operator++(int);

Effects: As if by:

reverse_iterator tmp = *this;
--current;
return tmp;

constexpr reverse_iterator& operator--();

Effects: As if by ++current.

Returns: *this.
constexpr reverse_iterator operator--(int);

Effects: As if by:
    reverse_iterator tmp = *this;
    ++current;
    return tmp;

constexpr reverse_iterator& operator+=(difference_type n);

Effects: As if by: current -= n;

Returns: *this.

constexpr reverse_iterator& operator-=(difference_type n);

Effects: As if by: current += n;

Returns: *this.

25.5.1.8 Comparisons [reverse.iter.cmp]

template<class Iterator1, class Iterator2>
constexpr bool operator==(const reverse_iterator<Iterator1>& x,
                          const reverse_iterator<Iterator2>& y);

Constraints: x.base() == y.base() is well-formed and convertible to bool.

Returns: x.base() == y.base().

template<class Iterator1, class Iterator2>
constexpr bool operator!=(const reverse_iterator<Iterator1>& x,
                          const reverse_iterator<Iterator2>& y);

Constraints: x.base() != y.base() is well-formed and convertible to bool.

Returns: x.base() != y.base().

template<class Iterator1, class Iterator2>
constexpr bool operator<(const reverse_iterator<Iterator1>& x,
                          const reverse_iterator<Iterator2>& y);

Constraints: x.base() < y.base() is well-formed and convertible to bool.

Returns: x.base() < y.base().

template<class Iterator1, class Iterator2>
constexpr bool operator<=(const reverse_iterator<Iterator1>& x,
                          const reverse_iterator<Iterator2>& y);

Constraints: x.base() <= y.base() is well-formed and convertible to bool.

Returns: x.base() <= y.base().

template<class Iterator1, class Iterator2>
constexpr bool operator>(const reverse_iterator<Iterator1>& x,
                          const reverse_iterator<Iterator2>& y);

Constraints: x.base() > y.base() is well-formed and convertible to bool.

Returns: x.base() > y.base().

template<class Iterator1, class Iterator2>
constexpr bool operator>=(const reverse_iterator<Iterator1>& x,
                          const reverse_iterator<Iterator2>& y);

Constraints: x.base() >= y.base() is well-formed and convertible to bool.

Returns: x.base() >= y.base().
template<class Iterator1, three_way_comparable_with<Iterator1> Iterator2>
    constexpr compare_three_way_result_t<Iterator1, Iterator2>
    operator<=>(const reverse_iterator<Iterator1>& x,
                const reverse_iterator<Iterator2>& y);

Returns: y.base() <=> x.base().

[Note 1: The argument order in the Returns: element is reversed because this is a reverse iterator. — end note]

25.5.1.9 Non-member functions

template<class Iterator1, class Iterator2>
    constexpr auto operator-(
        const reverse_iterator<Iterator1>& x,
        const reverse_iterator<Iterator2>& y) -> decltype(y.base() - x.base());

Returns: y.base() - x.base().

template<class Iterator>
    constexpr reverse_iterator<Iterator> operator+(iter_difference_t<Iterator> n,
        const reverse_iterator<Iterator>& x);

Returns: reverse_iterator<Iterator>(x.base() - n).

friend constexpr iter_rvalue_reference_t<Iterator> iter_move(const reverse_iterator& i) noexcept;

Effects: Equivalent to:
auto tmp = i.base();
return ranges::iter_move(--tmp);

Remarks: The exception specification is equivalent to:
is_nothrow_copy_constructible_v<Iterator> &&
noexcept(ranges::iter_move(--declval<Iterator&>()))

friend constexpr void iter_swap(const reverse_iterator& x,
    const reverse_iterator<Iterator2>& y) noexcept;

Effects: Equivalent to:
auto xtmp = x.base();
auto ytmp = y.base();
ranges::iter_swap(--xtmp, --ytmp);

Remarks: The exception specification is equivalent to:
is_nothrow_copy_constructible_v<Iterator> &&
is_nothrow_copy_constructible_v<Iterator2> &&
noexcept(ranges::iter_swap(--declval<Iterator&>(), --declval<Iterator2&>()))

template<class Iterator>
    constexpr reverse_iterator<Iterator> make_reverse_iterator(Iterator i);

Returns: reverse_iterator<Iterator>(i).

25.5.2 Insert iterators

25.5.2.1 General

To make it possible to deal with insertion in the same way as writing into an array, a special kind of iterator adaptors, called insert iterators, are provided in the library. With regular iterator classes,
while (first != last) *result++ = *first++;
causes a range [first, last) to be copied into a range starting with result. The same code with result being an insert iterator will insert corresponding elements into the container. This device allows all of the copying algorithms in the library in the insert mode instead of the regular overwrite mode.

An insert iterator is constructed from a container and possibly one of its iterators pointing to where insertion takes place if it is neither at the beginning nor at the end of the container. Insert iterators
meet the requirements of output iterators. \texttt{operator*} returns the insert iterator itself. The assignment \texttt{operator=(\texttt{const T} & \texttt{x})} is defined on insert iterators to allow writing into them, it inserts \texttt{x} right before where the insert iterator is pointing. In other words, an insert iterator is like a cursor pointing into the container where the insertion takes place. \texttt{back_insert_iterator} inserts elements at the end of a container, \texttt{front_insert_iterator} inserts elements at the beginning of a container, and \texttt{insert_iterator} inserts elements where the iterator points to in a container. \texttt{back_insert_iterator}, \texttt{front_insert_iterator}, and \texttt{insert_iterator} are three functions making the insert iterators out of a container.

\subsection*{25.5.2.2 Class template back_insert_iterator}

\subsection*{25.5.2.2.1 General}

namespace std {
    template<class Container>
    class back_insert_iterator {
        protected:
            Container* container;

        public:
            using iterator_category = output_iterator_tag;
            using value_type = void;
            using difference_type = ptrdiff_t;
            using pointer = void;
            using reference = void;
            using container_type = Container;

            constexpr explicit back_insert_iterator(Container& x);
            constexpr back_insert_iterator& operator=(const typename Container::value_type& value);
            constexpr back_insert_iterator& operator=(typename Container::value_type&& value);
            constexpr back_insert_iterator& operator*();
            constexpr back_insert_iterator& operator++();
            constexpr back_insert_iterator operator++(int);
    };
}

\subsection*{25.5.2.2.2 Operations}

constexpr explicit back_insert_iterator(Container& x);
\hspace{1em}1
\hspace{1em}\textit{Effects}: Initializes \texttt{container} with \texttt{addressof(x)}.

constexpr back_insert_iterator& operator=(const typename Container::value_type& value);
\hspace{1em}2
\hspace{1em}\textit{Effects}: As if by: \texttt{container->push_back(value)};
\hspace{1em}\textit{Returns}: \texttt{*this}.

constexpr back_insert_iterator& operator=(typename Container::value_type&& value);
\hspace{1em}3
\hspace{1em}\textit{Effects}: As if by: \texttt{container->push_back(std::move(value))};
\hspace{1em}\textit{Returns}: \texttt{*this}.

constexpr back_insert_iterator& operator*();
\hspace{1em}4
\hspace{1em}\textit{Returns}: \texttt{*this}.

constexpr back_insert_iterator& operator++();
\hspace{1em}5
\hspace{1em}\textit{Returns}: \texttt{*this}.

constexpr back_insert_iterator operator++(int);
\hspace{1em}6
\hspace{1em}\textit{Returns}: \texttt{*this}.

\subsection*{25.5.2.2.3 back_inserter}

template<class Container>
constexpr back_insert_iterator<Container> back_inserter(Container& x);
\hspace{1em}1
\hspace{1em}\textit{Returns}: \texttt{back_insert_iterator<Container>(x)}. 
25.5.2.3 Class template front_insert_iterator

25.5.2.3.1 General

namespace std {
    template<class Container>
    class front_insert_iterator {
    protected:
        Container* container;

    public:
        using iterator_category = output_iterator_tag;
        using value_type = void;
        using difference_type = ptrdiff_t;
        using pointer = void;
        using reference = void;
        using container_type = Container;

        constexpr explicit front_insert_iterator(Container& x);
        constexpr front_insert_iterator& operator=(const typename Container::value_type& value);
        constexpr front_insert_iterator& operator=(typename Container::value_type&& value);
        constexpr front_insert_iterator& operator*();
        constexpr front_insert_iterator& operator++();
        constexpr front_insert_iterator operator++(int);
    }
}

25.5.2.3.2 Operations

constexpr explicit front_insert_iterator(Container& x);

1 Effects: Initializes container with addressof(x).

constexpr front_insert_iterator& operator=(const typename Container::value_type& value);

2 Effects: As if by: container->push_front(value);
3 Returns: *this.

constexpr front_insert_iterator& operator=(typename Container::value_type&& value);

4 Effects: As if by: container->push_front(std::move(value));
5 Returns: *this.

constexpr front_insert_iterator& operator*();

6 Returns: *this.

constexpr front_insert_iterator& operator++();

7 Returns: *this.

25.5.2.3.3 front_inserter

template<class Container>
constexpr front_insert_iterator<Container> front_inserter(Container& x);

1 Returns: front_insert_iterator<Container>(x).

25.5.2.4 Class template insert_iterator

25.5.2.4.1 General

namespace std {
    template<class Container>
    class insert_iterator {
    protected:
        Container* container;
        ranges::iterator_t<Container> iter;

§ 25.5.2.4.1
25.5.2.4.2 Operations

constexpr insert_iterator(Container& x, ranges::iterator_t<Container> i);

Effects: Initializes container with addressof(x) and iter with i.

constexpr insert_iterator& operator=(const typename Container::value_type& value);

Effects: As if by:

iter = container->insert(iter, value);
++iter;

Returns: *this.

constexpr insert_iterator& operator=(typename Container::value_type&& value);

Effects: As if by:

iter = container->insert(iter, std::move(value));
++iter;

Returns: *this.

constexpr insert_iterator& operator*();

Returns: *this.

constexpr insert_iterator& operator++();
constexpr insert_iterator& operator++(int);

Returns: *this.

25.5.2.4.3 inserter

template<class Container>
constexpr insert_iterator<Container> inserter(Container& x, ranges::iterator_t<Container> i);

Returns: insert_iterator<Container>(x, i).

25.5.3 Constant iterators and sentinels

25.5.3.1 General

Class template basic_const_iterator is an iterator adaptor with the same behavior as the underlying iterator except that its indirection operator implicitly converts the value returned by the underlying iterator’s indirection operator to a type such that the adapted iterator is a constant iterator (25.3). Some generic algorithms can be called with constant iterators to avoid mutation.

Specializations of basic_const_iterator are constant iterators.
25.5.3.2 Alias templates

```cpp
template<indirectly_readable It>
using iter_const_reference_t =
    common_reference_t<const iter_value_t<It>&&, iter_reference_t<It>>;

template<class It>
concept constant_iterator =
    // exposition only
    input_iterator<It> && same_as<iter_const_reference_t<It>, iter_reference_t<It>>;

template<input_iterator I>
using const_iterator = see below;

1 Result: If I models constant_iterator, I. Otherwise, basic_const_iterator<I>.

template<semiregular S>
using const_sentinel = see below;

2 Result: If S models input_iterator, const_iterator<S>. Otherwise, S.
```

25.5.3.3 Class template basic_const_iterator

```cpp
namespace std {
    template<class I>
    concept not-a-const_iterator = see below; // exposition only

    template<indirectly_readable I>
    using iter-const-rvalue-reference-t =
        // exposition only
        common_reference_t<const iter_value_t<I>&&, iter_rvalue_reference_t<I>>;

    template<input_iterator Iterator>
    class basic_const_iterator {
        Iterator current_ = Iterator();
    
        using reference = iter_const_reference_t<Iterator>;
        using rvalue-reference =
            // exposition only
            iter-const-rvalue-reference-t<Iterator>;

    public:
        using iterator_concept = see below;
        using iterator_category = see below; // not always present
        using value_type = iter_value_t<Iterator>;
        using difference_type = iter_difference_t<Iterator>;

        basic_const_iterator() requires default_initializable<Iterator> = default;
        constexpr basic_const_iterator(Iterator current);
        template<convertible_to<Iterator> U>
            constexpr basic_const_iterator(basic_const_iterator<U> current);
        template<different-from<basic_const_iterator> T>
            requires convertible_to<T, Iterator>
            constexpr basic_const_iterator(T&& current);

        constexpr const_iterator& base() const & noexcept;
        constexpr Iterator base() &&;
        constexpr reference operator*() const;
        constexpr const auto* operator->() const
            requires is_lvalue_reference_v<iter_reference_t<Iterator>> &&
            same_as<remove_cvref_t<iter_reference_t<Iterator>>, value_type>;

        constexpr basic_const_iterator& operator++();
        constexpr void operator++(int);
        constexpr basic_const_iterator operator++(int) requires forward_iterator<Iterator>;

        constexpr basic_const_iterator& operator--() requires bidirectional_iterator<Iterator>;
        constexpr basic_const_iterator operator--(int) requires bidirectional_iterator<Iterator>;
    }
}
```
constexpr basic_const_iterator& operator+=(difference_type n) 
    requires random_access_iterator<Iterator>;
constexpr basic_const_iterator& operator-=(difference_type n) 
    requires random_access_iterator<Iterator>;
constexpr 
    reference 
    operator[] (difference_type n) const 
    requires random_access_iterator<Iterator>;

template<sentinel_for<Iterator> S> 
    constexpr bool operator==(const S& s) const;

template<not-a-const-iterator CI> 
    requires constant_iterator<CI> && convertible_to<Iterator const& , CI> 
    constexpr auto operator<=>(const CI&) const
    requires constant_iterator<CI> && convertible_to<Iterator, CI> 
    constexpr auto operator<=>(const CI&) &&

constexpr bool operator<(const basic_const_iterator& y) const 
    requires random_access_iterator<Iterator>;
constexpr bool operator>(const basic_const_iterator& y) const 
    requires random_access_iterator<Iterator>;
constexpr bool operator<=(const basic_const_iterator& y) const 
    requires random_access_iterator<Iterator>;
constexpr bool operator>=(const basic_const_iterator& y) const 
    requires random_access_iterator<Iterator>;
constexpr auto operator<=>(const basic_const_iterator& y) const 
    requires random_access_iterator<Iterator> && three_way_comparable<Iterator>;

template<different-from<basic_const_iterator> I> 
    constexpr bool operator<(const I& y) const 
    requires random_access_iterator<Iterator> && totally_ordered_with<Iterator, I>;

template<not-a-const-iterator I> 
    friend constexpr bool operator<(const I& x, const basic_const_iterator& y) 
    requires random_access_iterator<Iterator> && totally_ordered_with<Iterator, I>;

friend constexpr basic_const_iterator operator+(const basic_const_iterator& i, 
    difference_type n) 
    requires random_access_iterator<Iterator>;
friend constexpr basic_const_iterator operator+(difference_type n, 
    const basic_const_iterator& i) 
    requires random_access_iterator<Iterator>;

§ 25.5.3.3
friend constexpr basic_const_iterator operator-(const basic_const_iterator& i,
    difference_type n)
    requires random_access_iterator<Iterator>;

template<sized_sentinel_for<Iterator> S>
constexpr difference_type operator-(const S& y) const;

friend constexpr difference_type operator-(const S& x, const basic_const_iterator& y);
friend constexpr
rvalue-reference
iter_move(const basic_const_iterator& i)
    noexcept(noexcept(static_cast<rvalue-reference>(ranges::iter_move(i.
        current_))))
{
    return static_cast<rvalue-reference>(ranges::iter_move(i.
        current_));
}
};

1 Given some type I, the concept not-a-const-iterator is defined as false if I is a specialization of basic_const_iterator and true otherwise.

25.5.3.4 Member types

basic_const_iterator<Iterator>::iterator_concept is defined as follows:

(1.1) — If Iterator models contiguous_iterator, then iterator_concept denotes contiguous_iterator_tag.
(1.2) — Otherwise, if Iterator models random_access_iterator, then iterator_concept denotes random_access_iterator_tag.
(1.3) — Otherwise, if Iterator models bidirectional_iterator, then iterator_concept denotes bidirectional_iterator_tag.
(1.4) — Otherwise, if Iterator models forward_iterator, then iterator_concept denotes forward_iterator_tag.
(1.5) — Otherwise, iterator_concept denotes input_iterator_tag.

The member typedef-name iterator_category is defined if and only if Iterator models forward_iterator. In that case, basic_const_iterator<Iterator>::iterator_category denotes the type iterator_traits<Iterator>::iterator_category.

25.5.3.5 Operations

constexpr basic_const_iterator(Iterator current);

Effects: Initializes current_ with std::move(current).

template<convertible_to<Iterator> U>
constexpr basic_const_iterator(basic_const_iterator<U> current);

Effects: Initializes current_ with std::move(current.current_).

template<different-from<basic_const_iterator> T>
requires convertible_to<T, Iterator>
constexpr basic_const_iterator(T&& current);

Effects: Initializes current_ with std::forward<T>(current).

conestexpr const Iterator& base() const & noexcept;

Effects: Equivalent to: return current_;

conestexpr Iterator base() &&;

Effects: Equivalent to: return std::move(current_);

conestexpr reference operator*() const;

Effects: Equivalent to: return static_cast<reference>(*current_);
constexpr const auto* operator->() const
  requires is_lvalue_reference_v<iter_reference_t<Iterator>> &&
  same_as<remove_cvref_t<iter_reference_t<Iterator>>, value_type>;

Returns: If Iterator models contiguous_iterator, to_address(*current_); otherwise, address-of(*current_).

constexpr basic_const_iterator& operator++();

Effects: Equivalent to:
  ++current_;  return *this;

constexpr void operator++(int);

Effects: Equivalent to: ++current_.

constexpr basic_const_iterator operator++(int) requires forward_iterator<Iterator>;

Effects: Equivalent to:
  auto tmp = *this;
  +++this;
  return tmp;

constexpr basic_const_iterator& operator--() requires bidirectional_iterator<Iterator>;

Effects: Equivalent to:
  --current_;  return *this;

constexpr basic_const_iterator operator--(int) requires bidirectional_iterator<Iterator>;

Effects: Equivalent to:
  auto tmp = *this;
  --*this;
  return tmp;

constexpr basic_const_iterator& operator+=(difference_type n) requires random_access_iterator<Iterator>;

constexpr basic_const_iterator& operator-=(difference_type n) requires random_access_iterator<Iterator>;

Let op be the operator.

Effects: Equivalent to:
  current_ op n;
  return *this;

constexpr reference operator[](difference_type n) const requires random_access_iterator<Iterator>

Effects: Equivalent to: return static_cast<reference>(current_[n]);

template<sentinel_for<Iterator> S>
constexpr bool operator==(const S& s) const;

Effects: Equivalent to: return current_ == s;

template<not-a-const-iterator CI>
requires constant_iterator<CI> && convertible_to<Iterator const&, CI>
constexpr operator CI() const &;

Returns: current_.

template<not-a-const-iterator CI>
requires constant_iterator<CI> && convertible_to<Iterator, CI>
constexpr operator CI() &&;

Returns: std::move(current_).
constexpr bool operator<(const basic_const_iterator& y) const
  requires random_access_iterator<Iterator>;
constexpr bool operator>(const basic_const_iterator& y) const
  requires random_access_iterator<Iterator>;
constexpr bool operator<=(const basic_const_iterator& y) const
  requires random_access_iterator<Iterator>;
constexpr bool operator>=(const basic_const_iterator& y) const
  requires random_access_iterator<Iterator>;
constexpr auto operator<=>(const basic_const_iterator& y) const
  requires random_access_iterator<Iterator> && three_way_comparable<Iterator>;

Let op be the operator.
Effects: Equivalent to: return current_ op y.current_;
template<not-a-const-iterator S>
    requires sized_sentinel_for<S, Iterator>
friend constexpr difference_type operator-(const S& x, const basic_const_iterator& y);

Effects: Equivalent to: return x - y.current_; 

25.5.4 Move iterators and sentinels

25.5.4.1 General

Class template move_iterator is an iterator adaptor with the same behavior as the underlying iterator except that its indirection operator implicitly converts the value returned by the underlying iterator's indirection operator to an rvalue. Some generic algorithms can be called with move iterators to replace copying with moving.

[Example 1:

```cpp
list<string> s;
// populate the list s

vector<string> v1(s.begin(), s.end()); // copies strings into v1
vector<string> v2(make_move_iterator(s.begin()),
                 make_move_iterator(s.end())); // moves strings into v2
```

—end example]

25.5.4.2 Class template move_iterator

namespace std {
    template<class Iterator>
class move_iterator {
    
public:
    using iterator_type = Iterator;
    using iterator_concept = see below; // not always present
    using iterator_category = see below;
    using value_type = iter_value_t<Iterator>;
    using difference_type = iter_difference_t<Iterator>;
    using pointer = Iterator;
    using reference = iter_rvalue_reference_t<Iterator>;
    
    constexpr move_iterator();
    constexpr explicit move_iterator(Iterator i);
    template<class U> constexpr move_iterator(const move_iterator<U>& u);
    template<class U> constexpr move_iterator& operator=(const move_iterator<U>& u);
    
    constexpr const Iterator& base() const & noexcept;
    constexpr Iterator base() &&;
    
    constexpr reference operator*() const;
    constexpr move_iterator& operator++();
    constexpr auto operator++(int);
    constexpr move_iterator& operator--();
    constexpr move_iterator operator--(int);
    constexpr move_iterator operator+(difference_type n) const;
    constexpr move_iterator& operator+=(difference_type n);
    constexpr move_iterator operator-(difference_type n) const;
    constexpr move_iterator& operator-=(difference_type n);
    
    template<sentinel_for<Iterator> S>
    friend constexpr bool operator==(const move_iterator& x, const move_sentinel<S>& y);
    template<sized_sentinel_for<Iterator> S>
    friend constexpr iter_difference_t<Iterator>
    operator-(const move_sentinel<S>& x, const move_iterator& y);
};


§ 25.5.4.2 © ISO/IEC 1164
friend constexpr iter_rvalue_reference_t<Iterator>
    iter_move(const move_iterator& i)
    noexcept(noexcept(ranges::iter_move(i.current)));

template<indirectly_swappable<Iterator> Iterator>
friend constexpr void
    iter_swap(const move_iterator& x, const move_iterator<Iterator2>& y)
    noexcept(noexcept(ranges::iter_swap(x.current, y.current)));

private:
    Iterator current;   // exposition only
};

1 The member typedef-name iterator_concept is defined as follows:

(1.1) — If Iterator models random_access_iterator, then iterator_concept denotes random_access_iterator_tag.
(1.2) — Otherwise, if Iterator models bidirectional_iterator, then iterator_concept denotes bidirectional_iterator_tag.
(1.3) — Otherwise, if Iterator models forward_iterator, then iterator_concept denotes forward_iterator_tag.
(1.4) — Otherwise, iterator_concept denotes input_iterator_tag.

2 The member typedef-name iterator_category is defined if and only if the qualified-id iterator_traits<Iterator>::iterator_category is valid and denotes a type. In that case, iterator_category denotes

(2.1) — random_access_iterator_tag if the type iterator_traits<Iterator>::iterator_category models derived_from<random_access_iterator_tag>, and
(2.2) — iterator_traits<Iterator>::iterator_category otherwise.

25.5.4.3 Requirements [move.iter.requirements]

1 The template parameter Iterator shall either meet the Cpp17InputIterator requirements (25.3.5.3) or model input_iterator (25.3.4.9). Additionally, if any of the bidirectional traversal functions are instantiated, the template parameter shall either meet the Cpp17BidirectionalIterator requirements (25.3.5.6) or model bidirectional_iterator (25.3.4.12). If any of the random access traversal functions are instantiated, the template parameter shall either meet the Cpp17RandomAccessIterator requirements (25.3.5.7) or model random_access_iterator (25.3.4.13).

25.5.4.4 Construction and assignment [move.iter.cons]

constexpr move_iterator();

Effects: Value-initializes current.

constexpr explicit move_iterator(Iterator i);

Effects: Initializes current with std::move(i).

template<class U> constexpr move_iterator(const move_iterator<U>& u);

Constraints: is_same_v<U, Iterator> is false and const U& models convertible_to<Iterator>.

Effects: Initializes current with u.current.

template<class U> constexpr move_iterator& operator=(const move_iterator<U>& u);

Constraints: is_same_v<U, Iterator> is false, const U& models convertible_to<Iterator>, and assignable_from<Iterator&, const U&> is modeled.

Effects: Assigns u.current to current.

Returns: *this.

25.5.4.5 Conversion [move.iter.op.conv]

constexpr const Iterator& base() const & noexcept;

Returns: current.
constexpr Iterator base() &&;

Returns: std::move(current).

25.5.4.6 Element access

constexpr reference operator*() const;
Effects: Equivalent to: return ranges::iter_move(current);

constexpr reference operator[](difference_type n) const;
Effects: Equivalent to: return ranges::iter_move(current + n);

25.5.4.7 Navigation

constexpr move_iterator& operator++();
Effects: As if by ++current.
Returns: *this.

constexpr auto operator++(int);
Effects: If Iterator models forward_iterator, equivalent to:
    move_iterator tmp = *this;
    ++current;
    return tmp;
Otherwise, equivalent to ++current.

constexpr move_iterator& operator--();
Effects: As if by --current.
Returns: *this.

constexpr move_iterator operator--(int);
Effects: As if by:
    move_iterator tmp = *this;
    --current;
    return tmp;

constexpr move_iterator operator+(difference_type n) const;
Returns: move_iterator(current + n).

constexpr move_iterator& operator+=(difference_type n);
Effects: As if by: current += n;
Returns: *this.

constexpr move_iterator operator-(difference_type n) const;
Returns: move_iterator(current - n).

constexpr move_iterator& operator-=(difference_type n);
Effects: As if by: current -= n;
Returns: *this.

25.5.4.8 Comparisons

template<class Iterator1, class Iterator2>
constexpr bool operator==(const move_iterator<Iterator1>& x,
const move_iterator<Iterator2>& y);

template<sentinel_for<Iterator> S>
friend constexpr bool operator==(const move_iterator& x,
const move_sentinel<S>& y);
Constraints: x.base() == y.base() is well-formed and convertible to bool.
Returns: x.base() == y.base().
```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator<(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

Constraints: x.base() < y.base() is well-formed and convertible to bool.
Returns: x.base() < y.base().

template<class Iterator1, class Iterator2>
constexpr bool operator<=(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

Constraints: y.base() < x.base() is well-formed and convertible to bool.
Returns: !(y < x).

template<class Iterator1, class Iterator2>
constexpr bool operator>(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

Constraints: y.base() < x.base() is well-formed and convertible to bool.
Returns: y < x.

template<class Iterator1, class Iterator2>
constexpr bool operator>=(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

Constraints: x.base() < y.base() is well-formed and convertible to bool.
Returns: !(x < y).

template<class Iterator1, class Iterator2>
constexpr compare_three_way_result_t<Iterator1, Iterator2> operator<=>(const move_iterator<Iterator1>& x,
const move_iterator<Iterator2>& y);

Returns: x.base() <=> y.base().

25.5.4.9 Non-member functions

[move.iter.nonmember]

template<class Iterator1, class Iterator2>
constexpr auto operator-(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y)-> decltype(x.base() - y.base());

template<sized_sentinel_for<Iterator> S>
friend constexpr iter_difference_t<Iterator> operator-(const move_sentinel<S>& x, const move_iterator& y);

Returns: x.base() - y.base().
```

§ 25.5.4.9 © ISO/IEC 1167
template<class Iterator>
constexpr move_iterator<Iterator> make_move_iterator(Iterator i);

Returns: move_iterator<Iterator>(std::move(i)).

25.5.4.10 Class template move_sentinel

Class template move_sentinel is a sentinel adaptor useful for denoting ranges together with move_iterator. When an input iterator type I and sentinel type S model sentinel_for<S, I>, move_sentinel<S> and move_iterator<I> model sentinel_for<move_sentinel<S>, move_iterator<I>> as well.

[Example 1: A move_if algorithm is easily implemented with copy_if using move_iterator and move_sentinel:

```cpp
template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, indirect_unary_predicate<I> Pred>
requires indirectly_movable<I, O>
void move_if(I first, S last, O out, Pred pred) {
    ranges::copy_if(move_iterator<I>{std::move(first)}, move_sentinel<S>{last}, std::move(out), pred);
}
```]

namespace std {
    template<semiregular S>
    class move_sentinel {
    public:
        constexpr move_sentinel();
        constexpr explicit move_sentinel(S s);
        template<class S2>
        requires convertible_to<const S2&, S>
        constexpr move_sentinel(const move_sentinel<S2>& s);
        template<class S2>
        requires assignable_from<S&, const S2&>
        constexpr move_sentinel& operator=(const move_sentinel<S2>& s);
        constexpr S base() const;
    
    private:
        S last; // exposition only
    
    }
}

25.5.4.11 Operations

constexpr move_sentinel();

Effects: Value-initializes last. If is_trivially_default_constructible_v<S> is true, then this constructor is a constexpr constructor.

constexpr explicit move_sentinel(S s);

Effects: Initializes last with std::move(s).

template<class S2>
requires convertible_to<const S2&, S>
constexpr move_sentinel(const move_sentinel<S2>& s);

Effects: Initializes last with s.last.

template<class S2>
requires assignable_from<S&, const S2&>
constexpr move_sentinel& operator=(const move_sentinel<S2>& s);

Effects: Equivalent to: last = s.last; return *this;

constexpr S base() const;

Returns: last.
25.5.5 Common iterators

25.5.5.1 Class template common_iterator

Class template `common_iterator` is an iterator/sentinel adaptor that is capable of representing a non-common range of elements (where the types of the iterator and sentinel differ) as a common range (where they are the same). It does this by holding either an iterator or a sentinel, and implementing the equality comparison operators appropriately.

[Note 1: The `common_iterator` type is useful for interfacing with legacy code that expects the begin and end of a range to have the same type. — end note]

[Example 1:

```cpp
template<class ForwardIterator>
void fun(ForwardIterator begin, ForwardIterator end);

list<int> s;
// populate the list
using CI = common_iterator<counted_iterator<list<int>::iterator>, default_sentinel_t>;
// call fun on a range of 10 ints
fun(CI(counted_iterator(s.begin(), 10)), CI(default_sentinel));
```

—end example]

namespace std {
    template<input_or_output_iterator I, sentinel_for<I> S>
    requires (!same_as<I, S> && copyable<I>)
    class common_iterator {
        public:
           constexpr common_iterator() requires default_initializable<I> = default;
           constexpr common_iterator(I i);
           constexpr common_iterator(S s);
            template<class I2, class S2>
            requires convertible_to<const I2&, I> && convertible_to<const S2&, S>
            constexpr common_iterator(const common_iterator<I2, S2>& x);
            template<class I2, class S2>
            requires convertible_to<const I2&, I> && convertible_to<const S2&, S> &&
            assignable_from<I&, const I2&> && assignable_from<S&, const S2&>
            constexpr common_iterator& operator=(const common_iterator<I2, S2>& x);

            constexpr decltype(auto) operator*();
            constexpr decltype(auto) operator*() const
                requires dereferenceable<const I>;
            constexpr auto operator->() const
                requires see below;

            constexpr common_iterator& operator++();
            constexpr decltype(auto) operator++(int);
            template<class I2, sentinel_for<I> S2>
            requires sentinel_for<S, I2>
            friend constexpr bool operator==(const common_iterator& x, const common_iterator<I2, S2>& y);
            template<class I2, sentinel_for<I> S2>
            requires sentinel_for<S, I2> && equality_comparable_with<I, I2>
            friend constexpr bool operator==(const common_iterator& x, const common_iterator<I2, S2>& y);

            template<sized_sentinel_for<I> I2, sized_sentinel_for<I> S2>
            requires sized_sentinel_for<S, I2>
            friend constexpr iter_difference_t<I2> operator-(
                const common_iterator& x, const common_iterator<I2, S2>& y);

            friend constexpr decltype(auto) iter_move(const common_iterator& i)
                noexcept(noexcept(ranges::iter_move(declval<const I&>())))
                requires input_iterator<I>;
    }
}
template<indirectly_swappable<I> I2, class S2>
friend constexpr void iter_swap(const common_iterator& x, const common_iterator<I2, S2>& y)
  noexcept(noexcept(ranges::iter_swap(declval<const I&>(), declval<const I2&>())))
private:
  variant<I, S> v_; // exposition only
};

template<class I, class S>
struct incrementable_traits<common_iterator<I, S>>
  { using difference_type = iter_difference_t<I>;
  }

template<input_iterator I, class S>
struct iterator_traits<common_iterator<I, S>>
  { using iterator_concept = see below;
    using iterator_category = see below; // not always present
    using value_type = iter_value_t<I>;
    using difference_type = iter_difference_t<I>;
    using pointer = see below;
    using reference = iter_reference_t<I>;
  };

25.5.5.2 Associated types

The nested typedef-name iterator_category of the specialization of iterator_traits for common_iterator<I, S> is defined if and only if iter_difference_t<I> is an integral type. In that case, iterator_category denotes forward_iterator_tag if the qualified-id iterator_traits<I>::iterator_category is valid and denotes a type that models derived_from<forward_iterator_tag>; otherwise it denotes input_iterator_tag.

The remaining nested typedef-names of the specialization of iterator_traits for common_iterator<I, S> are defined as follows:

(2.1) — iterator_concept denotes forward_iterator_tag if I models forward_iterator; otherwise it denotes input_iterator_tag.
(2.2) — Let a denote an lvalue of type const common_iterator<I, S>. If the expression a.operator->() is well-formed, then pointer denotes decltype(a.operator->()). Otherwise, pointer denotes void.

25.5.5.3 Constructors and conversions

constexpr common_iterator(I i);
  Effects: Initializes v_ as if by v_{in_place_type<I>, std::move(i)}.

constexpr common_iterator(S s);
  Effects: Initializes v_ as if by v_{in_place_type<S>, std::move(s)}.

template<class I2, class S2>
requires convertible_to<const I2&, I> && convertible_to<const S2&, S>
 constexpr common_iterator(const common_iterator<I2, S2>& x);
  Preconditions: x.v_.valueless_by_exception() is false.
  Effects: Initializes v_ as if by v_{in_place_index<i>, get<i>(x.v_)}, where i is x.v_.index().

template<class I2, class S2>
requires convertible_to<const I2&, I> && convertible_to<const S2&, S> && assignable_from<I&, const I2&, const S2&>
  constexpr common_iterator& operator=(const common_iterator<I2, S2>& x);
  Preconditions: x.v_.valueless_by_exception() is false.
  Effects: Equivalent to:
(6.1) — If v_.index() == x.v_.index(), then get<i>(v_) = get<i>(x.v_).
(6.2) — Otherwise, v_.emplace<i>(get<i>(x.v_)).
where \( i \) is \( x.v_.\text{index}() \).

Returns: \(*\text{this}\).

### 25.5.5.4 Accessors

```cpp
constexpr decltype(auto) operator*();

constexpr decltype(auto) operator*() const
    requires dereferenceable<\&\& I>;
```

**Preconditions:** holds_alternative<\&\& I>(v_) is true.

**Effects:** Equivalent to: return *get<\&\& I>(v_);

```cpp
constexpr auto operator->() const
    requires see below;
```

**Preconditions:** holds_alternative<\&\& I>(v_) is true.

**Effects:**

(5.1) If I is a pointer type or if the expression get<\&\& I>(v_).operator->() is well-formed, equivalent to:

return get<\&\& I>(v_);

(5.2) Otherwise, if iter_reference_t<\&\& I> is a reference type, equivalent to:

auto\&\& tmp = *get<\&\& I>(v_);

return addressof(tmp);

(5.3) Otherwise, equivalent to: return proxy(*get<\&\& I>(v_)); where proxy is the exposition-only class:

```cpp
class proxy {
    iter_value_t<I> keep_;  
    constexpr proxy(iter_reference_t<\&\& I>&& x) : keep_(std::move(x)) {}  
    public:
        constexpr const iter_value_t<\&\& I>* operator->() const noexcept {  
            return addressof(keep_);  
        }
    }
};
```

### 25.5.5.5 Navigation

```cpp
constexpr common_iterator& operator++();
```

**Preconditions:** holds_alternative<\&\& I>(v_) is true.

**Effects:** Equivalent to ++get<\&\& I>(v_).

```cpp
constexpr decltype(auto) operator++(int);
```

**Preconditions:** holds_alternative<\&\& I>(v_) is true.

**Effects:** If I models forward_iterator, equivalent to:

```cpp
common_iterator tmp = *this;
++*this;
return tmp;
```

Otherwise, if requires(I& i) { { *i++ } \rightarrow can-reference; } is true or

indirectly_readable<\&\& I> \&\& constructible_from<iter_value_t<\&\& I>, iter_reference_t<\&\& I>>

is false, equivalent to:

return get<\&\& I>(v_)+;
Otherwise, equivalent to:

```cpp
postfix-proxy p(**this);
**this;
return p;
```

where `postfix-proxy` is the exposition-only class:

```cpp
class postfix-proxy {
    iter_value_t<I> keep_
    constexpr postfix-proxy(iter_reference_t<I>&& x)
        : keep_(std::forward<iter_reference_t<I>>(x)) {} 
public:
    constexpr const iter_value_t<I>& operator*() const noexcept {
        return keep_; 
    }
};
```

### 25.5.5.6 Comparisons

#### template<class I2, sentinel_for<I> S2>
```cpp
friend constexpr bool operator==(const common_iterator& x, const common_iterator<I2, S2>& y);
```

1. **Preconditions**: `x.v_.valueless_by_exception()` and `y.v_.valueless_by_exception()` are each false.
2. **Returns**: `true` if `i == j`, and otherwise `get<i>(x.v_) == get<j>(y.v_)`, where `i` is `x.v_.index()` and `j` is `y.v_.index()`.

#### template<class I2, sentinel_for<I> S2>
```cpp
friend constexpr bool operator==(const common_iterator& x, const common_iterator<I2, S2>& y);
```

3. **Preconditions**: `x.v_.valueless_by_exception()` and `y.v_.valueless_by_exception()` are each false.
4. **Returns**: `true` if `i` and `j` are each 1, and otherwise `get<i>(x.v_) == get<j>(y.v_)`, where `i` is `x.v_.index()` and `j` is `y.v_.index()`.

#### template<sized_sentinel_for<I> I2, sized_sentinel_for<I> S2>
```cpp
friend constexpr iter_difference_t<I2> operator-(const common_iterator& x, const common_iterator<I2, S2>& y);
```

5. **Preconditions**: `x.v_.valueless_by_exception()` and `y.v_.valueless_by_exception()` are each false.
6. **Returns**: `0` if `i` and `j` are each 1, and otherwise `get<i>(x.v_) - get<j>(y.v_)`, where `i` is `x.v_.index()` and `j` is `y.v_.index()`.

### 25.5.5.7 Customizations

#### friend constexpr decltype(auto) iter_move(const common_iterator& i)
```cpp
noexcept(noexcept(ranges::iter_move(declval<const I&>())))
```

1. **Preconditions**: `holds_alternative<I>(i.v_)` is true.
2. **Effects**: Equivalent to: `return ranges::iter_move(get<I>(i.v_));`

#### template<indirectly_swappable<I> I2, class S2>
```cpp
friend constexpr void iter_swap(const common_iterator& x, const common_iterator<I2, S2>& y)
```

3. **Preconditions**: `holds_alternative<I>(x.v_)` and `holds_alternative<I2>(y.v_)` are each true.
4. **Effects**: Equivalent to `ranges::iter_swap(get<I>(x.v_), get<I2>(y.v_)).`
25.5.6 Default sentinel [default.sentinel]

namespace std {
    struct default_sentinel_t { };
}

Class `default_sentinel_t` is an empty type used to denote the end of a range. It can be used together with iterator types that know the bound of their range (e.g., `counted_iterator` (25.5.7.1)).

25.5.7 Counted iterators [iterators.counted]

25.5.7.1 Class template counted_iterator [counted.iterator]

Class template `counted_iterator` is an iterator adaptor with the same behavior as the underlying iterator except that it keeps track of the distance to the end of its range. It can be used together with `default_sentinel` in calls to generic algorithms to operate on a range of $N$ elements starting at a given position without needing to know the end position a priori.

[Example 1:]

```cpp
list<string> s;
// populate the list s with at least 10 strings
vector<string> v;
// copies 10 strings into v:
ranges::copy(counted_iterator(s.begin(), 10), default_sentinel, back_inserter(v));
```

End example

Two values $i_1$ and $i_2$ of types `counted_iterator<I1>` and `counted_iterator<I2>` refer to elements of the same sequence if and only if there exists some integer $n$ such that `next(i1.base(), i1.count() + n)` and `next(i2.base(), i2.count() + n)` refer to the same (possibly past-the-end) element.

```cpp
namespace std {
    template<input_or_output_iterator I>
    class counted_iterator {
        public:
            using iterator_type = I;
            using value_type = iter_value_t<I>;
            // present only
            // if I models indirectly_readable
            using difference_type = iter_difference_t<I>;
            using iterator_concept = typename I::iterator_concept;
            // present only
            // if the qualified-id I::iterator_concept is valid and denotes a type
            using iterator_category = typename I::iterator_category;
            // present only
            // if the qualified-id I::iterator_category is valid and denotes a type
            constexpr counted_iterator() requires default_initializable<I> = default;
            constexpr counted_iterator(I x, iter_difference_t<I> n);
            template<class I2>
            requires convertible_to<const I2&, I>
            constexpr counted_iterator(const counted_iterator<I2>& x);

            constexpr const I& base() const & noexcept;
            constexpr I base() &&;
            constexpr iter_difference_t<I> count() const noexcept;
            constexpr decltype(auto) operator*();
            constexpr decltype(auto) operator*() const
                requires dereferenceable<const I>;
            constexpr auto operator->() const noexcept
                requires contiguous_iterator<I>;

            constexpr counted_iterator& operator++();
            constexpr decltype(auto) operator++(int);
            constexpr counted_iterator operator++(int)
                requires forward_iterator<I>;
    }
```

§ 25.5.7.1 © ISO/IEC 1173
constexpr counted_iterator& operator--() 
  requires bidirectional_iterator<I>
constexpr counted_iterator operator--(int) 
  requires bidirectional_iterator<I>
constexpr counted_iterator operator+((iter_difference_t<I> n) const 
  requires random_access_iterator<I>
friend constexpr counted_iterator operator+(( 
    iter_difference_t<I> n, const counted_iterator& x) 
  requires random_access_iterator<I>
constexpr counted_iterator& operator+=(iter_difference_t<I> n) 
  requires random_access_iterator<I>
constexpr counted_iterator operator-(iter_difference_t<I> n) const 
  requires random_access_iterator<I>
template<common_with<I> I2> 
  friend constexpr iter_difference_t<I2> operator-( 
    const counted_iterator& x, const counted_iterator<I2>& y); 
friend constexpr iter_difference_t<I> operator-( 
  default_sentinel_t, const counted_iterator& y); 
constexpr counted_iterator& operator-=(iter_difference_t<I> n) 
  requires random_access_iterator<I>
constexpr decltype(auto) operator[](iter_difference_t<I> n) const 
  requires random_access_iterator<I>
friend constexpr counted_iterator I2> 
  friend constexpr bool operator==( 
    const counted_iterator& x, const counted_iterator<I2>& y));
friend constexpr bool operator==( 
  default_sentinel_t, const counted_iterator& y);
friend constexpr strong_ordering operator<=>( 
  const counted_iterator& x, const counted_iterator<I2>& y); 
friend constexpr decltype(auto) iter_move(const counted_iterator& i) 
  noexcept(ranges::iter_move(i.current)) 
  requires input_iterator<I>
friend constexpr iterator_traits<counted_iterator<I>> : iterator_traits<I> 
  noexcept(ranges::iter_move(x.current, y.current))
private: 
  I current = I(); 
  iter_difference_t<I> length = 0; 
};

25.5.7.2 Constructors and conversions

constexpr counted_iterator(I i, iter_difference_t<I> n);

1  Preconditions: n >= 0.
2  Effects: Initializes current with std::move(i) and length with n.
template<class I2>
requires convertible_to<const I2&, I>
constexpr counted_iterator(const counted_iterator<I2>& x);

Effects: Initializes current with x.current and length with x.length.

template<class I2>
requires assignable_from<I&, const I2&>
constexpr counted_iterator& operator=(const counted_iterator<I2>& x);

Effects: Assigns x.current to current and x.length to length.

25.5.7.3 Accessors

constexpr const I& base() const & noexcept;

Effects: Equivalent to: return current;

constexpr I base() &&;

Returns: std::move(current).

constexpr iter_difference_t<I> count() const noexcept;

Effects: Equivalent to: return length;

25.5.7.4 Element access

constexpr decltype(auto) operator*();
constexpr decltype(auto) operator*() const
requires dereferenceable<const I>;

Preconditions: length > 0 is true.

Effects: Equivalent to: return *current;

constexpr auto operator->() const noexcept
requires contiguous_iterator<I>;

Effects: Equivalent to: return to_address(current);

constexpr decltype(auto) operator[](iter_difference_t<I> n) const
requires random_access_iterator<I>;

Preconditions: n < length.

Effects: Equivalent to: return current[n];

25.5.7.5 Navigation

constexpr counted_iterator& operator++();

Preconditions: length > 0.

Effects: Equivalent to:
++current;
--length;
return *this;

constexpr decltype(auto) operator++(int);

Preconditions: length > 0.

Effects: Equivalent to:
--length;
try { return current++; }
catch(...) { ++length; throw; }

constexpr counted_iterator operator++(int)
requires forward_iterator<I>;

Effects: Equivalent to:
counted_iterator tmp = *this;
++*this;
return tmp;

constexpr counted_iterator& operator--() requires bidirectional_iterator<I>;

Effects: Equivalent to:
- --current;
+ length;
return *this;

constexpr counted_iterator operator--(int) requires bidirectional_iterator<I>;

Effects: Equivalent to:
counted_iterator tmp = *this;
--*this;
return tmp;

constexpr counted_iterator operator+(iter_difference_t<I> n) const requires random_access_iterator<I>;

Effects: Equivalent to:
return counted_iterator(current + n, length - n);

friend constexpr counted_iterator operator+(iter_difference_t<I> n, const counted_iterator& x) requires random_access_iterator<I>;

Effects: Equivalent to: return x + n;

constexpr counted_iterator& operator+=(iter_difference_t<I> n) requires random_access_iterator<I>;

Preconditions: n <= length.

Effects: Equivalent to:
current += n;
length -= n;
return *this;

constexpr counted_iterator operator-(iter_difference_t<I> n) const requires random_access_iterator<I>;

Effects: Equivalent to: return counted_iterator(current - n, length + n);

template<common_with<I> I2>
friend constexpr iter_difference_t<I2> operator-(
    const counted_iterator& x, const counted_iterator<I2>& y);

Preconditions: x and y refer to elements of the same sequence (25.5.7.1).

Effects: Equivalent to: return y.length - x.length;

friend constexpr iter_difference_t<I> operator-(
    const counted_iterator& x, default_sentinel_t);

Effects: Equivalent to: return -x.length;

friend constexpr iter_difference_t<I> operator-(
    default_sentinel_t, const counted_iterator& y);

Effects: Equivalent to: return y.length;

constexpr counted_iterator& operator-=(iter_difference_t<I> n) requires random_access_iterator<I>;

Preconditions: -n <= length.

Effects: Equivalent to:
current -= n;

§ 25.5.7.5
length += n;
return *this;

25.5.7.6 Comparisons

```cpp
template<common_with<I> I2>
friend constexpr bool operator==(const counted_iterator& x, const counted_iterator<I2>& y);
```

1 Preconditions: x and y refer to elements of the same sequence (25.5.7.1).
2 Effects: Equivalent to: return x.length == y.length;

```cpp
friend constexpr bool operator==(const counted_iterator& x, default_sentinel_t);
```

3 Effects: Equivalent to: return x.length == 0;

```cpp
template<common_with<I> I2>
friend constexpr strong_ordering operator<=>(const counted_iterator& x, const counted_iterator<I2>& y);
```

4 Preconditions: x and y refer to elements of the same sequence (25.5.7.1).
5 Effects: Equivalent to: return y.length <=> x.length;

[Note 1: The argument order in the Effects: element is reversed because length counts down, not up. — end note]

25.5.7.7 Customizations

```cpp
friend constexpr decltype(auto) iter_move(const counted_iterator& i)
    noexcept(noexcept(ranges::iter_move(i.current)))
    requires input_iterator<I>;
```

1 Preconditions: i.length > 0 is true.
2 Effects: Equivalent to: return ranges::iter_move(i.current);

```cpp
template<indirectly_swappable<I> I2>
friend constexpr void iter_swap(const counted_iterator& x, const counted_iterator<I2>& y);
```

3 Preconditions: Both x.length > 0 and y.length > 0 are true.
4 Effects: Equivalent to ranges::iter_swap(x.current, y.current).

25.5.8 Unreachable sentinel

Class `unreachable_sentinel_t` can be used with any `weakly_incrementable` type to denote the “upper bound” of an unbounded interval.

1 [Example 1:
```cpp
char* p;
// set p to point to a character buffer containing newlines
char* nl = find(p, unreachable_sentinel, '\n');
```
Provided a newline character really exists in the buffer, the use of unreachable_sentinel above potentially makes the call to `find` more efficient since the loop test against the sentinel does not require a conditional branch. — end example]

```cpp
namespace std {
    struct unreachable_sentinel_t {
        template<weakly_incrementable I>
            friend constexpr bool operator==(unreachable_sentinel_t, const I&) noexcept
                { return false; }
    };
}
```
25.6 Stream iterators

25.6.1 General

To make it possible for algorithmic templates to work directly with input/output streams, appropriate iterator-like class templates are provided.

[Example 1:

```cpp
partial_sum(istream_iterator<double, char>(cin),
            istream_iterator<double, char>(),
            ostream_iterator<double, char>(cout, "\n");
```

reads a file containing floating-point numbers from cin, and prints the partial sums onto cout. — end example]

25.6.2 Class template istream_iterator

25.6.2.1 General

The class template `istream_iterator` is an input iterator (25.3.5.3) that reads successive elements from the input stream for which it was constructed.

```cpp
namespace std {
    template<class T, class charT = char, class traits = char_traits<charT>,
             class Distance = ptrdiff_t>
    class istream_iterator {
        public:
            using iterator_category = input_iterator_tag;
            using value_type = T;
            using difference_type = Distance;
            using pointer = const T*;
            using reference = const T&;
            using char_type = charT;
            using traits_type = traits;
            using istream_type = basic_istream<charT,traits>;

            constexpr istream_iterator();
            constexpr istream_iterator(default_sentinel_t);
            istream_iterator(istream_type& s);
            constexpr istream_iterator(const istream_iterator& x) noexcept(see below);
            ~istream_iterator() = default;
            istream_iterator& operator=(const istream_iterator&) = default;

            const T& operator*() const;
            const T* operator->() const;
            istream_iterator& operator++();
            istream_iterator operator++(int);

            friend bool operator==(const istream_iterator& i, default_sentinel_t);

        private:
            basic_istream<charT,traits>* in_stream; // exposition only
            T value; // exposition only
        }
    } // istream_iterator
}
```

The type `T` shall meet the `Cpp17DefaultConstructible`, `Cpp17CopyConstructible`, and `Cpp17CopyAssignable` requirements.

25.6.2.2 Constructors and destructor

```cpp
constexpr istream_iterator();
constexpr istream_iterator(default_sentinel_t);
```

*Effects:* Constructs the end-of-stream iterator, value-initializing `value`.

*Postconditions:* `in_stream == nullptr` is true.

*Remarks:* If the initializer `T()` in the declaration `auto x = T();` is a constant initializer (7.7), then these constructors are `constexpr` constructors.
istream_iterator(istream_type& s);

*Effects:* Initializes in_stream with addressof(s), value-initializes value, and then calls operator++().

constexpr istream_iterator(const istream_iterator& x) noexcept(see below);

*Effects:* Initializes in_stream with x.in_stream and initializes value with x.value.

*Remarks:* An invocation of this constructor may be used in a core constant expression if and only if the initialization of value from x.value is a constant subexpression (3.14). The exception specification is equivalent to is_nothrow_copy_constructible_v<T>.

~istream_iterator() = default;

*Remarks:* If is_trivially_destructible_v<T> is true, then this destructor is trivial.

### 25.6.2.3 Operations [istream.iterator.ops]

const T& operator*() const;

*Preconditions:* in_stream != nullptr is true.

*Returns:* value.

const T* operator->() const;

*Preconditions:* in_stream != nullptr is true.

*Returns:* addressof(value).

istream_iterator& operator++();

*Preconditions:* in_stream != nullptr is true.

*Effects:* Equivalent to:

```cpp
if (!(*in_stream >> value))
in_stream = nullptr;
```

*Returns:* *this.

istream_iterator operator++(int);

*Preconditions:* in_stream != nullptr is true.

*Effects:* Equivalent to:

```cpp
istream_iterator tmp = *this;
++*this;
return tmp;
```

### 25.6.3 Class template ostream_iterator [ostream.iterator]

#### 25.6.3.1 General [ostream.iterator.general]

*ostream_iterator* writes (using operator<<) successive elements onto the output stream from which it was constructed. If it was constructed with charT* as a constructor argument, this string, called a *delimiter string*, is written to the stream after every T is written.

```cpp
namespace std {
  template<class T, class charT = char, class traits = char_traits<charT>>
  class ostream_iterator {
    public:
      using iterator_category = output_iterator_tag;
      using value_type = void;
      using difference_type = ptrdiff_t;
```

```cpp
} // namespace std
```
using pointer = void;
using reference = void;
using char_type = charT;
using traits_type = traits;
using ostream_type = basic_ostream<charT,traits>;

ostream_iterator(ostream_type& s);
ostream_iterator(ostream_type& s, const charT* delimiter);
~ostream_iterator();
ostream_iterator& operator=(const ostream_iterator&);
ostream_iterator& operator=(const T& value);
ostream_iterator& operator*();
ostream_iterator& operator++();
ostream_iterator& operator++(int);

private:
    basic_ostream<charT,traits>* out_stream;     // exposition only
    const charT* delim;                          // exposition only
};

25.6.3.2 Constructors and destructor

ostream_iterator(ostream_type& s);

Effects: Initializes out_stream with addressof(s) and delim with nullptr.

ostream_iterator(ostream_type& s, const charT* delimiter);

Effects: Initializes out_stream with addressof(s) and delim with delimiter.

25.6.3.3 Operations

ostream_iterator& operator=(const T& value);

Effects: As if by:
*out_stream << value;
if (delim)
*out_stream << delim;
return *this;

ostream_iterator& operator*();

Returns: *this.

ostream_iterator& operator++();

Returns: *this.

ostream_iterator& operator++(int);

Returns: *this.

25.6.4 Class template istreambuf_iterator

25.6.4.1 General

The class template istreambuf_iterator defines an input iterator (25.3.5.3) that reads successive characters from the streambuf for which it was constructed. operator* provides access to the current input character, if any. Each time operator++ is evaluated, the iterator advances to the next input character. If the end of stream is reached (streambuf_type::sgetc() returns traits::eof()), the iterator becomes equal to the end-of-stream iterator value. The default constructor istreambuf_iterator() and the constructor istreambuf_iterator(nullptr) both construct an end-of-stream iterator object suitable for use as an end-of-range. All specializations of istreambuf_iterator shall have a trivial copy constructor, a constexpr default constructor, and a trivial destructor.

The result of operator*() on an end-of-stream iterator is undefined. For any other iterator value a char_type value is returned. It is impossible to assign a character via an input iterator.
namespace std {
    template<class charT, class traits = char_traits<charT> >
    class istreambuf_iterator {
public:
    using iterator_category = input_iterator_tag;
    using value_type = charT;
    using difference_type = typename traits::off_type;
    using pointer = unspecified;
    using reference = charT;
    using char_type = charT;
    using traits_type = traits;
    using int_type = typename traits::int_type;
    using streambuf_type = basic_streambuf<charT,traits>;
    using istream_type = basic_istream<charT,traits>;

    // 25.6.4.2, class istreambuf_iterator::proxy
    class proxy;
    // exposition only

    constexpr istreambuf_iterator() noexcept;
    constexpr istreambuf_iterator(default_sentinel_t) noexcept;
    istreambuf_iterator(const istreambuf_iterator&) noexcept = default;
    ~istreambuf_iterator() = default;
    istreambuf_iterator(istream_type& s) noexcept;
    istreambuf_iterator(streambuf_type* s) noexcept;
    istreambuf_iterator(const proxy& p) noexcept;
    istreambuf_iterator& operator=(const istreambuf_iterator&) noexcept = default;

    charT operator*() const;
    istreambuf_iterator& operator++();
    proxy operator++(int);

    bool equal(const istreambuf_iterator& b) const;
    friend bool operator==(const istreambuf_iterator& i, default_sentinel_t s);

private:
    streambuf_type* sbuf_;  // exposition only
    
};

25.6.4.2 Class istreambuf_iterator::proxy

Class istreambuf_iterator<charT,traits>::proxy is for exposition only. An implementation is permitted to provide equivalent functionality without providing a class with this name. Class istreambuf_iterator<charT,traits>::proxy provides a temporary placeholder as the return value of the post-increment operator (operator++). It keeps the character pointed to by the previous value of the iterator for some possible future access to get the character.

namespace std {
    template<class charT, class traits>
    class istreambuf_iterator<charT, traits>::proxy {
    // exposition only
    
    private:
        charT keep_;  // exposition only
        
    public:
        charT operator*() { return keep_; }
        
    };  // proxy

25.6.4.3 Constructors

For each istreambuf_iterator constructor in this subclause, an end-of-stream iterator is constructed if and only if the exposition-only member sbuf_ is initialized with a null pointer value.

constexpr istreambuf_iterator() noexcept;

1
25.6.4.4 Operations

`charT operator*() const;`  
**Returns:** The character obtained via the `streambuf` member `sbuf_->sgetc()`.

`istreambuf_iterator& operator++();`  
**Effects:** As if by `sbuf_->sbumpc()`.

`proxy operator++(int);`  
**Returns:** `*this`.

`bool equal(const istreambuf_iterator& b) const;`  
**Returns:** `true` if and only if both iterators are at end-of-stream, or neither is at end-of-stream, regardless of what `streambuf` object they use.

```cpp
template<class charT, class traits>
bool operator==(const istreambuf_iterator<charT, traits>& a, const istreambuf_iterator<charT, traits>& b);`  
**Returns:** `a.equal(b)`.

`friend bool operator==(const istreambuf_iterator& i, default_sentinel_t s);`  
**Returns:** `i.equal(s)`.

25.6.5 Class template `ostreambuf_iterator`  

25.6.5.1 General

The class template `ostreambuf_iterator` writes successive characters onto the output stream from which it was constructed.

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class ostreambuf_iterator {
        public:
            using iterator_category = output_iterator_tag;
            using value_type = void;
            using difference_type = ptrdiff_t;
            using pointer = void;
            using reference = void;
            using char_type = charT;
            using traits_type = traits;
            using streambuf_type = basic_streambuf<charT, traits>;
            using ostream_type = basic_ostream<charT, traits>;

            ostreambuf_iterator(ostream_type& s) noexcept;
            ostreambuf_iterator(streambuf_type* s) noexcept;
            ostreambuf_iterator& operator=(charT c);
    }
}`
```
ostreambuf_iterator& operator*();
ostreambuf_iterator& operator++();
ostreambuf_iterator& operator++(int);
bool failed() const noexcept;

private:
    streambuf_type* sbuf_;          // exposition only
};

25.6.5.2 Constructors [ostreambuf.iter.cons]

ostreambuf_iterator(ostream_type& s) noexcept;
   Preconditions: s.rdbuf() is not a null pointer.
   Effects: Initializes sbuf_ with s.rdbuf().

ostreambuf_iterator(streambuf_type* s) noexcept;
   Preconditions: s is not a null pointer.
   Effects: Initializes sbuf_ with s.

25.6.5.3 Operations [ostreambuf.iter.ops]

ostreambuf_iterator& operator=(charT c);
   Effects: If failed() yields false, calls sbuf_->sputc(c); otherwise has no effect.
   Returns: *this.

ostreambuf_iterator& operator*();
   Returns: *this.

ostreambuf_iterator& operator++();
ostreambuf_iterator& operator++(int);
   Returns: *this.

bool failed() const noexcept;
   Returns: true if in any prior use of member operator=, the call to sbuf_->sputc() returned
   traits::eof(); or false otherwise.

25.7 Range access [iterator.range]

In addition to being available via inclusion of the <iterator> header, the function templates in 25.7 are
available when any of the following headers are included: <array> (24.3.2), <deque> (24.3.3), <flat_map>
(24.6.4), <flat_set> (24.6.5), <forward_list> (24.3.4), <inplace_vector> (24.3.7), <list> (24.3.5),
<map> (24.4.2), <regex> (32.3), <set> (24.4.3), <span> (24.7.2.1), <string> (23.4.2), <string_view>
(23.3.2), <unordered_map> (24.5.2), <unordered_set> (24.5.3), and <vector> (24.3.6).

template<class C> constexpr auto begin(C& c) -> decltype(c.begin());
template<class C> constexpr auto begin(const C& c) -> decltype(c.begin());
   Returns: c.begin().

template<class C> constexpr auto end(C& c) -> decltype(c.end());
template<class C> constexpr auto end(const C& c) -> decltype(c.end());
   Returns: c.end().

template<class T, size_t N> constexpr T* begin(T (&array)[N]) noexcept;
   Returns: array.

template<class T, size_t N> constexpr T* end(T (&array)[N]) noexcept;
   Returns: array + N.
template<class C> constexpr auto cbegin(const C& c) noexcept(noexcept(std::begin(c)))
    -> decltype(std::begin(c));
Returns: std::begin(c).

template<class C> constexpr auto cend(const C& c) noexcept(noexcept(std::end(c)))
    -> decltype(std::end(c));
Returns: std::end(c).

template<class C> constexpr auto rbegin(const C& c) -> decltype(c.rbegin());
template<class C> constexpr auto rend(const C& c) -> decltype(c.rend());
Returns: c.rbegin(), c.rend().

template<class E> constexpr reverse_iterator<const E*> rbegin(initializer_list<E> il);
Returns: reverse_iterator<const E*>(il.end()).

template<class E> constexpr reverse_iterator<const E*> rend(initializer_list<E> il);
Returns: reverse_iterator<const E*>(il.begin()).

template<class C> constexpr auto crbegin(const C& c) -> decltype(std::rbegin(c));
Returns: std::rbegin(c).

template<class C> constexpr auto crend(const C& c) -> decltype(std::rend(c));
Returns: std::rend(c).

template<class C> constexpr auto size(const C& c) -> decltype(c.size());
Returns: c.size().

template<class C> constexpr auto ssize(const C& c)
    -> common_type_t<ptrdiff_t, make_signed_t<decltype(c.size())>>;
Effects: Equivalent to:
    return static_cast<common_type_t<ptrdiff_t, make_signed_t<decltype(c.size())>>>(c.size());

template<class C> constexpr auto data(C& c) -> decltype(c.data());

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template<class C> constexpr auto data(const C& c) -> decltype(c.data());

Returns: c.data() .

template<class T, size_t N> constexpr T* data(T (&array)[N]) noexcept;

Returns: array .

template<class E> constexpr const E* data(initializer_list<E> il) noexcept;

Returns: il.begin() .
26 Ranges library

26.1 General

1 This Clause describes components for dealing with ranges of elements.

2 The following subclauses describe range and view requirements, and components for range primitives and range generators as summarized in Table 95.

Table 95 — Ranges library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.3</td>
<td>Range access</td>
</tr>
<tr>
<td>26.4</td>
<td>Requirements</td>
</tr>
<tr>
<td>26.5</td>
<td>Range utilities</td>
</tr>
<tr>
<td>26.6</td>
<td>Range factories</td>
</tr>
<tr>
<td>26.7</td>
<td>Range adaptors</td>
</tr>
<tr>
<td>26.8</td>
<td>Range generators</td>
</tr>
</tbody>
</table>

26.2 Header <ranges> synopsis

```cpp
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2
#include <iterator> // see 25.2

namespace std::ranges {
    inline namespace unspecified {
        // 26.3, range access
        inline constexpr unspecified begin = unspecified; // freestanding
        inline constexpr unspecified end = unspecified; // freestanding
        inline constexpr unspecified cbegin = unspecified; // freestanding
        inline constexpr unspecified cend = unspecified; // freestanding
        inline constexpr unspecified rbegin = unspecified; // freestanding
        inline constexpr unspecified rend = unspecified; // freestanding
        inline constexpr unspecified crbegin = unspecified; // freestanding
        inline constexpr unspecified crend = unspecified; // freestanding
        inline constexpr unspecified size = unspecified; // freestanding
        inline constexpr unspecified ssize = unspecified; // freestanding
        inline constexpr unspecified empty = unspecified; // freestanding
        inline constexpr unspecified data = unspecified; // freestanding
        inline constexpr unspecified cdata = unspecified; // freestanding
    }

    // 26.4.2, ranges
    template<class T>
        concept range = see below; // freestanding
    template<class T>
        constexpr bool enable_borrowed_range = false; // freestanding
    template<class T>
        concept borrowed_range = see below; // freestanding
    template<class T>
        using iterator_t = decltype(ranges::begin(declval<T&>())); // freestanding
    template<class R>
        using sentinel_t = decltype(ranges::end(declval<R&>())); // freestanding
}
```

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template<range R>
using const_iterator_t = decltype(ranges::cbegin(declval<R&>())); // freestanding

template<range R>
using const_sentinel_t = decltype(ranges::cend(declval<R&>())); // freestanding

template<range R>
using range_difference_t = iter_difference_t<iterator_t<R>>; // freestanding

template<sized_range R>
using range_size_t = decltype(ranges::size(declval<R&>())); // freestanding

template<range R>
using range_value_t = iter_value_t<iterator_t<R>>; // freestanding

template<range R>
using range_reference_t = iter_reference_t<iterator_t<R>>; // freestanding

template<range R>
using range_const_reference_t = iter_const_reference_t<iterator_t<R>>; // freestanding

template<range R>
using range_rvalue_reference_t = iter_rvalue_reference_t<iterator_t<R>>; // freestanding

template<range R>
using range_common_reference_t = iter_common_reference_t<iterator_t<R>>; // freestanding

// 26.4.3, sized ranges
template<class>
constexpr bool disable_sized_range = false; // freestanding

template<class T>
concept sized_range = see below; // freestanding

// 26.4.4, views
template<class T>
constexpr bool enable_view = see below; // freestanding

struct view_base {}; // freestanding

template<class T>
concept view = see below; // freestanding

// 26.4.5, other range refinements
template<class R, class T>
concept output_range = see below; // freestanding

template<class T>
concept input_range = see below; // freestanding

template<class T>
concept forward_range = see below; // freestanding

template<class T>
concept bidirectional_range = see below; // freestanding

template<class T>
concept random_access_range = see below; // freestanding

template<class T>
concept contiguous_range = see below; // freestanding

template<class T>
concept common_range = see below; // freestanding

template<class T>
concept viewable_range = see below; // freestanding

template<class T>
concept constant_range = see below; // freestanding
// 26.5.3, class template view_interface
template<class D>
  requires is_class_v<D> && same_as<D, remove_cv_t<D> >>
class view_interface; // freestanding

// 26.5.4, sub-ranges
enum class subrange_kind : bool { unsized, sized }; // freestanding
template<input_or_output_iterator I, sentinel_for<I> S = I, subrange_kind K = see below>
  requires (K == subrange_kind::sized || !sized_sentinel_for<S, I>)
class subrange; // freestanding

template<class I, class S, subrange_kind K>
  constexpr bool enable_borrowed_range<subrange<I, S, K>> = true; // freestanding

template<size_t N, class I, class S, subrange_kind K>
  requires (N == 0 && copyable<I>) || N == 1)
  constexpr auto get(const subrange<I, S, K>& r); // freestanding

namespace std {
  using ranges::get;
}

namespace std::ranges {
  // 26.5.5, dangling iterator handling
  struct dangling;

  // 26.5.6, class template elements_of
  template<range R, class Allocator = allocator<byte>>
    struct elements_of;

template<range R>
  using borrowed_iterator_t = see below; // freestanding

template<range R>
  using borrowed_subrange_t = see below; // freestanding

  // 26.5.7, range conversions
  template<class C, input_range R, class... Args> requires (!view<C>)
    constexpr C to(R&& r, Args&&... args); // freestanding
  template<template<class...> class C, input_range R, class... Args>
    constexpr auto to(R&& r, Args&&... args); // freestanding
  template<class C, class... Args> requires (!view<C>)
    constexpr auto to(Args&&... args); // freestanding
  template<template<class...> class C, class... Args>
    constexpr auto to(Args&&... args); // freestanding

  // 26.6.2, empty view
  template<class T>
    requires is_object_v<T>
class empty_view; // freestanding

template<class T>
  constexpr bool enable_borrowed_range<empty_view<T>> = true; // freestanding

namespace views {
  template<class T>
    constexpr empty_view<T> empty{}; // freestanding
}
// 26.6.3, single view
template<move_constructible T>
    requires is_object_v<T>
class single_view;
    // freestanding

namespace views { inline constexpr unspecified single = unspecified; }
    // freestanding

template<bool Const, class T>
    using maybe_const = conditional_t<Const, const T, T>;
    // exposition only

// 26.6.4, iota view
template<weakly_incrementable W, semiregular Bound = unreachable_sentinel_t>
    requires weakly-equality-comparable-with<W, Bound> && copyable<W>
class iota_view;
    // freestanding

template<class W, class Bound>
    constexpr bool enable_borrowed_range<iota_view<W, Bound>> = true;
    // freestanding

namespace views { inline constexpr unspecified iota = unspecified; }
    // freestanding

// 26.6.5, repeat view
template<move_constructible T, semiregular Bound = unreachable_sentinel_t>
    requires see below
class repeat_view;
    // freestanding

namespace views { inline constexpr unspecified repeat = unspecified; }
    // freestanding

// 26.6.6, istream view
template<movable Val, class CharT, class Traits = char_traits<CharT>>
    requires see below
class basic_istream_view;

template<class Val>
    using istream_view = basic_istream_view<Val, char>;

template<class Val>
    using wistream_view = basic_istream_view<Val, wchar_t>;

namespace views { template<class T> constexpr unspecified istream = unspecified; }

// 26.7.2, range adaptor objects
template<class D>
    requires is_class_v<D> && same_as<D, remove_cv_t<D>>
class range_adaptor_closure { };
    // freestanding

// 26.7.6, all view
namespace views {
    inline constexpr unspecified all = unspecified;
        // freestanding

    template<viewable_range R>
        using all_t = decltype(all(declval<R>()));
    } // freestanding

// 26.7.6.2, ref view
template<range R>
    requires is_object_v<R>
class ref_view;
    // freestanding

template<class T>
    constexpr bool enable_borrowed_range<ref_view<T>> = true;
    // freestanding

// 26.7.6.3, owning view
template<range R>
    requires see below
class owning_view;
    // freestanding
template<class T>
constexpr bool enable_borrowed_range<owning_view<T>> =
  enable_borrowed_range<T>;

// 26.7.7, as rvalue view
template<class V>
requires input_range<V>
class as_rvalue_view;

namespace views { inline constexpr unspecified as_rvalue = unspecified; }

// 26.7.8, filter view
template<input_range V, indirect_unary_predicate<iterator_t<V>> Pred>
requires view<V> && is_object_v<Pred>
class filter_view;

namespace views { inline constexpr unspecified filter = unspecified; }

// 26.7.9, transform view
template<input_range V, move_constructible F>
requires view<V> && is_object_v<F> &&
  regular_invocable<F&, range_reference_t<V>> &&
  can_reference<invoke_result_t<F&, range_reference_t<V>>> class transform_view;

namespace views { inline constexpr unspecified transform = unspecified; }

// 26.7.10, take view
template<class T>
constexpr bool enable_borrowed_range<take_view<T>> =
  enable_borrowed_range<T>;

namespace views { inline constexpr unspecified take = unspecified; }

// 26.7.11, take while view
template<class V, class Pred>
requires input_range<V> && is_object_v<Pred> &&
  indirect_unary_predicate<const Pred, iterator_t<V>>
class take_while_view;

namespace views { inline constexpr unspecified take_while = unspecified; }

// 26.7.12, drop view
template<class T>
constexpr bool enable_borrowed_range<drop_view<T>> =
  enable_borrowed_range<T>;

namespace views { inline constexpr unspecified drop = unspecified; }

// 26.7.13, drop while view
template<class V, class Pred>
requires input_range<V> && is_object_v<Pred> &&
  indirect_unary_predicate<const Pred, iterator_t<V>>
class drop_while_view;

namespace views { inline constexpr unspecified drop_while = unspecified; }
template<class T, class Pred>
constexpr bool enable_borrowed_range<drop_while_view<T, Pred>> =
    enable_borrowed_range<T>;

namespace views { inline constexpr unspecified drop_while = unspecified; }

// 26.7.14, join view
template<input_range V>
    requires view<V> && input_range_range_reference_t<V>
class join_view;
namespace views { inline constexpr unspecified join = unspecified; }

// 26.7.15, join with view
template<input_range V, forward_range Pattern>
    requires see below
class join_with_view;
namespace views { inline constexpr unspecified join_with = unspecified; }

// 26.7.16, lazy split view
template<class R>
    concept tiny-range = see below; // exposition only

template<input_range V, forward_range Pattern>
    requires view<V> && view<Pattern> &&
    indirectly_comparable<iterator_t<V>, iterator_t<Pattern>>, ranges::equal_to &&
    (forward_range<V> || tiny_range<Pattern>)
class lazy_split_view;
namespace views { inline constexpr unspecified lazy_split = unspecified; }

// 26.7.17, split view
template<forward_range V, forward_range Pattern>
    requires view<V> && view<Pattern> &&
    indirectly_comparable<iterator_t<V>, iterator_t<Pattern>>, ranges::equal_to
class split_view;
namespace views { inline constexpr unspecified split = unspecified; }

// 26.7.18, concat view
template<input_range... Views>
    requires see below
class concat_view;
namespace views { inline constexpr unspecified concat = unspecified; }

// 26.7.19, counted view
namespace views { inline constexpr unspecified counted = unspecified; }

// 26.7.20, common view
template<View V>
    requires (!common_range<V> && copyable<iterator_t<V>>)  
class common_view;

template<class T>
    constexpr bool enable_borrowed_range<common_view<T>> =
        enable_borrowed_range<T>;
namespace views { inline constexpr unspecified common = unspecified; }
// 26.7.21, reverse view
template<view V>
    requires bidirectional_range<V>
class reverse_view;  // freestanding

template<class T>
    constexpr bool enable_borrowed_range<reverse_view<T>> = enable_borrowed_range<T>;  // freestanding

namespace views { inline constexpr unspecified reverse = unspecified; }  // freestanding

// 26.7.22, as const view
template<input_range R>
    constexpr auto& possibly-const-range(R& r) noexcept {
        if constexpr (constant_range<const R> && !constant_range<R>) {
            return const_cast<const R&>(r);
        } else {
            return r;
        }
    }

template<view V>
    requires input_range<V>
class as_const_view;  // freestanding

template<class T>
    constexpr bool enable_borrowed_range<as_const_view<T>> = enable_borrowed_range<T>;  // freestanding

namespace views { inline constexpr unspecified as_const = unspecified; }  // freestanding

// 26.7.23, elements view
template<input_range V, size_t N>
    requires see below
class elements_view;  // freestanding

template<class T, size_t N>
    constexpr bool enable_borrowed_range<elements_view<T, N>> = enable_borrowed_range<T>;  // freestanding

template<class R>
    using keys_view = elements_view<R, 0>;  // freestanding
template<class R>
    using values_view = elements_view<R, 1>;  // freestanding

namespace views {
    template<size_t N>
        constexpr unspecified elements = unspecified;  // freestanding
    inline constexpr auto keys = elements<0>;  // freestanding
    inline constexpr auto values = elements<1>;  // freestanding
}

// 26.7.24, enumerate view
template<view V>
    requires see below
class enumerate_view;  // freestanding

template<class View>
    constexpr bool enable_borrowed_range<enumerate_view<View>> = enable_borrowed_range<View>;  // freestanding

namespace views { inline constexpr unspecified enumerate = unspecified; }  // freestanding
// 26.7.25, zip view
template<input_range... Views>
  requires (view<Views> && ...) && (sizeof...(Views) > 0)
class zip_view; // freestanding

template<class... Views>
  constexpr bool enable_borrowed_range<zip_view<Views...>> =
    (enable_borrowed_range<Views> && ...); // freestanding

namespace views { inline constexpr unspecified zip = unspecified; }

// 26.7.26, zip transform view
template<move_constructible F, input_range... Views>
  requires (view<Views> && ...) && (sizeof...(Views) > 0) && is_object_v<F> &&
    regular_invocable<F&, range_reference_t<Views>...> &&
    can_reference<invoke_result_t<F&, range_reference_t<Views>...>>
class zip_transform_view; // freestanding

namespace views { inline constexpr unspecified zip_transform = unspecified; }

// 26.7.27, adjacent view
template<forward_range V, size_t N>
  requires view<V> && (N > 0)
class adjacent_view; // freestanding

template<class V, size_t N>
  constexpr bool enable_borrowed_range<adjacent_view<V, N>> =
    enable_borrowed_range<V>; // freestanding

namespace views { 
  template<size_t N>
    constexpr unspecified adjacent = unspecified; // freestanding
  inline constexpr auto pairwise = adjacent<2>; // freestanding
}

// 26.7.28, adjacent transform view
template<forward_range V, move_constructible F, size_t N>
  requires see below
class adjacent_transform_view; // freestanding

namespace views { 
  template<size_t N>
    constexpr unspecified adjacent_transform = unspecified; // freestanding
  inline constexpr auto pairwise_transform = adjacent_transform<2>; // freestanding
}

// 26.7.29, chunk view
template&view V
  requires input_range<V>
class chunk_view; // freestanding

template&view V
  requires forward_range<V>
class chunk_view<V>; // freestanding

template<class V>
  constexpr bool enable_borrowed_range<chunk_view<V>> =
    forward_range<V> && enable_borrowed_range<V>; // freestanding

namespace views { inline constexpr unspecified chunk = unspecified; }

§ 26.2
// 26.7.30, slide view
template<forward_range V>
    requires view<V>
class slide_view; // freestanding

template<class V>
    constexpr bool enable_borrowed_range<slide_view<V>> = enable_borrowed_range<V>; // freestanding

namespace views { inline constexpr unspecified slide = unspecified; } // freestanding

// 26.7.31, chunk by view
template<forward_range V, indirect_binary_predicate<iterator_t<V>, iterator_t<V>> Pred>
    requires view<V> && is_object_v<Pred>
class chunk_by_view; // freestanding

namespace views { inline constexpr unspecified chunk_by = unspecified; } // freestanding

// 26.7.32, stride view
template<input_range V>
    requires view<V>
class stride_view; // freestanding

template<class V>
    constexpr bool enable_borrowed_range<stride_view<V>> = enable_borrowed_range<V>; // freestanding

namespace views { inline constexpr unspecified stride = unspecified; } // freestanding

// 26.7.33, cartesian product view
template<input_range First, forward_range... Vs>
    requires (view<First> && ... && view<Vs>)
class cartesian_product_view; // freestanding

namespace views { inline constexpr unspecified cartesian_product = unspecified; } // freestanding

namespace std {
    namespace views = ranges::views; // freestanding

    template<class T> struct tuple_size;
    template<
        size_t I, class T>
struct tuple_element; // freestanding

    template<class I, class S, ranges::subrange_kind K>
struct tuple_size<ranges::subrange<I, S, K>>
    : integral_constant<
size_t, 2> {};

    template<class I, class S, ranges::subrange_kind K>
struct tuple_element<0, ranges::subrange<I, S, K>> {
    using type = I;
};

    template<class I, class S, ranges::subrange_kind K>
struct tuple_element<1, ranges::subrange<I, S, K>> {
    using type = S;
};

    template<class I, class S, ranges::subrange_kind K>
struct tuple_element<0, const ranges::subrange<I, S, K>> {
    using type = I;
};

    template<class I, class S, ranges::subrange_kind K>
struct tuple_element<1, const ranges::subrange<I, S, K>> {
    using type = S;
};

}
struct from_range_t { explicit from_range_t() = default; };  // freestanding
inline constexpr from_range_t from_range{};  // freestanding
}

Within this Clause, for an integer-like type `X` (25.3.4.4), `make-unsigned-like-t<X>` denotes `make_unsigned_-t<X>` if `X` is an integer type; otherwise, it denotes a corresponding unspecified unsigned-integer-like type of the same width as `X`. For an expression `x` of type `X`, `to-unsigned-like(x)` is `x` explicitly converted to `make-unsigned-like-t<X>`.

Also within this Clause, `make-signed-like-t<X>` for an integer-like type `X` denotes `make_signed_t<X>` if `X` is an integer type; otherwise, it denotes a corresponding unspecified signed-integer-like type of the same width as `X`.

26.3 Range access

26.3.1 General

In addition to being available via inclusion of the `<ranges>` header, the customization point objects in 26.3 are available when the header `<iterator>` (25.2) is included.

Within 26.3, the reified object of a subexpression `E` denotes

1. the same object as `E` if `E` is a glvalue, or
2. the result of applying the temporary materialization conversion (7.3.5) to `E` otherwise.

26.3.2 `ranges::begin`

The name `ranges::begin` denotes a customization point object (16.3.3.3.5).

Given a subexpression `E` with type `T`, let `t` be an lvalue that denotes the reified object for `E`. Then:

1. If `E` is an rvalue and `enable_borrowed_range<remove_cv_t<T>>` is false, `ranges::begin(E)` is ill-formed.
2. Otherwise, if `T` is an array type (9.3.4.5) and `remove_all_extents_t<T>` is an incomplete type, `ranges::begin(E)` is ill-formed with no diagnostic required.
3. Otherwise, if `T` is an array type, `ranges::begin(E)` is expression-equivalent to `t + 0`.
4. Otherwise, if `auto(t.begin())` is a valid expression whose type models `input_or_output_iterator`, `ranges::begin(E)` is expression-equivalent to `auto(t.begin())`.
5. Otherwise, if `T` is a class or enumeration type and `auto(begin(t))` is a valid expression whose type models `input_or_output_iterator` where the meaning of `begin` is established as-if by performing argument-dependent lookup only (6.5.4), then `ranges::begin(E)` is expression-equivalent to that expression.
6. Otherwise, `ranges::begin(E)` is ill-formed.

[Note 1: Diagnosable ill-formed cases above result in substitution failure when `ranges::begin(E)` appears in the immediate context of a template instantiation. — end note]

[Note 2: Whenever `ranges::begin(E)` is a valid expression, its type models `input_or_output_iterator`. — end note]

26.3.3 `ranges::end`

The name `ranges::end` denotes a customization point object (16.3.3.3.5).

Given a subexpression `E` with type `T`, let `t` be an lvalue that denotes the reified object for `E. Then:

1. If `E` is an rvalue and `enable_borrowed_range<remove_cv_t<T>>` is false, `ranges::end(E)` is ill-formed.
2. Otherwise, if `T` is an array type (9.3.4.5) and `remove_all_extents_t<T>` is an incomplete type, `ranges::end(E)` is ill-formed with no diagnostic required.
3. Otherwise, if `T` is an array of unknown bound, `ranges::end(E)` is ill-formed.
4. Otherwise, if `T` is an array, `ranges::end(E)` is expression-equivalent to `t + extent_v<T>.
5. Otherwise, if `auto(t.end())` is a valid expression whose type models `sentinel_for<iterator_t<T>>` then `ranges::end(E)` is expression-equivalent to `auto(t.end())`.

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(2.6) Otherwise, if \( T \) is a class or enumeration type and \( \text{auto}(\text{end}(t)) \) is a valid expression whose type models \( \text{sentinel_for<\text{iterator}_t<T>>} \), where the meaning of \( \text{end} \) is established as-if by performing argument-dependent lookup only (6.5.4), then \( \text{ranges}::\text{end}(E) \) is expression-equivalent to that expression.

(2.7) Otherwise, \( \text{ranges}::\text{end}(E) \) is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when \( \text{ranges}::\text{end}(E) \) appears in the immediate context of a template instantiation. —end note]

4 [Note 2: Whenever \( \text{ranges}::\text{end}(E) \) is a valid expression, the types \( S \) and \( I \) of \( \text{ranges}::\text{end}(E) \) and \( \text{ranges}::\text{begin}(E) \) model \( \text{sentinel_for}<S,I> \). —end note]

26.3.4 \( \text{ranges}::\text{cbegin} \)

The name \( \text{ranges}::\text{cbegin} \) denotes a customization point object (16.3.3.3.5). Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). Then:

(1.1) If \( E \) is a vvalue and \( \text{enable_borrowed_range<remove_cv_t<T>>()} \) is false, \( \text{ranges}::\text{cbegin}(E) \) is ill-formed.

(1.2) Otherwise, let \( U \) be \( \text{ranges}::\text{begin}(\text{possibly-const-range}(t)) \). \( \text{ranges}::\text{cbegin}(E) \) is expression-equivalent to \( \text{const_iterator<decltype(U)>}(U) \).

2 [Note 1: Whenever \( \text{ranges}::\text{cbegin}(E) \) is a valid expression, its type models \( \text{input_or_output_iterator} \) and \( \text{constant_iterator} \). —end note]

26.3.5 \( \text{ranges}::\text{cend} \)

The name \( \text{ranges}::\text{cend} \) denotes a customization point object (16.3.3.3.5). Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). Then:

(1.1) If \( E \) is a vvalue and \( \text{enable_borrowed_range<remove_cv_t<T>>()} \) is false, \( \text{ranges}::\text{cend}(E) \) is ill-formed.

(1.2) Otherwise, let \( U \) be \( \text{ranges}::\text{end}(\text{possibly-const-range}(t)) \). \( \text{ranges}::\text{cend}(E) \) is expression-equivalent to \( \text{const_sentinel}<\text{decltype}(U)>\end{note}

2 [Note 1: Whenever \( \text{ranges}::\text{cend}(E) \) is a valid expression, the types \( S \) and \( I \) of the expressions \( \text{ranges}::\text{cend}(E) \) and \( \text{ranges}::\text{cbegin}(E) \) model \( \text{sentinel_for}<S,I> \). If \( S \) models \( \text{input_iterator} \), then \( S \) also models \( \text{constant_iterator} \). —end note]

26.3.6 \( \text{ranges}::\text{rbegin} \)

The name \( \text{ranges}::\text{rbegin} \) denotes a customization point object (16.3.3.3.5).

2 Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). Then:

(2.1) If \( E \) is a vvalue and \( \text{enable_borrowed_range<remove_cv_t<T>>()} \) is false, \( \text{ranges}::\text{rbegin}(E) \) is ill-formed.

(2.2) Otherwise, if \( T \) is an array type (9.3.4.5) and \( \text{remove_all_extents_t<}T\text{>} \) is an incomplete type, \( \text{ranges}::\text{rbegin}(E) \) is ill-formed with no diagnostic required.

(2.3) Otherwise, if \( \text{auto(t.rbegin())} \) is a valid expression whose type models \( \text{input_or_output_iterator} \), \( \text{ranges}::\text{rbegin}(E) \) is expression-equivalent to \( \text{auto(t.rbegin())} \).

(2.4) Otherwise, if \( T \) is a class or enumeration type and \( \text{auto(rbegin(t))} \) is a valid expression whose type models \( \text{input_or_output_iterator} \) where the meaning of \( \text{rbegin} \) is established as-if by performing argument-dependent lookup only (6.5.4), then \( \text{ranges}::\text{rbegin}(E) \) is expression-equivalent to that expression.

(2.5) Otherwise, if both \( \text{ranges}::\text{begin}(t) \) and \( \text{ranges}::\text{end}(t) \) are valid expressions of the same type which models \( \text{bidirectional_iterator} \) (25.3.4.12), \( \text{ranges}::\text{rbegin}(E) \) is expression-equivalent to \( \text{make_reverse_iterator(ranges::end(t))} \).

(2.6) Otherwise, \( \text{ranges}::\text{rbegin}(E) \) is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when \( \text{ranges}::\text{rbegin}(E) \) appears in the immediate context of a template instantiation. —end note]

4 [Note 2: Whenever \( \text{ranges}::\text{rbegin}(E) \) is a valid expression, its type models \( \text{input_or_output_iterator} \). —end note]
26.3.7 ranges::rend

The name ranges::rend denotes a customization point object (16.3.3.3.5).

Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. Then:

(1.1) If E is an rvalue and enable_borrowed_range<remove_cv_t<T>> is false, ranges::rend(E) is ill-formed.

(1.2) Otherwise, let U be ranges::rend(possibly-const-range(t)). ranges::rend(E) is expression-equivalent to const_iterator<decltype(U)>().

2 [Note 1: Whenever ranges::rend(E) is a valid expression, its type models input_or_output_iterator and constant_iterator. — end note]

26.3.8 ranges::crbegin

The name ranges::crbegin denotes a customization point object (16.3.3.3.5). Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. Then:

(1.1) If E is an rvalue and enable_borrowed_range<remove_cv_t<T>> is false, ranges::crbegin(E) is ill-formed.

(1.2) Otherwise, let U be ranges::crbegin(possibly-const-range(t)). ranges::crbegin(E) is expression-equivalent to const_iterator<decltype(U)>().

2 [Note 1: Whenever ranges::crbegin(E) is a valid expression, the types S and I of the expressions ranges::rend(E) and ranges::begin(E) model sentinel_for<S, I>. — end note]

26.3.9 ranges::crend

The name ranges::crend denotes a customization point object (16.3.3.3.5). Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. Then:

(1.1) If E is an rvalue and enable_borrowed_range<remove_cv_t<T>> is false, ranges::crend(E) is ill-formed.

(1.2) Otherwise, let U be ranges::crend(possibly-const-range(t)). ranges::crend(E) is expression-equivalent to const_iterator<decltype(U)>().

2 [Note 1: Whenever ranges::crend(E) is a valid expression, the types S and I of the expressions ranges::crend(E) and ranges::crbegin(E) model sentinel_for<S, I>. If S models input_iterator, then S also models constant_iterator. — end note]

26.3.10 ranges::size

The name ranges::size denotes a customization point object (16.3.3.3.5).

Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. Then:

(1.1) If T is an array of unknown bound (9.3.4.5), ranges::size(E) is ill-formed.

(1.2) Otherwise, if T is an array type, ranges::size(E) is expression-equivalent to auto(extent_v<T>).

(1.3) Otherwise, if disable sized_range<remove_cv_t<T>> (26.4.3) is false and auto(t.size()) is a valid expression of integer-like type (25.3.4.4), ranges::size(E) is expression-equivalent to auto(t.size()).
Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). If \( \text{ranges}::\text{size}(t) \) is ill-formed, \( \text{ranges}::\text{size}(E) \) is ill-formed. Otherwise let \( D \) be \( \text{make-s signed-like}<\text{decltype}(\text{ranges}::\text{size}(t)), \text{ptrdiff_t}> \), or \( \text{ptdiff} t \) if it is wider than that type; \( \text{ranges}::\text{size}(E) \) is expression-equivalent to \( \text{static_cast}<D>(\text{ranges}::\text{size}(t)) \).

### 26.3.11 ranges::ssize

The name \( \text{ranges}::\text{ssize} \) denotes a customization point object (16.3.3.3.5).

Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). If \( \text{ranges}::\text{size}(t) \) is ill-formed, \( \text{ranges}::\text{ssize}(E) \) is ill-formed. Otherwise let \( D \) be \( \text{make-s signed-like}<\text{decltype}(\text{ranges}::\text{size}(t))> \), or \( \text{ptdiff} t \) if it is wider than that type; \( \text{ranges}::\text{ssize}(E) \) is expression-equivalent to \( \text{static_cast}<D>(\text{ranges}::\text{size}(t)) \).

### 26.3.12 ranges::empty

The name \( \text{ranges}::\text{empty} \) denotes a customization point object (16.3.3.3.5).

Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). Then:

1. If \( t \) is an array of unknown bound (9.3.4.5), \( \text{ranges}::\text{empty}(E) \) is ill-formed.
2. Otherwise, if \( \text{bool}(t.\text{empty}()) \) is a valid expression, \( \text{ranges}::\text{empty}(E) \) is expression-equivalent to \( \text{bool}(t.\text{empty}()) \).
3. Otherwise, if \( (\text{ranges}::\text{size}(t) == 0) \) is a valid expression, \( \text{ranges}::\text{empty}(E) \) is expression-equivalent to \( (\text{ranges}::\text{size}(t) == 0) \).

### 26.3.13 ranges::data

The name \( \text{ranges}::\text{data} \) denotes a customization point object (16.3.3.3.5).

Given a subexpression \( E \) with type \( T \), let \( t \) be an lvalue that denotes the reified object for \( E \). Then:

1. If \( E \) is an rvalue and \( \text{enable_borrowed_range}<\text{remove_cv_t}<T>> \) is false, \( \text{ranges}::\text{data}(E) \) is ill-formed.
2. Otherwise, if \( T \) is an array type (9.3.4.5) and \( \text{remove_all_extents_t}<T> \) is an incomplete type, \( \text{ranges}::\text{data}(E) \) is ill-formed with no diagnostic required.
3. Otherwise, if \( \text{auto}(t.\text{data}()) \) is a valid expression of pointer to object type, \( \text{ranges}::\text{data}(E) \) is expression-equivalent to \( \text{auto}(t.\text{data}()) \).
4. Otherwise, if \( \text{ranges}::\text{begin}(t) \) is a valid expression whose type models \( \text{contiguous_iterator} \), \( \text{ranges}::\text{data}(E) \) is expression-equivalent to \( \text{to_address}(\text{ranges}::\text{begin}(t)) \).

### Notes

1. Diagnosable ill-formed cases above result in substitution failure when \( \text{ranges}::\text{size}(E) \) appears in the immediate context of a template instantiation. —end note
2. Whenever \( \text{ranges}::\text{data}(E) \) is a valid expression, its type is integer-like. —end note

---

\( \text{N4986} \)
**ranges::cdata**

```cpp
template<class T>
constexpr auto
as_const_pointer(const T* p) noexcept { return p; } // exposition only
```

1 The name `ranges::cdata` denotes a customization point object (16.3.3.3.5). Given a subexpression `E` with type `T`, let `t` be an lvalue that denotes the reified object for `E`. Then:

1.1 If `E` is an rvalue and `enable_borrowed_range<remove_cv_t<T>>` is false, `ranges::cdata(E)` is ill-formed.

1.2 Otherwise, `ranges::cdata(E)` is expression-equivalent to `as_const_pointer(ranges::data(possibly const-range(t)))`.

2 [Note 1: Whenever `ranges::cdata(E)` is a valid expression, it has pointer to constant object type. —end note]

### 26.4 Range requirements

#### 26.4.1 General

1 Ranges are an abstraction that allows a C++ program to operate on elements of data structures uniformly. Calling `ranges::begin` on a range returns an object whose type models `input_or_output_iterator` (25.3.4.6). Calling `ranges::end` on a range returns an object whose type `S`, together with the type `I` of the object returned by `ranges::begin`, models `sentinel_for<S, I>`. The library formalizes the interfaces, semantics, and complexity of ranges to enable algorithms and range adaptors that work efficiently on different types of sequences.

2 The `range` concept requires that `ranges::begin` and `ranges::end` return an iterator and a sentinel, respectively. The `sized_range` concept refines `range` with the requirement that `ranges::size` be amortized \(\Theta(1)\). The `view` concept specifies requirements on a `range` type to provide operations with predictable complexity.

3 Several refinements of `range` group requirements that arise frequently in concepts and algorithms. Common ranges are ranges for which `ranges::begin` and `ranges::end` return objects of the same type. Random access ranges are ranges for which `ranges::begin` returns a type that models `random_access_iterator` (25.3.4.13). (Contiguous, bidirectional, forward, input, and output ranges are defined similarly.) Viewable ranges can be converted to views.

#### 26.4.2 Ranges

1 The `range` concept defines the requirements of a type that allows iteration over its elements by providing an iterator and sentinel that denote the elements of the range.

```cpp
template<class T>
concept range =
    requires(T& t) {
        ranges::begin(t); // sometimes equality-preserving (see below)
        ranges::end(t);
    };
```

2 Given an expression `t` such that `decltype((t))` is `T&`, `T` models `range` only if

2.1 `ranges::begin(t), ranges::end(t)` denotes a range (25.3.1),

2.2 both `ranges::begin(t)` and `ranges::end(t)` are amortized constant time and non-modifying, and

2.3 if the type of `ranges::begin(t)` models `forward_iterator`, `ranges::begin(t)` is equality-preserving.

3 [Note 1: Equality preservation of both `ranges::begin` and `ranges::end` enables passing a range whose iterator type models `forward_iterator` to multiple algorithms and making multiple passes over the range by repeated calls to `ranges::begin` and `ranges::end`. Since `ranges::begin` is not required to be equality-preserving when the return type does not model `forward_iterator`, it is possible for repeated calls to not return equal values or to not be well-defined. —end note]

```cpp
template<class T>
concept borrowed_range =
```
range<T> && (is_lvalue_reference_v<T> || enable_borrowed_range<remove_cvref_t<T>>);

Let U be remove_reference_t<T> if T is an rvalue reference type, and T otherwise. Given a variable u of type U, T models borrowed_range only if the validity of iterators obtained from u is not tied to the lifetime of that variable.

[Note 2: Since the validity of iterators is not tied to the lifetime of a variable whose type models borrowed_range, a function with a parameter of such a type can return iterators obtained from it without danger of dangling. — end note]

template<class>
constexpr bool enable_borrowed_range = false;

Remarks: Pursuant to 16.4.5.2.1, users may specialize enable_borrowed_range for cv-unqualified program-defined types. Such specializations shall be usable in constant expressions (7.7) and have type const bool.

[Example 1: Each specialization S of class template subrange (26.5.4) models borrowed_range because

(7.1) — enable_borrowed_range<S> is specialized to have the value true, and

(7.2) — S’s iterators do not have validity tied to the lifetime of an S object because they are “borrowed” from some other range.

— end example]

26.4.3 Sized ranges

The sized_range concept refines range with the requirement that the number of elements in the range can be determined in amortized constant time using ranges::size.

template<class T>
concept sized_range =ange<T> && requires(T t) { ranges::size(t); };

Given an lvalue t of type remove_reference_t<T>, T models sized_range only if

(2.1) — ranges::size(t) is amortized \( O(1) \), does not modify t, and is equal to ranges::distance(ranges::begin(t), ranges::end(t)), and

(2.2) — if iterator_t<T> models forward_iterator, ranges::size(t) is well-defined regardless of the evaluation of ranges::begin(t).

[Note 1: ranges::size(t) is otherwise not required to be well-defined after evaluating ranges::begin(t). For example, it is possible for ranges::size(t) to be well-defined for a sized_range whose iterator type does not model forward_iterator only if evaluated before the first call to ranges::begin(t). — end note]

template<class>
constexpr bool disable_sized_range = false;

Remarks: Pursuant to 16.4.5.2.1, users may specialize disable_sized_range for cv-unqualified program-defined types. Such specializations shall be usable in constant expressions (7.7) and have type const bool.

[Note 2: disable_sized_range allows use of range types with the library that satisfy but do not in fact model sized_range. — end note]

26.4.4 Views

The view concept specifies the requirements of a range type that has the semantic properties below, which make it suitable for use in constructing range adaptor pipelines (26.7).

template<class T>
concept view =ange<T> && movable<T> && enable_view<T>;

T models view only if

(2.1) — T has \( O(1) \) move construction; and

(2.2) — move assignment of an object of type T is no more complex than destruction followed by move construction; and
— if \( N \) copies and/or moves are made from an object of type \( T \) that contained \( M \) elements, then those \( N \) objects have \( \Theta(N + M) \) destruction; and

— \( \text{copy_constructible}<T> \) is false, or \( T \) has \( \Theta(1) \) copy construction; and

— \( \text{copyable}<T> \) is false, or copy assignment of an object of type \( T \) is no more complex than destruction followed by copy construction.

\[ (2.3) \]

[Note 1: The constraints on copying and moving imply that a moved-from object of type \( T \) has \( \Theta(1) \) destruction. — end note]

\[ (2.4) \]

\[ (2.5) \]

[Example 1: Examples of views are:

— A \textbf{range} type that wraps a pair of iterators.

— A \textbf{range} type that holds its elements by \texttt{shared_ptr} and shares ownership with all its copies.

— A \textbf{range} type that generates its elements on demand.

A container such as \texttt{vector<string>} does not meet the semantic requirements of \texttt{view} since copying the container copies all of the elements, which cannot be done in constant time. — end example]

Since the difference between \textbf{range} and \texttt{view} is largely semantic, the two are differentiated with the help of \texttt{enable_view}.

\[
\text{template<class T>}
\]

\[
\text{constexpr bool enable_view = derived_from<T, view_base> || is-derived-from-view-interface<T>;} // exposition only
\]

For a type \( T \), \( \text{is-derived-from-view-interface}<T> \) is \texttt{true} if and only if \( T \) has exactly one public base class \texttt{view_interface}<\texttt{U}> for some type \( \texttt{U} \) and \( T \) has no base classes of type \texttt{view_interface}<\texttt{V}> for any other type \( \texttt{V} \).

Remarks: Pursuant to 16.4.5.2.1, users may specialize \texttt{enable_view} to \texttt{true} for cv-unqualified program-defined types which model \texttt{view}, and \texttt{false} for types which do not. Such specializations shall be usable in constant expressions (7.7) and have type \texttt{const bool}.

### 26.4.5 Other range refinements

The \textbf{output_range} concept specifies requirements of a \textbf{range} type for which \texttt{ranges::begin} returns a model of \texttt{output_iterator} (25.3.4.10). \textbf{input_range}, \textbf{forward_range}, \textbf{bidirectional_range}, and \textbf{random_access_range} are defined similarly.

\[
\text{template<class R, class T>}
\]

\[
\text{concept output_range = range<R> \&\& output_iterator<iterator_t<R>, T>;}
\]

\[
\text{template<class T>}
\]

\[
\text{concept input_range = range<T> \&\& input_iterator<iterator_t<T>;}
\]

\[
\text{template<class T>}
\]

\[
\text{concept forward_range = input_range\&\& forward_iterator<iterator_t<T>;}
\]

\[
\text{template<class T>}
\]

\[
\text{concept bidirectional_range = forward_range\&\& bidirectional_iterator<iterator_t<T>;}
\]

\[
\text{template<class T>}
\]

\[
\text{concept random_access_range = bidirectional_range\&\& random_access_iterator<iterator_t<T>;}
\]

\[
\text{contiguous_range} \] additionally requires that the \texttt{ranges::data} customization point object (26.3.13) is usable with the range.
template<class T>
concept contiguous_range =
    random_access_range<T> && contiguous_iterator<iterator_t<T>> &&
    requires(T t) {
        { ranges::data(t) } -> same_as<add_pointer_t<range_reference_t<T>>>;
    };

Given an expression t such that decltype((t)) is T&, T models contiguous_range only if to_address( ranges::begin(t)) == ranges::data(t) is true.

The common_range concept specifies requirements of a range type for which ranges::begin and ranges::end return objects of the same type.

[Example 1: The standard containers (Clause 24) model common_range. — end example]

template<class T>
concept common_range =
    range<T> && same_as<iterator_t<T>, sentinel_t<T>>;

template<class R>
constexpr bool is-initializer-list = see below; // exposition only

For a type R, is-initializer-list<R> is true if and only if remove_cvref_t<R> is a specialization of initializer_list.

The viewable_range concept specifies the requirements of a range type that can be converted to a view safely.

template<class T>
concept viewable_range =
    range<T> && ((view<remove_cvref_t<T>> && constructible_from<remove_cvref_t<T>, T>) ||
                  (!view<remove_cvref_t<T>> && (is_lvalue_reference_v<T> || (movable<remove_reference_t<T>> && !is-initializer-list<T>))));

The constant_range concept specifies the requirements of a range type whose elements are not modifiable.

template<class T>
concept constant_range =
    input_range<T> && constant_iterator<iterator_t<T>>;

26.5 Range utilities [range.utility]

26.5.1 General [range.utility.general]

The components in 26.5 are general utilities for representing and manipulating ranges.

26.5.2 Helper concepts [range.utility.helpers]

Many of the types in 26.5 are specified in terms of the following exposition-only concepts:

template<class R>
concept simple-view = // exposition only
    view<R> && range<const R> &&
    same_as<iterator_t<R>, iterator_t<const R>> &&
    same_as<sentinel_t<R>, sentinel_t<const R>>;

template<class I>
concept has-arrow = // exposition only
    input_iterator<I> && (is_pointer_v<I> || requires(I i) { i.operator->(); });

template<class T, class U>
concept different-from = // exposition only
    !same_as<remove_cvref_t<T>, remove_cvref_t<U>>;

template<class R>
concept range-with-movable-references = // exposition only
    input_range<R> && move_constructible<range_reference_t<R>> &&
    move_constructible<range_rvalue_reference_t<R>>;

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26.5.3 View interface

26.5.3.1 General

The class template `view_interface` is a helper for defining view-like types that offer a container-like interface. It is parameterized with the type that is derived from it.

```cpp
namespace std::ranges {
    template<class D>
    requires is_class_v<D> && same_as<D, remove_cv_t<D>>
    class view_interface {
        private:
            constexpr D& derived() noexcept { // exposition only
                return static_cast<D&>(*this);
            }
            constexpr const D& derived() const noexcept { // exposition only
                return static_cast<const D&>(*this);
            }
        public:
            constexpr bool empty() requires sized_range<D> || forward_range<D> {  
                if constexpr (sized_range<D>)
                    return ranges::size(derived()) == 0;
                else
                    return ranges::begin(derived()) == ranges::end(derived());
            }
            constexpr bool empty() const requires sized_range<const D> || forward_range<const D> {  
                if constexpr (sized_range<const D>)
                    return ranges::size(derived()) == 0;
                else
                    return ranges::begin(derived()) == ranges::end(derived());
            }
            constexpr auto cbegin() requires input_range<D> {
                return ranges::cbegin(derived());
            }
            constexpr auto cbegin() const requires input_range<const D> {
                return ranges::cbegin(derived());
            }
            constexpr auto cend() requires input_range<D> {
                return ranges::cend(derived());
            }
            constexpr auto cend() const requires input_range<const D> {
                return ranges::cend(derived());
            }
            constexpr explicit operator bool() requires forward_range<D> && sized_sentinel_for<sentinel_t<D>, iterator_t<D>> {  
                return !ranges::empty(derived());
            }
            constexpr explicit operator bool() const requires forward_range<const D> && sized_sentinel_for<const sentinel_t<D>, iterator_t<D>> {  
                return !ranges::empty(derived());
            }
            constexpr auto data() requires contiguous_iterator<iterator_t<D>> {  
                return to_address(ranges::begin(derived()));
            }
            constexpr auto data() const requires range<const D> && contiguous_iterator<iterator_t<const D>> {  
                return to_address(ranges::begin(derived()));
            }
            constexpr auto size() requires forward_range<D> && sized_sentinel_for<sentinel_t<D>, iterator_t<D>> {  
                return to_unsigned_like(ranges::end(derived()) - ranges::begin(derived()));
            }
    }
}
```
constexpr auto size() const requires forward_range<const D> &&
sized_sentinel_for<sentinel_t<const D>, iterator_t<const D>>
{
    return to_unsigned_like(ranges::end(derived()) - ranges::begin(derived()));
}

constexpr decltype(auto) front() requires forward_range<D>;
constexpr decltype(auto) front() const requires forward_range<const D>;

constexpr decltype(auto) back() requires bidirectional_range<D> && common_range<D>;
constexpr decltype(auto) back() const
    requires bidirectional_range<const D> && common_range<const D>;

template<random_access_range R = D>
constexpr decltype(auto) operator[](range_difference_t<R> n) {
    return ranges::begin(derived())[n];
}

namespace std::ranges {
  template<class From, class To>
  concept uses-nonqualification-pointer-conversion = 
      // exposition only
      is_pointer_v<From> && is_pointer_v<To>
      && !convertible_to<remove_pointer_t<From>(*)[], remove_pointer_t<To>(*)[]>
    ;

  template<class From, class To>
  concept convertible-to-non-slicing = 
      // exposition only
      convertible_to<From, To> && !uses-nonqualification-pointer-conversion<decay_t<From>, decay_t<To>>;

  template<class T, class U, class V>
  concept pair-like-convertible-from = 
      // exposition only
      !ranges<T> && !is_reference_v<T> && pair_like<T> &&
      constructible_from<T, U, V> &&

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convertible-to-non-slicing<U, tuple_element_t<0, T>> &&
convertible_to<V, tuple_element_t<1, T>>;

template<input_or_output_iterator I, sentinel_for<I> S = I, subrange_kind K =
sized_sentinel_for<S, I> ? subrange_kind::sized : subrange_kind::unsized>
requires (K == subrange_kind::sized || sized_sentinel_for<S, I>)
class subrange : public view_interface<subrange<I, S, K>> {
private:
    static constexpr bool StoreSize =
        // exposition only
        K == subrange_kind::sized && !sized_sentinel_for<S, I>;
    I begin_{ = I();
        // exposition only
    S end_{ = S();
        // exposition only
    make_unsigned_like_t<iter_difference_t<I>> size_ = 0;
        // exposition only; present only
        // if StoreSize is true
public:
    subrange() requires default_initializable<I> = default;

    constexpr subrange(convertible-to-non-slicing<I> auto i, S s) requires (!StoreSize);

    constexpr subrange(convertible-to-non-slicing<I> auto i, S s,
        make_unsigned_like_t<iter_difference_t<I>> n)
        requires (K == subrange_kind::sized);

    template<different_from<subrange> R>
        requires borrowed_range<R> &&
        convertible_to_non_slicing<iterator_t<R>, I> &&
        convertible_to<sentinel_t<R>, S>
    constexpr subrange(R&& r) requires (!StoreSize || sized_range<R>);

    template<borrowed_range R>
        requires convertible_to_non_slicing<iterator_t<R>, I> &&
        convertible_to<sentinel_t<R>, S>
    constexpr subrange(R&& r, make_unsigned_like_t<iter_difference_t<I>> n)
        requires (K == subrange_kind::sized)
        : subrange{ranges::begin(r), ranges::end(r), n} {}

    template<different_from<subrange> PairLike>
        requires pair_like_convertible_from<PairLike, const I&, const S&>
    constexpr operator PairLike() const;

    constexpr I begin() const requires copyable<I>;
    [[nodiscard]] constexpr I begin() requires (!copyable<I>);
    constexpr S end() const;

    constexpr bool empty() const;
    constexpr make_unsigned_like_t<iter_difference_t<I>> size() const
        requires (K == subrange_kind::sized);

    [[nodiscard]] constexpr subrange next(iter_difference_t<I> n = 1) const &
        requires forward_iterator<I>;
    [[nodiscard]] constexpr subrange next(iter_difference_t<I> n = 1) &&;
    [[nodiscard]] constexpr subrange prev(iter_difference_t<I> n = 1) const
        requires bidirectional_iterator<I>;
    constexpr subrange& advance(iter_difference_t<I> n);
};

template<input_or_output_iterator I, sentinel_for<I> S>
    subrange(I, S) -> subrange<I, S>;

template<input_or_output_iterator I, sentinel_for<I> S>
    subrange(I, S, make_unsigned_like_t<iter_difference_t<I>>) ->
    subrange<I, S, subrange_kind::sized>;

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template<borrowed_range R>
    subrange(R&&) ->
        subrange<iterator_t<R>, sentinel_t<R>,
            (sized_range<R> || sized_sentinel_for<sentinel_t<R>, iterator_t<R>>) ? subrange_kind::sized : subrange_kind::unsized;  

template<borrowed_range R>
    subrange(R&&, make_unsigned_like_t<range_difference_t<R>>) ->
        subrange<iterator_t<R>, sentinel_t<R>, subrange_kind::sized>;  

26.5.4.2 Constructors and conversions

constexpr subrange(convertible-to-non-slicing<I> auto i, S s) requires (!StoreSize);  

    Preconditions: [i, s) is a valid range.  
    Effects: Initializes begin_ with std::move(i) and end_ with s.  

customexpr subrange(convertible-to-non-slicing<I> auto i, S s,  
    make_unsigned_like_t<iter_difference_t<I>> n) requires (K == subrange_kind::sized);  

    Preconditions: [i, s) is a valid range, and n == to_unsigned_like(ranges::distance(i, s)) is true.  
    Effects: Initializes begin_ with std::move(i) and end_ with s. If StoreSize is true, initializes size_ with n.  

    [Note 1: Accepting the length of the range and storing it to later return from size() enables subrange to model sized_range even when it stores an iterator and sentinel that do not model sized_sentinel_for. — end note]  

template<different-from<subrange> R>
    requires borrowed_range<R> &&  
        convertible-to-non-slicing<iterator_t<R>, I> &&  
        convertible_to<sentinel_t<R>, S>  
    constexpr subrange(R&& r) requires (!StoreSize || sized_range<R>);  

    Effects: Equivalent to:  

(6.1)    — If StoreSize is true, subrange(r, static_cast<decltype(size_)>((ranges::size(r)))).  
(6.2)    — Otherwise, subrange(ranges::begin(r), ranges::end(r)).  

template<different-from<subrange> PairLike>  
    requires pair-like-convertible-from<PairLike, const I&, const S&>  
    constexpr operator PairLike() const;  

    Effects: Equivalent to: return PairLike(begin_, end_);  

26.5.4.3 Accessors

constexpr I begin() const requires copyable<I>;  

    Effects: Equivalent to: return begin_;  

[[nolambda]] constexpr I begin() requires (!copyable<I>);  

    Effects: Equivalent to: return std::move(begin_);  

customexpr S end() const;  

    Effects: Equivalent to: return end_;  

customexpr bool empty() const;  

    Effects: Equivalent to: return begin_ == end_;  

customexpr make_unsigned-like-t<iter_difference_t<I>> size() const  
    requires (K == subrange_kind::sized);  

    Effects:  

(5.1)    — If StoreSize is true, equivalent to: return size_;
— Otherwise, equivalent to: `return to-unsigned-like(end_ - begin_);`

```cpp
[[nodiscard]] constexpr subrange next(iter_difference_t<I> n = 1) const &
  requires forward_iterator<I>;
```

**Effects:** Equivalent to:

```cpp
auto tmp = *this;
tmp.advance(n);
return tmp;
```

```cpp
[[nodiscard]] constexpr subrange next(iter_difference_t<I> n = 1) &&;
```

**Effects:** Equivalent to:

```cpp
advance(n);
return std::move(*this);
```

```cpp
[[nodiscard]] constexpr subrange prev(iter_difference_t<I> n = 1) const
  requires bidirectional_iterator<I>;
```

**Effects:** Equivalent to:

```cpp
auto tmp = *this;
tmp.advance(-n);
return tmp;
```

```cpp
constexpr subrange& advance(iter_difference_t<I> n);
```

**Effects:** Equivalent to:

```cpp
if constexpr (bidirectional_iterator<I>) {
  if (n < 0) {
    ranges::advance(begin_, n);
    if constexpr (StoreSize)
      size_ += to-unsigned-like(-n);
    return *this;
  }
}
auto d = n - ranges::advance(begin_, n, end_);
if constexpr (StoreSize)
  size_ -= to-unsigned-like(d);
return *this;
```

```cpp
template<size_t N, class I, class S, subrange_kind K>
  requires ((N == 0 && copyable<I>) || N == 1)
  constexpr auto get(const subrange<I, S, K>& r);
```

```cpp
template<size_t N, class I, class S, subrange_kind K>
  requires (N < 2)
  constexpr auto get(subrange<I, S, K>&& r);
```

**Effects:** Equivalent to:

```cpp
if constexpr (N == 0)
  return r.begin();
else
  return r.end();
```

### 26.5.5 Dangling iterator handling

The type `dangling` is used together with the template aliases `borrowed_iterator_t` and `borrowed_subrange_t`. When an algorithm that typically returns an iterator into, or a subrange of, a range argument is called with an rvalue range argument that does not model `borrowed_range` (26.4.2), the return value possibly refers to a range whose lifetime has ended. In such cases, the type `dangling` is returned instead of an iterator or subrange.

```cpp
namespace std::ranges {
  struct dangling {
    constexpr dangling() noexcept = default;
    constexpr dangling(auto&&...) noexcept ()
```

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Example 1:

```cpp
vector<int> f();
on auto result1 = ranges::find(f(), 42); // #1
static_assert(same_as<decltype(result1), ranges::dangling>);
```

```cpp
auto vec = f();
on auto result2 = ranges::find(vec, 42); // #2
static_assert(same_as<decltype(result2), vector<int>::iterator>);
```

```cpp
auto result3 = ranges::find(ranges::subrange{vec}, 42); // #3
static_assert(same_as<decltype(result3), vector<int>::iterator>);
```

The call to `ranges::find` at #1 returns `ranges::dangling` since `f()` is an rvalue `vector`; it is possible for the `vector` to be destroyed before a returned iterator is dereferenced. However, the calls at #2 and #3 both return iterators since the lvalue `vec` and specializations of `subrange` model `borrowed_range`. — end example

For a type `R` that models `range`:

- (3.1) if `R` models `borrowed_range`, then `borrowed_iterator_t<R>` denotes `iterator_t<R>`, and `borrowed_subrange_t<R>` denotes `subrange<iterator_t<R>>`;
- (3.2) otherwise, both `borrowed_iterator_t<R>` and `borrowed_subrange_t<R>` denote `dangling`.

26.5.6 Class template elements_of

Specializations of `elements_of` encapsulate a range and act as a tag in overload sets to disambiguate when a range should be treated as a sequence rather than a single value.

Example 1:

```cpp
template<bool YieldElements>
generator<any> f(ranges::input_range auto&& r) {
    if constexpr (YieldElements)
        co_yield ranges::elements_of(r); // yield each element of r
    else
        co_yield r; // yield r as a single value
}
```

— end example

```cpp
namespace std::ranges {
    template<range R, class Allocator = allocator<byte>>
    struct elements_of {
        [[no_unique_address]] R range;
        Allocator allocator = Allocator();
    };

template<class R, class Allocator = allocator<byte>>
    elements_of(R&&, Allocator = Allocator()) -> elements_of<R&&, Allocator>;
}
```

26.5.7 Range conversions

26.5.7.1 General

The range conversion functions construct an object (usually a container) from a range, by using a constructor taking a range, a `from_range_t` tagged constructor, or a constructor taking a pair of iterators, or by inserting each element of the range into the default-constructed object.

ranges::to is applied recursively, allowing the conversion of a range of ranges.

Example 1:

```cpp
string_view str = "the quick brown fox";
auto words = views::split(str, ' ') | to<vector<string>>();
// words is vector<string>{"the", "quick", "brown", "fox"}
```

Let `reservable-container` be defined as follows:
template<class Container>
constexpr bool reservable_container = // exposition only
sized_range<Container> &&
requires(Container& c, range_size_t<Container> n) {
    c.reserve(n);
    { c.capacity() } -> same_as<decltype(n)>;
    { c.max_size() } -> same_as<decltype(n)>;
};

Let `container-appendable` be defined as follows:

```cpp
template<class Container, class Ref>
constexpr bool container-appendable = // exposition only
requires(Container& c, Ref&& ref) {
    requires (requires { c.emplace_back(std::forward<Ref>(ref)); } ||
        requires { c.push_back(std::forward<Ref>(ref)); } ||
        requires { c.emplace(c.end(), std::forward<Ref>(ref)); } ||
        requires { c.insert(c.end(), std::forward<Ref>(ref)); });
};
```

Let `container-append` be defined as follows:

```cpp
template<class Container>
constexpr auto container-append(Container& c) { // exposition only
    return [&c]<class Ref>(Ref&& ref) {
        if constexpr (requires { c.emplace_back(declval<Ref>()); })
            c.emplace_back(std::forward<Ref>(ref));
        else if constexpr (requires { c.push_back(declval<Ref>()); })
            c.push_back(std::forward<Ref>(ref));
        else if constexpr (requires { c.emplace(c.end(), declval<Ref>()); })
            c.emplace(c.end(), std::forward<Ref>(ref));
        else
            c.insert(c.end(), std::forward<Ref>(ref));
    };
}
```

26.5.7.2 `ranges::to` [range.utility.conv.to]

```cpp
template<class C, input_range R, class... Args> requires (!view<C>)
constexpr C to(R&& r, Args&&... args);
```

1 **Mandates:** C is a cv-unqualified class type.

2 **Returns:** An object of type C constructed from the elements of r in the following manner:

1. If C does not satisfy `input_range` or `convertible_to<range_reference_t<R>, range_value_t<C>>` is true:
   1.1 If `constructible_from<C, R, Args...>` is true:
      ```cpp
      C(std::forward<R>(r), std::forward<Args>(args)...)
      ```
   1.2 Otherwise, if `constructible_from<C, from_range_t, R, Args...>` is true:
      ```cpp
      C(from_range, std::forward<R>(r), std::forward<Args>(args)...)
      ```
   1.3 Otherwise, if
      1.3.1 `common_range<R>` is true,
      2.1.3.2 the qualified-id `iterator_traits<iterator_t<R>>::iterator_category` is valid and denotes a type that models `derived_from<input_iterator_tag>`, and
      2.1.3.3 `constructible_from<C, iterator_t<R>, sentinel_t<R>, Args...>` is true:
      ```cpp
      C(ranges::begin(r), ranges::end(r), std::forward<Args>(args)...)
      ```
   1.4 Otherwise, if
      1.4.1 `constructible_from<C, Args...>` is true, and
      1.4.2 `container-appendable<C, range_reference_t<R>>` is true:
template<template<class...> class C, input_range R, class... Args>
constexpr auto to(R&& r, Args&&... args);

Let \textbf{input\text{-}iterator} be an exposition-only type:

struct input\text{-}iterator { // exposition only
  using iterator\_category = input\_iterator\_tag;
  using value\_type = range\_value\_t<R>;
  using difference\_type = ptrdiff\_t;
  using pointer = add_pointer\_t<range\_reference\_t<R>>;
  using reference = range\_reference\_t<R>;
  reference operator*() const;
  pointer operator->() const;
  input\_iterator\& operator++();
  input\_iterator operator++(int);
  bool operator==(const input\_iterator\&) const;
};

\textit{[Note 1: input\text{-}iterator meets the syntactic requirements of Cpp17InputIterator. — end note]}

Let \textbf{DEDUCE\_EXPR} be defined as follows:

\begin{align*}
  &\text{C(declval<R>(), declval<Args>()...) if that is a valid expression,} \\
  &\text{otherwise, C(from_range, declval<R>(), declval<Args>()...) if that is a valid expression,} \\
  &\text{otherwise,} \\
  &\text{C(declval<input\_iterator>(), declval<input\_iterator>(), declval<Args>()...)} \\
\end{align*}

\textit{if that is a valid expression,}

\textit{otherwise, the program is ill-formed.}

\textbf{26.5.7.3 \textsc{ranges::to} adaptors} \hfill \textit{[range.utility.conv.adaptors]}

template<class C, class... Args> requires (!view<C>)
constexpr auto to(Args\&\&... args);

\begin{enumerate}
\item \textit{Mandates: For the first overload, C is a cv-unqualified class type.}
\item \textit{Returns: A range adaptor closure object \texttt{(26.7.2) f} that is a perfect forwarding call wrapper (22.10.4) with the following properties:}
\item \textmd{It has no target object.}
\item \textmd{Its bound argument entities \texttt{bound\_args} consist of objects of types \texttt{decay\_t<Args>... direct-non-list-initialized with std::forward<Args>(args)...}, respectively.}
\item \textmd{Its call pattern is \texttt{to<C>(r, bound\_args...),} where \texttt{r} is the argument used in a function call expression of \texttt{f}.}
\end{enumerate}

\textbf{26.6 Range factories} \hfill \textit{[range.factories]}

\textbf{26.6.1 General} \hfill \textit{[range.factories.general]}

\begin{enumerate}
\item Subclause 26.6 defines \textit{range factories}, which are utilities to create a view.
\end{enumerate}
Range factories are declared in namespace `std::ranges::views`.

### 26.6.2 Empty view

#### 26.6.2.1 Overview

`empty_view` produces a view of no elements of a particular type.

[Example 1:]
```
auto e = views::empty<int>;
static_assert(ranges::empty(e));
static_assert(0 == e.size());
```

### 26.6.2.2 Class template `empty_view`

```
namespace std::ranges {
    template<class T>
    requires is_object_v<T>
    class empty_view : public view_interface<empty_view<T>> {
        public:
            static constexpr T* begin() noexcept { return nullptr; }
            static constexpr T* end() noexcept { return nullptr; }
            static constexpr T* data() noexcept { return nullptr; }
            static constexpr size_t size() noexcept { return 0; }
            static constexpr bool empty() noexcept { return true; }
    }
}
```

### 26.6.3 Single view

#### 26.6.3.1 Overview

`single_view` produces a view that contains exactly one element of a specified value.

[Example 1:]
```
for (int i : views::single(4))
    cout << i; // prints 4
```

#### 26.6.3.2 Class template `single_view`

```
namespace std::ranges {
    template<move_constructible T>
    requires is_object_v<T>
    class single_view : public view_interface<single_view<T>> {
        private:
            movable-box<T> value_; // exposition only (see 26.7.3)
        public:
            single_view() requires default_initializable<T> = default;
            constexpr explicit single_view(const T& t) requires copy_constructible<T>;
            constexpr explicit single_view(T&& t);
            template<class... Args>
            requires constructible_from<T, Args...>
            constexpr explicit single_view(in_place_t, Args&&... args);
            constexpr T* begin() noexcept;
            constexpr const T* begin() const noexcept;
            constexpr T* end() noexcept;
            constexpr const T* end() const noexcept;
            static constexpr bool empty() noexcept;
            static constexpr size_t size() noexcept;
            constexpr T* data() noexcept;
            constexpr const T* data() const noexcept;
    }
}
```
template<class T>
    single_view(T) -> single_view<T>;

constexpr explicit single_view(const T& t) requires copy_constructible<T>;
1  Effects: Initializes value_ with t.
constexpr explicit single_view(T&& t);
2  Effects: Initializes value_ with std::move(t).

template<class... Args>
    requires constructible_from<T, Args...>
    constexpr explicit single_view(in_place_t, Args&&... args);
3  Effects: Initializes value_ as if by value_{in_place, std::forward<Args>(args)...}.

constexpr T* begin() noexcept;
constexpr const T* begin() const noexcept;
4  Effects: Equivalent to: return data();
constexpr T* end() noexcept;
constexpr const T* end() const noexcept;
5  Effects: Equivalent to: return data() + 1;
static constexpr bool empty() noexcept;
6  Effects: Equivalent to: return false;
static constexpr size_t size() noexcept;
7  Effects: Equivalent to: return 1;
constexpr T* data() noexcept;
constexpr const T* data() const noexcept;
8  Effects: Equivalent to: return value_.operator->();

26.6.4 Iota view

26.6.4.1 Overview

1 Iota_view generates a sequence of elements by repeatedly incrementing an initial value.
2 The name views::iota denotes a customization point object (16.3.3.3.5). Given subexpressions E and F, the expressions views::iota(E) and views::iota(E, F) are expression-equivalent to iota_view<decay_t<declytype((E))>>>(E) and iota_view(E, F), respectively.

[Example 1:
for (int i : views::iota(1, 10))
    cout << i << ' '; // prints 1 2 3 4 5 6 7 8 9
— end example]

26.6.4.2 Class template iota_view

namespace std::ranges {
    template<class I>
        concept decrementable = see below; // exposition only

template<class I>
        concept advanceable = see below; // exposition only

template<weakly_incrementable W, semiregular Bound = unreachable_sentinel_t>
    requires weakly-equality-comparable-with<W, Bound> && copyable<W>
class iota_view : public view_interface<iota_view<W, Bound>> {
    private:
        // 26.6.4.3, class iota_view::iterator
Let \( \text{IOTA-DIFF-T}(W) \) be defined as follows:

1. If \( W \) is not an integral type, or if it is an integral type and \( \text{sizeof(iter_difference_t}<W> \) ) is greater than \( \text{sizeof}(W) \), then \( \text{IOTA-DIFF-T}(W) \) denotes \( \text{iter_difference_t}<W> \).
2. Otherwise, \( \text{IOTA-DIFF-T}(W) \) is a signed integer type of width greater than the width of \( W \) if such a type exists.
3. Otherwise, \( \text{IOTA-DIFF-T}(W) \) is an unspecified signed-integer-like type (25.3.4.4) of width not less than the width of \( W \).

[Note 1: It is unspecified whether this type satisfies weakly_incrementable. — end note]

The exposition-only decrementable concept is equivalent to:

```
template<class I>
concept decrementable =
    // exposition only
    incrementable<I> && requires(I i) {
        { --i } -> same_as<I&>;
        { i-- } -> same_as<I>;
    };
```

When an object is in the domain of both pre- and post-decrement, the object is said to be decrementable.

Let \( a \) and \( b \) be equal objects of type \( I \). \( I \) models decrementable only if

1. If \( a \) and \( b \) are decrementable, then the following are all true:
   1. \( \text{addressof}(-a) == \text{addressof}(a) \)
   2. \( \text{bool}(a-- == b) \)
   3. \( \text{bool}((\text{void}a--, a) == --b) \)
   4. \( \text{bool}(++(--a) == b) \).

2. If \( a \) and \( b \) are incrementable, then \( \text{bool}(-(-++a) == b) \).

The exposition-only advanceable concept is equivalent to:

```
template<class I>
concept advanceable =
    // exposition only
    decrementable<I> && totally_ordered<I> && requires(I i, const I j, const IOTA-DIFF-T<I> n) {
```
Let $D$ be $\text{IOTA-DIFF-T}(I)$. Let $a$ and $b$ be objects of type $I$ such that $b$ is reachable from $a$ after $n$ applications of $++a$, for some value $n$ of type $D$. $I$ models *advanceable* only if

\begin{align}
(5.1) & \quad (a += n) \text{ is equal to } b \\
(5.2) & \quad \text{addressof}(a += n) \text{ is equal to } \text{addressof}(a). \\
(5.3) & \quad I(a + n) \text{ is equal to } (a += n). \\
(5.4) & \quad \text{For any two positive values } x \text{ and } y \text{ of type } D, \text{ if } I(a + D(x + y)) \text{ is well-defined, then } I(a + D(x + y)) \text{ is equal to } I(I(a + x) + y). \\
(5.5) & \quad I(a + D(0)) \text{ is equal to } a. \\
(5.6) & \quad \text{If } I(a + D(n - 1)) \text{ is well-defined, then } I(a + n) \text{ is equal to } I(I(c) \{ \text{return ++c; } \}(I(a + D(n - 1))). \\
(5.7) & \quad (b += -n) \text{ is equal to } a. \\
(5.8) & \quad (b -= n) \text{ is equal to } a. \\
(5.9) & \quad \text{addressof}(b -= n) \text{ is equal to } \text{addressof}(b). \\
(5.10) & \quad I(b - n) \text{ is equal to } (b -= n). \\
(5.11) & \quad D(b - a) \text{ is equal to } n. \\
(5.12) & \quad D(a - b) \text{ is equal to } D(-n). \\
(5.13) & \quad \text{bool}(a \leq b) \text{ is true.}
\end{align}

```cpp
constexpr explicit iota_view(W value);

\textit{Preconditions:} Bound denotes $\text{unreachable_sentinel_t}$ or Bound() is reachable from value. When $W$ and Bound model totally_ordered_with, then $\text{bool(value} \leq \text{Bound()})$ is true.

\textit{Effects:} Initializes $value_\text{ with value}.
```

```cpp
constexpr explicit iota_view(type_identity_t<W> value, type_identity_t<Bound> bound);

\textit{Preconditions:} Bound denotes $\text{unreachable_sentinel_t}$ or bound is reachable from value. When $W$ and Bound model totally_ordered_with, then $\text{bool(value} \leq \text{bound})$ is true.

\textit{Effects:} Initializes $value_\text{ with value and bound_ with bound}.
```

```cpp
constexpr explicit iota_view(iterator first, see below last);

\textit{Effects:} Equivalent to:

\begin{align}
(10.1) & \quad \text{If same_as}$<W, \text{ Bound}>$ \text{ is true, iota_view(first.value_, last.value_).} \\
(10.2) & \quad \text{Otherwise, if Bound denotes unreachable_sentinel_t, iota_view(first.value_, last).} \\
(10.3) & \quad \text{Otherwise, iota_view(first.value_, last.bound_).}
\end{align}

\textit{Remarks:} The type of last is:

\begin{align}
(11.1) & \quad \text{If same_as}$<W, \text{ Bound}>$ \text{ is true, iterator.} \\
(11.2) & \quad \text{Otherwise, if Bound denotes unreachable_sentinel_t, Bound.} \\
(11.3) & \quad \text{Otherwise, sentinel.}
\end{align}

```cpp
constexpr iterator begin() const;

\textit{Effects:} Equivalent to: return iterator{value_};
```

```cpp
constexpr auto end() const;

\textit{Effects:} Equivalent to:
```

§ 26.6.4.2 ©ISO/IEC 1214
if constexpr (same_as<Bound, unreachable_sentinel_t>)
    return unreachable_sentinel;
else
    return sentinel{bound_};

constexpr iterator end() const requires same_as<W, Bound>;
14 Effects: Equivalent to: return iterator{bound_};

constexpr bool empty() const;
15 Effects: Equivalent to: return value_ == bound_;

constexpr auto size() const requires see below;
16 Effects: Equivalent to:
    if constexpr (is-integer-like<W> && is-integer-like<Bound>)
        return (value_ < 0)
            ? ((bound_ < 0)
                ? to-unsigned-like(-value_) - to-unsigned-like(-bound_)
                : to-unsigned-like(bound_) + to-unsigned-like(-value_))
            : to-unsigned-like(-bound_) - to-unsigned-like(value_);
    else
        return to-unsigned-like(bound_ - value_);
17 Remarks: The expression in the requires-clause is equivalent to:
    (same_as<W, Bound> && advanceable<W>) || (is-integer-like<W> && is-integer-like<Bound>) ||
    sized_sentinel_for<Bound, W>

26.6.4.3 Class iota_view::iterator
namespace std::ranges {
    template<weakly_incrementable W, semiregular Bound>
    requires weakly-equality-comparable-with<W, Bound> && copyable<W>
    struct iota_view<W, Bound>::iterator {
        private:
            W value_ = W(); // exposition only

        public:
            using iterator_concept = see below; // present only if W models incrementable and
                                                // IOTA-DIFF-T(W) is an integral type
            using iterator_category = input_iterator_tag;
            using value_type = W;
            using difference_type = IOTA-DIFF-T(W);

            iterator() requires default_initializable<W> = default;
            constexpr explicit iterator(W value);

            constexpr W operator*() const noexcept(is_nothrow_copy_constructible_v<W>)
                requires advanceable<W>;
            constexpr iterator& operator++();
            constexpr void operator++(int);
            constexpr iterator operator++(int) requires incrementable<W>;

            constexpr iterator& operator--() requires decrementable<W>;
            constexpr iterator operator--(int) requires decrementable<W>;

            constexpr iterator& operator+=(difference_type n)
                requires advanceable<W>;
            constexpr iterator& operator-=(difference_type n)
                requires advanceable<W>;
            constexpr W operator[](difference_type n) const
                requires advanceable<W>;

            friend constexpr bool operator==(const iterator& x, const iterator& y)
                requires equality_comparable<W>;

§ 26.6.4.3 ©ISO/IEC 1215
friend constexpr bool operator<(const iterator& x, const iterator& y)  
  requires totally_ordered<W>;
friend constexpr bool operator>(const iterator& x, const iterator& y)  
  requires totally_ordered<W>;
friend constexpr bool operator<=(const iterator& x, const iterator& y)  
  requires totally_ordered<W>;
friend constexpr bool operator>=(const iterator& x, const iterator& y)  
  requires totally_ordered<W>;
friend constexpr auto operator<=>(const iterator& x, const iterator& y)  
  requires totally_ordered<W> && three_way_comparable<W>;
friend constexpr iterator operator+(iterator i, difference_type n)  
  requires advanceable<W>;
friend constexpr iterator operator+(difference_type n, iterator i)  
  requires advanceable<W>;
friend constexpr iterator operator-(iterator i, difference_type n)  
  requires advanceable<W>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y)  
  requires advanceable<W>;
}

1 iterator::iterator_concept is defined as follows:
(1.1) — If W models advanceable, then iterator_concept is random_access_iterator_tag.
(1.2) — Otherwise, if W models decrementable, then iterator_concept is bidirectional_iterator_tag.
(1.3) — Otherwise, if W models incrementable, then iterator_concept is forward_iterator_tag.
(1.4) — Otherwise, iterator_concept is input_iterator_tag.

2 [Note 1: Overloads for iter_move and iter_swap are omitted intentionally. — end note]

constexpr explicit iterator(W value);

Effects: Initializes value_ with value.

constexpr W operator*() const noexcept(is_nothrow_copy_constructible_v<W>);

Effects: Equivalent to: return value_; [Note 2: The noexcept clause is needed by the default iter_move implementation. — end note]

constexpr iterator& operator++();

Effects: Equivalent to:
++value_;  
return *this;

constexpr void operator++(int);

Effects: Equivalent to +++this.

constexpr iterator operator++(int) requires incrementable<W>;

Effects: Equivalent to:
auto tmp = *this;  
++this;  
return tmp;

constexpr iterator& operator--() requires decrementable<W>;

Effects: Equivalent to:
--value_;  
return *this;

constexpr iterator operator--(int) requires decrementable<W>;

Effects: Equivalent to:
auto tmp = *this;
--*this;
return tmp;

constexpr iterator& operator+=(difference_type n)
    requires advanceable<W>;

   Effects: Equivalent to:

if constexpr (is-integer-like<W> && !is-signed-integer-like<W>) {
    if (n >= difference_type(0))
        value_ += static_cast<W>(n);
    else
        value_ -= static_cast<W>(-n);
} else {
    value_ += n;
}
return *this;

constexpr iterator& operator-=(difference_type n)
    requires advanceable<W>;

   Effects: Equivalent to:

if constexpr (is-integer-like<W> && !is-signed-integer-like<W>) {
    if (n >= difference_type(0))
        value_ -= static_cast<W>(n);
    else
        value_ += static_cast<W>(-n);
} else {
    value_ -= n;
}
return *this;

constexpr W operator[](difference_type n) const
    requires advanceable<W>;

   Effects: Equivalent to: return W(value_ + n);

friend constexpr bool operator==(const iterator& x, const iterator& y)
    requires equality_comparable<W>;

   Effects: Equivalent to: return x.value_ == y.value_;

friend constexpr bool operator<(const iterator& x, const iterator& y)
    requires totally_ordered<W>;

   Effects: Equivalent to: return x.value_ < y.value_;

friend constexpr bool operator>(const iterator& x, const iterator& y)
    requires totally_ordered<W>;

   Effects: Equivalent to: return y < x;

friend constexpr bool operator<=(const iterator& x, const iterator& y)
    requires totally_ordered<W>;

   Effects: Equivalent to: return !(y < x);

friend constexpr bool operator>=(const iterator& x, const iterator& y)
    requires totally_ordered<W>;

   Effects: Equivalent to: return !(x < y);

friend constexpr auto operator<=>(const iterator& x, const iterator& y)
    requires totally_ordered<W> && three_way_comparable<W>;

   Effects: Equivalent to: return x.value_ <=> y.value_;

§ 26.6.4.3
friend constexpr iterator operator+(iterator i, difference_type n)
  requires advanceable<W>;

  Effects: Equivalent to:
  
i += n;
  return i;

friend constexpr iterator operator+(difference_type n, iterator i)
  requires advanceable<W>;

  Effects: Equivalent to: return i + n;

friend constexpr iterator operator-(iterator i, difference_type n)
  requires advanceable<W>;

  Effects: Equivalent to:
  
i -= n;
  return i;

friend constexpr difference_type operator-(const iterator& x, const iterator& y)
  requires advanceable<W>;

  Effects: Equivalent to:
  
  using D = difference_type;
  if constexpr (is-integer-like<W>) {
    if constexpr (is-signed-integer-like<W>)
      return D(D(x.value_) - D(y.value_));
    else
      return (y.value_ > x.value_)
        ? D(-D(y.value_ - x.value_))
        : D(x.value_ - y.value_);
  } else {
    return x.value_ - y.value_;
  }

§ 26.6.4.4 Class iota_view::sentinel

namespace std::ranges {
  template<weakly_incrementable W, semiregular Bound>
    requires weakly-equality-comparable-with<W, Bound> && copyable<W>
  struct iota_view<W, Bound>::sentinel {
    private:
    Bound bound_ = Bound(); // exposition only

    public:
    sentinel() = default;
    constexpr explicit sentinel(Bound bound);

    friend constexpr bool operator==(const iterator& x, const sentinel& y);

    friend constexpr iter_difference_t<W> operator-(const iterator& x, const sentinel& y)
      requires sized_sentinel_for<Bound, W>;
    friend constexpr iter_difference_t<W> operator-(const sentinel& x, const iterator& y)
      requires sized_sentinel_for<Bound, W>;
  };
}

constexpr explicit sentinel(Bound bound);

  Effects: Initializes bound_ with bound.

friend constexpr bool operator==(const iterator& x, const sentinel& y);

  Effects: Equivalent to: return x.value_ == y.bound_;

§ 26.6.4.4
friend constexpr iter_difference_t<W> operator-(const iterator& x, const sentinel& y)  
requires sized_sentinel_for<Bound, W>;  

Effects: Equivalent to: return x.value_ – y.bound_;  

friend constexpr iter_difference_t<W> operator-(const sentinel& x, const iterator& y)  
requires sized_sentinel_for<Bound, W>;  

Effects: Equivalent to: return -(y - x);  

### 26.6.5 Repeat view

#### 26.6.5.1 Overview

repeat_view generates a sequence of elements by repeatedly producing the same value.

The name views::repeat denotes a customization point object (16.3.3.3.5). Given subexpressions E and F, the expressions views::repeat(E) and views::repeat(E, F) are expression-equivalent to repeat_view<decay_t<decltype((E))>>(E) and repeat_view(E, F), respectively.

[Example 1:]

```cpp
for (int i : views::repeat(17, 4))
    cout << i << ' ';  
// prints 17 17 17 17
```

#### 26.6.5.2 Class template repeat_view

```cpp
namespace std::ranges {
    template<class T>  
    concept integer_like_with_usable_difference_type =  // exposition only
        is_signed_integer_like<T> || (is_integer_like<T> && weakly_incrementable<T>);

    template<move_constructible T, semiregular Bound = unreachable_sentinel_t>  
    requires (is_object_v<T> && same_as<T, remove_cv_t<T>> &&
        (integer_like_with_usable_difference_type<Bound> ||
        same_as<Bound, unreachable_sentinel_t>))  
    class repeat_view : public view_interface<repeat_view<T, Bound>> {
        private:
            // 26.6.5.3, class repeat_view::iterator
            struct iterator;  // exposition only
        
            movable_box<T> value_;  // exposition only, see 26.7.3
            Bound bound_ = Bound();  // exposition only

        public:
            repeat_view() requires default_initializable<T> = default;

            constexpr explicit repeat_view(const T& value, Bound bound = Bound())  
                requires copy_constructible<T>;
            constexpr explicit repeat_view(T&& value, Bound bound = Bound());
            template<class... TArgs, class... BoundArgs>  
                requires constructible_from<T, TArgs...> &&
                    constructible_from<Bound, BoundArgs...>  
                constexpr explicit repeat_view(piecewise_construct_t,  
                    tuple<TArgs...> value_args, tuple<BoundArgs...> bound_args = tuple<>());

            constexpr iterator begin() const;
            constexpr iterator end() const requires (!same_as<Bound, unreachable_sentinel_t>);
            constexpr unreachable_sentinel_t end() const noexcept;

            constexpr auto size() const requires (!same_as<Bound, unreachable_sentinel_t>);

        }  

    template<class T, class Bound = unreachable_sentinel_t>  
    repeat_view(T, Bound = Bound()) -> repeat_view<T, Bound>;  
}
```
constexpr explicit repeat_view(const T& value, Bound bound = Bound())
requires copy_constructible<T>;

Preconditions: If Bound is not unreachable_sentinel_t, bound \geq 0.

Effects: Initializes value_ with value and bound_ with bound.

constexpr explicit repeat_view(T&& value, Bound bound = Bound());

Preconditions: If Bound is not unreachable_sentinel_t, bound \geq 0.

Effects: Initializes value_ with std::move(value) and bound_ with bound.

template<class... TArgs, class... BoundArgs>
requires constructible_from<T, TArgs...> &&
constructible_from<Bound, BoundArgs...>
constexpr explicit repeat_view(piecewise_construct_t,
tuple<TArgs...> value_args, tuple<BoundArgs...> bound_args = tuple<>{});

Effects: Initializes value_ with make_from_tuple<T>(std::move(value_args)) and initializes
bound_ with make_from_tuple<Bound>(std::move(bound_args)). The behavior is undefined if Bound
is not unreachable_sentinel_t and bound_ is negative.

constexpr iterator begin() const;

Effects: Equivalent to:
return iterator(addressof(*value_));

constexpr iterator end() const requires (!same_as<Bound, unreachable_sentinel_t>);

Effects: Equivalent to:
return iterator(addressof(*value_), bound_);

constexpr unreachable_sentinel_t end() const noexcept;

Effects: Equivalent to:
return unreachable_sentinel;

constexpr auto size() const requires (!same_as<Bound, unreachable_sentinel_t>);

Effects: Equivalent to:
return to_unsigned_like(bound_);

### 26.6.5.3 Class repeat_view::iterator

namespace std::ranges {

template<move_constructible T, semiregular Bound>
requires (is_object_v<T> && same_as<T, remove_cv_t<T>> &&
(integer-like-with-usable-difference-type<Bound> ||
same_as<Bound, unreachable_sentinel_t>))
class repeat_view<T, Bound>::iterator {

private:
using index-type = // exposition only
    conditional_t<same_as<Bound, unreachable_sentinel_t>, ptrdiff_t, Bound>; // exposition only
const T* value_ = nullptr;
index-type current_ = index-type(); // exposition only

constexpr explicit iterator(const T* value, index-type b = index-type()); // exposition only

public:
using iterator_concept = random_access_iterator_tag;
using iterator_category = random_access_iterator_tag;
using value_type = T;
using difference_type = see below;

iterator() = default;

constexpr const T& operator*() const noexcept;

constexpr iterator& operator++();
constexpr iterator operator++(int);

constexpr iterator& operator--();
constexpr iterator operator--(int);

§ 26.6.5.3 ©ISO/IEC 1220
constexpr iterator& operator+=(difference_type n);  
constexpr iterator& operator-=(difference_type n);  
constexpr const T& operator[](difference_type n) const noexcept;

friend constexpr bool operator==(const iterator& x, const iterator& y);  
friend constexpr auto operator<=>(const iterator& x, const iterator& y);  
friend constexpr iterator operator+(iterator i, difference_type n);  
friend constexpr iterator operator+(difference_type n, iterator i);  
friend constexpr iterator operator-((iterator i, difference_type n));  
friend constexpr difference_type operator-(const iterator& x, const iterator& y);
}

1 If is-signed-integer-like<index-type> is true, the member typedef-name difference_type denotes index-type. Otherwise, it denotes IOTA-DIFF-T(index-type) (26.6.4.2).

castexpr explicit iterator(const T* value, index-type b = index-type());  

2 Preconditions: If Bound is not unreachable_sentinel_t, b ≥ 0.
3 Effects: Initializes value_ with value and current_ with b.

constexpr const T& operator*() const noexcept;

4 Effects: Equivalent to: return *value_;  

castexpr iterator& operator++();  
5 Effects: Equivalent to:  
  ++current_;  
  return *this;

castexpr iterator operator++(int);  
6 Effects: Equivalent to:  
  auto tmp = *this;  
  +++this;  
  return tmp;

constexpr iterator& operator--();  
7 Preconditions: If Bound is not unreachable_sentinel_t, current_ > 0.
8 Effects: Equivalent to:  
  --current_;  
  return *this;

constexpr iterator operator--(int);  
9 Effects: Equivalent to:  
  auto tmp = *this;  
  --*this;  
  return tmp;

constexpr iterator& operator+=(difference_type n);  
10 Preconditions: If Bound is not unreachable_sentinel_t, current_ + n ≥ 0.
11 Effects: Equivalent to:  
  current_ += n;  
  return *this;

constexpr iterator& operator-=(difference_type n);  
12 Preconditions: If Bound is not unreachable_sentinel_t, current_ − n ≥ 0.
13 Effects: Equivalent to:  
  current_ -= n;
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return *this;

constexpr const T& operator[](difference_type n) const noexcept;

Effects: Equivalent to: return *(this + n);

friend constexpr bool operator==(const iterator& x, const iterator& y);

Effects: Equivalent to: return x.current_ == y.current_;

friend constexpr auto operator<=>(const iterator& x, const iterator& y);

Effects: Equivalent to: return x.current_ <== y.current_;

friend constexpr iterator operator+(iterator i, difference_type n);

friend constexpr iterator operator+(difference_type n, iterator i);

Effects: Equivalent to:
    i += n;
    return i;

friend constexpr iterator operator-(iterator i, difference_type n);

Effects: Equivalent to:
    i -= n;
    return i;

friend constexpr difference_type operator-(const iterator& x, const iterator& y);

Effects: Equivalent to:
    return static_cast<difference_type>(x.current_) - static_cast<difference_type>(y.current_);

26.6.6 Istream view

26.6.6.1 Overview

basic_istream_view models input_range and reads (using operator>> ) successive elements from its corresponding input stream.

The name views::istream<T> denotes a customization point object (16.3.3.3.5). Given a type T and a subexpression E of type U, if U models derived_from<basic_istream<typename U::char_type, typename U::traits_type>>, then the expression views::istream<T>(E) is expression-equivalent to basic_istream_view<T, typename U::char_type, typename U::traits_type>(E); otherwise, views::istream<T>(E) is ill-formed.

[Example 1]:
    auto ints = iostreamstream(“0 1 2 3 4”);
    ranges::copy(views::istream<int>(ints), ostream_iterator<int>{cout, "-"});
    // prints 0-1-2-3-4-
    — end example]

26.6.6.2 Class template basic_istream_view

namespace std::ranges {
    template<class Val, class CharT, class Traits>
    concept stream-extractable = // exposition only
        requires(basic_istream<CharT, Traits>& is, Val& t) {
            is >> t;
        };

    template<movable Val, class CharT, class Traits = char_traits<CharT>>
    requires default_initializable<Val> &
            stream-extractable<Val, CharT, Traits>
    class basic_istream_view : public view_interface<basic_istream_view<Val, CharT, Traits>> {
        public:
            constexpr explicit basic_istream_view(basic_istream<CharT, Traits>& stream);
constexpr auto begin() {
    *stream_ >> value_
    return iterator{*this};
}

constexpr default_sentinel_t end() const noexcept;

private:
    // 26.6.6.3, class basic_istream_view::iterator
    struct iterator;       // exposition only
    basic_istream<CharT, Traits>* stream_;         // exposition only
    Val value_ = Val();                     // exposition only
};

constexpr explicit basic_istream_view(basic_istream<CharT, Traits>& stream);

Effects: Initializes stream_ with addressof(stream).

constexpr default_sentinel_t end() const noexcept;

Effects: Equivalent to: return default_sentinel;

26.6.6.3 Class basic_istream_view::iterator

namespace std::ranges {
    template<movable Val, class CharT, class Traits>
    requires default_initializable<Val> &&
    stream-extractable<Val, CharT, Traits>
    class basic_istream_view<Val, CharT, Traits>::iterator {
        public:
            using iterator_concept = input_iterator_tag;
            using difference_type = ptrdiff_t;
            using value_type = Val;

            constexpr explicit iterator(basic_istream_view& parent) noexcept;

            iterator(const iterator&) = delete;
            iterator(iterator&&) = default;

            iterator& operator=(const iterator&) = delete;
            iterator& operator=(iterator&&) = default;

            iterator& operator++();
            void operator++(int);

            Val& operator*() const;

            friend bool operator==(const iterator& x, default_sentinel_t);

        private:
            basic_istream_view* parent_;        // exposition only
        }
    };

constexpr explicit iterator(basic_istream_view& parent) noexcept;

Effects: Initializes parent_ with addressof(parent).

iterator& operator++();

Effects: Equivalent to:
    *parent_->stream_ >> parent_->value_
    return *this;

void operator++(int);

Effects: Equivalent to **this.
Val& operator*() const;

Effects: Equivalent to: return parent_->value_;

friend bool operator==(const iterator& x, default_sentinel_t);

Effects: Equivalent to: return !x.parent_->stream_

26.7 Range adaptors [range.adaptors]

26.7.1 General [range.adaptors.general]

Subclause 26.7 defines range adaptors, which are utilities that transform a range into a view with custom behaviors. These adaptors can be chained to create pipelines of range transformations that evaluate lazily as the resulting view is iterated.

Range adaptors are declared in namespace std::ranges::views.

The bitwise or operator is overloaded for the purpose of creating adaptor chain pipelines. The adaptors also support function call syntax with equivalent semantics.

[Example 1:

```cpp
vector<int> ints{0,1,2,3,4,5};
auto even = [](int i) { return 0 == i % 2; };
auto square = [](int i) { return i * i; };
for (int i : ints | views::filter(even) | views::transform(square)) {
    cout << i << ' ' ; // prints 0 4 16
}
assert(ranges::equal(ints | views::filter(even), views::filter(ints, even)));
—end example]

26.7.2 Range adaptor objects [range.adaptor.object]

A range adaptor closure object is a unary function object that accepts a range argument. For a range adaptor closure object C and an expression R such that decltype((R)) models range, the following expressions are equivalent:

C(R)
R | C

Given an additional range adaptor closure object D, the expression C | D produces another range adaptor closure object E. E is a perfect forwarding call wrapper (22.10.4) with the following properties:

(1.1) — Its target object is an object d of type decay_t<decltype((D))> direct-non-list-initialized with D.
(1.2) — It has one bound argument entity, an object c of type decay_t<decltype((C))> direct-non-list-initialized with C.
(1.3) — Its call pattern is d(c(arg)), where arg is the argument used in a function call expression of E.

The expression C | D is well-formed if and only if the initializations of the state entities of E are all well-formed.

Given an object t of type T, where

(2.1) — t is a unary function object that accepts a range argument,
(2.2) — T models derived_from<range_adaptor_closure<T>>,
(2.3) — T has no other base classes of type range_adaptor_closure<U> for any other type U, and
(2.4) — T does not model range
then the implementation ensures that t is a range adaptor closure object.

The template parameter D for range_adaptor_closure may be an incomplete type. If an expression of type cv D is used as an operand to the | operator, D shall be complete and model derived_from<range_adaptor_closure<D>>. The behavior of an expression involving an object of type cv D as an operand to the | operator is undefined if overload resolution selects a program-defined operator| function.

If an expression of type cv U is used as an operand to the | operator, where U has a base class of type range_adaptor_closure<T> for some type T other than U, the behavior is undefined.

The behavior of a program that adds a specialization for range_adaptor_closure is undefined.
A range adaptor object is a customization point object (16.3.3.5) that accepts a viewable_range as its first argument and returns a view.

If a range adaptor object accepts only one argument, then it is a range adaptor closure object.

If a range adaptor object adaptor accepts more than one argument, then let range be an expression such that decltype((range)) models viewable_range, let args... be arguments such that adaptor(range, args...) is a well-formed expression as specified in the rest of subclause 26.7, and let BoundArgs be a pack that denotes decay_t<decltype((args))>... The expression adaptor(args...) produces a range adaptor closure object f that is a perfect forwarding call wrapper (22.10.4) with the following properties:

1. Its target object is a copy of adaptor.
2. Its bound argument entities bound_args consist of objects of types BoundArgs... direct-non-list-initialized with std::forward<decltype((args))>(args)..., respectively.
3. Its call pattern is adaptor(r, bound_args...), where r is the argument used in a function call expression of f.

The expression adaptor(args...) is well-formed if and only if the initialization of the bound argument entities of the result, as specified above, are all well-formed.

26.7.3 Movable wrapper

Many types in this subclause are specified in terms of an exposition-only class template movable-box<T> behaves exactly like optional<T> with the following differences:

1. movable-box<T> constrains its type parameter T with move_constructible<T> && is_object_v<T>.
2. The default constructor of movable-box<T> is equivalent to:
   ```cpp
cpp
   constexpr movable-box() noexcept(is_nothrow_default_constructible_v<T>)
   requires default_initializable<T>:
   movable-box(in_place) {}
   ```
3. If copyable<T> is not modeled, the copy assignment operator is equivalent to:
   ```cpp
cpp
   constexpr movable-box& operator=(const movable-box& that)
   noexcept(is_nothrow_copy_constructible_v<T>)
   requires copy_constructible<T> {
   if (this != addressof(that)) {
   if (that) emplace(*that);
   else reset();
   }
   return *this;
   }
   ```
4. If movable<T> is not modeled, the move assignment operator is equivalent to:
   ```cpp
cpp
   constexpr movable-box& operator=(movable-box&& that)
   noexcept(is_nothrow_move_constructible_v<T>) {
   if (this != addressof(that)) {
   if (that) emplace(std::move(*that));
   else reset();
   }
   return *this;
   }
   ```

Recommended practice:

1. If copy_constructible<T> is true, movable-box<T> should store only a T if either T models copyable, or is_nothrow_move_constructible_v<T> && is_nothrow_copy_constructible_v<T> is true.
2. Otherwise, movable-box<T> should store only a T if either T models movable or is_nothrow_move_constructible_v<T> is true.

26.7.4 Non-propagating cache

Some types in 26.7 are specified in terms of an exposition-only class template non-propagating-cache<T> behaves exactly like optional<T> with the following differences:

1. non-propagating-cache<T> constrains its type parameter T with is_object_v<T>.
The copy constructor is equivalent to:

```cpp
constexpr non-propagating-cache(const non-propagating-cache&) noexcept {}
```

The move constructor is equivalent to:

```cpp
constexpr non-propagating-cache(non-propagating-cache&& other) noexcept {
other.reset();
}
```

The copy assignment operator is equivalent to:

```cpp
constexpr non-propagating-cache& operator=(const non-propagating-cache& other) noexcept {
if (addressof(other) != this)
reset();
return *this;
}
```

The move assignment operator is equivalent to:

```cpp
constexpr non-propagating-cache& operator=(non-propagating-cache&& other) noexcept {
reset();
other.reset();
return *this;
}
```

`non-propagating-cache<T>` has an additional member function template specified as follows:

```cpp
template<class I>
constexpr T& emplace-deref(const I& i); // exposition only
```

**Mandates:** The declaration `T t(*i);` is well-formed for some invented variable `t`.

*Note 1:* If `*i` is a prvalue of type `cv T`, there is no requirement that it is movable (9.4.1). — end note

**Effects:** Calls `reset()`. Then direct-non-list-initializes the contained value with `*i`.

**Postconditions:** `*this` contains a value.

**Returns:** A reference to the new contained value.

**Throws:** Any exception thrown by the initialization of the contained value.

**Remarks:** If an exception is thrown during the initialization of `T`, `*this` does not contain a value, and the previous value (if any) has been destroyed.

---

2 [Note 2: `non-propagating-cache` enables an input view to temporarily cache values as it is iterated over. — end note]

### 26.7.5 Range adaptor helpers

```cpp
namespace std::ranges {
    template<class F, class Tuple>
    constexpr auto tuple-transform(F&& f, Tuple&& t) { // exposition only
        return apply([&]<class... Ts>(Ts&&... elements) {
            return tuple<invoke_result_t<F&, Ts>...>(invoke(f, std::forward<Ts>(elements))...);
        }, std::forward<Tuple>(t));
    }

    template<class F, class Tuple>
    constexpr void tuple-for-each(F&& f, Tuple&& t) { // exposition only
        apply([&]<class... Ts>(Ts&&... elements) {
            invoke(f, std::forward<Ts>(elements)), ...;
        }, std::forward<Tuple>(t));
    }

    template<class T>
    constexpr T& as-lvalue(T&& t) { // exposition only
        return static_cast<T&>(t);
    }
}
```
```cpp
template<
    bool Const, class... Views>
concep all-random-access = // exposition only
    (random_access_range<
        maybe-const<Const, Views>> && ...);

template<
    bool Const, class... Views>
concep all-bidirectional = // exposition only
    (bidirectional_range<
        maybe-const<Const, Views>> && ...);

template<
    bool Const, class... Views>
concep all-forward = // exposition only
    (forward_range<
        maybe-const<Const, Views>> && ...);

}}

26.7.6  All view

26.7.6.1  General

views::all returns a view that includes all elements of its range argument.

The name views::all denotes a range adaptor object (26.7.2). Given a subexpression E, the expression
views::all(E) is expression-equivalent to:

(2.1) — decay-copy(E) if the decayed type of E models view.

(2.2) — Otherwise, ref_view(E) if that expression is well-formed.

(2.3) — Otherwise, owning_view(E).

26.7.6.2  Class template ref_view

ref_view is a view of the elements of some other range.

namespace std::ranges {

    template<
        range R>
    requires is_object_v<R>
    class ref_view : public view_interface<ref_view<R>> {
        private:
            R* r_; // exposition only

        public:
            template<
                different-from<ref_view> T>
            requires see below
            constexpr ref_view(T&& t);

            constexpr R& base() const { return *r_; }

            constexpr iterator_t<R> begin() const { return ranges::begin(*r_); }
            constexpr sentinel_t<R> end() const { return ranges::end(*r_); }

            constexpr bool empty() const
                requires requires { ranges::empty(*r_); }
                { return ranges::empty(*r_); }

            constexpr auto size() const requires sized_range<R>
                { return ranges::size(*r_); }

            constexpr auto data() const requires contiguous_range<R>
                { return ranges::data(*r_); }
    }

    template<class R>
    ref_view(R&) -> ref_view<R>;

}

template<
    different-from<ref_view> T>
requires see below
    constexpr ref_view(T&& t);

Effects: Initializes r_ with addressof(static_cast<R&>(std::forward<T>(t))).

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1227
Remarks: Let \( \text{FUN} \) denote the exposition-only functions

\[
\begin{align*}
\text{void FUN}(R&); \\
\text{void FUN}(R&&) = \text{delete};
\end{align*}
\]

The expression in the \textit{requires-clause} is equivalent to:

\[
\text{convertible_to}\langle T, R& \rangle && \text{requires} \{ \text{FUN}(\text{declval}\langle T \rangle()); \}
\]

26.7.6.3 Class template owning_view

\texttt{owning\_view} is a move-only view of the elements of some other range.

\begin{verbatim}
namespace std::ranges {
    template<range R>
    requires movable<R> && (!is-initializer-list<R>) // see 26.4.5
    class owning_view : public view_interface<owning_view<R>> {
        private:
            R r_ = R(); // exposition only
        public:
            owning_view() requires default_initializable<R> = default;
            owning_view(R&& t);
            owning_view(owning_view&&) = default;
            owning_view& operator=(owning_view&&) = default;
            constexpr R& base() & noexcept { return r_; }
            constexpr const R& base() const & noexcept { return r_; }
            constexpr R&& base() && noexcept { return std::move(r_); }
            constexpr const R&& base() const && noexcept { return std::move(r_); }
            constexpr iterator_t<R> begin() { return ranges::begin(r_); }
            constexpr sentinel_t<R> end() { return ranges::end(r_); }
            constexpr auto begin() const requires range<const R> { return ranges::begin(r_); }
            constexpr auto end() const requires range<const R> { return ranges::end(r_); }
            constexpr bool empty() requires requires { ranges::empty(r_); } { return ranges::empty(r_); }
            constexpr bool empty() const requires requires { ranges::empty(r_); } { return ranges::empty(r_); }
            constexpr auto size() requires sized_range<R> { return ranges::size(r_); }
            constexpr auto size() const requires sized_range<const R> { return ranges::size(r_); }
            constexpr auto data() requires contiguous_range<R> { return ranges::data(r_); }
            constexpr auto data() const requires contiguous_range<const R> { return ranges::data(r_); }
    };
}
\end{verbatim}

\texttt{constexpr owning_view(R&& t);}  

\textit{Effects:} Initializes \texttt{r_} with \texttt{std::move(t)}.

26.7.7 As rvalue view

26.7.7.1 Overview

\texttt{as\_rvalue\_view} presents a view of an underlying sequence with the same behavior as the underlying sequence except that its elements are rvalues. Some generic algorithms can be called with an \texttt{as\_rvalue\_view} to replace copying with moving.
The name `views::as_rvalue` denotes a range adaptor object (26.7.2). Let `E` be an expression and let `T` be `decltype((E))`. The expression `views::as_rvalue(E)` is expression-equivalent to:

1. `views::all(E)` if `T` models `input_range` and `same_as<range_rvalue_reference_t<T>, range_reference_t<T>>` is true.
2. Otherwise, `as_rvalue_view(E)`.

[Example 1:

```cpp
template<class R> as_rvalue_view<R&&> -> as_rvalue_view<views::all_t<R>>;
```

`constexpr explicit as_rvalue_view(V base)`;

Effects: Initializes `base_` with `std::move(base)`.

26.7.8 Filter view

26.7.8.1 Overview

`filter_view` presents a view of the elements of an underlying sequence that satisfy a predicate.
The name `views::filter` denotes a range adaptor object (26.7.2). Given subexpressions E and P, the expression `views::filter(E, P)` is expression-equivalent to `filter_view(E, P).

Example 1:
```cpp
vector<int> is{ 0, 1, 2, 3, 4, 5, 6 };
auto evens = views::filter(is, [] (int i) { return 0 == i % 2; });
for (int i : evens)
    cout << i << ' ' // prints 0 2 4 6
```

26.7.8.2 Class template filter_view

```
namespace std::ranges {
    template<input_range V, indirect_unary_predicate<iterator_t<V>> Pred>
    requires view<V> && is_object_v<Pred>
    class filter_view : public view_interface<filter_view<V, Pred>> {
    private:
        V base_ = V(); // exposition only
        movable-box<Pred> pred_; // exposition only

    // 26.7.8.3, class filter_view::iterator
    class iterator;
    // exposition only

    // 26.7.8.4, class filter_view::sentinel
    class sentinel;
    // exposition only

    public:
        filter_view() requires default_initializable<V> && default_initializable<Pred> = default;
        constexpr explicit filter_view(V base, Pred pred);
        constexpr V base() const & requires copy_constructible<V> { return base_; }
        constexpr V base() && { return std::move(base_); }
        constexpr const Pred& pred() const;
        constexpr iterator begin();
        constexpr auto end() {
            if constexpr (common_range<V>)
                return iterator{this, ranges::end(base_)};
            else
                return sentinel{this};
        }
    }

    template<class R, class Pred>
    constexpr explicit filter_view(V base, Pred pred) -> filter_view<views::all_t<R>, Pred>;
    }
```

1. **Effects**: Initializes `base_` with `std::move(base)` and initializes `pred_` with `std::move(pred)`.

2. **Effects**: Equivalent to: return `*pred_`;

3. **Preconditions**: `pred_.has_value()` is true.

4. **Returns**: `{*this, ranges::find_if(base_, ref(*pred_))}`.

5. **Remarks**: In order to provide the amortized constant time complexity required by the range concept when `filter_view` models `forward_range`, this function caches the result within the `filter_view` for use on subsequent calls.
namespace std::ranges {
    template<input_range V, indirect Unary Predicate<iterator_t<V>> Pred>
    requires view<V> & is_object_v<Pred>
    class filter_view<V, Pred>::iterator {
        private:
            iterator_t<V> current_ = iterator_t<V>();  // exposition only
            filter_view* parent_ = nullptr;            // exposition only

        public:
            using iterator_concept = see below;        // not always present
            using iterator_category = see below;        // not always present
            using value_type = range_value_t<V>;
            using difference_type = range_difference_t<V>;

            iterator() requires default_initializable<iterator_t<V>> = default;
            constexpr iterator(filter_view& parent, iterator_t<V> current);

            constexpr const iterator_t<V>& base() const & noexcept;
            constexpr iterator_t<V> base() &&;
            constexpr range_reference_t<V> operator*() const;
            constexpr iterator_t<V> operator->() const requires has_arrow<iterator_t<V>> && copyable<iterator_t<V>>;

            constexpr iterator& operator++();
            constexpr void operator++(int);
            constexpr iterator operator++(int) requires forward_range<V>;

            constexpr iterator& operator--() requires bidirectional_range<V>;
            constexpr iterator operator--(int) requires bidirectional_range<V>;

            friend constexpr bool operator==(const iterator& x, const iterator& y) requires equality_comparable<iterator_t<V>>;

            friend constexpr range_rvalue_reference_t<V> iter_move(const iterator& i) noexcept(noexcept(ranges::iter_move(i.current_)));

            friend constexpr void iter_swap(const iterator& x, const iterator& y) noexcept(noexcept(ranges::iter_swap(x.current_, y.current_))) requires indirectly_swappable<iterator_t<V>>;
        }
    }
}

1 Modification of the element a `filter_view::iterator` denotes is permitted, but results in undefined behavior if the resulting value does not satisfy the filter predicate.

2 `iterator::iterator_concept` is defined as follows:

(2.1) — If V models `bidirectional_range`, then `iterator_concept` denotes `bidirectional_iterator_tag`.

(2.2) — Otherwise, if V models `forward_range`, then `iterator_concept` denotes `forward_iterator_tag`.

(2.3) — Otherwise, `iterator_concept` denotes `input_iterator_tag`.

3 The member typedef-name `iterator_category` is defined if and only if V models `forward_range`. In that case, `iterator::iterator_category` is defined as follows:

(3.1) — Let C denote the type `iterator_traits<iterator_t<V>>::iterator_category`.

(3.2) — If C models `derived_from<bidirectional_iterator_tag>`, then `iterator_category` denotes `bidirectional_iterator_tag`.

(3.3) — Otherwise, if C models `derived_from<forward_iterator_tag>`, then `iterator_category` denotes `forward_iterator_tag`.

(3.4) — Otherwise, `iterator_category` denotes C.
constexpr iterator(filter_view& parent, iterator_t<V> current);

Effects: Initializes current_ with std::move(current) and parent_ with addressof(parent).

constexpr const iterator_t<V>& base() const & noexcept;

Effects: Equivalent to: return current_

constexpr iterator_t<V> base() &;&

Effects: Equivalent to: return std::move(current_);

constexpr range_reference_t<V> operator*() const;

Effects: Equivalent to: return *current_

constexpr iterator_t<V> operator++();

Effects: Equivalent to:

    current_ = ranges::find_if(std::move(++current_), ranges::end(parent_->base_),
                               ref(*parent_->pred_));
    return *this;

constexpr void operator++(int);

Effects: Equivalent to **this.

constexpr iterator operator++(int) requires forward_range<V>;

Effects: Equivalent to:

    auto tmp = *this;
    **this;
    return tmp;

constexpr iterator& operator--() requires bidirectional_range<V>;

Effects: Equivalent to:

    do
      --current_;
    while (!invoke(*parent_->pred_, *current_));
    return *this;

constexpr iterator& operator--(int) requires bidirectional_range<V>;

Effects: Equivalent to:

    auto tmp = *this;
    --*this;
    return tmp;

friend constexpr bool operator==(const iterator& x, const iterator& y)
    requires equality_comparable<iterator_t<V>>;

Effects: Equivalent to: return x.current_ == y.current_

friend constexpr range_rvalue_reference_t<V> iter_move(const iterator& i)
    noexcept(ranges::iter_move(i.current_));

Effects: Equivalent to: return ranges::iter_move(i.current_);

friend constexpr void iter_swap(const iterator& x, const iterator& y)
    noexcept(ranges::iter_swap(x.current_, y.current_))
    requires indirectly_swappable<iterator_t<V>>;

Effects: Equivalent to ranges::iter_swap(x.current_, y.current_).

26.7.8.4 Class filter_view::sentinel
namespace std::ranges {
  template<input_range V, indirect_unary_predicate<iterator_t<V>> Pred>
  requires view<V> && is_object_v<Pred>
  class filter_view<V, Pred>::sentinel {
    private:
      sentinel_t<V> end_ = sentinel_t<V>();  // exposition only

    public:
      sentinel() = default;
      constexpr explicit sentinel(filter_view& parent);

      constexpr sentinel_t<V> base() const;

      friend constexpr bool operator==(const iterator x, const sentinel& y);
  }

  constexpr explicit sentinel(filter_view& parent);

  Effects: Initializes end_ with ranges::end(parent.base_).

  constexpr sentinel_t<V> base() const;
  Effects: Equivalent to: return end_;

  friend constexpr bool operator==(const iterator x, const sentinel& y);
  Effects: Equivalent to: return x.current_ == y.end_;
}

26.7.9 Transform view

26.7.9.1 Overview

transform_view presents a view of an underlying sequence after applying a transformation function to each element.

The name views::transform denotes a range adaptor object (26.7.2). Given subexpressions E and F, the expression views::transform(E, F) is expression-equivalent to transform_view(E, F).

[Example 1:
  vector<int> is( 0, 1, 2, 3, 4 );
  auto squares = views::transform(is, [] (int i) { return i * i; });
  for (int i : squares)
    cout << i << ' '; // prints 0 1 4 9 16
  —end example]

26.7.9.2 Class template transform_view

namespace std::ranges {
  template<input_range V, move_constructible F>
  requires view<V> && is_object_v<F> &&
      regular_invocable<F&>, range_reference_t<V>> &&
      can-reference<invoke_result_t<F&>, range_reference_t<V>>>
  class transform_view : public view_interface<transform_view<V, F>> {
    private:
      // 26.7.9.3, class template transform_view::iterator
      template<bool> struct iterator;
      // exposition only

      // 26.7.9.4, class template transform_view::sentinel
      template<bool> struct sentinel;
      // exposition only

    V base_ = V();
    movable-box<F> fun_;  // exposition only

    public:
      transform_view() requires default_initializable<V> && default_initializable<F> = default;
      constexpr explicit transform_view(V base, F fun);
  }
}
constexpr V base() const & requires copy_constructible<V> { return base_; }
constexpr V base() && { return std::move(base_); }

constexpr iterator<false> begin();
constexpr iterator<true> begin() const
    requires range<const V> &&
    regular_invocable<const F&, range_reference_t<const V>>;

constexpr sentinel<false> end();
constexpr iterator<false> end() requires common_range<V>;
constexpr sentinel<true> end() const
    requires range<const V> &&
    regular_invocable<const F&, range_reference_t<const V>>;

constexpr auto size() requires sized_range<V> { return ranges::size(base_); }
constexpr auto size() const requires sized_range<const V>
    { return ranges::size(base_); }
};

template<class R, class F>
transform_view(R&&, F) -> transform_view<views::all_t<R>, F>;

constexpr explicit transform_view(V base, F fun);

1. **Effects**: Initializes base_ with std::move(base) and fun_ with std::move(fun).

constexpr iterator<false> begin();
2. **Effects**: Equivalent to:
   
   return iterator<false>{*this, ranges::begin(base_)};

constexpr iterator<true> begin() const
    requires range<const V> &&
    regular_invocable<const F&, range_reference_t<const V>>;
3. **Effects**: Equivalent to:
   
   return iterator<true>{*this, ranges::begin(base_)};

constexpr sentinel<false> end();
4. **Effects**: Equivalent to:
   
   return sentinel<false>{ranges::end(base_)};

constexpr iterator<false> end() requires common_range<V>;
5. **Effects**: Equivalent to:
   
   return iterator<false>{*this, ranges::end(base_)};

constexpr sentinel<true> end() const
    requires range<const V> &&
    regular_invocable<const F&, range_reference_t<const V>>;
6. **Effects**: Equivalent to:
   
   return sentinel<true>{ranges::end(base_)};

constexpr iterator<true> end() const
    requires common_range<const V> &&
    regular_invocable<const F&, range_reference_t<const V>>;
7. **Effects**: Equivalent to:
   
   return iterator<true>{*this, ranges::end(base_)};
26.7.9.3 Class template `transform_view::iterator`

```cpp
namespace std::ranges {
    template<input_range V, move_constructible F>
    requires view<V> && is_object_v<F> &&
        regular_invocable<F&, range_reference_t<V>> &&
        can_reference<invoke_result_t<F&, range_reference_t<V>>>>
    template<bool Const>
    class transform_view<V, F>::iterator {
        private:
            using Parent = maybe_const<Const, transform_view>; // exposition only
            using Base = maybe_const<Const, V>; // exposition only
            iterator_t<Base> current_ = iterator_t<Base>(); // exposition only
            Parent* parent_ = nullptr; // exposition only

        public:
            using iterator_concept = see below; // not always present
            using iterator_category = see below
            using value_type = remove_cvref_t<invoke_result_t<maybe-const<Const, F>&, range_reference_t<Base>>>;
            using difference_type = range_difference_t<Base>;

            iterator() requires default_initializable<iterator_t<Base>> = default;
            constexpr iterator(Parent& parent, iterator_t<Base> current);
            constexpr iterator(iterator<!Const> i) requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;
            constexpr const iterator_t<Base>& base() const & noexcept;
            constexpr iterator_t<Base>& base() &&;
            constexpr decltype(auto) operator*() const noexcept(noexcept(invoke(*parent_->fun_, *current_))) {
                return invoke(*parent_->fun_, *current_);
            }
            constexpr iterator& operator++();
            constexpr void operator++(int);
            constexpr iterator operator++(int) requires forward_range<Base>;
            constexpr iterator& operator--();
            constexpr void operator--(int) requires bidirectional_range<Base>;
            constexpr iterator operator+=(difference_type n) requires random_access_range<Base>;
            constexpr iterator operator-=(difference_type n) requires random_access_range<Base>;
            constexpr decltype(auto) operator[](difference_type n) const requires random_access_range<Base> {
                return invoke(*parent_->fun_, current_[n]);
            }
            friend constexpr bool operator==(const iterator& x, const iterator& y) requires equality_comparable<iterator_t<Base>>;
            friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;
            friend constexpr bool operator>(const iterator& x, const iterator& y) requires random_access_range<Base>;
            friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;
            friend constexpr bool operator>=(const iterator& x, const iterator& y) requires random_access_range<Base>;
            friend constexpr auto operator<=>(const iterator& x, const iterator& y) requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;
    }
}
```
friend constexpr iterator operator+(iterator i, difference_type n) requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, iterator i) requires random_access_range<Base>;
friend constexpr iterator operator-(iterator i, difference_type n) requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator x, const iterator y) requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

};

1 iterator::iterator_concept is defined as follows:
   (1.1) If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
   (1.2) Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
   (1.3) Otherwise, if Base models forward_range, then iterator_concept denotes forward_iterator_tag.
   (1.4) Otherwise, iterator_concept denotes input_iterator_tag.

2 The member typedef-name iterator_category is defined if and only if Base models forward_range. In that case, iterator::iterator_category is defined as follows: Let C denote the type iterator_traits<iterator_t<Base>>::iterator_category.
   (2.1) If is_reference_v<invoke_result_t<maybe-const<Const, F>&, range_reference_t<Base>>> is true, then
       (2.1.1) if C models derived_from<contiguous_iterator_tag>, iterator_category denotes random_access_iterator_tag;
       (2.1.2) otherwise, iterator_category denotes C.
   (2.2) Otherwise, iterator_category denotes input_iterator_tag.

constexpr iterator(Parent& parent, iterator_t<Base> current);
3 Effects: Initializes current_ with std::move(current) and parent_ with addressof(parent).

customexpr iterator(Iterator<Const> i) requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;
4 Effects: Initializes current_ with std::move(i.current_) and parent_ with i.parent_.

customexpr const iterator_t<Base>& base() const & noexcept;
5 Effects: Equivalent to: return current_;

customexpr iterator_t<Base>& base() &&;
6 Effects: Equivalent to: return std::move(current_);

customexpr iterator& operator++();
7 Effects: Equivalent to:
   ++current_; return *this;

customexpr void operator++(int);
8 Effects: Equivalent to ++current_.

customexpr iterator operator++(int) requires forward_range<Base>;
9 Effects: Equivalent to:
   auto tmp = *this; +++this; return tmp;
constexpr iterator & operator--() requires bidirectional_range<Base>;

**Effects:** Equivalent to:

```cpp
--current_;  
return *this;
```

customexpr iterator operator--(int) requires bidirectional_range<Base>;

**Effects:** Equivalent to:

```cpp
auto tmp = *this;  
--*this;  
return tmp;
```

customexpr iterator & operator+=(difference_type n)  
requires random_access_range<Base>;

**Effects:** Equivalent to:

```cpp
current_ += n;  
return *this;
```

customexpr iterator & operator-=(difference_type n)  
requires random_access_range<Base>;

**Effects:** Equivalent to:

```cpp
current_ -= n;  
return *this;
```

friend constexpr bool operator==(const iterator & x, const iterator & y)  
requires equality_comparable<iterator_t<Base>>;

**Effects:** Equivalent to: return x.current_ == y.current_;

friend constexpr bool operator<(<const iterator & x, const iterator & y)  
requires random_access_range<Base>;

**Effects:** Equivalent to: return x.current_ < y.current_;

friend constexpr bool operator>(<const iterator & x, const iterator & y)  
requires random_access_range<Base>;

**Effects:** Equivalent to: return y < x;

friend constexpr bool operator<=(<const iterator & x, const iterator & y)  
requires random_access_range<Base>;

**Effects:** Equivalent to: return !(y < x);

friend constexpr bool operator>=(<const iterator & x, const iterator & y)  
requires random_access_range<Base>;

**Effects:** Equivalent to: return !(x < y);

friend constexpr auto operator<=>(<<const iterator & x, const iterator & y)  
requires random_access_range<Base> & three_way_comparable<iterator_t<Base>>;

**Effects:** Equivalent to: return x.current_ <=> y.current_;

friend constexpr iterator operator+(iterator i, difference_type n)  
requires random_access_range<Base>;

friend constexpr iterator operator+(difference_type n, iterator i)  
requires random_access_range<Base>;

**Effects:** Equivalent to: return iterator{i.parent_, i.current_ + n};

friend constexpr iterator operator-(iterator i, difference_type n)  
requires random_access_range<Base>;

**Effects:** Equivalent to: return iterator{i.parent_, i.current_ - n};
friend constexpr difference_type operator-(const(iterator&) x, const iterator&) y) {
    requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;
    Effects: Equivalent to: return x.current_ - y.current_;
}

26.7.9.4 Class template transform_view::sentinel

namespace std::ranges {
    template<input_range V, move_constructible F>
    requires view<V> && is_object_v<F> &&
    regular_invocable<F&, range_reference_t<V>> &&
    can-reference<invoke_result_t<F&, range_reference_t<V>>>;
    template<bool Const>
    class transform_view<V, F>::sentinel {
        private:
            using Parent = maybe-const<Const, transform_view>; // exposition only
            using Base = maybe-const<Const, V>; // exposition only
            sentinel_t<Base> end_ = sentinel_t<Base>(); // exposition only
        public:
            sentinel() = default;
            constexpr explicit sentinel(sentinel_t<Base> end);
            constexpr sentinel(sentinel<!Const> i)
                requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
            constexpr sentinel_t<Base> base() const;
            template<bool OtherConst>
            requires sentinel_for<sentinel_t<Base>, iterator_t<Maybe-const<OtherConst, V>>>
            friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
            template<bool OtherConst>
            requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Maybe-const<OtherConst, V>>>
            friend constexpr range_difference_t<Maybe-const<OtherConst, V>>
            operator-(const iterator<OtherConst>& x, const sentinel& y);
        }
        constexpr explicit sentinel(sentinel_t<Base> end);
        Effects: Initializes end_ with end.
        constexpr sentinel(sentinel<!Const> i)
            requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
        Effects: Initializes end_ with std::move(i.end_).
        constexpr sentinel_t<Base> base() const;
        Effects: Equivalent to: return end_;
        template<bool OtherConst>
        requires sentinel_for<sentinel_t<Base>, iterator_t<Maybe-const<OtherConst, V>>>
        friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
        Effects: Equivalent to: return x.current_ == y.end_;
        template<bool OtherConst>
        requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Maybe-const<OtherConst, V>>>
        friend constexpr range_difference_t<Maybe-const<OtherConst, V>>
        operator-(const iterator<OtherConst>& x, const sentinel& y);
        Effects: Equivalent to: return x.current_ - y.end_;
template<bool OtherConst>
  requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
  operator-(const sentinel& y, const iterator<OtherConst>& x);

Effects: Equivalent to: return y.end_ - x.current_;

26.7.10 Take view

26.7.10.1 Overview

take_view produces a view of the first \( N \) elements from another view, or all the elements if the adapted view contains fewer than \( N \).

The name views::take denotes a range adaptor object (26.7.2). Let \( E \) and \( F \) be expressions, let \( T \) be remove_cvref_t<decltype((E))>, and let \( D \) be range_difference_t<decltype((E))>. If decltype((F)) does not model convertible_to<D>, views::take(E, F) is ill-formed. Otherwise, the expression views::take(E, F) is expression-equivalent to:

(2.1) — If \( T \) is a specialization of empty_view (26.6.2.2), then ((void)F, decay-copy(E)), except that the evaluations of \( E \) and \( F \) are indeterminately sequenced.

(2.2) — Otherwise, if \( T \) models random_access_range and sized_range and is a specialization of span (24.7.2.2), basic_string_view (23.3), or subrange (26.5.4), then \( U(ranges::begin(E), ranges::begin(E) + std::min<D>(ranges::distance(E), F)) \), except that \( E \) is evaluated only once, where \( U \) is a type determined as follows:

(2.2.1) — if \( T \) is a specialization of span, then \( U \) is span<typename T::element_type>;

(2.2.2) — otherwise, if \( T \) is a specialization of basic_string_view, then \( U \) is \( T \);

(2.2.3) — otherwise, \( T \) is a specialization of subrange, and \( U \) is subrange<iterator_t<T>;;

(2.3) — otherwise, if \( T \) is a specialization of iota_view (26.6.4.2) that models random_access_range and sized_range, then \( iota_view(*ranges::begin(E), *(ranges::begin(E) + std::min<D>(ranges::distance(E), F))) \), except that \( E \) is evaluated only once.

(2.4) — Otherwise, if \( T \) is a specialization of repeat_view (26.6.5.2):

(2.4.1) — if \( T \) models sized_range, then \( views::repeat(*E.value_, std::min<D>(ranges::distance(E), F)) \)

otherwise, views::repeat(*E.value_, static_cast<D>(F)).

(2.5) — Otherwise, take_view(E, F).

Example 1:

`vector<int> is{0,1,2,3,4,5,6,7,8,9};
for (int i : is | views::take(5))
  cout << i << ' '; // prints 0 1 2 3 4``

end example]

26.7.10.2 Class template take_view

namespace std::ranges {
  template<view V>
  class take_view : public view_interface<take_view<V>> {
    private:
      V base_ = V(); // exposition only
      range_difference_t<V> count_ = 0; // exposition only

      // 26.7.10.3, class template take_view::sentinel
    template<bool> class sentinel;
      // exposition only

    public:
      take_view() requires default_initializable<V> = default;
      constexpr explicit take_view(V base, range_difference_t<V> count);
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constexpr V base() const & requires copy_constructible<V> { return base_; }  
constexpr V base() && { return std::move(base_); }

constexpr auto begin() requires (!simple_view,V) { 
  if constexpr (sized_range<V>) { 
    if constexpr (random_access_range<V>) { 
      return ranges::begin(base_); 
    } else { 
      auto sz = range_difference_t<V>(size()); 
      return counted_iterator(ranges::begin(base_), sz); 
    } 
  } else if constexpr (sized_sentinel_for<sentinel_t<V>, iterator_t<V>>) { 
    auto it = ranges::begin(base_); 
    auto sz = std::min(count_, ranges::end(base_) - it); 
    return counted_iterator(std::move(it), sz); 
  } else { 
    return counted_iterator(ranges::begin(base_), count_); 
  } 
}

constexpr auto begin() const requires range<const V> { 
  if constexpr (sized_range<const V>) { 
    if constexpr (random_access_range<const V>) { 
      return ranges::begin(base_); 
    } else { 
      auto sz = range_difference_t<const V>(size()); 
      return counted_iterator(ranges::begin(base_), sz); 
    } 
  } else if constexpr (sized_sentinel_for<sentinel_t<const V>, iterator_t<const V>>) { 
    return default_sentinel; 
  } else { 
    return sentinel<false>{ranges::end(base_)}; 
  } 
}

constexpr auto end() requires (!simple_view,V) { 
  if constexpr (sized_range<V>) { 
    if constexpr (random_access_range<V>) { 
      return ranges::begin(base_) + range_difference_t<V>(size()); 
    } else { 
      return default_sentinel; 
    } 
  } else if constexpr (sized_sentinel_for<sentinel_t<V>, iterator_t<V>>) { 
    return default_sentinel; 
  } else { 
    return sentinel<false>{ranges::end(base_)}; 
  } 
}

constexpr auto end() const requires range<const V> { 
  if constexpr (sized_range<const V>) { 
    if constexpr (random_access_range<const V>) { 
      return ranges::begin(base_) + range_difference_t<const V>(size()); 
    } else { 
      return default_sentinel; 
    } 
  } else if constexpr (sized_sentinel_for<sentinel_t<const V>, iterator_t<const V>>) { 
    return default_sentinel; 
  } else { 
    return sentinel<true>{ranges::end(base_)}; 
  } 
}
constexpr auto size() requires sized_range<V> {
    auto n = ranges::size(base_);
    return ranges::min(n, static_cast<decltype(n)>(count_));
}
constexpr auto size() const requires sized_range<const V> {
    auto n = ranges::size(base_);
    return ranges::min(n, static_cast<decltype(n)>(count_));
};

template<class R>
    take_view(R&&, range_difference_t<R>)
-> take_view<views::all_t<R>>;

constexpr explicit take_view(V base, range_difference_t<V> count);

1 Preconditions: count >= 0 is true.
2 Effects: Initializes base_ with std::move(base) and count_ with count.

26.7.10.3 Class template take_view::sentinel

namespace std::ranges {
    template<view V>
    template<bool Const>
    class take_view<V>::sentinel {
        private:
            using Base = maybe-const<Const, V>;
            template<bool OtherConst>
                using CI = counted_iterator<iterator_t<maybe-const<OtherConst, V>>;  // exposition only
            sentinel_t<Base> end_ = sentinel_t<Base>();
        // exposition only

        public:
            sentinel() = default;
            constexpr explicit sentinel(sentryl_t<Base> end);
            constexpr sentinel(sentryl_t<!Const> s)
            requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
            constexpr sentinel_t<Base> base() const;

            friend constexpr bool operator==(const CI<Const>& y, const sentinel& x);
            template<bool OtherConst = !Const>
            requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
            friend constexpr bool operator==(const CI<OtherConst>& y, const sentinel& x);
        }
    }

    constexpr explicit sentinel(sentryl_t<Base> end);
    1 Effects: Initializes end_ with end.
    constexpr sentinel(sentryl_t<!Const> s)
    requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
    2 Effects: Initializes end_ with std::move(s.end_).
    constexpr sentinel_t<Base> base() const;
    3 Effects: Equivalent to: return end_;
    friend constexpr bool operator==(const CI<Const>& y, const sentinel& x);

§ 26.7.10.3 © ISO/IEC 1241
template<bool OtherConst = !Const>
  requires sentinel_for<sentinel_t<Base>, iterator_t<maybe_const<OtherConst, V>>>
friend constexpr bool operator==(const CI<OtherConst>& y, const sentinel& x);

Effects: Equivalent to: return y.count() == 0 || y.base() == x.end;

26.7.11 Take while view
26.7.11.1 Overview

Given a unary predicate `pred` and a view `r`, `take_while_view` produces a view of the range `ranges::begin(r).ranges::find_if_not(r, pred)`.

The name `views::take_while` denotes a range adaptor object (26.7.2). Given subexpressions `E` and `F`, the expression `views::take_while(E, F)` is expression-equivalent to `take_while_view(E, F).

Example 1:
```c++
auto input = istringstream("0 1 2 3 4 5 6 7 8 9");
auto small = [](const auto x) noexcept { return x < 5; };
auto small_ints = views::istream<int>(input) | views::take_while(small);
for (const auto i : small_ints) {
  cout << i << ' ';
}  // prints 0 1 2 3 4
auto i = 0;
input >> i;
cout << i;  // prints 6
```

26.7.11.2 Class template `take_while_view`

```c++
namespace std::ranges {
  template<view V, class Pred>
  requires input_range<V> && is_object_v<Pred> &&
    indirect_unary_predicate<const Pred, iterator_t<V>>
  class take_while_view : public view_interface<take_while_view<V, Pred>> {
    // 26.7.11.3, class template `take_while_view::sentinel`
    template<bool> class sentinel;
    // exposition only
    V base_ = V(); // exposition only
    movable-box<Pred> pred_; // exposition only

  public:
    take_while_view() requires default_initializable<V> && default_initializable<Pred> = default;
    constexpr explicit take_while_view(V base, Pred pred);  
constexpr V base() const & requires copy_constructible<V> { return base_; }
    constexpr auto begin() requires (!simple_view<V>) {
      return ranges::begin(base_); }
    constexpr auto begin() const
      requires range<const V> && indirect_unary_predicate<const Pred, iterator_t<const V>>
      { return ranges::begin(base_); }
    constexpr auto end() requires (!simple_view<V>)
      { return sentinel<false>(ranges::end(base_), addressof(*pred_)); }
    constexpr auto end() const
      requires range<const V> &&
        indirect_unary_predicate<const Pred, iterator_t<const V>>
      { return sentinel<true>(ranges::end(base_), addressof(*pred_)); }
  };
```
template<class R, class Pred>
    take_while_view(R&&, Pred) -> take_while_view<views::all_t<R>, Pred>;
}

constexpr explicit take_while_view(V base, Pred pred);

Effects: Initializes base_ with std::move(base) and pred_ with std::move(pred).

constexpr const Pred& pred() const;

Effects: Equivalent to: return *pred;

26.7.11.3 Class template take_while_view::sentinel

namespace std::ranges {
    template<class V, class Pred>
        requires input_range<V> && is_object_v<Pred> &&
            indirect_unary_predicate<const Pred, iterator_t<V>>
    template<bool Const = false>
        class take_while_view<V, Pred>::sentinel {
            using Base = maybe-const<Const, V>;
            // exposition only
            sentinel_t<Base> end_ = sentinel_t<Base>();
            // exposition only
            const Pred* pred_ = nullptr;
            // exposition only
        public:
            sentinel() = default;
            constexpr explicit sentinel(sentinel_t<Base> end, const Pred* pred);
            constexpr sentinel(sentinel_t<!Const> s)
                requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

            constexpr sentinel_t<Base> base() const { return end_; }

            friend constexpr bool operator==(const iterator_t<Base>& x, const sentinel& y);
            template<bool OtherConst = !Const>
                requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
            friend constexpr bool operator==(const iterator_t<maybe-const<OtherConst, V>>& x, const sentinel& y);
        }
    }

    constexpr explicit sentinel(sentinel_t<Base> end, const Pred* pred);

    Effects: Initializes end_ with end and pred_ with pred.

    constexpr sentinel(sentinel<!Const> s)
        requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

    Effects: Initializes end_ with std::move(s.end_) and pred_ with s.pred_.

    friend constexpr bool operator==(const iterator_t<Base>& x, const sentinel& y);
    template<bool OtherConst = !Const>
        requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
    friend constexpr bool operator==(const iterator_t<maybe-const<OtherConst, V>>& x, const sentinel& y);

    Effects: Equivalent to: return y.end_ == x || !invoke(*y.pred_, *x);

26.7.12 Drop view

26.7.12.1 Overview

drop_view produces a view excluding the first N elements from another view, or an empty range if the adapted view contains fewer than N elements.

The name views::drop denotes a range adaptor object (26.7.2). Let E and F be expressions, let T be remove_cvref_t<decltype((E))>, and let D be range_difference_t<decltype((E))>. If decltype((F)) does not
model convertible_to<D>, views::drop(E, F) is ill-formed. Otherwise, the expression views::drop(E, F) is expression-equivalent to:

(2.1) — If T is a specialization of empty_view (26.6.2.2), then ((void)F, decay-copy(E)), except that the evaluations of E and F are indeterminately sequenced.

(2.2) — Otherwise, if T models random_access_range and sized_range and is

(2.2.1) — a specialization of span (24.7.2.2),
(2.2.2) — a specialization of basic_string_view (23.3),
(2.2.3) — a specialization of iota_view (26.6.4.2), or
(2.2.4) — a specialization of subrange (26.5.4) where T::StoreSize is false, then U(ranges::begin(E) + std::min<D>(ranges::distance(E), F), ranges::end(E)), except that E is evaluated only once, where U is span<typename T::element_type> if T is a specialization of span and T otherwise.

(2.3) — Otherwise, if T is a specialization of subrange that models random_access_range and sized_range, then

T(ranges::begin(E) + std::min<D>(ranges::distance(E), F), ranges::end(E), to-unsigned-like(ranges::distance(E) - std::min<D>(ranges::distance(E), F))), except that E and F are each evaluated only once.

(2.4) — Otherwise, if T is a specialization of repeat_view (26.6.5.2):

(2.4.1) — if T models sized_range, then views::repeat(*E.value_, ranges::distance(E) - std::min<D>(ranges::distance(E), F)) except that E is evaluated only once;
(2.4.2) — otherwise, ((void)F, decay-copy(E)), except that the evaluations of E and F are indeterminately sequenced.

(2.5) — Otherwise, drop_view(E, F).

[Example 1]

```cpp
auto ints = views::iota(0) | views::take(10);
for (auto i : ints | views::drop(5)) {
    cout << i << ' ';
} // prints 5 6 7 8 9
```

— end example]
const auto c = static_cast<decltype(s)>(count_);
return s < c ? 0 : s - c;

constexpr auto size() const requires sized_range<const V> {
const auto s = ranges::size(base_);
const auto c = static_cast<decltype(s)>(count_);
return s < c ? 0 : s - c;
}

private:
V base_ = V(); // exposition only
range_difference_t<V> count_ = 0; // exposition only
};

template<class R>
drop_view(R&&, range_difference_t<R>) -> drop_view<views::all_t<R>>;

constexpr explicit drop_view(V base, range_difference_t<V> count);

Preconditions: count >= 0 is true.

Effects: Initializes base_ with std::move(base) and count_ with count.

costexpr auto begin()
requires (!simple-view<V> && random_access_range<const V> && sized_range<const V>));

constexpr auto begin() const
requires random_access_range<const V> && sized_range<const V>;

Returns: ranges::next(ranges::begin(base_), count_, ranges::end(base_)).

Remarks: In order to provide the amortized constant-time complexity required by the
range concept when drop_view models forward_range, the first overload caches the result within the drop_view for
use on subsequent calls.

[Note 1: Without this, applying a reverse_view over a drop_view would have quadratic iteration complexity.
—end note]

26.7.13 Drop while view [range.drop.while]

26.7.13.1 Overview [range.drop.while.overview]

Given a unary predicate pred and a view r, drop_while_view produces a view of the range
[ranges::find_if_not(r, pred), ranges::end(r)].

The name views::drop_while denotes a range adaptor object (26.7.2). Given subexpressions E and F, the
expression views::drop_while(E, F) is expression-equivalent to drop_while_view(E, F).

[Example 1:
constexpr auto source = " \t \t \t hello there"sv;
auto is_invisible = [](const auto x) { return x == ' ' || x == '\t'; };
auto skip_ws = views::drop_while(source, is_invisible);
for (auto c : skip_ws) {
    cout << c; // prints hello there with no leading space
}
—end example]

26.7.13.2 Class template drop_while_view [range.drop.while.view]

namespace std::ranges {
  template<view V, class Pred>
  requires input_range<V> && is_object_v<Pred> &&
  indirect_unary_predicate<const Pred, iterator_t<V>>
  class drop_while_view : public view_interface<drop_while_view<V, Pred>> {
    public:
      drop_while_view() requires default_initializable<V> && default_initializable<Pred> = default;
      constexpr explicit drop_while_view(V base, Pred pred);
constexpr V base() const & requires copy_constructible<V> { return base_; }  
constexpr V base() && { return std::move(base_); }  

constexpr const Pred& pred() const;  
constexpr auto begin();  
constexpr auto end() { return ranges::end(base_); }  

private:  
V base_ = V(); // exposition only  
movable-box<Pred> pred_; // exposition only  
};  

template<class R, class Pred>  
drop_while_view(R&&, Pred) -> drop_while_view<views::all_t<R>, Pred>;  

constexpr explicit drop_while_view(V base, Pred pred);  

Effects: Initializes base_ with std::move(base) and pred_ with std::move(pred).  

constexpr const Pred& pred() const;  

Effects: Equivalent to: return *pred_;  

Preconditions: pred_.has_value() is true.  

Returns: ranges::find_if_not(base_, cref(*pred_)).  

Remarks: In order to provide the amortized constant-time complexity required by the range concept when drop_while_view models forward_range, the first call caches the result within the drop_while_view for use on subsequent calls.  

[Note 1: Without this, applying a reverse_view over a drop_while_view would have quadratic iteration complexity. — end note]  

26.7.14 Join view  
26.7.14.1 Overview  

join_view flattens a view of ranges into a view.  

The name views::join denotes a range adaptor object (26.7.2). Given a subexpression E, the expression views::join(E) is expression-equivalent to join_view<views::all_t<decltype((E))>>(E).  

[Example 1:  
vector<string> ss{"hello", " ", "world", "!"};  
for (char ch : ss | views::join)  
cout << ch; // prints hello world!  
— end example]  

26.7.14.2 Class template join_view  

namespace std::ranges {  
    template<input_range V>  
        requires view<V> && input_range<range_reference_t<V>>  
        class join_view : public view_interface<join_view<V>> {  
            private:  
                using InnerRng = range_reference_t<V>; // exposition only  

                // 26.7.14.3, class template join_view::iterator  
                template<bool Const>  
                    struct iterator; // exposition only  

                // 26.7.14.4, class template join_view::sentinel  
                template<bool Const>  
                    struct sentinel; // exposition only  
            }  
        }  
}
V base_ = V(); // exposition only

non-propagating-cache iterator_t<V>&& outer_; // exposition only, present only
// when !forward_range<V>
non-propagating-cache remove_cv_t<InnerRng>&& inner_; // exposition only, present only
// if is_reference_v<InnerRng> is false

public:
join_view() requires default_initializable<V> = default;
constexpr explicit join_view(V base);

constexpr V base() const & requires copy_constructible<V> { return base_; }
constexpr V base() && { return std::move(base_); }

constexpr auto begin() {
    if constexpr (forward_range<V>) {
        constexpr bool use_const = simple-view<V> && is_reference_v<InnerRng>;
        return iterator<use_const>(*this, ranges::begin(base_));
    } else {
        outer_ = ranges::begin(base_);
        return iterator<false>(*this);
    }
}

constexpr auto begin() const
    requires forward_range<const V> &&
    is_reference_v<range_reference_t<const V>> &&
    input_range<range_reference_t<const V>>
{ return iterator<true>(*this, ranges::begin(base_)); }

constexpr auto end() {
    if constexpr (forward_range<V> &&
    is_reference_v<InnerRng> &&
    forward_range<InnerRng> &&
    common_range<V> &&
    common_range<InnerRng>)
    return iterator<simple-view<V>>{*this, ranges::end(base_)};
    else
    return sentinel<simple-view<V>>{*this};
}

constexpr auto end() const
    requires forward_range<const V> &&
    is_reference_v<range_reference_t<const V>> &&
    input_range<range_reference_t<const V>>
{ if constexpr (forward_range<range_reference_t<const V>> &&
    common_range<const V> &&
    common_range<range_reference_t<const V>>)
    return iterator<true>(*this, ranges::end(base_));
    else
    return sentinel<true>(*this);
}

);

};

template<class R>
explicit join_view(R&&) -> join_view<views::all_t<R>>;

constexpr explicit join_view(V base);

Effects: Initializes base_ with std::move(base).

26.7.14.3 Class template join_view::iterator [range.join.iterator]
namespace std::ranges {
    template<input_range V>
    requires view<V> && input_range<range_reference_t<V>>
    template<bool Const>
    struct join_view<V>::iterator {
        private:
            using Parent = maybe-const<Const, join_view>; // exposition only
            using Base = maybe-const<Const, V>; // exposition only
            using OuterIter = iterator_t<Base>; // exposition only
            using InnerIter = iterator_t<range_reference_t<Base>>; // exposition only

        static constexpr bool ref-is-glvalue = // exposition only
            is_reference_v<range_reference_t<Base>>;

        OuterIter outer_ = OuterIter(); // exposition only, present only
        optional<InnerIter> inner_; // exposition only
        Parent* parent_ = nullptr; // exposition only

        constexpr void satisfy(); // exposition only
        constexpr OuterIter& outer(); // exposition only
        constexpr const OuterIter& outer() const; // exposition only

        constexpr iterator(Parent& parent, OuterIter outer) // exposition only
            requires forward_range<Base>;
        constexpr explicit iterator(Parent& parent) // exposition only
            requires (!forward_range<Base>);

        public:
            using iterator_concept = see below;
            using iterator_category = see below; // not always present
            using value_type = range_value_t<range_reference_t<Base>>;
            using difference_type = see below;

            iterator() = default;
            constexpr iterator(iterator<!Const> i) // exposition only
                requires Const &&
                convertible_to<iterator_t<V>, OuterIter> &&
                convertible_to<iterator_t<InnerRng>, InnerIter>;

            constexpr decltype(auto) operator*() const { return **inner_; }

            constexpr InnerIter operator->() const // exposition only
                requires has-arrow<InnerIter> && copyable<InnerIter>;

            constexpr iterator& operator++();
            constexpr void operator++(int);
            constexpr iterator& operator++(int) // exposition only
                requires ref-is-glvalue && forward_range<Base> &&
                forward_range<range_reference_t<Base>>;

            constexpr iterator& operator--(); // exposition only
            requires ref-is-glvalue && bidirectional_range<Base> &&
            bidirectional_range<range_reference_t<Base>> &&
            common_range<range_reference_t<Base>>;

            constexpr iterator operator--(int) // exposition only
                requires ref-is-glvalue && bidirectional_range<Base> &&
                bidirectional_range<range_reference_t<Base>> &&
                common_range<range_reference_t<Base>>;
    }
}

§ 26.7.14.3
friend constexpr bool operator==(const iterator& x, const iterator& y)
requires ref-is-glvalue && forward_range<Base> && equality_comparable<iterator_t<range_reference_t<Base>>;
if (*inner_ != ranges::end(inner))
    return;

if constexpr (ref-is-glvalue)
    inner_.reset();

constexpr iterator(Parent& parent, OuterIter outer)
    requires forward_range<Base>;

Effects: Initializes outer_ with std::move(outer) and parent_ with addressof(parent); then calls satisfy().

constexpr explicit iterator(Parent& parent)
    requires (!forward_range<Base>);

Effects: Initializes parent_ with addressof(parent); then calls satisfy().

constexpr iterator(iterator<Const> i)
    requires Const &&
        convertible_to<iterator_t<V>, OuterIter> &&
        convertible_to<iterator_t<InnerRng>, InnerIter>;

Effects: Initializes outer_ with std::move(i.outer_), inner_ with std::move(i.inner_), and
        parent_ with i.parent_.

[Note 1: Const can only be true when Base models forward_range. — end note]

constexpr InnerIter operator->() const
    requires has-arrow<InnerIter> && copyable<InnerIter>;

Effects: Equivalent to: return *inner_;

constexpr operator++();

Let inner-range be:

(12.1) If ref-is-glvalue is true, *outer().
(12.2) Otherwise, *parent_->inner_.

Effects: Equivalent to:

if (++*inner_ == ranges::end(as-lvalue(inner-range))) {
    ++outer();
    satisfy();
} else {
    return *this;
}

constexpr void operator++(int);

Effects: Equivalent to: +++this.

constexpr operator++(int)
    requires ref-is-glvalue && forward_range<Base> &&
        forward_range<range_reference_t<Base>>;

Effects: Equivalent to:

auto tmp = *this;
+++this;
return tmp;

constexpr operator--()
    requires ref-is-glvalue && bidirectional_range<Base> &&
        bidirectional_range<range_reference_t<Base>> &&
        common_range<range_reference_t<Base>>;

Effects: Equivalent to:

if (outer_ == ranges::end(parent_.base_))
    inner_ = ranges::end(as-lvalue(*--outer_));
while (*inner_ == ranges::begin(as-lvalue(*outer_)))
    *inner_ = ranges::end(as-lvalue(*--outer_));
constexpr iterator operator--(int) requires ref-is-glvalue && bidirectional_range<Base> && bidirectional_range<range_reference_t<Base>> && common_range<range_reference_t<Base>>;

Effects: Equivalent to:
auto tmp = *this;
--*this;
return tmp;

friend constexpr bool operator==(const iterator& x, const iterator& y) requires ref-is-glvalue && forward_range<Base> && equality_comparable<iterator_t<range_reference_t<Base>>>;

Effects: Equivalent to: return x.outer_ == y.outer_ && x.inner_ == y.inner_;

friend constexpr void iter_swap(const iterator& x, const iterator& y) noexcept(noexcept(ranges::iter_swap(*x.inner_, *y.inner_))) requires indirectly_swappable<InnerIter>;

Effects: Equivalent to: return ranges::iter_swap(*x.inner_, *y.inner_);

26.7.14.4 Class template join_view::sentinel

namespace std::ranges {
    template<input_range V>
    requires view<V> && input_range<range_reference_t<V>>
    template<bool Const>
    struct join_view<V>::sentinel {
        private:
            using Parent = maybe-const<Const, join_view>; // exposition only
            using Base = maybe-const<Const, V>; // exposition only
            sentinel_t<Base> end_ = sentinel_t<Base>(); // exposition only

        public:
            sentinel() = default;

            constexpr explicit sentinel(Parent& parent);
            constexpr sentinel(sentinel<Const> s) requires Const && convertible_to<sentinel_t<V>>, sentinel_t<Base>>;

        }; // sentinel<V>

    } // struct join_view<V>::sentinel

    template<bool OtherConst>
    requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>> friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel<OtherConst>& y);

    constexpr explicit sentinel(Parent& parent);

Effects: Initializes end_ with ranges::end(parent.base_).

constexpr sentinel(sentinel<Const> s)
    requires Const && convertible_to<sentinel_t<V>>, sentinel_t<Base>>;

Effects: Initializes end_ with std::move(s.end_).

template<bool OtherConst>
    requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>> friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel<OtherConst>& y);

Effects: Equivalent to: return x.outer() == y.end_;
26.7.15 Join with view

26.7.15.1 Overview

`join_with_view` takes a view and a delimiter, and flattens the view, inserting every element of the delimiter in between elements of the view. The delimiter can be a single element or a view of elements.

The name `views::join_with` denotes a range adaptor object (26.7.2). Given subexpressions E and F, the expression `views::join_with(E, F)` is expression-equivalent to `join_with_view(E, F)`.

[Example 1:

```cpp
vector<string> vs = {"the", "quick", "brown", "fox"};
for (char c : vs | views::join_with('-' )) {
    cout << c;
}
// The above prints the-quick-brown-fox
```

--- end example]

26.7.15.2 Class template `join_with_view`

```cpp
namespace std::ranges {

    template<class R>
    concept bidirectional_common = bidirectional_range<R> && common_range<R>;
    // exposition only

template<input_range V, forward_range Pattern>
    requires view<V> && input_range<range_reference_t<V>>
    && view<Pattern>
    && concatable<range_reference_t<V>, Pattern>
    class join_with_view : public view_interface<join_with_view<V, Pattern>> {
        using InnerRng = range_reference_t<V>;
        // exposition only

        V base_ = V();
        // exposition only
        non-propagating-cache<iterator_t<V>> outer_it_;
        // exposition only, present only
        when !forward_range<V>
        non-propagating-cache<remove_cv_t<InnerRng>> inner_;
        // if is_reference_v<InnerRng> is false
        Pattern pattern_ = Pattern();
        // exposition only

        // 26.7.15.3, class template join_with_view::iterator
        template<bool Const> struct iterator;
        // exposition only

        // 26.7.15.4, class template join_with_view::sentinel
        template<bool Const> struct sentinel;
        // exposition only

    public:
        join_with_view()
            requires default_initializable<V> && default_initializable<Pattern> = default;
        constexpr explicit join_with_view(V base, Pattern pattern);
        template<input_range R>
            requires constructible_from<R, views::all_t<R> > &&
            constructible_from<Pattern, single_view<range_value_t<InnerRng>>>,
        constexpr explicit join_with_view(R&& r, range_value_t<InnerRng> e);
        constexpr V base() const & requires copy_constructible<V> { return base_; }
        constexpr V base() && { return std::move(base_); }

        constexpr auto begin() {
            if constexpr (forward_range<R>){
                constexpr bool use_const =
                    simple_view<R> && is_reference_v<InnerRng> && simple_view<Pattern>;
                return iterator<use_const>(this, ranges::begin(base_));
            } else {
                outer_it_ = ranges::begin(base_);
            }
        }
}
```

§ 26.7.15 © ISO/IEC 1252
return iterator<false>(*this);
}
}
constexpr auto begin() const
requires forward_range<const V> &&
  forward_range<const Pattern> &&
  is_reference_v<range_reference_t<const V>> &&
  input_range<range_reference_t<const V>> &&
  concatable<range_reference_t<const V>, const Pattern> { 
  return iterator<true>(*this, ranges::begin(base_));
}
constexpr auto end() {
if constexpr (forward_range<V> &&
  is_reference_v<InnerRng> && forward_range<InnerRng> &&
  common_range<V> && common_range<InnerRng>)
  return iterator<simple-view<V> && simple-view<Pattern>>{*this, ranges::end(base_)};
else
  return sentinel<simple-view<V> && simple-view<Pattern>>{*this};
}
constexpr auto end() const
requires forward_range<const V> && forward_range<const Pattern> &&
  is_reference_v<range_reference_t<const V>> &&
  input_range<range_reference_t<const V>> &&
  concatable<range_reference_t<const V>, const Pattern> {
  using InnerConstRng = range_reference_t<const V>;
  if constexpr (forward_range<InnerConstRng> &&
    common_range<const V> && common_range<InnerConstRng>)
    return iterator<true>(*this, ranges::end(base_));
  else
    return sentinel<true>(*this);
}
};

template<class R, class P>
join_with_view(R&&, P&&) -> join_with_view<views::all_t<R>, views::all_t<P>>;

template<input_range R>
requires constructible_from<V, views::all_t<R>> &&
  constructible_from<Pattern, single_view<range_value_t<InnerRng>>> 
constexpr explicit join_with_view(R&& r, range_value_t<InnerRng> e){
  using Base = range_reference_t<R>;
  return join_with_view(View{r, range_value_t<InnerRng>(e)});
}

constexpr explicit join_with_view(V base, Pattern pattern);  
1  Effects: Initializes base_ with std::move(base) and pattern_ with std::move(pattern).

template<input_range R>
requires constructible_from<V, views::all_t<R>> &&
  constructible_from<Pattern, single_view<range_value_t<InnerRng>>> 
constexpr explicit join_with_view(View{R&& r, range_value_t<InnerRng>(e)});

2  Effects: Initializes base_ with views::all(std::forward<R>(r)) and pattern_ with views::single(std::move(e)).

26.7.15.3 Class template join_with_view::iterator

namespace std::ranges {
  template<input_range V, forward_range Pattern>
  requires view<V> && input_range<range_reference_t<V>> &&
    view<Pattern> && concatable<range_reference_t<V>, Pattern>
  template<bool Const>
  class join_with_view<V, Pattern>::iterator {
    using Parent = maybe-const<Const, join_with_view>;  // exposition only
    using Base = maybe-const<Const, V>;  // exposition only
    using InnerBase = range_reference_t<Base>;  // exposition only
    using PatternBase = maybe-const<Const, Pattern>;  // exposition only
  }
}
using OuterIter = iterator_t<Base>;  // exposition only
using InnerIter = iterator_t<InnerBase>;  // exposition only
using PatternIter = iterator_t<PatternBase>;  // exposition only

static constexpr bool ref-is-glvalue = is_reference_v<InnerBase>;  // exposition only

Parent* parent_ = nullptr;  // exposition only
OuterIter outer_it_ = OuterIter();  // exposition only, present only
// if Base models forward_range
variant<PatternIter, InnerIter> inner_it_;  // exposition only

constexpr iteration<Parent& parent, OuterIter outer>
  requires forward_range<Base>;  // exposition only
constexpr explicit iteration<Parent& parent>
  requires noexcept(forward_range<Base>);  // exposition only
constexpr OuterIter& outer();  // exposition only
constexpr const OuterIter& outer() const;  // exposition only
constexpr auto& update-inner();  // exposition only
constexpr auto& get-inner();  // exposition only
constexpr void satisfy();  // exposition only

public:
  using iterator_concept = see below;
  using iterator_category = see below;
  // not always present
  using value_type = see below;
  using difference_type = see below;

  iterator() = default;
  constexpr iteration(iterator<Const i>)
    requires Const && convertible_to<iterator_t<V>, OuterIter> &&
    convertible_to<iterator_t<InnerRng>, InnerIter> &&
    convertible_to<iterator_t<Pattern>, PatternIter>;

  constexpr decltype(auto) operator*() const;
  constexpr iteration& operator++();
  constexpr void operator++(int);
  constexpr iteration& operator++(int)
    requires ref-is-glvalue && forward_iterator<OuterIter> &&
    forward_iterator<InnerIter>;

  constexpr iteration& operator--();
  requires ref-is-glvalue && bidirectional_range<Base> &&
  bidirectional-common<InnerBase> && bidirectional-common<PatternBase>;
  constexpr iteration& operator--(int)
    requires ref-is-glvalue && bidirectional_range<Base> &&
    bidirectional-common<InnerBase> && bidirectional-common<PatternBase>;

  friend constexpr bool operator==(const iteration& x, const iteration& y)
    requires ref-is-glvalue && forward_range<Base> &&
    equality_comparable<InnerIter>;

  friend constexpr decltype(auto) iter_move(const iteration& x) {
    using rvalue_reference = common_reference_t<
      iteration_rvalue_reference_t<InnerIter>,
      iteration_rvalue_reference_t<PatternIter>>;
    return visit<rvalue_reference>(ranges::iter_move, x.inner_it_);
  }

  friend constexpr void iter_swap(const iteration& x, const iteration& y)
    requires indirectly_swappable<InnerIter, PatternIter> {
    visit(ranges::iter_swap, x.inner_it_, y.inner_it_);
  }

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iterator::iterator_concept is defined as follows:

1. If ref-is-glvalue is true, Base models bidirectional_range, and InnerBase and PatternBase each model bidirectional_common, then iterator_concept denotes bidirectional_iterator_tag.

2. Otherwise, if ref-is-glvalue is true and Base and InnerBase each model forward_range, then iterator_concept denotes forward_iterator_tag.

3. Otherwise, iterator_concept denotes input_iterator_tag.

The member typedef-name iterator_category is defined if and only if ref-is-glvalue is true, and Base and InnerBase each model forward_range. In that case, iterator::iterator_category is defined as follows:

1. Let OUTERC denote iterator_traits<OuterIter>::iterator_category, let INNERC denote iterator_traits<InnerIter>::iterator_category, and let PATTERNC denote iterator_traits<PatternIter>::iterator_category.

2. If
   is_reference_v<common_reference_t<iter_reference_t<InnerIter>, iter_reference_t<PatternIter>>> is false, iterator_category denotes input_iterator_tag.

3. Otherwise, if OUTERC, INNERC, and PATTERNC each model derived_from<bidirectional_iterator_category> and InnerBase and PatternBase each model common_range, iterator_category denotes bidirectional_iterator_tag.

4. Otherwise, if OUTERC, INNERC, and PATTERNC each model derived_from<forward_iterator_category>, iterator_category denotes forward_iterator_tag.

5. Otherwise, iterator_category denotes input_iterator_tag.

iterator::value_type denotes the type:

common_type_t<iter_value_t<InnerIter>, iter_value_t<PatternIter>>

iterator::difference_type denotes the type:

common_type_t<
    iter_difference_t<OuterIter>,
    iter_difference_t<InnerIter>,
    iter_difference_t<PatternIter>>

castexpr OuterIter& outer();
castexpr const OuterIter& outer() const;

Returns: outer_it. if Base models forward_range; otherwise, *parent_→outer_it_.

constexpr auto& update-inner();

Effects: Equivalent to:

if constexpr (ref-is-glvalue) return as-lvalue(*outer());
else return parent_→inner_.emplace-deref(outer());

constexpr auto& get-inner();

Effects: Equivalent to:

if constexpr (ref-is-glvalue) return as-lvalue(*outer());
else return *parent_→inner_;
while (true) {
    if (inner_it_.index() == 0) {
        if (std::get<0>(inner_it_) != ranges::end(parent_->pattern_))
            break;
        inner_it_.template emplace<1>(ranges::begin(update-inner()));
    } else {
        if (std::get<1>(inner_it_) != ranges::end(get-inner()))
            break;
        if (++outer() == ranges::end(parent_->base_)) {
            if constexpr (ref-is-glvalue)
                inner_it_.template emplace<0>();
            break;
        }
        inner_it_.template emplace<0>(ranges::begin(parent_->pattern_));
    }
}

[Note 1: join_with_view iterators use the satisfy function to skip over empty inner ranges. — end note]

constexpr iterator(Parent& parent, OuterIter outer)
requires forward_range<Base>;
constexpr explicit iterator(Parent& parent)
requires (!forward_range<Base>);

9 Effects: Initializes parent_ with addressof(parent). For the first overload, also initializes outer_it_ with std::move(outer). Then, equivalent to:
if (outer() != ranges::end(parent_->base_)) {
    inner_it_.template emplace<1>(ranges::begin(update-inner()));
satisfy();
}

constexpr iterator(iterator<!Const> i)
requires Const & convertible_to<iterator_t<InnerRng>, InnerIter> &
convertible_to<iterator_t<Pattern>, PatternIter>;

10 Effects: Initializes outer_it_ with std::move(i.outer_it_) and parent_ with i.parent_. Then, equivalent to:
if (i.inner_it_.index() == 0)
    inner_it_.template emplace<0>(std::get<0>(std::move(i.inner_it_)));
else
    inner_it_.template emplace<1>(std::get<1>(std::move(i.inner_it_)));

[Note 2: Const can only be true when Base models forward_range. — end note]

constexpr decltype(auto) operator*() const;
12 Effects: Equivalent to:
using reference =
    common_reference_t<iter_reference_t<InnerIter>, iter_reference_t<PatternIter>>;
return visit([](auto& it) -> reference { return *it; }, inner_it_);

constexpr iterator& operator++();
13 Effects: Equivalent to:
visit([](auto& it) { ++it; }, inner_it_);
satisfy();
return *this;

constexpr void operator++(int);
14 Effects: Equivalent to +++this.

constexpr iterator operator++(int)
requires ref-is-glvalue & forward_iterator<OuterIter> &
forward_iterator<InnerIter>;
15 Effects: Equivalent to:

§ 26.7.15.3 © ISO/IEC

1256
iterator tmp = *this;
++*this;
return tmp;

constexpr iterator& operator--() const
requires ref-is-glvalue & bidirectional_range<Base> &
  bidirectional-common<InnerBase> & bidirectional-common<PatternBase>;

Effects: Equivalent to:

if (outer_it_ == ranges::end(parent_->base_)) {
  auto& inner = *__--outer_it_;  
  inner_it_.template emplace<1>(ranges::end(inner));
}

while (true) {
  if (inner_it_.index() == 0) {
    auto& it = std::get<0>(inner_it_);
    if (it == ranges::begin(parent_->pattern_)) {
      auto& inner = *--outer_it_;  
      inner_it_.template emplace<1>(ranges::end(inner));
    } else {
      break;
    }
  } else {
    auto& it = std::get<1>(inner_it_);
    auto& inner = *__outer_it_;  
    if (it == ranges::begin(inner)) {
      inner_it_.template emplace<0>(ranges::end(parent_->pattern_));
    } else {
      break;
    }
  }
}
visit([](auto& it){ --it; }, inner_it_);
return *this;

constexpr iterator operator--(int) const
requires ref-is-glvalue & bidirectional_range<Base> &
  bidirectional-common<InnerBase> & bidirectional-common<PatternBase>;

Effects: Equivalent to:

iterator tmp = *this;
--*this;
return tmp;

friend constexpr bool operator==(const iterator& x, const iterator& y)
requires ref-is-glvalue & forward_range<Base> &
  equality_comparable<InnerIter>;

Effects: Equivalent to:

return x.outer_it_ == y.outer_it_ && x.inner_it_ == y.inner_it_;

26.7.15.4 Class template join_with_view::sentinel

namespace std::ranges {
  template<input_range V, forward_range Pattern>
  requires view<V> & input_range<range_reference_t<V>>
    & view<Pattern> & concatable<range_reference_t<V>, Pattern>
  template<bool Const>
  class join_with_view<V, Pattern>::sentinel {
    using Parent = maybe-const<Const, join_with_view>;  // exposition only
    using Base = maybe-const<Const, V>;
    sentinel_t<Base> end_ = sentinel_t<Base>();  // exposition only
    constexpr explicit sentinel(Parent& parent);  // exposition only

} 

§ 26.7.15.4
public:
    sentinel() = default;
    constexpr sentinel(sentinel<!Const> s)
        requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

    template<bool OtherConst>
    requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>;
    friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
};

constexpr explicit sentinel(Parent& parent);

Effects: Initializes end with ranges::end(parent.base_).

constexpr sentinel(sentinel<!Const> s)
    requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

Effects: Initializes end with std::move(s.end_).

template<bool OtherConst>
requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>;
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

Effects: Equivalent to: return x.outer() == y.end_;

26.7.16 Lazy split view

26.7.16.1 Overview

Lazy_split_view takes a view and a delimiter, and splits the view into subranges on the delimiter. The delimiter can be a single element or a view of elements.

The name views::lazy_split denotes a range adaptor object (26.7.2). Given subexpressions E and F, the expression views::lazy_split(E, F) is expression-equivalent to lazy_split_view(E, F).

Example 1:

```cpp
string str("the quick brown fox");
for (auto word : str | views::lazy_split(' ')) {
    for (char ch : word)
        cout << ch;
    cout << '*';
}
```

// The above prints the*quick*brown*fox*
— end example]

26.7.16.2 Class template lazy_split_view

namespace std::ranges {
    template<auto> struct require_constant;
    // exposition only

    template<class R>
    concept tiny_range =
        sized_range<R> &&
        requires { typename require_constant<remove_reference_t<R>::size()>; } &&
        (remove_reference_t<R>::size() <= 1);

    template<input_range V, forward_range Pattern>
    requires view<V> && view<Pattern> &&
        indirectly_comparable<iterator_t<V>, iterator_t<Pattern>, ranges::equal_to> &&
        (forward_range<V> || tiny_range<Pattern>)
    class lazy_split_view : public view_interface<lazy_split_view<V, Pattern>> {
        private:
            V base_ = V();
            // exposition only
            Pattern pattern_ = Pattern();
            // exposition only
            non-propagating-cache<iterator_t<V>> current_;
            // exposition only, present only
            // if forward_range<V> is false

    // 26.7.16 § 26.7.16 © ISO/IEC 1258
// 26.7.16.3, class template lazy_split_view::outer-iterator
template<bool> struct outer_iterator; // exposition only

// 26.7.16.5, class template lazy_split_view::inner-iterator
template<bool> struct inner_iterator; // exposition only

public:
lazy_split_view()
    requires default_initializable<V> && default_initializable<Pattern> = default;
    constexpr explicit lazy_split_view(V base, Pattern pattern);

template<input_range R>
    requires constructible_from<V, views::all_t<R>> &&
        constructible_from<Pattern, single_view<range_value_t<R>>>
    constexpr explicit lazy_split_view(R&& r, range_value_t<R> e);

cconstexpr V base() const & requires copy_constructible<V> { return
    base_;
} constexpr V base() && { return std::move(
    base_);
}

cconstexpr auto begin() {
    if constexpr (forward_range<V>) {
        return outer_iterator<
            simple_view<V> && simple_view<
            Pattern>>{this, ranges::begin(
                base_)};
    } else {
        current_ = ranges::begin(base_);
        return outer_iterator<false>{*this};
    }
}

cconstexpr auto begin() const requires forward_range<V> && forward_range<const V> {
    return outer_iterator<
        simple_view<V> && simple_view<
        Pattern>>{this, ranges::begin(
            base_)};
}

cconstexpr auto end() requires forward_range<V> && common_range<V> {
    return outer_iterator<
        simple_view<V> && simple_view<
        Pattern>>{this, ranges::end(
            base_)};
}

cconstexpr auto end() const {
    if constexpr (forward_range<V> && forward_range<const V> && common_range<const V>)
        return outer_iterator<true>{this, ranges::end(base_)};
    else
        return default_sentinel;
}

};
template<class R, class P>
lazy_split_view(R&&, P&&) -> lazy_split_view<views::all_t<R>, views::all_t<P>>;

template<input_range R>
lazy_split_view(R&&, range_value_t<R>)
    -> lazy_split_view<views::all_t<R>, single_view<range_value_t<R>>>;

cconstexpr explicit lazy_split_view(V base, Pattern pattern);
  
  Effects: Initializes base_ with std::move(base), and pattern_ with std::move(pattern).

template<input_range R>
    requires constructible_from<V, views::all_t<R>> &&
        constructible_from<Pattern, single_view<range_value_t<R>>>
    constexpr explicit lazy_split_view(R&& r, range_value_t<R> e);
  
  Effects: Initializes base_ with views::all(std::forward<R>(r)), and pattern_ with views::
        single(std::move(e)).
26.7.16.3  Class template lazy_split_view::outer-iterator

```cpp
namespace std::ranges {
    template<input_range V, forward_range Pattern>
        requires view<V> && view<Pattern> &&
            indirectly_comparable<iterator_t<V>, iterator_t<Pattern>>, ranges::equal_to &&
                (forward_range<V> || tiny-range<Pattern>)
    template<bool Const>
        struct lazy_split_view<V, Pattern>::
            outer-iterator {
            private:
                using Parent = maybe-const<Const, lazy_split_view>;  // exposition only
                using Base = maybe-const<Const, V>;  // exposition only
                Parent* parent_ = nullptr;  // exposition only
                iterator_t<Base> current_ = iterator_t<Base>();  // exposition only, present only
                // if V models forward_range
                bool trailing_empty_ = false;  // exposition only

            public:
                using iterator_concept = conditional_t<forward_range<Base>, forward_iterator_tag, input_iterator_tag>;
                using iterator_category = input_iterator_tag;  // present only if Base models forward_range

                // 26.7.16.4, class lazy_split_view::outer-iterator::value_type
                struct value_type;
                using difference_type = range_difference_t<Base>;

                outer-iterator() = default;
                constexpr explicit outer-iterator(Parent& parent)  
                    requires (!forward_range<Base>);
                constexpr outer-iterator(Parent& parent, iterator_t<Base> current)  
                    requires forward_range<Base>;
                constexpr outer-iterator(outer-iterator<!Const> i)  
                    requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;

                constexpr value_type operator*() const;
                constexpr outer-iterator& operator++();
                constexpr decltype(auto) operator++(int) {
                    if constexpr (forward_range<Base>) {
                        auto tmp = *this;
                        +++this;
                        return tmp;
                    } else
                        +++this;
                }

                friend constexpr bool operator==(const outer-iterator& x, const outer-iterator& y)  
                    requires forward_range<Base>;

                friend constexpr bool operator==(const outer-iterator& x, default_sentinel_t);
            };
```

1 Many of the specifications in 26.7.16 refer to the notional member `current` of `outer-iterator`. `current` is equivalent to `current_` if `V` models `forward_range`, and `*parent_` if `V` models `forward_range`, and `*parent_->current_` otherwise.

2 *Effects:* Initializes `parent_` with `addressof(parent)`. 

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1260
constexpr outer_iterator(Parent& parent, iterator_t<Base> current)
requires forward_range<Base>;

**Effects**: Initializes `parent_` with `addressof(parent)` and `current_` with `std::move(current)`.

constexpr outer_iterator(outer_iterator<lConst> i)
requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;

**Effects**: Initializes `parent_` with `i.parent_`, `current_` with `std::move(i.current_)`, and `trailing_empty_` with `i.trailing_empty_`.

constexpr value_type operator*() const;

**Effects**: Equivalent to: `return value_type{*this};`

constexpr outer_iterator& operator++();

**Effects**: Equivalent to:

```cpp
const auto end = ranges::end(parent_->base_);
if (current == end) {
    trailing_empty_ = false;
    return *this;
}
const auto [pbegin, pend] = subrange(parent_->pattern_);
if (pbegin == pend) ++current;
else if constexpr (tiny_range<Pattern>) {
    current = ranges::find(std::move(current), end, *pbegin);
    if (current != end) {
        ++current;
        trailing_empty_ = true;
    }
} else {
    do {
        auto [b, p] = ranges::mismatch(current, end, pbegin, pend);
        if (p == pend) {
            current = b;
            if (current == end)
                trailing_empty_ = true;
            break;
        // The pattern matched; skip it
        }
    } while (++current != end);
}
return *this;
```

friend constexpr bool operator==(const outer_iterator& x, const outer_iterator& y)
requires forward_range<Base>;

**Effects**: Equivalent to:

```cpp
return x.current_ == y.current_ && x.trailing_empty_ == y.trailing_empty_;
```

friend constexpr bool operator==(const outer_iterator& x, default_sentinel_t);

**Effects**: Equivalent to:

```cpp
return x.current == ranges::end(x.parent_->base_) && !x.trailing_empty_;
```

### 26.7.16.4 Class lazy_split_view::outer_iterator::value_type

```cpp
namespace std::ranges {
    template<input_range V, forward_range Pattern>
    requires view<V> && view<Pattern> &&
    indirectly_comparable<iterator_t<V>, iterator_t<Pattern>, ranges::equal_to> &&
    (forward_range<V> || tiny_range<Pattern>)
    template<bool Const>
    struct lazy_split_view<V, Pattern>::outer_iterator<Const>::value_type
        : view_interface<value_type> {
    private:
```
outer-iterator i_ = outer-iterator();      // exposition only
constexpr explicit value_type(outer-iterator i);    // exposition only

public:
constexpr inner-iterator<Const> begin() const;
constexpr default_sentinel_t end() const noexcept;
};

constexpr explicit value_type(outer-iterator i);

Effects: Initializes i_ with std::move(i).

constexpr inner-iterator<Const> begin() const;
Effects: Equivalent to: return inner-iterator<Const>{i_};

constexpr default_sentinel_t end() const noexcept;
Effects: Equivalent to: return default_sentinel;

26.7.16.5 Class template lazy_split_view::inner-iterator

namespace std::ranges {
  template<input_range V, forward_range Pattern>
  requires view<V> && view<Pattern> &&
  indirectly_comparable<iterator_t<V>, iterator_t<Pattern>, ranges::equal_to> &&
  (forward_range<V> || tiny-range<Pattern>)
  template<bool Const>
  struct lazy_split_view<V, Pattern>::inner-iterator {
    private:
    using Base = maybe-const<Const, V>;     // exposition only
    outer-iterator<Const> i_ = outer-iterator<Const>();   // exposition only
    bool incremented_ = false;     // exposition only

    public:
    using iterator_concept = typename outer-iterator<Const>::iterator_concept;

    using iterator_category = see below;     // present only if Base
    // models forward_range

    using value_type = range_value_t<Base>;
    using difference_type = range_difference_t<Base>;

    inner-iterator() = default;
    constexpr explicit inner-iterator(outer-iterator<Const> i);

    constexpr const iterator_t<Base>& base() const & noexcept;    // forward_range
    constexpr iterator_t<Base> base() && requires forward_range<V>;

    constexpr decltype(auto) operator*() const { return *i_.current; }

    constexpr inner-iterator& operator++();
    constexpr decltype(auto) operator++(int) {
      if constexpr (forward_range<Base>) {
        auto tmp = *this;
        ***this;
        return tmp;
      } else
        ***this;
    }

    friend constexpr bool operator==(const inner-iterator& x, const inner-iterator& y)
    requires forward_range<Base>;

    friend constexpr bool operator==(const inner-iterator& x, default_sentinel_t);

  };
};
friend constexpr decltype(auto) iter_move(const inner_iterator& i) noexcept(noexcept(ranges::iter_move(i.i_.current))) {
    return ranges::iter_move(i.i_.current);
}

friend constexpr void iter_swap(const inner_iterator& x, const inner_iterator& y) noexcept(noexcept(ranges::iter_swap(x.i_.current, y.i_.current)))
    requires indirectly_swappable<iterator_t<Base>>;
};

1 If Base does not model forward_range there is no member iterator_category. Otherwise, the typedef-name iterator_category denotes:

(1.1) — forward_iterator_tag if iterator_traits<iterator_t<Base>>::iterator_category models derived_from<forward_iterator_tag>;

(1.2) — otherwise, iterator_traits<iterator_t<Base>>::iterator_category.

constexpr explicit inner_iterator(outer_iterator<Const> i);

Effects: Initializes i_ with std::move(i).

constexpr const iterator_t<Base>& base() const & noexcept;

Effects: Equivalent to: return i_.current;

constexpr iterator_t<Base> base() && requires forward_range<V>;

Effects: Equivalent to: return std::move(i_.current);

constexpr inner_iterator& operator++();

Effects: Equivalent to:
    incremented_ = true;
    if constexpr (!forward_range<Base>) {
        if constexpr (Pattern::size() == 0) {
            return *this;
        }
    } +=i_.current;
    return *this;

friend constexpr bool operator==(const inner_iterator& x, const inner_iterator& y) requires forward_range<Base>;

Effects: Equivalent to: return x.i_.current == y.i_.current;

friend constexpr bool operator==(const inner_iterator& x, default_sentinel_t);

Effects: Equivalent to:
    auto [pcur, pend] = subrange{x.i_.parent_->pattern_};
    auto end = ranges::end(x.i_.parent_->base_);
    if constexpr (tiny_range<Pattern>) {
        const auto & cur = x.i_.current;
        if (cur == end) return true;
        if (pcur == pend) return x.incremented_;
        return *cur == *pcur;
    } else {
        auto cur = x.i_.current;
        if (cur == end) return true;
        if (pcur == pend) return x.incremented_;
        do {
            if (*cur != *pcur) return false;
            if (++pcur == pend) return true;
        } while (++cur != end);
        return false;
    }

§ 26.7.16.5 ©ISO/IEC 1263
friend constexpr void iter_swap(const inner_iterator& x, const inner_iterator& y)
    noexcept(noexcept(ranges::iter_swap(x.i_.current, y.i_.current)))
    requires indirectly_swappable<iterator_t<Base>>;

8 Effects: Equivalent to ranges::iter_swap(x.i_.current, y.i_.current).

26.7.17 Split view

26.7.17.1 Overview

split_view takes a view and a delimiter, and splits the view into subranges on the delimiter. The delimiter can be a single element or a view of elements.

The name views::split denotes a range adaptor object (26.7.2). Given subexpressions E and F, the expression views::split(E, F) is expression-equivalent to split_view(E, F).

[Example 1:

    string str("the quick brown fox");
    for (auto word : views::split(str, ' ')) {
      cout << string_view(word) << '+';
    }
    // The above prints the*quick*brown*fox*

—end example]

26.7.17.2 Class template split_view

namespace std::ranges {
    template<forward_range V, forward_range Pattern>
    requires view<V> && view<Pattern> &&
        indirectly_comparable<iterator_t<V>, iterator_t<Pattern>, ranges::equal_to>
    class split_view : public view_interface<split_view<V, Pattern>> {

        private:
            V base_ = V();                   // exposition only
            Pattern pattern_ = Pattern();   // exposition only

        // 26.7.17.3, class split_view::iterator
        struct iterator;
        // exposition only

        // 26.7.17.4, class split_view::sentinel
        struct sentinel;
        // exposition only

        public:
            split_view() requires default_initializable<V> && default_initializable<Pattern> = default;
            constexpr explicit split_view(V base, Pattern pattern);

            template<forward_range R>
            requires constructible_from<V, views::all_t<R>> &&
                constructible_from<Pattern, single_view<range_value_t<R>>>;
            constexpr explicit split_view(R&& r, range_value_t<R> e);

            constexpr V base() const & requires copy_constructible<V> { return base_; }
            constexpr V base() && { return std::move(base_); }

            constexpr iterator begin();

            constexpr auto end() {
                if constexpr (common_range<V>) {
                    return iterator{(*this, ranges::end(base_), {})};
                } else {
                    return sentinel{(*this, {})};
                }
            }

            constexpr subrange<iterator_t<V>> find_next(iterator_t<V>); // exposition only
    };
}
```cpp
template<class R, class P>
split_view(R&&, P&&) -> split_view<views::all_t<R>, views::all_t<P>>;

template<forward_range R>
split_view(R&&, range_value_t<R>)
    -> split_view<views::all_t<R>, single_view<range_value_t<R>>>;

constexpr explicit split_view(V base, Pattern pattern);

Effects: Initializes base_ with std::move(base), and pattern_ with std::move(pattern).

template<forward_range R>
requires constructible_from<V, views::all_t<R>> &&
constructible_from<Pattern, single_view<range_value_t<R>>>
constexpr explicit split_view(R&& r, range_value_t<R> e);

Effects: Initializes base_ with views::all(std::forward<R>(r)), and pattern_ with views::
single(std::move(e)).

constexpr iterator begin();

Returns: {*this, ranges::begin(base_), find-next(ranges::begin(base_))}.

Remarks: In order to provide the amortized constant time complexity required by the range
concept, this function caches the result within the split_view for use on subsequent calls.

constexpr subrange<iterator_t<V>> find-next(iterator_t<V> it);

Effects: Equivalent to:
auto [b, e] = ranges::search(subrange(it, ranges::end(base_)), pattern_);
if (b != ranges::end(base_) && ranges::empty(pattern_)) {
    ++b;
    ++e;
}
return {b, e};

§ 26.7.17.3 Class split_view::iterator
```
constexpr iterator(split_view& parent, iterator_t<V> current, subrange<iterator_t<V>> next);

**Effects**: Initializes parent_ with addressof(parent), cur_ with std::move(current), and next_ with std::move(next).

constexpr iterator_t<V> base() const;

**Effects**: Equivalent to: return cur_;

constexpr value_type operator*() const;

**Effects**: Equivalent to:

```cpp
return {cur_, next_.begin()};
```

constexpr iterator& operator++();

**Effects**: Equivalent to:

```cpp
cur_ = next_.begin();
if (cur_ != ranges::end(parent_->base_)) {
  cur_ = next_.end();
  if (cur_ == ranges::end(parent_->base_)) {
    trailing_empty_ = true;
    next_ = {cur_, cur_};
  } else {
    next_ = parent_->find-next(cur_);
  }
} else {
  trailing_empty_ = false;
}
return *this;
```

constexpr iterator operator++(int);

**Effects**: Equivalent to:

```cpp
auto tmp = *this;
++*this;
return tmp;
```

friend constexpr bool operator==(const iterator& x, const sentinel& y);

**Effects**: Equivalent to:

```cpp
return x.cur_ == y.end_ && x.trailing_empty_ == y.trailing_empty_;```

### § 26.7.17.4 Class split_view::sentinel

```cpp
namespace std::ranges {
  template<forward_range V, forward_range Pattern>
  requires view<V> && view<Pattern> &&
  indirectly_comparable<iterator_t<V>, iterator_t<Pattern>, ranges::equal_to>
  struct split_view<V, Pattern>::sentinel {
    private:
      sentinel_t<V> end_ = sentinel_t<V>(); // exposition only
    public:
      sentinel() = default;
      constexpr explicit sentinel(split_view& parent);
      
      friend constexpr bool operator==(const iterator& x, const sentinel& y);
    };
26.7.18 Concat view

26.7.18.1 Overview

concat_view presents a view that concatenates all the underlying ranges.

1 The name views::concat denotes a customization point object (16.3.3.3.5). Given a pack of subexpressions Es..., the expression views::concat(Es...) is expression-equivalent to

\[ \text{views::all(Es...)} \] if Es is a pack with only one element whose type models input_range,

\[ \text{concat_view(Es...)} \] otherwise,

2 Example 1:

```cpp
vector<int> v1{1, 2, 3}, v2{4, 5}, v3{3};
array a{6, 7, 8};
auto s = views::single(9);
for (auto&& i : views::concat(v1, v2, v3, a, s)) {
    print("{} ", i);  // prints 1 2 3 4 5 6 7 8 9
}
```

26.7.18.2 Class template concat_view

namespace std::ranges {

    template<class... Rs>
    using concat-reference-t = common_reference_t<range_reference_t<Rs>...>;  // exposition only

    template<class... Rs>
    using concat-value-t = common_type_t<range_value_t<Rs>...>;  // exposition only

    template<class... Rs>
    using concat-rvalue-reference-t =
    // exposition only
    common_reference_t<range_rvalue_reference_t<Rs>...>

    template<class... Rs>
    concept concat-indirectly-readable = see below;  // exposition only

    template<class... Rs>
    concept concatable = see below;  // exposition only

    template<Bool Const, class... Rs>
    concept concat-is-random-access = see below;  // exposition only

    template<Bool Const, class... Rs>
    concept concat-is-bidirectional = see below;  // exposition only

    template<input_range... Views>
    requires (view<View...> && ...) && (sizeof...(Views) > 0) &&
    concatable<View...>
    class concat_view : public view_interface<concat_view<View...>> {

        tuple<View...> views_;  // exposition only

        // 26.7.18.3, class template concat_view::iterator
        template<bool> class iterator;

    }

    template<bool> class iterator,
    // exposition only

    public:

    constexpr concat_view() = default;
    constexpr explicit concat_view(Views... views);

    constexpr iterator<false> begin() requires (!simple-view<View...> && ...));
    constexpr iterator<true> begin() const
    requires (range<Const Views> && ...) && concatable<Const Views...>;

    constexpr auto end() requires (!simple-view<View...> && ...));
    constexpr auto end() const
    requires (range<Const Views> && ...) && concatable<Const Views...>;

    constexpr auto size() requires (sized_range<View...> && ...));
    constexpr auto size() const requires (sized_range<Const Views> && ...));
};
template<class... R>
    concat_view(R&&...) -> concat_view<views::all_t<R>...>;}

template<class... Rs>
concept concat-indirectly-readable = see below; // exposition only

1 The exposition-only concat-indirectly-readable concept is equivalent to:

    template<class Ref, class RRef, class It>
    concept concat-indirectly-readable-impl =
        requires (const It it) {
            {*it} -> convertible_to<Ref>;
            {ranges::iter_move(it)} -> convertible_to<RRef>;
        };

    template<class... Rs>
    concept concat-indirectly-readable =
        // exposition only
        common_reference_with<concat-reference-t<Rs...>&&,
            common_reference_with<concat-reference-t<Rs...>&&,
                common_reference_with<concat-reference-t<Rs...>&&,
                    common_reference_with<concat-reference-t<Rs...>&&,
                        common_reference_with<concat-reference-t<Rs...>&&,
                            common_reference_with<concat-reference-t<Rs...>&&,
                                common_reference_with<concat-reference-t<Rs...>&&,
                                    common_reference_with<concat-reference-t<Rs...>&&,
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                                                                                                                                                                            common_reference_with<concat-reference-t<Rs...>&&,
                                                                                                                common_reference_with<concat-reference-t<Rs...>&&,
                                                    \begin{verbatim}
    template<bool Const, class... Rs>
    concept concat-is-random-access = see below; // exposition only

2 The exposition-only concatable concept is equivalent to:

    template<class... Rs>
    concept concatable = requires {
        typename concat-reference-t<Rs...>;
        typename concat-value-t<Rs...>;
        typename concat-rvalue-reference-t<Rs...>;
    } && concat-indirectly-readable<Rs...>;

    template<bool Const, class... Rs>
    concept concat-is-random-access = see below; // exposition only

3 Let Fs be the pack that consists of all elements of Rs except the last element, then concat-is-random-access
    is equivalent to:

    template<bool Const, class... Rs>
    concept concat-is-random-access =
        all-random-access<Const, Rs...> \&\&
        (common_range<maybe-const<Const, Fs>> \&\& ...);

    template<bool Const, class... Rs>
    concept concat-is-bidirectional = see below; // exposition only

4 Let Fs be the pack that consists of all elements of Rs except the last element, then concat-is-bidirectional
    is equivalent to:

    template<bool Const, class... Rs>
    concept concat-is-bidirectional =
        all-bidirectional<Const, Rs...> \&\&
        (common_range<maybe-const<Const, Fs>> \&\& ...);

constexpr explicit concat_view(Views... views);

Effects: Initializes views_ with std::move(views)....

constexpr iterator<false> begin() requires (!((simple_view<Views> \&\& ...)));
**constexpr iterator<true> begin() const**

requires (range<const Views> && ...) && concatable<const Views...>;

**Effects:** Let \( is-const \) be \( \text{true} \) for the const-qualified overload, and \( \text{false} \) otherwise. Equivalent to:

```cpp
iterator<is-const> it(this, in_place_index<0>, ranges::begin(std::get<0>(views_)));
```

```cpp
it.template satisfy<0>();
```

```cpp
return it;
```

**constexpr auto end() requires (!((simple-view<Views> && ...));**

**constexpr auto end() const requires (range<const Views> && ...) && concatable<const Views...>**;

**Effects:** Let \( is-const \) be \( \text{true} \) for the const-qualified overload, and \( \text{false} \) otherwise. Equivalent to:

```cpp
constexpr auto N = sizeof...(Views);
if constexpr (common_range<maybe-const<is-const, Views...[N - 1]>>) {
  return iterator<is-const>(this, in_place_index<N - 1>,
    ranges::end(std::get<N - 1>(views_)));
} else {
  return default_sentinel;
}
```

**constexpr auto size() requires (sized_range<Views> && ...);**

**constexpr auto size() const requires (sized_range<const Views> && ...);**

**Effects:** Equivalent to:

```cpp
return apply(
    [](auto... sizes) {
      using CT = make-unsigned-like-t<common_type_t<decltype(sizes)...>>;
      return (CT(sizes) + ...);
    },
    tuple-transform(ranges::size, views_));
```

---

### 26.7.18.3 Class concat_view::iterator

```cpp
class concat_view<Views...>::iterator {
  public:
    using iterator_category = see below; // not always present
    using iterator_concept = see below;
    using value_type = concat-value-t<maybe-const<Const, Views>>;
    using difference_type = common_type_t<range_difference_t<maybe-const<Const, Views>>>;

  private:
    using base_iter =
      variant<iterator_t<maybe-const<Const, Views>>...>; // exposition only

    maybe-const<Const, concat_view>* parent_ = nullptr; // exposition only
    base_iter it_; // exposition only

  template<size_t N> constexpr void satisfy(); // exposition only
  template<size_t N> constexpr void prev(); // exposition only
  template<size_t N> constexpr void advance_fwd(difference_type offset, difference_type steps); // exposition only
  template<size_t N> constexpr void advance_bwd(difference_type offset, difference_type steps); // exposition only

  namespace std::ranges {
    template<input_range... Views>
      requires (view<Views> && ...) && (sizeof...(Views) > 0) && concatable<Views...>
    template<bool Const>
    class concat_view<Views...>::iterator {
      public:
        using iterator_category = see below; // not always present
        using iterator_concept = see below;
        using value_type = concat-value-t<maybe-const<Const, Views>>;
        using difference_type = common_type_t<range_difference_t<maybe-const<Const, Views>>>;

      private:
        using base_iter =
          variant<iterator_t<maybe-const<Const, Views>>...>; // exposition only

        maybe-const<Const, concat_view>* parent_ = nullptr; // exposition only
        base_iter it_; // exposition only

        template<size_t N> constexpr void satisfy(); // exposition only
        template<size_t N> constexpr void prev(); // exposition only
        template<size_t N> constexpr void advance_fwd(difference_type offset, difference_type steps); // exposition only
        template<size_t N> constexpr void advance_bwd(difference_type offset, difference_type steps); // exposition only
    }
```
template<class... Args>
constexpr explicit iterator(maybe-const<Const, concat_view>* parent, // exposition only Args&&... args)
    requires constructible_from<base_iter, Args&&...>;

public:
    iterator() = default;
    constexpr iterator(iterator<!Const> i)
        requires Const && (convertible_to<iterator_t<Views>, iterator_t<const Views>> && ...);
    constexpr decltype(auto) operator*() const;
    constexpr iterator& operator++();
    constexpr void operator++(int);
    constexpr iterator& operator++(int)
        requires all-forward<Const, Views...>;
    constexpr iterator& operator--();
    constexpr iterator operator--(int)
        requires concat-is-bidirectional<Const, Views...>;
    constexpr iterator operator--(int)
        requires concat-is-random-access<Const, Views...>;
    constexpr iterator operator[](difference_type n)
        requires concat-is-random-access<Const, Views...>;
    constexpr iterator& operator+=(difference_type n)
        requires concat-is-random-access<Const, Views...>;
    constexpr iterator& operator-=(difference_type n)
        requires concat-is-random-access<Const, Views...>;
    constexpr decltype(auto) operator[](difference_type n) const
        requires concat-is-random-access<Const, Views...>;
    friend constexpr bool operator==(const iterator& x, const iterator& y)
        requires (equality_comparable<iterator_t<maybe-const<Const, Views>>> && ...);
    friend constexpr bool operator==(const iterator& it, default_sentinel_t);
    friend constexpr bool operator<(const iterator& x, const iterator& y)
        requires all-random-access<Const, Views...>;
    friend constexpr bool operator>(const iterator& x, const iterator& y)
        requires all-random-access<Const, Views...>;
    friend constexpr bool operator<=(const iterator& x, const iterator& y)
        requires all-random-access<Const, Views...>;
    friend constexpr bool operator>=(const iterator& x, const iterator& y)
        requires all-random-access<Const, Views...>;
    friend constexpr auto operator<=>(const iterator& x, const iterator& y)
        requires (all-random-access<Const, Views...> &&
                   (three_way_comparable<iterator_t<maybe-const<Const, Views>>> && ...));
    friend constexpr iterator operator+(const iterator& it, difference_type n)
        requires concat-is-random-access<Const, Views...>;
    friend constexpr iterator operator+(difference_type n, const iterator& it)
        requires concat-is-random-access<Const, Views...>;
    friend constexpr iterator operator-(const iterator& it, difference_type n)
        requires concat-is-random-access<Const, Views...>;
    friend constexpr difference_type operator-(const iterator& it, difference_type n)
        requires see below;
    friend constexpr difference_type operator-(const iterator& x, const iterator& y)
        requires see below;
    friend constexpr difference_type operator-(default_sentinel_t, const iterator& x)
        requires see below;
    friend constexpr decltype(auto) iter_move(const iterator& it) noexcept(see below);
    friend constexpr void iter_swap(const iterator& x, const iterator& y) noexcept(see below)
        requires see below;

1 iterator::iterator_concept is defined as follows:

(1.1) If concat-is-random-access<Const, Views...> is modeled, then iterator_concept denotes random_access_iterator_tag.
N4986

— Otherwise, if \textit{concat-is-bidirectional}<\textit{Const}, \textit{Views}...> is modeled, then \textit{iterator_concept} denotes \textit{bidirectional_iterator_tag}.

— Otherwise, if \textit{all-forward}<\textit{Const}, \textit{Views}...> is modeled, then \textit{iterator_concept} denotes \textit{forward_iterator_tag}.

— Otherwise, \textit{iterator_concept} denotes \textit{input_iterator_tag}.

2 The member \textit{typedef-name} \textit{iterator_category} is defined if and only if \textit{all-forward}<\textit{Const}, \textit{Views}...> is modeled. In that case, \textit{iterator::iterator_category} is defined as follows:

— If is_reference_v<concat-reference-t<maybe-const<\textit{Const}, \textit{Views}...>> is false, then \textit{iterator_category} denotes \textit{input_iterator_tag}.

— Otherwise, let \textit{Cs} denote the pack of types iterator_traits<iterator_t<maybe-const<\textit{Const}, \textit{Views}>>>::iterator_category...

— If (derived_from<Cs, random_access_iterator_tag> && ...) && concat-is-random-access<\textit{Const}, \textit{Views}...> is true, \textit{iterator_category} denotes \textit{random_access_iterator_tag}.

— Otherwise, if (derived_from<Cs, bidirectional_iterator_tag> && ...) && concat-is--bidirectional<\textit{Const}, \textit{Views}...> is true, \textit{iterator_category} denotes \textit{bidirectional_iterator_tag}.

— Otherwise, if (derived_from<Cs, forward_iterator_tag> && ...) is true, \textit{iterator_category} denotes \textit{forward_iterator_tag}.

— Otherwise, \textit{iterator_category} denotes \textit{input_iterator_tag}.

\begin{verbatim}
template<size_t N>
constexpr void satisfy(); // exposition only

Effects: Equivalent to:

if constexpr (N < (sizeof...(Views) - 1)) {
  if (std::get<N>(it_) == ranges::end(std::get<N>(parent_->views_))) {
    it_.templateemplace<N + 1>(ranges::begin(std::get<N + 1>(parent_->views_)));
    satisfy<N + 1>();
  }
}

template<size_t N>
constexpr void prev(); // exposition only

Effects: Equivalent to:

if constexpr (N == 0) {
  --std::get<0>(it_);
} else {
  if (std::get<N>(it_) == ranges::begin(std::get<N>(parent_->views_))) {
    it_.templateemplace<N - 1>(ranges::end(std::get<N - 1>(parent_->views_)));
    prev<N - 1>();
  } else {
    --std::get<N>(it_);  
  }
}

template<size_t N>
constexpr void advance-fwd(difference_type offset, difference_type steps); // exposition only

Effects: Equivalent to:

using underlying_diff_type = iter_difference_t<variant_alternative_t<N, base_iter>>;
if constexpr (N == sizeof...(Views) - 1) {
  std::get<N>(it_) += static_cast<underlying_diff_type>(steps);
} else {
  auto n_size = ranges::distance(std::get<N>(parent_->views_));
  if (offset + steps < n_size) {
    std::get<N>(it_) += static_cast<underlying_diff_type>(steps);
  } else {
    it_.templateemplace<N + 1>(ranges::begin(std::get<N + 1>(parent_->views_)));
    advance-fwd<N + 1>(0, offset + steps - n_size);
  }
}
\end{verbatim}
template<size_t N>
constexpr void advance-bwd(difference_type offset, difference_type steps); // exposition only

Effects: Equivalent to:

using underlying_diff_type = iter_difference_t<variant_alternative_t<N, base-iter>>;
if constexpr (N == 0) {
  std::get<N>(it_) -= static_cast<underlying_diff_type>(steps);
} else {
  if (offset >= steps) {
    std::get<N>(it_) -= static_cast<underlying_diff_type>(steps);
  } else {
    auto prev_size = ranges::distance(std::get<N - 1>(parent_->views_));
    it_.template emplace<N - 1>(ranges::end(std::get<N - 1>(parent_->views_)));
    advance-bwd<N - 1>(prev_size, steps - offset);
  }
}

template<class... Args>
constexpr explicit iterator (maybe-const<Const, concat_view>* parent, // exposition only
                           Args&&... args)
  requires constructible_from<base-iter, Args&&...>;

Effects: Initializes parent_ with parent, and initializes it_ with std::forward<Args>(args)....

constexpr iterator (iterator<Const> it)
  requires Const &&
  (convertible_to<iterator_t<Views>, iterator_t<const Views>> && ...);

Preconditions: it.it_.valueless_by_exception() is false.

Effects: Initializes parent_ with it.parent_, and let i be it.it_.index(), initializes it_ with
base-iter(in_place_index<i>, std::get<i>(std::move(it.it_))).

castexpr decltype(auto) operator*() const;

Preconditions: it.it_.valueless_by_exception() is false.

Effects: Equivalent to:

using reference = concat-reference-t<maybe-const<Const, Views>...>;
return std::visit([](auto&& it) -> reference { return *it; },
  it_);

castexpr iterator& operator++();

Preconditions: it.it_.valueless_by_exception() is false.

Effects: Let i be it.it_.index(). Equivalent to:

++std::get<i>(it_);
satisfy<i>();
return *this;

castexpr void operator++(int);

Effects: Equivalent to:

**this;

castexpr iterator operator++(int)
  requires all-forward<Const, Views>...;

Effects: Equivalent to:

auto tmp = *this,
  **this;
return tmp;
constexpr iterator & operator--()
  requires concat-is-bidirectional<Const, Views...>;
  
  **Preconditions:** \( \text{it\_}.\text{valueless\_by\_exception}() \) is false.
  
  **Effects:** Let \( i \) be \( \text{it\_}.\text{index}() \). Equivalent to:
  
  ```
  prev<i>();
  return *this;
  ```

constexpr iterator operator--(int)
  requires concat-is-bidirectional<Const, Views...>;
  
  **Effects:** Equivalent to:
  
  ```
  auto tmp = *this;
  --*this;
  return tmp;
  ```

constexpr iterator & operator+=(difference_type n)
  requires concat-is-random-access<Const, Views...>;
  
  **Preconditions:** \( \text{it\_}.\text{valueless\_by\_exception}() \) is false.
  
  **Effects:** Let \( i \) be \( \text{it\_}.\text{index}() \). Equivalent to:
  
  ```
  if (n > 0) {
    advance-fwd<i>(std::get<i>(\text{it\_}) - ranges::begin(std::get<i>(parent_\rightarrow views_))), n);
  } else if (n < 0) {
    advance-bwd<i>(std::get<i>(\text{it\_}) - ranges::begin(std::get<i>(parent_\rightarrow views_))), -n);
  }
  return *this;
  ```

constexpr iterator & operator-=(difference_type n)
  requires concat-is-random-access<Const, Views...>;
  
  **Effects:** Equivalent to:
  
  ```
  *this += -n;
  return *this;
  ```

constexpr decltype(auto) operator[](difference_type n) const
  requires concat-is-random-access<Const, Views...>;
  
  **Effects:** Equivalent to:
  
  ```
  return *((*this) + n);
  ```

friend constexpr bool operator==(const iterator & x, const iterator & y)
  requires (equality_comparable<iterator_t<maybe-const<Const, Views>>> && ...);
  
  **Preconditions:** \( x.\text{it\_}.\text{valueless\_by\_exception}() \) and \( y.\text{it\_}.\text{valueless\_by\_exception}() \) are each false.
  
  **Effects:** Equivalent to:
  
  ```
  return x.\text{it\_} == y.\text{it\_};
  ```

friend constexpr bool operator==(const iterator & it, default_sentinel_t);
  
  **Preconditions:** \( \text{it\_}.\text{valueless\_by\_exception}() \) is false.
  
  **Effects:** Equivalent to:
  
  ```
  constexpr auto last_idx = sizeof...(Views) - 1;
  return it.\text{it\_}.\text{index}() == last_idx &&
  ranges::end(std::get<last_idx>(it.parent_\rightarrow views_)));
  ```

friend constexpr bool operator<(const iterator & x, const iterator & y)
  requires all-random-access<Const, Views...>;
  
friend constexpr bool operator>(const iterator & x, const iterator & y)
  requires all-random-access<Const, Views...>;
  
friend constexpr bool operator<=(const iterator & x, const iterator & y)
  requires all-random-access<Const, Views...>;
  
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§ 26.7.18.3
friend constexpr bool operator>=(const iterator& x, const iterator& y)  
requires all-random-access<Const, Views...>;  
friend constexpr auto operator<=>(const iterator& x, const iterator& y)  
requires (all-random-access<Const, Views...> &&  
three_way_comparable<iterator_t<maybe-const<Const, Views>>> && ...));

 Preconditions: x.it_.valueless_by_exception() and y.it_.valueless_by_exception() are each false.

Let op be the operator.

 Effects: Equivalent to:  
return x.it_ op y.it_;

friend constexpr iterator operator+(const iterator& it, difference_type n)  
requires concat-is-random-access<Const, Views...>;

 Effects: Equivalent to:  
auto temp = it;  
temp += n;  
return temp;

friend constexpr iterator operator+(difference_type n, const iterator& it)  
requires concat-is-random-access<Const, Views...>;

 Effects: Equivalent to:  
return it + n;

friend constexpr iterator operator-(const iterator& it, difference_type n)  
requires concat-is-random-access<Const, Views...>;

 Effects: Equivalent to:  
auto temp = it;  
temp -= n;  
return temp;

friend constexpr difference_type operator-(const iterator& x, const iterator& y)  
requires concat-is-random-access<Const, Views...>;

 Preconditions: x.it_.valueless_by_exception() and y.it_.valueless_by_exception() are each false.

 Effects: Let i_x denote x.it_.index() and i_y denote y.it_.index().

— If i_x > i_y, let d_x be ranges::distance(std::begin(std::get<i_y>(y.it_)),  
ranges::end(std::get<i_y>(y.parent_->views()))), d_y be ranges::distance(ranges::begin(std::get<i_x>(x.parent_->views())), std::get<i_x>(x.it_)). Let s denote the sum of the sizes of all the ranges std::get<i>(x.parent_->views_) for every integer i in the range [i_y + 1, sizeof...(Views)] if there is any, and 0 otherwise, of type difference_type, equivalent to:  
return d_y + s + d_x;

— otherwise, if i_x < i_y is true, equivalent to:  
return -(y - x);

— otherwise, equivalent to:  
return std::get<i_x>(x.it_) - std::get<i_y>(y.it_);

friend constexpr difference_type operator-(const iterator& x, default_sentinel_t)  
requires see below;

 Preconditions: x.it_.valueless_by_exception() is false.

 Effects: Let i_x denote x.it_.index(), d_x be ranges::distance(std::begin(std::get<i_x>(x.it_)),  
ranges::end(std::get<i_x>(x.parent_->views()))). Let s denote the sum of the sizes of all the ranges std::get<i>(x.parent_->views_) for every integer i in the range [i_x + 1, sizeof...(Views)] if there is any, and 0 otherwise, of type difference_type, equivalent to:  
return -(d_x + s);
Remarks: Let Fs be the pack that consists of all elements of Views except the first element, the expression in the requires-clause is equivalent to:

\[
(sized_sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<Const, Views>> \&\& ...) \&\& \\
(sized_range<maybe-const<Const, Fs>> \&\& ...)
\]

friend constexpr difference_type operator-(default_sentinel_t, const iterator& x) requires see below;

Effects: Equivalent to:

\[
\text{return } -(x - \text{default_sentinel});
\]

Remarks: Let Fs be the pack that consists of all elements of Views except the first element, the expression in the requires-clause is equivalent to:

\[
(sized_sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<Const, Views>> \&\& ...) \&\& \\
(sized_range<maybe-const<Const, Fs>> \&\& ...)
\]

friend constexpr decltype(auto) iter_move(const iterator& it) noexcept(see below);

Preconditions: \(it\.\_\_.valueless\_by\_exception()\) is false.

Effects: Equivalent to:

\[
\text{return std::visit(}[\text{con}t\text{a}nt\text{ auto& } i) \\
\rightarrow \text{concat-rvalue-reference-t<maybe-const<Const, Views>...} \{ \\
\text{return ranges::iter_move(i); \\
\}, \\
\text{it.\_\_);}
\]

Remarks: The exception specification is equivalent to:

\[
((\text{is_nothrow\_invocable}\_v<\text{decltype(ranges::iter\_move),} \\
\text{const iterator\_t<maybe-const<Const, Views>>,} \&\& \&\& \\
\text{is_nothrow\_convertible}\_v<\text{range\_rvalue\_reference\_t<maybe-const<Const, Views>>,} \\
\text{concat\_rvalue\_reference\_t<maybe-const<Const, Views>...>>) \&\& \&\& ...)
\]

friend constexpr void iter_swap(const iterator& x, const iterator& y) noexcept(see below) requires see below;

Preconditions: \(x\.\_\_.valueless\_by\_exception()\) and \(y\.\_\_.valueless\_by\_exception()\) are each false.

Effects: Equivalent to:

\[
\text{std::visit(}[\text{con}t\text{a}nt\text{ auto& } it1, const auto& it2) \{ \\
\text{if constexpr (is_same}\_v<\text{decltype(it1), decltype(it2)>}) \{ \\
\text{ranges::iter\_swap(it1, it2); \\
\} \text{else} \{ \\
\text{ranges::swap(*x, *y); \\
\} \\
\text{x.\_\_}, y.\_\_);}
\]

Remarks: The exception specification is equivalent to

\[
(\text{noexcept(ranges::swap(*x, *y))} \&\& \ldots \&\& \text{noexcept(ranges::iter\_swap(its, its))})
\]

where its is a pack of lvalues of type const iterator\_t<maybe-const<Const, Views>> respectively.

The expression in the requires-clause is equivalent to

\[
\text{swappable\_with<iter\_reference\_t<iterator>, iter\_reference\_t<iterator> \&\& ... \&\& indirectly\_swappable<iterator\_t<maybe-const<Const, Views>>>}
\]

### 26.7.19 Counted view [range.counted]

A counted view presents a view of the elements of the counted range \((25.3.1) i + [0, n)\) for an iterator \(i\) and non-negative integer \(n\).
The name `views::counted` denotes a customization point object (16.3.3.5). Let \( E \) and \( F \) be expressions, let \( T \) be `decay_t< decltype((E)) >`, and let \( D \) be `iter_difference_t<T>`. If `decltype((F))` does not model `convertible_to<D>`, `views::counted(E, F)` is ill-formed.

[Note 1: This case can result in substitution failure when `views::counted(E, F)` appears in the immediate context of a template instantiation. — end note]

Otherwise, `views::counted(E, F)` is expression-equivalent to:

1. If \( T \) models `contiguous_iterator`, then `span(to_address(E), static_cast<size_t>(static_cast<D>(F)))`.
2. Otherwise, if \( T \) models `random_access_iterator`, then `subrange(E, E + static_cast<D>(F))`, except that \( E \) is evaluated only once.
3. Otherwise, `subrange(counted_iterator(E, F), default_sentinel)`.

**26.7.20 Common view**  

**26.7.20.1 Overview**

`common_view` takes a view which has different types for its iterator and sentinel and turns it into a view of the same elements with an iterator and sentinel of the same type.

[Note 1: `common_view` is useful for calling legacy algorithms that expect a range's iterator and sentinel types to be the same. — end note]

The name `views::common` denotes a range adaptor object (26.7.2). Given a subexpression \( E \), the expression `views::common(E)` is expression-equivalent to:

1. `views::all(E)`, if `decltype((E))` models `common_range` and `views::all(E)` is a well-formed expression.
2. Otherwise, `common_view{E}`.

**Example 1:**

```cpp
// Legacy algorithm:
template<class ForwardIterator>
size_t count(ForwardIterator first, ForwardIterator last);

template<forward_range R>
void my_algo(R&& r)
{
    auto&& common = views::common(r);
    auto cnt = count(common.begin(), common.end());
    // ...
}
```

**26.7.20.2 Class template `common_view`**

```cpp
namespace std::ranges {
    template<view V>
    requires (!common_range<V> && copyable<iterator_t<V>>)
    class common_view : public view_interface<common_view<V>>
    {
        private:
            V base_ = V(); // exposition only

        public:
            common_view() requires default_initializable<V> = default;

            constexpr explicit common_view(V r);

            constexpr V base() const & requires copy_constructible<V> { return base_; }
            constexpr V base() && { return std::move(base_); }

            constexpr auto begin() requires (!simple_view<V>) {
                if constexpr (random_access_range<V> && sized_range<V>)
                    return ranges::begin(base_);
                else
                    return common_iterator<iterator_t<V>, sentinel_t<V>>(ranges::begin(base_));
            }
        }
    }
}
```
constexpr auto begin() const requires range<const V> {
    if constexpr (random_access_range<const V> && sized_range<const V>)
        return ranges::begin(base_);
    else
        return common_iterator<iterator_t<const V>, sentinel_t<const V>>(ranges::begin(base_));
}

constexpr auto end() requires (!simple_view<V>) {
    if constexpr (random_access_range<V> && sized_range<V>)
        return ranges::begin(base_) + ranges::distance(base_);
    else
        return common_iterator<iterator_t<V>, sentinel_t<V>>(ranges::end(base_));
}

constexpr auto end() const requires range<const V> {
    if constexpr (random_access_range<const V> && sized_range<const V>)
        return ranges::begin(base_) + ranges::distance(base_);
    else
        return common_iterator<iterator_t<const V>, sentinel_t<const V>>(ranges::end(base_));
}

constexpr auto size() requires sized_range<V> {
    return ranges::size(base_);
}

constexpr auto size() const requires sized_range<const V> {
    return ranges::size(base_);
}

};

template<class R>
common_view(R&&) -> common_view<views::all_t<R>>;

constexpr explicit common_view(V base);

Effects: Initializes base_ with std::move(base).

26.7.21 Reverse view [range.reverse]

26.7.21.1 Overview [range.reverse.overview]

The name views::reverse denotes a range adaptor object (26.7.2). Given a subexpression E, the expression views::reverse(E) is expression-equivalent to:

1. If the type of E is a (possibly cv-qualified) specialization of reverse_view, then E.base().
2. Otherwise, if the type of E is cv subrange<reverse_iterator<I>, reverse_iterator<I>, K> for some iterator type I and value K of type subrange_kind,
   2.1. If K is subrange_kind::sized, then subrange<I, I, K>(E.end().base(), E.begin().base(), E.size());
   2.2. Otherwise, subrange<I, I, K>(E.end().base(), E.begin().base()).
   However, in either case E is evaluated only once.
3. Otherwise, reverse_view(E).

[Example 1:

  vector<int> is {0,1,2,3,4};
  for (int i : is | views::reverse)
    cout « i « ' '; // prints 4 3 2 1 0

  — end example]
26.7.21.2 Class template reverse_view

```cpp
namespace std::ranges {
    template<view V>
    requires bidirectional_range<V>
    class reverse_view : public view_interface<reverse_view<V>> {
        private:
            V base_ = V(); // exposition only

        public:
            reverse_view() requires default_initializable<V> = default;
            constexpr explicit reverse_view(V r);
            constexpr V base() const & requires copy_constructible<V> { return base_; }
            constexpr V base() && { return std::move(base_); }
            constexpr reverse_iterator<iterator_t<V>> begin();
            constexpr auto begin() const requires common_range<const V> {
                return ranges::size(base_);
            }
            constexpr reverse_iterator<iterator_t<V>> end();
            constexpr auto end() const requires common_range<const V> {
                return ranges::size(base_);
            }
    };
    template<class R>
    reverse_view(R&&) -> reverse_view<views::all_t<R>>;

    constexpr explicit reverse_view(V base);
    Effects: Initializes base_ with std::move(base).
    constexpr reverse_iterator<iterator_t<V>> begin();
    Returns:
    make_reverse_iterator(ranges::next(ranges::begin(base_), ranges::end(base_)))
    Remarks: In order to provide the amortized constant time complexity required by the range concept,
    this function caches the result within the reverse_view for use on subsequent calls.
    constexpr reverse_iterator<iterator_t<V>> end();
    constexpr auto end() const requires common_range<const V> {
        return ranges::size(base_);
    }
}
```

26.7.22 As const view

26.7.22.1 Overview

`as_const_view` presents a view of an underlying sequence as constant. That is, the elements of an `as_const_view` cannot be modified.

The name `views::as_const` denotes a range adaptor object (26.7.2). Let `E` be an expression, let `T` be `decltype((E))`, and let `U` be `remove_cvref_t<T>`. The expression `views::as_const(E)` is expression-equivalent to:
If views::all_t<T> models constant_range, then views::all(E).

Otherwise, if U denotes empty_view<X> for some type X, then auto(views::empty<const X>)(E).

Otherwise, if U denotes span<X, Extent> for some type X and some extent Extent, then span<const X, Extent>(E).

Otherwise, if U denotes ref_view<X> for some type X and const X models constant_range, then ref_view(static_cast<const X&>(E.base())).

Otherwise, if E is an lvalue, const U models constant_range, and U does not model view, then ref_view(static_cast<const U&>(E)).

Otherwise, as_const_view(E).

Example 1:

```cpp
template<constant_range R>
void cant_touch_this(R&&);

vector<char> hammer = {'m', 'c'};
span<char> beat = hammer;
cant_touch_this(views::as_const(beat)); // will not modify the elements of hammer
```

26.7.22.2 Class template as_const_view

```cpp
namespace std::ranges {
    template<typename V>
    requires input_range<V>
    class as_const_view : public view_interface<as_const_view<V>> {
        V base_ = V(); // exposition only
        
        public:
        as_const_view() requires default_initializable<V> = default;
        constexpr explicit as_const_view(V base);
        
        constexpr V base() const & requires copy_constructible<V> { return base_; }
        constexpr V base() && { return std::move(base_); }
        
        constexpr auto begin() requires (!is_simple_view<V>) { return ranges::cbegin(base_); }
        constexpr auto begin() const requires range<const V> { return ranges::cbegin(base_); }
        
        constexpr auto end() requires (!is_simple_view<V>) { return ranges::cend(base_); }
        constexpr auto end() const requires range<const V> { return ranges::cend(base_); }
        
        constexpr auto size() requires sized_range<V> { return ranges::size(base_); }
        constexpr auto size() const requires sized_range<const V> { return ranges::size(base_); }
    };

    template<class R>
    as_const_view(R&&) -> as_const_view<views::all_t<R>>;
}
```

Effects: Initializes base_ with std::move(base).

26.7.23 Elements view

26.7.23.1 Overview

elements_view takes a view of tuple-like values and a size_t, and produces a view with a value-type of the \(N\)th element of the adapted view’s value-type.

The name views::elements<N> denotes a range adaptor object (26.7.2). Given a subexpression E and constant expression N, the expression views::elements<N>(E) is expression-equivalent to elements_view<views::all_t<decltype((E))>, N>(E).
Example 1:

```cpp
class example
class historical_figures = map{
  pair("Lovelace"sv, 1815),
  {"Turing"sv, 1912},
  {"Babbage"sv, 1791},
  {"Hamilton"sv, 1936} ;
};
auto names = historical_figures | views::elements<0>;
for (auto&& name : names) {
  cout << name << ' ' ;  // prints Babbage Hamilton Lovelace Turing
}

auto birth_years = historical_figures | views::elements<1>
for (auto&& born : birth_years) {
  cout << born << ' ' ;  // prints 1791 1936 1815 1912
}
```

Example 2:

```cpp
class example
auto names = historical_figures | views::keys;
for (auto&& name : names) {
  cout << name << ' ' ;  // prints Babbage Hamilton Lovelace Turing
}
```

Example 3:

```cpp
class example
auto is_even = [](const auto x) { return x % 2 == 0; };
cout << ranges::count_if(historical_figures | views::values, is_even);  // prints 2
```

keys_view is an alias for elements_view<R, 0>, and is useful for extracting keys from associative containers.

values_view is an alias for elements_view<R, 1>, and is useful for extracting values from associative containers.

26.7.23.2 Class template elements_view

```cpp
namespace std::ranges {
  template<class T, size_t N>
  concept has-tuple-element =  // exposition only
    tuple-like<T> && N < tuple_size_v<T> ;

template<class T, size_t N>
  concept returnable-element =  // exposition only
    is_reference_v<T> || move_constructible<tuple_element_t<N, T>> ;

template<input_range V, size_t N>
  requires view<V> && has-tuple-element<range_value_t<V>, N> &&
    has-tuple-element<remove_reference_t<range_reference_t<V>>, N> &&
    returnable-element<range_reference_t<V>, N>
  class elements_view : public view_interface<elements_view<V, N>> {
    public:
      elements_view() requires default_initializable<V> = default;
      constexpr explicit elements_view(V base);

      constexpr V base() const & requires copy_constructible<V> { return base ; }  
      constexpr V base() && { return std::move(base) ; }  

      constexpr auto begin() requires (!simple-view<V>)
      { return std::begin(base) ; }  
      constexpr auto begin() const requires range<const V>
      { return std::begin(base) ; }  
```
constexpr auto end() requires (!
  simple-view<V> && !common_range<V>)
{ return sentinel<false>{ranges::end(base_)}; }

constexpr auto end() requires (!
  simple-view<V> && common_range<V>)
{ return iterator<false>{ranges::end(base_)}; }

constexpr auto end() const requires range<
  const V>
{ return sentinel<true>{ranges::end(base_)}; }

constexpr auto end() const requires common_range<
  const V>
{ return iterator<true>{ranges::end(base_)}; }

constexpr auto size() requires sized_range<V>
{ return ranges::size(base_); }

constexpr auto size() const requires sized_range<
  const V>
{ return ranges::size(base_); }

private:
  // 26.7.23.3, class template elements_view::iterator
  template<bool> class iterator;
  // exposition only

  // 26.7.23.4, class template elements_view::sentinel
  template<bool> class sentinel;
  // exposition only

  V base_ = V();
  // exposition only
};

constexpr explicit elements_view(V base);

Effects: Initializes base_ with std::move(base).

26.7.23.3 Class template elements_view::iterator

namespace std::ranges {
  template<input_range V, size_t N>
  requires view<V> && has-tuple-element<
    range_value_t<V>, N> &&
    has-tuple-element<
      remove_reference_t<
        range_reference_t<V>>, N> &&
    returnable-element<
      range_reference_t<V>, N>
  template<bool Const>
  class elements_view<V, N>::iterator {
    using Base = maybe-const<
      Const, V>;
    // exposition only

    iterator_t<Base> current_ = iterator_t<Base>{};
    // exposition only

    static constexpr decltype(auto) get-element(
      const iterator_t<Base>& i);     // exposition only

  public:

    using iterator_concept = see below;
    using iterator_category = see below;
    // not always present

    using value_type = remove_cvref_t<
      tuple_element_t<N, range_value_t<Base>>>{
      using difference_type = range_difference_t<Base>;

      iterator() requires default_initializable<
        iterator_t<Base>> = default;
      constexpr explicit iterator(iterator_t<Base> current);

      iterator(\iterator<\Const> i)
      requires Const && convertible_to<
        iterator_t<V>, iterator_t<Base>>;

      constexpr const iterator_t<Base>& base() const noexcept;
      constexpr iterator_t<Base> base() &&;

      constexpr decltype(auto) operator*() const
      { return get-element(current_); }
  }
constexpr iterator& operator++();
constexpr void operator++(int);
constexpr iterator operator++(int) requires forward_range<Base>;

constexpr iterator& operator--() requires bidirectional_range<Base>;
constexpr iterator operator--(int) requires bidirectional_range<Base>;

constexpr iterator& operator+=(difference_type x) requires random_access_range<Base>;
constexpr iterator& operator-=(difference_type x) requires random_access_range<Base>;

constexpr decltype(auto) operator[](difference_type n) const
    { return get_element(current_ + n); }

friend constexpr bool operator==(const iterator x, const iterator& y) requires equality_comparable<iterator_t<Base>>;
friend constexpr bool operator<(const iterator x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator>(const iterator x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator<=(const iterator x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator>=(const iterator x, const iterator& y) requires random_access_range<Base>;
friend constexpr auto operator<=>(const iterator x, const iterator& y) requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;
friend constexpr iterator operator+(const iterator x, difference_type y) requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type x, const iterator& y) requires random_access_range<Base>;
friend constexpr iterator operator-(const iterator x, difference_type y) requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

1 The member typedef-name iterator_concept is defined as follows:
1.1 If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
1.2 Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
1.3 Otherwise, if Base models forward_range, then iterator_concept denotes forward_iterator_tag.
1.4 Otherwise, iterator_concept denotes input_iterator_tag.

2 The member typedef-name iterator_category is defined if and only if Base models forward_range. In that case, iterator_category is defined as follows: Let C denote the type iterator_traits<iterator_t<Base>>::iterator_category.
2.1 If std::get<N>(*current_) is an rvalue, iterator_category denotes input_iterator_tag.
2.2 Otherwise, if C models derived_from<random_access_iterator_tag>, iterator_category denotes random_access_iterator_tag.
2.3 Otherwise, iterator_category denotes C.

static constexpr decltype(auto) get_element(const iterator_t<Base>& i);

Effects: Equivalent to:
if constexpr (is_reference_v<range_reference_t<Base>>) {
    return std::get<N>(*i);
} else {
    using E = remove_cv_t<
tuple_element_t<N, range_reference_t<Base>>;
    return static_cast<E>(std::get<N>(*i));
}

constexpr explicit iterator(iterator_t<Base> current);

Effects: Initializes current_ with std::move(current).

constexpr iterator(iterator_t<!Const> i)
requires Const && convertible_to<
iterator_t<V>, iterator_t<Base>>;

Effects: Initializes current_ with std::move(i.current_).

constexpr const iterator_t<Base>& base() const & noexcept;

Effects: Equivalent to: return current_

constexpr iterator_t<Base>& base() &&;

Effects: Equivalent to: return std::move(current_);

constexpr iterator& operator++();

Effects: Equivalent to:
++current_
return *this;

constexpr void operator++(int);

Effects: Equivalent to: ++current_

constexpr iterator operator++(int) requires forward_range<Base>;

Effects: Equivalent to:
auto temp = *this;
++current_
return temp;

constexpr iterator& operator--() requires bidirectional_range<Base>;

Effects: Equivalent to:
--current_
return *this;

constexpr iterator operator--(int) requires bidirectional_range<Base>;

Effects: Equivalent to:
auto temp = *this;
--current_
return temp;

constexpr iterator& operator+=(difference_type n)
requires random_access_range<Base>;

Effects: Equivalent to:
current_ += n;
return *this;

constexpr iterator& operator-=(difference_type n)
requires random_access_range<Base>;

Effects: Equivalent to:
current_ -= n;
return *this;
friend constexpr bool operator==(const iterator& x, const iterator& y) requires equality_comparable<Base>;  
   Effects: Equivalent to: return x.current_ == y.current_;  
friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;  
   Effects: Equivalent to: return x.current_ < y.current_;  
friend constexpr bool operator>(const iterator& x, const iterator& y) requires random_access_range<Base>;  
   Effects: Equivalent to: return y < x;  
friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;  
   Effects: Equivalent to: return !(y < x);  
friend constexpr bool operator>=(const iterator& x, const iterator& y) requires random_access_range<Base>;  
   Effects: Equivalent to: return !(x < y);  
friend constexpr auto operator<=>(const iterator& x, const iterator& y) requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;  
   Effects: Equivalent to: return x.current_ <=> y.current_;  
friend constexpr iterator operator+(const iterator& x, difference_type y) requires random_access_range<Base>;  
   Effects: Equivalent to: return iterator{ x } += y;  
friend constexpr iterator operator+(difference_type x, const iterator& y) requires random_access_range<Base>;  
   Effects: Equivalent to: return y + x;  
friend constexpr iterator operator-(const iterator& x, difference_type y) requires random_access_range<Base>;  
   Effects: Equivalent to: return iterator{ x } -= y;  
friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;  
   Effects: Equivalent to: return x.current_ - y.current_;  

26.7.23.4 Class template elements_view::sentinel

namespace std::ranges {
  template<input_range V, size_t N>
   requires view<V> && has-tuple-element<range_value_t<V>, N> &&
      has-tuple-element<remove_reference_t<range_reference_t<V>>, N> &&
      returnable-element<range_reference_t<V>, N>
  
  template<bool Const>
  class elements_view<V, N>::sentinel {
    private:
      using Base = maybe-const<Const, V>; // exposition only
      sentinel_t<Base> end_ = sentinel_t<Base>(); // exposition only
    
    public:
      sentinel() = default;
      constexpr explicit sentinel(sentinel_t<Base> end); // exposition only
      sentinel(sentinel_t<Base> other) requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
      
      constexpr sentinel_t<Base> base() const;
  }
} // range.elements.sentinel

§ 26.7.23.4
template<bool OtherConst>
    requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

template<bool OtherConst>
    requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
    operator-(const iterator<OtherConst>& x, const sentinel& y);

template<bool OtherConst>
    requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
    operator-(const sentinel& x, const iterator<OtherConst>& y);

constexpr explicit sentinel(sentinel_t<Base> end);
Effects: Initializes end_ with end.

constexpr sentinel(sentinel<!Const> other)
requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
Effects: Initializes end_ with std::move(other.end_).

constexpr sentinel_t<Base> base() const;
Effects: Equivalent to: return end_; 

template<bool OtherConst>
    requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
Effects: Equivalent to: return x.current_ == y.end_; 

template<bool OtherConst>
    requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
    operator-(const iterator<OtherConst>& x, const sentinel& y);
Effects: Equivalent to: return x.current_ - y.end_; 

template<bool OtherConst>
    requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
    operator-(const sentinel& x, const iterator<OtherConst>& y);
Effects: Equivalent to: return x.end_ - y.current_; 

26.7.24 Enumerate view 
26.7.24.1 Overview 
Enumerate view is a view whose elements represent both the position and value from a sequence of elements.

Example 1:
```cpp
vector<int> vec{ 1, 2, 3 };  
for (auto [index, value] : views::enumerate(vec))
    cout << index << ":" << value << " "; // prints 0:1 1:2 2:3
```
—end example

26.7.24.2 Class template enumerate_view 

namespace std::ranges {
    template<view V>
    requires range-with-movable-references<V>
    class enumerate_view : public view_interface<enumerate_view<V>> { 
        V base_ = V();
    // exposition only
// 26.7.24.3, class template enumerate_view::iterator
template<bool Const>
class iterator;  // exposition only

// 26.7.24.4, class template enumerate_view::sentinel
template<bool Const>
class sentinel;  // exposition only

public:
    constexpr enumerate_view() requires default_initializable<V> = default;
    constexpr explicit enumerate_view(V base);

    constexpr auto begin() requires (! simple_view<V>)
        { return iterator<false>(ranges::begin(base_), 0); }
    constexpr auto begin() const requires range_with_movable_references<const V>
        { return iterator<true>(ranges::begin(base_), 0); }

    constexpr auto end() requires (! simple_view<V>) {
        if constexpr (forward_range<V> && common_range<V> && sized_range<V>)
            return iterator<false>(ranges::end(base_), ranges::distance(base_));
        else
            return sentinel<false>(ranges::end(base_));
    }
    constexpr auto end() const requires range_with_movable_references<const V> {
        if constexpr (forward_range<const V> && common_range<const V> && sized_range<const V>)
            return iterator<true>(ranges::end(base_), ranges::distance(base_));
        else
            return sentinel<true>(ranges::end(base_));
    }

    constexpr auto size() requires sized_range<V> {
        return ranges::size(base_); }
    constexpr auto size() const requires sized_range<const V> {
        return ranges::size(base_); }

    constexpr V base() const & requires copy_constructible<V> { return base_; }
    constexpr V base() && { return std::move(base_); }

};

template<class R>
enumerate_view(R&&) -> enumerate_view<views::all_t<R>>;

constexpr explicit enumerate_view(V base);

Effects: Initializes base_ with std::move(base).

26.7.24.3 Class template enumerate_view::iterator

namespace std::ranges {
    template<view V>
        requires range_with_movable_references<V>
template<bool Const>
class enumerate_view<V>::iterator {
    using Base = maybe_const<Const, V>;
        // exposition only

    public:
        using iterator_category = input_iterator_tag;
        using iterator_concept = see below;
        using difference_type = range_difference_t<Base>;
        using value_type = tuple<difference_type, range_value_t<Base>>;

    private:
        using reference_type =
            // exposition only
tuple<difference_type, range_reference_t<Base>>;
iterator_t<Base> current_ = iterator_t<Base>(); // exposition only
difference_type pos_ = 0; // exposition only

constexpr explicit
iterator(iterator_t<Base> current, difference_type pos); // exposition only

public:
iterator() requires default_initializable<iterator_t<Base>> = default;
constexpr iterator(iterator_t<Const> i)
    requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;

constexpr iterator_t<Base>& base() const & noexcept;
constexpr iterator_t<Base>& base() &&;
constexpr difference_type index() const noexcept;
constexpr auto operator*() const {
    return reference_type(pos_, *current_);
}

constexpr iterator& operator++();
constexpr void operator++(int);
constexpr iterator operator++(int) requires forward_range<Base>;

constexpr iterator& operator+=(difference_type x)
    requires random_access_range<Base>;
constexpr iterator operator+=(difference_type x)
    requires random_access_range<Base>;

constexpr auto operator[](difference_type n) const
    requires random_access_range<Base>
    { return reference_type(pos_ + n, current_[n]); }

friend constexpr bool operator==(const iterator& x, const iterator& y) noexcept;
friend constexpr strong_ordering operator<=>(const iterator& x, const iterator& y) noexcept;

friend constexpr iterator operator+(const iterator& x, difference_type y)
    requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type x, const iterator& y)
    requires random_access_range<Base>;
friend constexpr iterator operator-(const iterator& x, difference_type y)
    requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y) noexcept;

friend constexpr auto iter_move(const iterator& i)
    noexcept(noexcept(ranges::iter_move(i.current_)) &&
              is_nothrow_move_constructible_v<range_rvalue_reference_t<Base>>) {
    return tuple<difference_type,
                 range_rvalue_reference_t<Base>>(i.pos_,
                                                  ranges::iter_move(i.current_));
}

1 The member typedef-name iterator::iterator_concept is defined as follows:

(1.1) — If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.

(1.2) — Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.

(1.3) — Otherwise, if Base models forward_range, then iterator_concept denotes forward_iterator_tag.

§ 26.7.24.3 ©ISO/IEC 1287
— Otherwise, iterator_concept denotes input_iterator_tag.

```c
constexpr explicit iterator(iterator_t<Base> current, difference_type pos);
```

**Effects:** Initializes current_ with std::move(current) and pos_ with pos.

```c
constexpr iterator(iterator_t<Const> i)
    requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;
```

**Effects:** Initializes current_ with std::move(i.current_) and pos_ with i.pos_.

```c
constexpr const iterator_t<Base>& base() const & noexcept;
```

**Effects:** Equivalent to: return current_.

```c
constexpr iterator_t<Base> base() &&;
```

**Effects:** Equivalent to: return std::move(current_);

```c
difference_type index() const noexcept;
```

**Effects:** Equivalent to: return pos_.

```c
constexpr iterator& operator++();
```

**Effects:** Equivalent to:

```c
++current_;
++pos_;
return *this;
```

```c
constexpr void operator++(int);
```

**Effects:** Equivalent to +++this.

```c
constexpr iterator operator++(int) requires forward_range<Base>;
```

**Effects:** Equivalent to:

```c
auto temp = *this;
+++this;
return temp;
```

```c
constexpr iterator& operator--() requires bidirectional_range<Base>;
```

**Effects:** Equivalent to:

```c
--current_;
--pos_;
return *this;
```

```c
constexpr iterator operator--(int) requires bidirectional_range<Base>;
```

**Effects:** Equivalent to:

```c
auto temp = *this;
--*this;
return temp;
```

```c
constexpr iterator& operator+=(difference_type n)
    requires random_access_range<Base>;
```

**Effects:** Equivalent to:

```c
current_ += n;
pos_ += n;
return *this;
```

```c
constexpr iterator& operator-=(difference_type n)
    requires random_access_range<Base>;
```

**Effects:** Equivalent to:

```c
current_ -= n;
pos_ -= n;
return *this;
```
friend constexpr bool operator==(const iterator& x, const iterator& y) noexcept;

14 Effects: Equivalent to: return x.pos_ == y.pos_;

friend constexpr strong_ordering operator<=>(const iterator& x, const iterator& y) noexcept;

15 Effects: Equivalent to: return x.pos_ <=> y.pos_;

friend constexpr iterator operator+(const iterator& x, difference_type y)
    requires random_access_range<Base>;

16 Effects: Equivalent to:
    auto temp = x;
    temp += y;
    return temp;

friend constexpr iterator operator+(difference_type x, const iterator& y)
    requires random_access_range<Base>;

17 Effects: Equivalent to: return y + x;

friend constexpr iterator operator-(const iterator& x, difference_type y)
    requires random_access_range<Base>;

18 Effects: Equivalent to:
    auto temp = x;
    temp -= y;
    return temp;

friend constexpr difference_type operator-(const iterator& x, const iterator& y) noexcept;

19 Effects: Equivalent to: return x.pos_ - y.pos_;

26.7.24.4 Class template enumerate_view::sentinel

namespace std::ranges {
    template<view V>
        requires range-with-movable-references<V>
    template<bool Const>
        class enumerate_view<V>::sentinel {
            using Base = maybe-const<Const, V>;  // exposition only
            sentinel_t<Base> end_ = sentinel_t<Base>();  // exposition only
            constexpr explicit sentinel(sentinel_t<Base> end);

        public:
            sentinel() = default;
            constexpr sentinel(sentinel<!Const> other)
                requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

            sentinel_t<Base> base() const;

            template<bool OtherConst>
                requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
                friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

            template<bool OtherConst>
                requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
                friend constexpr range_difference_t<maybe-const<OtherConst, V>>
                    operator-(const iterator<OtherConst>& x, const sentinel& y);

            template<bool OtherConst>
                requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
                friend constexpr range_difference_t<maybe-const<OtherConst, V>>
                    operator-(const sentinel& x, const iterator<OtherConst>& y);
        };
    }

§ 26.7.24.4 © ISO/IEC 1289
constexpr explicit sentinel(sentinel_t<Base> end);

  *Effects:* Initializes `end` with `std::move(end)`.

constexpr sentinel(sentinel<!Const> other)
  requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

  *Effects:* Initializes `end` with `std::move(other.end)`.

constexpr sentinel_t<Base> base() const;

  *Effects:* Equivalent to: return `end`.

template<bool OtherConst>
  requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>;
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

  *Effects:* Equivalent to: return `x.current_ == y.end`.

template<bool OtherConst>
  requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>;
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
  operator-(const iterator<OtherConst>& x, const sentinel& y);

  *Effects:* Equivalent to: return `x.current_ - y.end`.

template<bool OtherConst>
  requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>;
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
  operator-(const sentinel& x, const iterator<OtherConst>& y);

  *Effects:* Equivalent to: return `x.end_ - y.current_`;

### 26.7.25 Zip view

#### 26.7.25.1 Overview

`zip_view` takes any number of views and produces a view of tuples of references to the corresponding elements of the constituent views.

The name `views::zip` denotes a customization point object (16.3.3.5). Given a pack of subexpressions `Es...`, the expression `views::zip(Es...)` is expression-equivalent to

1. auto(&views::empty<tuple<>>) if `Es` is an empty pack,
2. otherwise, `zip_view<views::all_t<decltype((Es))>>>(Es...)`.

**Example 1:**

```cpp
class z = views::zip(v, l);
range_reference_t<decltype(z)> f = z.front(); // f is a tuple<int&, char&>
```

```cpp
for (auto& [x, y] : z) {
  cout << "(\"" << x << "\", \"" << y << ") \n; // prints (1, a) (2, b)
}
```

**Example 2:**

```cpp
namespace std::ranges {

  template<>
  concept zip_is_common =  // exposition only
      (sizeof...(Rs) == 1 && (common_range<Rs> && ...)) ||
      (!bidirectional_range<Rs> && ... && (common_range<Rs> && ...)) ||
      (random_access_range<Rs> && ... && (sized_range<Rs> && ...));

} // namespace std::ranges
```
template<input_range... Views>
requires (view<Views> && ... && (sizeof...(Views) > 0))
class zip_view : public view_interface<zip_view<Views...>> {
    tuple<Views...> views_;
    // exposition only
}

// 26.7.25.3, class template zip_view::iterator
template<bool> class iterator;
    // exposition only

// 26.7.25.4, class template zip_view::sentinel
template<bool> class sentinel;
    // exposition only

public:
    zip_view() = default;
    constexpr explicit zip_view(Views... views);

    constexpr auto begin() requires (!((simple-view<Views> && ...)) {
        return iterator<false>((tuple-transform(ranges::begin, views_));
    } constexpr auto begin() const requires (range<const Views> && ...) {
        return iterator<true>((tuple-transform(ranges::begin, views_));
    }
    constexpr auto end() requires (!((simple-view<Views> && ...)) {
        if constexpr (!zip-is-common<Views...>) {
            return sentinel<false>((tuple-transform(ranges::end, views_));
        } else if constexpr ((random_access_range<Views> && ...)) {
            return begin() + iter_difference_t<iterator<false>>(size());
        } else {
            return iterator<false>((tuple-transform(ranges::end, views_));
        }
    }
    constexpr auto end() const requires (range<const Views> && ...) {
        if constexpr (!zip-is-common<const Views...>) {
            return sentinel<true>((tuple-transform(ranges::end, views_));
        } else if constexpr ((random_access_range<const Views> && ...)) {
            return begin() + iter_difference_t<iterator<true>>(size());
        } else {
            return iterator<true>((tuple-transform(ranges::end, views_));
        }
    }
    constexpr auto size() requires (sized_range<Views> && ...);
    constexpr auto size() const requires (sized_range<const Views> && ...);
};

template<class... Rs>
zip_view(Rs&&...) -> zip_view<views::all_t<Rs>...>;

1 Two zip_view objects have the same underlying sequence if and only if the corresponding elements of views_ are equal (18.2) and have the same underlying sequence.

[Note 1: In particular, comparison of iterators obtained from zip_view objects that do not have the same underlying sequence is not required to produce meaningful results (25.3.4.11). — end note]

2 Effects: Initializes views_ with std::move(views)....

3 Effects: Equivalent to:

    return apply([](auto... sizes) {
        using CT = make_unsigned_like_t<common_type_t<decltype(sizes)...>>;

§ 26.7.25.2 © ISO/IEC 1291
```
26.7.25.3 Class template zip_view::iterator

namespace std::ranges {
    template<input_range... Views>
    requires (view<Views> && ...) && (sizeof...(Views) > 0)
    template<bool Const>
    class zip_view<Views...>::iterator {
        tuple<iterator_t<
            maybe-const<Const, Views>>...> current;  // exposition only
        // exposition only
    public:
        using iterator_category = input_iterator_tag;
        // not always present
        using iterator_concept = see below;
        using value_type = tuple<range_value_t<
            maybe-const<Const, Views>>...>;
        using difference_type = common_type_t<range_difference_t<
            maybe-const<Const, Views>>...>;
        iterator() = default;
        constexpr iterator(decltype(this) i)
            requires Const && (convertible_to<iterator_t<Views>, iterator_t<const Views>> && ...);
        constexpr auto operator*() const;
        constexpr iterator& operator++();
        constexpr void operator++(int);
        constexpr iterator& operator--() requires all-bidirectional<Const, Views...>;
        constexpr iterator operator--(int) requires all-bidirectional<Const, Views...>;
        constexpr iterator& operator+=(difference_type x) requires all-random-access<Const, Views...>;
        constexpr iterator& operator-=(difference_type x) requires all-random-access<Const, Views...>;
        constexpr auto operator[](difference_type n) const requires all-random-access<Const, Views...>;
        friend constexpr bool operator==(const iterator& x, const iterator& y)
            requires (equality_comparable<iterator_t<
                maybe-const<Const, Views>>, iterator_t<const Views>>, & ...);
        friend constexpr auto operator<(const iterator& l, const iterator& r) noexcept(see below)
            requires (indirectly_swappable<iterator_t<
                maybe-const<Const, Views>>, iterator_t<const Views>> && ...);
    }  

    1 iterator::iterator_concept is defined as follows:

(1.1) — If all-random-access<Const, Views...> is modeled, then iterator_concept denotes random-access_iterator_tag.
```
— Otherwise, if all-bidirectional<Const, Views...> is modeled, then iterator_concept denotes bidirectional_iterator_tag.

— Otherwise, if all-forward<Const, Views...> is modeled, then iterator_concept denotes forward_iterator_tag.

— Otherwise, iterator_concept denotes input_iterator_tag.

iterator::iterator_category is present if and only if all-forward<Const, Views...> is modeled.

If the invocation of any non-const member function of iterator exits via an exception, the iterator acquires a singular value.

constexpr explicit iterator(tuple<iterator_t<maybe-const<Const, Views>>>... current);

Effects: Initializes current_ with std::move(current).

constexpr iterator(iterator<Const> i)
  requires Const & (convertible_to<iterator_t<Views>, iterator_t<const Views>> && ...);

Effects: Initializes current_ with std::move(i.current_).

constexpr auto operator*() const;

Effects: Equivalent to:

    return tuple-transform(
        [](auto& i) -> decltype(auto) { return *i; }, current_);

constexpr iterator& operator++();

Effects: Equivalent to:

    tuple-for-each(
        [](auto& i) { ++i; }, current_);
    return *this;

constexpr void operator++(int);

Effects: Equivalent to +++this.

constexpr iterator operator++(int) requires all-forward<Const, Views...>;

Effects: Equivalent to:

    auto tmp = *this;
    +++this;
    return tmp;

constexpr iterator& operator--() requires all-bidirectional<Const, Views...>

Effects: Equivalent to:

    tuple-for-each(
        [](auto& i) { --i; }, current_);
    return *this;

constexpr iterator operator--(int) requires all-bidirectional<Const, Views...>

Effects: Equivalent to:

    auto tmp = *this;
    --*this;
    return tmp;

constexpr iterator& operator+=(difference_type x)
  requires all-random-access<Const, Views...>;

Effects: Equivalent to:

    tuple-for-each(
        [&]<class I>(I& i) { i += iter_difference_t<I>(x); }, current_);
    return *this;

constexpr iterator& operator-=(difference_type x)
  requires all-random-access<Const, Views...>;

Effects: Equivalent to:

    tuple-for-each(
        [&]<class I>(I& i) { i -= iter_difference_t<I>(x); }, current_);
    return *this;
constexpr auto operator[](difference_type n) const

Effects: Equivalent to:

return tuple-transform([&]<class I>(I& i) -> decltype(auto) {
    return i[iter_difference_t<I>(n)];
}, current_);

friend constexpr bool operator==(const iterator& x, const iterator& y)
requires (equality_comparable<iterator_t<maybe-const<Const, Views>>> && ...);

Returns:

(15.1) — x.current_ == y.current_ if all-bidirectional<Const, Views...> is true.
(15.2) — Otherwise, true if there exists an integer 0 ≤ i < sizeof...(Views) such that
    std::get<i>(x.current_) == std::get<i>(y.current_)) is true.

[Note 1: This allows zip_view to model common_range when all constituent views model common_range.
— end note]
(15.3) — Otherwise, false.

friend constexpr auto operator<=>(const iterator& x, const iterator& y)
requires all-random-access<Const, Views...>;

Returns: x.current_ <=> y.current_.

friend constexpr iterator operator+(const iterator& i, difference_type n)
requires all-random-access<Const, Views...>;
friend constexpr iterator operator+(difference_type n, const iterator& i)
requires all-random-access<Const, Views...>;

Effects: Equivalent to:

auto r = i;
r += n;
return r;

friend constexpr difference_type operator-(const iterator& x, const iterator& y)
requires (sized_sentinel_for<iterator_t<maybe-const<Const, Views>>>,
    iterator_t<maybe-const<Const, Views>>> && ...);

Let DIST(i) be difference_type(std::get<i>(x.current_) - std::get<i>(y.current_)).

Returns: The value with the smallest absolute value among DIST(n) for all integers 0 ≤ n <
    sizeof...(Views).

friend constexpr auto iter_move(const iterator& i) noexcept(see below);

Effects: Equivalent to:

return tuple-transform(ranges::iter_move, i.current_);

Remarks: The exception specification is equivalent to:
( noexcept(ranges::iter_move(declval<const iterator_t<maybe-const<Const,
    Views>>> &)) && ...) &&
(is_nothrow_move_constructible_v<range_rvalue_reference_t<maybe-const<Const,
    Views>>> && ...)

friend constexpr void iter_swap(const iterator& l, const iterator& r) noexcept(see below)
requires (indirectly_swappable<iterator_t<maybe-const<Const, Views>>> && ...);

Effects: For every integer 0 ≤ i < sizeof...(Views), performs:
ranges::iter_swap(std::get<i>(l.current_), std::get<i>(r.current_))

Remarks: The exception specification is equivalent to the logical AND of the following expressions:

noexcept(ranges::iter_swap(std::get<i>(l.current_), std::get<i>(r.current_)))

for every integer 0 ≤ i < sizeof...(Views).

§ 26.7.25.4 Class template zip_view::sentinel

namespace std::ranges {

  template<input_range... Views>
  requires (view<Views> && ...) && (sizeof...(Views) > 0)
  template<bool Const>
  class zip_view<Views...>::sentinel {
    tuple<sentinel_t<maybe-const<Const, Views>>>... end; // exposition only
    constexpr explicit sentinel(tuple<sentinel_t<maybe-const<Const, Views>>>... end); // exposition only
  public:
    sentinel() = default;
    constexpr sentinel(sentinel<!Const> i)
      requires Const && (convertible_to<sentinel_t<Views>, sentinel_t<const Views>> && ...);
    template<bool OtherConst>
    requires (sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<OtherConst, Views>>> && ...)
    friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
    template<bool OtherConst>
    requires (sized_sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<OtherConst, Views>>> && ...)
    friend constexpr common_type_t<range_difference_t<maybe-const<OtherConst, Views>>>... operator-(const sentinel& y, const iterator<OtherConst>& x);
  }

  constexpr explicit sentinel(tuple<sentinel_t<maybe-const<Const, Views>>>... end);

  Effects: Initializes end_ with end.

  constexpr sentinel(sentinel<!Const> i)
    requires Const && (convertible_to<sentinel_t<Views>, sentinel_t<const Views>> && ...);
  Effects: Initializes end_ with std::move(i.end_).

  template<bool OtherConst>
  requires (sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<OtherConst, Views>>> && ...)
  friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

  Returns: true if there exists an integer 0 ≤ i < sizeof...(Views) such that bool(std::get<i>(x.current_) == std::get<i>(y.end_)) is true. Otherwise, false.

  template<bool OtherConst>
  requires (sized_sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<OtherConst, Views>>> && ...)
  friend constexpr common_type_t<range_difference_t<maybe-const<OtherConst, Views>>>... operator-(const sentinel& y, const iterator<OtherConst>& x);

  Returns: The value with the smallest absolute value among DIST(n) for all integers 0 ≤ n < sizeof...(Views).

} // namespace std::ranges

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template<bool OtherConst>
  requires (sized_sentinel_for<sentinel_t<maybe-const<Const, Views>>, iterator_t<maybe-const<OtherConst, Views>>> & & ...)
friend constexpr common_type_t<range_difference_t<maybe-const<OtherConst, Views>>> operator-(const sentinel& y, const iterator<OtherConst>& x);

Effects: Equivalent to: return -(x - y);

26.7.26 Zip transform view

26.7.26.1 Overview

`zip_transform_view` takes an invocable object and any number of views and produces a view whose $M$th element is the result of applying the invocable object to the $M$th elements of all views.

The name `views::zip_transform` denotes a customization point object (16.3.3.3.5). Let $F$ be a subexpression, and let $E_s...$ be a pack of subexpressions.

1. If $E_s$ is an empty pack, let $F_D$ be `decay_t<decltype((F))>`. If `move_constructible<FD> & regular_invocable<FD&>` is false, or if `decay_t<invoke_result_t<FD&>>` is not an object type, `views::zip_transform(F, Es...)` is ill-formed.

2. Otherwise, the expression `views::zip_transform(F, Es...)` is expression-equivalent to `((void)F, auto(views::empty<decay_t<invoke_result_t<FD&>>>))`

3. Otherwise, the expression `views::zip_transform(F, Es...)` is expression-equivalent to `zip_transform_view(F, Es...)`.

Example 1:

```cpp
vector v1 = {1, 2};
vector v2 = {4, 5, 6};
for (auto i : views::zip_transform(plus(), v1, v2)) {
  cout << i << ' ' // prints 5 7
}
```

26.7.26.2 Class template zip_transform_view

```cpp
namespace std::ranges {
  template<move_constructible F, input_range... Views>
  requires (view<View> & & ...) & & (sizeof...(Views) > 0) & & is_object_v<F> & & regular_invocable<F, range_reference_t<View>..., ...> & & can_reference<invoke_result_t<F, range_reference_t<View>..., ...> class zip_transform_view : public view_interface<zip_transform_view<F, Views...>> {
    movable_box<F> fun_; // exposition only
    zip_view<Views...> zip_; // exposition only

    using InnerView = zip_view<Views...>; // exposition only
    template<bool Const>
      using ziperator = iterator_t<maybe-const<Const, InnerView>>; // exposition only
    template<bool Const>
      using zentinel = sentinel_t<maybe-const<Const, InnerView>>; // exposition only

    // 26.7.26.3, class template zip_transform_view::iterator
template<bool> class iterator; // exposition only

    // 26.7.26.4, class template zip_transform_view::sentinel
template<bool> class sentinel; // exposition only

  public:
    zip_transform_view() = default;

    constexpr explicit zip_transform_view(F fun, Views... views);
    constexpr auto begin() { return iterator(false)(*this, zip_.begin()); }
```

§ 26.7.26.2 © ISO/IEC 1296
constexpr auto begin() const
    requires range<const InnerView> &&
    regular_invocable<const F&, range_reference_t<const Views>...> {
        return iterator<true>(*this, zip_.begin());
    }

castexpr auto end() {
    if constexpr (common_range<InnerView>) {
        return iterator<false>(*this, zip_.end());
    } else {
        return sentinel<false>(zip_.end());
    }
}

castexpr auto end() const
    requires range<const InnerView> &&
    regular_invocable<const F&, range_reference_t<const Views>...> {
    if constexpr (common_range<const InnerView>) {
        return iterator<true>(*this, zip_.end());
    } else {
        return sentinel<true>(zip_.end());
    }
}

castexpr auto size() requires sized_range<InnerView> {
    return zip_.size();
}

castexpr auto size() const requires sized_range<const InnerView> {
    return zip_.size();
}
};

template<class F, class... Rs>
zip_transform_view(F, Rs&&...) -> zip_transform_view<F, views::all_t<Rs>...>;

constexpr explicit zip_transform_view(F fun, Views... views);

Effects: Initializes fun_ with std::move(fun) and zip_ with std::move(views)....

26.7.26.3 Class template zip_transform_view::iterator [range.zip.transform.iterator]

namespace std::ranges {
    template<move_constructible F, input_range... Views>
    requires (view<Views> && ... && (sizeof...(Views) > 0) && is_object_v<F> &&
             regular_invocable<F&, range_reference_t<Views>...> &&
             can_reference<invoke_result_t<F&, range_reference_t<Views>...>, invoke_result_t<F, range_reference_t<Views>...>>
    template<bool Const>
    class zip_transform_view<F, Views...>::iterator {
        using Parent = maybe-const<Const, zip_transform_view>; // exposition only
        using Base = maybe-const<Const, InnerView>; // exposition only
        Parent* parent_ = nullptr;
        ziperator<Const> inner_; // exposition only
    
    constexpr iterator(Parent& parent, ziperator<Const> inner); // exposition only

    public:
        using iterator_category = see below; // not always present
        using iterator_concept = typename ziperator<Const>::iterator_concept;
        using value_type = remove_cvref_t<invoke_result_t<maybe-const<Const, F>&, range_reference_t<maybe-const<Const, Views>...>>;
        using difference_type = range_difference_t<Base>;

    
    } // class zip_transform_view<F, Views...>::iterator

§ 26.7.26.3 © ISO/IEC 1297
The member typedef-name iterator::iterator_category is defined if and only if Base models forward_range. In that case, iterator::iterator_category is defined as follows:

1. If
   
   invoke_result_t<maybe-const<Const, F>&, range_reference_t<maybe-const<Const, Views>>...>

   is not a reference, iterator_category denotes input_iterator_tag.

2. Otherwise, let Cs denote the pack of types iterator_traits<iterator_t<maybe-const<Const, Views>>>::iterator_category....

3. If (derived_from<Cs, random_access_iterator_tag> && ...) is true, iterator_category denotes random_access_iterator_tag.

4. Otherwise, if (derived_from<Cs, bidirectional_iterator_tag> && ...) is true, iterator_category denotes bidirectional_iterator_tag.

5. Otherwise, if (derived_from<Cs, forward_iterator_tag> && ...) is true, iterator_category denotes forward_iterator_tag.

6. Otherwise, iterator_category denotes input_iterator_tag.

constexpr iterator (Parent& parent, ziperator<Const> inner);

**Effects:** Initializes parent_ with addressof(parent) and inner_ with std::move(inner).

constexpr iterator (iterator<!Const> i)

**Requires:** Const && convertible_to<ziperator<false>, ziperator<Const>>;

**Effects:** Initializes parent_ with i, parent_ and inner_ with std::move(i, inner_).

constexpr decltype(auto) operator*() const noexcept(see below);

**Effects:** Equivalent to:

§ 26.7.26.3 © ISO/IEC 1298
return apply([&](const auto&... iters) -> decltype(auto) {
    return invoke(*parent_->fun_, *iters...);
}, inner_.current_);}

Remarks: Let Is be the pack 0, 1, ..., (sizeof...(Views)-1). The exception specification is equivalent to: noexcept(invoke(*parent_->fun_, *std::get<Is>(inner_.current_)...)).

constexpr iterator& operator++();

Effects: Equivalent to:
++inner_
return *this;

constexpr void operator++(int);

Effects: Equivalent to: +++this.

constexpr iterator operator++(int) requires forward_range<Base>;

Effects: Equivalent to:
auto tmp = *this;
+++this;
return tmp;

constexpr iterator& operator--() requires bidirectional_range<Base>;

Effects: Equivalent to:
--inner_
return *this;

constexpr iterator operator--(int) requires bidirectional_range<Base>;

Effects: Equivalent to:
auto tmp = *this;
--*this;
return tmp;

constexpr iterator& operator+=(difference_type x) requires random_access_range<Base>;

Effects: Equivalent to:
inner_ += x;
return *this;

constexpr iterator& operator-=(difference_type x) requires random_access_range<Base>;

Effects: Equivalent to:
inner_ -= x;
return *this;

constexpr decltype(auto) operator[](difference_type n) const requires random_access_range<Base>;

Effects: Equivalent to:
return apply([&](const auto&... iters) -> decltype(auto) {
    return invoke(*parent_->fun_, *iters[iter_difference_t<Is>(n)]...);
}, inner_.current_);}

friend constexpr bool operator==(const iterator& x, const iterator& y) requires equality_comparable<ziperator<Const>>;

friend constexpr auto operator<=>(const iterator& x, const iterator& y) requires random_access_range<Base>;

Let op be the operator.

Effects: Equivalent to: return x.inner_ op y.inner_;
friend constexpr iterator operator+(const iterator& i, difference_type n) requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator& i) requires random_access_range<Base>;
    
Effects: Equivalent to: return iterator(*i.parent_, i.inner_ + n);
friend constexpr iterator operator-(const iterator& i, difference_type n) requires random_access_range<Base>;
    
Effects: Equivalent to: return iterator(*i.parent_, i.inner_ - n);
friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<ziperator<Const>, ziperator<Const>>;
    
Effects: Equivalent to: return x.inner_ - y.inner_;

26.7.26.4 Class template zip_transform_view::sentinel

namespace std::ranges {
    template<move_constructible F, input_range... Views>
        requires (view<Views> && ... && (sizeof...(Views) > 0) && is_object_v<F> &&
                    regular_invocable<F&, range_reference_t<Views>...> &&
                    can-reference<invoke_result_t<F&, range_reference_t<Views>...>>
    template<bool Const>
        class zip_transform_view<F, Views...>::sentinel {
            zentinel<Const> inner_; // exposition only
            constexpr explicit sentinel(sentinel<Const> inner) { // exposition only
                sentinel() = default;
                constexpr sentinel(sentinel<!Const> i)
                    requires Const && convertible_to<sentinel<false>, sentinel<Const>>;
                template<bool OtherConst>
                    requires sentinel_for<sentinel<Const>, ziperator<OtherConst>>
                    friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
                template<bool OtherConst>
                    requires sized_sentinel_for<sentinel<Const>, ziperator<OtherConst>>
                    friend constexpr range_difference_t<maybe-const<OtherConst, InnerView>>
                        operator-(const iterator<OtherConst>& x, const sentinel& y);
                template<bool OtherConst>
                    requires sized_sentinel_for<sentinel<Const>, ziperator<OtherConst>>
                    friend constexpr range_difference_t<maybe-const<OtherConst, InnerView>>
                        operator-(const sentinel& x, const iterator<OtherConst>& y);
            }
            
            constexpr explicit sentinel(sentinel<Const> inner);
                
Effects: Initializes inner_ with inner.
            
           constexpr sentinel(sentinel<!Const> i)
                requires Const && convertible_to<sentinel<false>, sentinel<Const>>;
                
Effects: Initializes inner_ with std::move(i.inner_).
            
            template<bool OtherConst>
                requires sentinel_for<sentinel<Const>, ziperator<OtherConst>>
                friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
                
Effects: Equivalent to: return x.inner_ == y.inner_;
            
            template<bool OtherConst>
                requires sized_sentinel_for<sentinel<Const>, ziperator<OtherConst>>
                friend constexpr range_difference_t<maybe-const<OtherConst, InnerView>>
                    operator-(const iterator<OtherConst>& x, const sentinel& y);

§ 26.7.26.4 © ISO/IEC 1300
template<br/>&lt;bool OtherConst&gt;<br/> requires sized_sentinel_for&lt;sentinel&lt;Const&gt;, zperator&lt;OtherConst&gt;&gt;<br/> friend constexpr range_difference_t&lt;maybe-const &lt;OtherConst, InnerView&gt;&gt;<br/> operator-(const sentinel & x, const iterator & y);<br/>

Effects: Equivalent to: return x.inner_ - y.inner_;

26.7.27 Adjacent view

26.7.27.1 Overview

adjacent_view takes a view and produces a view whose \(M\)th element is a tuple of references to the \(M\)th through \((M + N - 1)\)th elements of the original view. If the original view has fewer than \(N\) elements, the resulting view is empty.

The name `views::adjacent<N>` denotes a range adaptor object (26.7.2). Given a subexpression \(E\) and a constant expression \(N\), the expression `views::adjacent<N>(E)` is expression-equivalent to

\[\begin{align*}
&((\text{void})E, \text{auto}(\text{views::empty&lt;tuple&gt;}) \text{if } \text{N is equal to } 0 \text{ and decltype((E)) models } \text{forward-range}, \\
&\text{otherwise, adjacent_view}(\text{views::all_t}&\text{decltype((E))}), \text{N}(E).
\end{align*}\]

Example 1:

```cpp
vector v = {1, 2, 3, 4};
for (auto i : v | views::adjacent<2>) {
    cout << "(\" \"<< std::get<0>(i) \" \". " \"<< std::get<1>(i) \" \") \n; // prints (1, 2) (2, 3) (3, 4)
}
```

—end example

Define `REPEAT(T, N)` as a pack of \(N\) types, each of which denotes the same type as \(T\).

26.7.27.2 Class template adjacent_view

```cpp
namespace std::ranges {
  template&lt;forward_range V, size_t N&gt;
  requires view&lt;V&gt; &amp;&amp; (N &gt; 0)
  class adjacent_view &lt;public view_interface &lt;adjacent_view&lt;V, N&gt;&gt; {
    V base_ = V();
    // exposition only

    // 26.7.27.3, class template adjacent_view::iterator
    template&lt;bool&gt; class iterator;
    // exposition only

    // 26.7.27.4, class template adjacent_view::sentinel
    template&lt;bool&gt; class sentinel;
    // exposition only

    struct as-sentinel{};
    // exposition only

    public:
      adjacent_view() requires default_initializable&lt;V&gt; = default;
      constexpr explicit adjacent_view(V base);

      constexpr V base() const & requires copy_constructible&lt;V&gt; { return base_; }
      constexpr V base() & requires (return std::move(base_));

      constexpr auto begin() requires (!simple_view&lt;V&gt;) {
        return iterator&lt;false&gt;(ranges::begin(base_), ranges::end(base_));
      }

      constexpr auto begin() const requires range&lt;const V&gt; {
        return iterator&lt;true&gt;(ranges::begin(base_), ranges::end(base_));
      }

      constexpr auto end() requires (!simple_view&lt;V&gt;) {
        if constexpr (common_range&lt;V&gt;) {
          return iterator&lt;false&gt;(as-sentinel{}, ranges::begin(base_), ranges::end(base_));
        } else {
```
```cpp
return sentinel<false>(ranges::end(base_));
}
}

constexpr auto end() const requires range<const V> {
    if constexpr (common_range<const V>) {
        return iterator<true>({as-sentinel{}), ranges::begin(base_), ranges::end(base_));
    } else {
        return sentinel<true>(ranges::end(base_));
    }
}

constexpr auto size() requires sized_range<V>;  
constexpr auto size() const requires sized_range<const V>;
}

constexpr explicit adjacent_view(V base);

 Effects: Initializes base_ with std::move(base).

constexpr auto size() requires sized_range<V>;  
constexpr auto size() const requires sized_range<const V>;

 Effects: Equivalent to:
using ST = decltype(ranges::size(base_));
using CT = common_type_t<ST, size_t>;
auto sz = static_cast<CT>(ranges::size(base_));
sz -= std::min<CT>(sz, N - 1);
return static_cast<ST>(sz);

6.7.27.3 Class template adjacent_view::iterator [range.adjacent.iterator]

namespace std::ranges {
    template<forward_range V, size_t N>
        requires view<V> && (N > 0)
    template<bool Const>
    class adjacent_view<V, N>::iterator {
        using Base = maybe-const<Const, V>;
        // exposition only
        array<iterator_t<Base>, N> current_ = array<iterator_t<Base>, N>();
        // exposition only
        constexpr iterator(iterator_t<Base> first, sentinel_t<Base> last);      
        // exposition only
        constexpr iterator(as-sentinel, iterator_t<Base> first, iterator_t<Base> last);      
        // exposition only

public:
    using iterator_category = input_iterator_tag;
    using iterator_concept = see below;
    using value_type = tuple<
        range_value_t<Base>, N>...;
    using difference_type = range_difference_t<Base>;

    iterator() = default;
    constexpr iterator(iterator<!Const> i)
        requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;

    constexpr auto operator*() const;
    constexpr iterator& operator++();
    constexpr iterator operator++(int);
    constexpr iterator& operator--();
    constexpr iterator operator--(int);

    constexpr iterator& operator+=(difference_type x)
        requires random_access_range<Base>;
    constexpr iterator& operator+=(difference_type x)
        requires random_access_range<Base>;


§ 26.7.27.3 © ISO/IEC 1302
```
constexpr auto operator[](difference_type n) const
    requires random_access_range<Base>;

friend constexpr bool operator==(const iterator& x, const iterator& y);
friend constexpr bool operator<(const iterator& x, const iterator& y)
    requires random_access_range<Base>;
friend constexpr bool operator>(const iterator& x, const iterator& y)
    requires random_access_range<Base>;
friend constexpr bool operator<=(const iterator& x, const iterator& y)
    requires random_access_range<Base>;
friend constexpr bool operator>=(const iterator& x, const iterator& y)
    requires random_access_range<Base>;
friend constexpr auto operator<=>(const iterator& x, const iterator& y)
    requires random_access_range<Base> &&
              three_way_comparable<iterator_t<Base>>;

friend constexpr iterator operator+(const iterator& i, difference_type n)
    requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator& i)
    requires random_access_range<Base>;
friend constexpr iterator operator-(const iterator& i, difference_type n)
    requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y)
    requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

friend constexpr auto iter_move(const iterator& i) noexcept(see below);
friend constexpr void iter_swap(const iterator& l, const iterator& r) noexcept(see below)
    requires indirectly_swappable<iterator_t<Base>>;

struct iterator_concept is defined as follows:

(1.1) — If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
(1.2) — Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
(1.3) — Otherwise, iterator_concept denotes forward_iterator_tag.

2 If the invocation of any non-const member function of iterator exits via an exception, the iterator acquires a singular value.

constexpr iterator(iterator_t<Base> first, sentinel_t<Base> last);

Postconditions: current_[0] == first is true, and for every integer 1 ≤ i < N, current_[i] ==
ranges::next(current_[i-1], 1, last) is true.

constexpr iterator(as-sentinel, iterator_t<Base> first, iterator_t<Base> last);

Postconditions: If Base does not model bidirectional_range, each element of current_ is equal to last. Otherwise,
current_[N-1] == last is true, and for every integer 0 ≤ i < (N − 1), current_[i] ==
ranges::prev(current_[i+1], 1, first) is true.

constexpr iterator(iterator<!Const> i)
    requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;

Effects: Initializes each element of current_ with the corresponding element of i.current_ as an
xvalue.

constexpr auto operator*() const;

Effects: Equivalent to:
              return tuple_transform([](auto& i) -> decltype(auto) { return *i; }, current_);

constexpr iterator& operator++();

Preconditions: current_.back() is incrementable.
Postconditions: Each element of `current_` is equal to `ranges::next(i)`, where `i` is the value of that element before the call.

Returns: `*this`.

```cpp
constexpr iterator operator++(int);
```

Effects: Equivalent to:

```cpp
    auto tmp = *this;
++*this;
return tmp;
```

```cpp
constexpr iterator& operator--() requires bidirectional_range<Base>;
```

Preconditions: `current_.front()` is decrements.

Postconditions: Each element of `current_` is equal to `ranges::prev(i)`, where `i` is the value of that element before the call.

Returns: `*this`.

```cpp
constexpr iterator operator--(int) requires bidirectional_range<Base>;
```

Effects: Equivalent to:

```cpp
    auto tmp = *this;
--*this;
return tmp;
```

```cpp
constexpr iterator& operator+=(difference_type x) requires random_access_range<Base>;
```

Preconditions: `current_.back() + x` has well-defined behavior.

Postconditions: Each element of `current_` is equal to `i + x`, where `i` is the value of that element before the call.

Returns: `*this`.

```cpp
constexpr iterator& operator-=(difference_type x) requires random_access_range<Base>;
```

Preconditions: `current_.front() - x` has well-defined behavior.

Postconditions: Each element of `current_` is equal to `i - x`, where `i` is the value of that element before the call.

Returns: `*this`.

```cpp
constexpr auto operator[](difference_type n) const requires random_access_range<Base>;
```

Effects: Equivalent to:

```cpp
    return tuple-transform([&](auto& i) -> decltype(auto) { return i[n]; }, current_);
```

```cpp
friend constexpr bool operator==(const iterator& x, const iterator& y);
```

Returns: `x.current_.back() == y.current_.back()`.

```cpp
friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;
```

Effects: Equivalent to: `return y < x`;

```cpp
friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;
```

Effects: Equivalent to: `return !(y < x);`
friend constexpr bool operator>=(const iterator& x, const iterator& y) requires random_access_range<Base>;

Effect: Equivalent to: return !(x < y);

friend constexpr auto operator<=>(const iterator& x, const iterator& y) requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;

Returns: x.current_.back() <=> y.current_.back().

friend constexpr iterator operator+(const iterator& i, difference_type n) requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator& i) requires random_access_range<Base>;

Effects: Equivalent to:
auto r = i;
r += n;
return r;

friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

Effects: Equivalent to: return x.current_.back() - y.current_.back();

friend constexpr iterator operator-(const iterator& i, difference_type n) requires random_access_range<Base>;

Effects: Equivalent to:
auto r = i;
r -= n;
return r;

friend constexpr auto iter_move(const iterator& i) noexcept(see below);

Effects: Equivalent to: return tuple-transform(ranges::iter_move, i.current_);

Remarks: The exception specification is equivalent to:

noexcept(ranges::iter_move(declval<const iterator_t<Base>&>())) &&
is_nothrow_move_constructible_v<range_rvalue_reference_t<Base>>

friend constexpr void iter_swap(const iterator& l, const iterator& r) noexcept(see below) requires indirectly_swappable<iterator_t<Base>>;

Preconditions: None of the iterators in l.current_ is equal to an iterator in r.current_.

Effects: For every integer 0 ≤ i < N, performs ranges::iter_swap(l.current_[i], r.current_[i]).

Remarks: The exception specification is equivalent to:

noexcept(ranges::iter_swap(declval<iterator_t<Base>>(), declval<iterator_t<Base>>()))

26.7.27.4 Class template adjacent_view::sentinel

namespace std::ranges {
template<forward_range V, size_t N>
requires view<V> && (N > 0)
template<bool Const>
class adjacent_view<V, N>::sentinel {
using Base = maybe_const<Const, V>; // exposition only
sentinel_t<Base> end_ = sentinel_t<Base>(); // exposition only
constexpr explicit sentinel(sentinel_t<Base> end); // exposition only

public:
sentinel() = default;
constexpr sentinel(sentinel<Const> i)
    requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

26.7.27.4 © ISO/IEC 1305
template<bool OtherConst>
   requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

template<bool OtherConst>
   requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
   operator-(const iterator<OtherConst>& x, const sentinel& y);

template<bool OtherConst>
   requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
   operator-(const sentinel& y, const iterator<OtherConst>& x);
{
}

constexpr explicit sentinel(sentinel_t<Base> end);

Effects: Initializes end_ with end.

constexpr sentinel(sentinel<!Const> i)
   requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

Effects: Initializes end_ with std::move(i.end_).

template<bool OtherConst>
   requires sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

Effects: Equivalent to: return x.current_.back() == y.end_;

template<bool OtherConst>
   requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
   operator-(const iterator<OtherConst>& x, const sentinel& y);

Effects: Equivalent to: return x.current_.back() - y.end_;

template<bool OtherConst>
   requires sized_sentinel_for<sentinel_t<Base>, iterator_t<maybe-const<OtherConst, V>>>
friend constexpr range_difference_t<maybe-const<OtherConst, V>>
   operator-(const sentinel& y, const iterator<OtherConst>& x);

Effects: Equivalent to: return y.end_ - x.current_.back();

26.7.28 Adjacent transform view

26.7.28.1 Overview

adjacent_transform_view takes an invocable object and a view and produces a view whose \(M\)th element is the result of applying the invocable object to the \(M\)th through \(M + N - 1\)th elements of the original view. If the original view has fewer than \(N\) elements, the resulting view is empty.

The name \texttt{views::adjacent_transform<N>} denotes a range adaptor object (26.7.2). Given subexpressions \(E\) and \(F\) and a constant expression \(N\):

\[\begin{align}
\text{(2.1)} & \quad \text{If } N = 0 \text{ and } \text{decltype}(E) \text{ models } \text{forward_range}, \text{views::adjacent_transform<N>}(E, F) \text{ is expression-equivalent to } ((\text{void})E, \text{views::zip_transform}(F)), \text{ except that the evaluations of } E \text{ and } F \text{ are indeterminately sequenced.} \\
\text{(2.2)} & \quad \text{Otherwise, the expression views::adjacent_transform<N>(E, F) is expression-equivalent to adj-
acent_transform_view<views::all_t<decltype((E))>, decay_t<decltype((F))>>, N>(E, F).}
\end{align}\]

[Example 1:

```cpp
vector v = {1, 2, 3, 4};

for (auto i : v | views::adjacent_transform<2>(std::multiplies())) {
   cout << i << ' '; // prints 2 6 12
}
```

— end example]
namespace std::ranges {
    template<forward_range V, move_constructible F, size_t N>
    requires view<V> && (N > 0) && is_object_v<F> &&
        regular_invocable<F&, REPEAT(range_reference_t<V>, N)...> &&
        can_reference<invoke_result_t<F&>, REPEAT(range_reference_t<V>, N)...>>
    class adjacent_transform_view : public view_interface<adjacent_transform_view<V, F, N>> {
        movable_box<F> fun_; // exposition only
        adjacent_view<V, N> inner_; // exposition only
        using InnerView = adjacent_view<V, N>; // exposition only
        template<bool Const>
        using inner_iterator = iterator_t<maybe_const<Const, InnerView>>; // exposition only
        template<bool Const>
        using inner_sentinel = sentinel_t<maybe_const<Const, InnerView>>; // exposition only
        // 26.7.28.3, class template adjacent_transform_view::iterator
        template<bool> class iterator;
        // exposition only
        // 26.7.28.4, class template adjacent_transform_view::sentinel
        template<bool> class sentinel;
        // exposition only
    public:
        adjacent_transform_view() = default;
        constexpr explicit adjacent_transform_view(V base, F fun);
        constexpr V base() const & requires copy_constructible<V> { return inner_.base(); }
        constexpr V base() && { return std::move(inner_.base()); }
        constexpr auto begin() {
            return iterator<false>(*this, inner_.begin());
        }
        constexpr auto begin() const requires range<const InnerView> &&
            regular_invocable<const F&, REPEAT(range_reference_t<const V>, N)...> {
            return iterator<true>(*this, inner_.begin());
        }
        constexpr auto end() {
            if constexpr (common_range<InnerView>) {
                return iterator<false>(*this, inner_.end());
            } else {
                return sentinel<false>(inner_.end());
            }
        }
        constexpr auto end() const requires range<const InnerView> &&
            regular_invocable<const F&, REPEAT(range_reference_t<const V>, N)...> {
            if constexpr (common_range<const InnerView>) {
                return iterator<true>(*this, inner_.end());
            } else {
                return sentinel<true>(inner_.end());
            }
        }
        constexpr auto size() requires sized_range<InnerView> {
            return inner_.size();
        }
        constexpr auto size() const requires sized_range<const InnerView> {
            return inner_.size();
    }
constexpr explicit adjacent_transform_view(V base, F fun);

Effects: Initializes fun_with std::move(fun) and inner_ with std::move(base).

26.7.28.3 Class template adjacent_transform_view::iterator

namespace std::ranges {
    template<forward_range V, move_constructible F, size_t N>
    requires view<V> && (N > 0) && is_object_v<F> &&
    regular_invocable<F&,
        REPEAT(range_reference_t<V>, N)...> &&
    can_reference<invoke_result_t<F&,
        REPEAT(range_reference_t<V>, N)...>>
    template<bool Const>
    class adjacent_transform_view<V, F, N>::iterator {
        using Parent = maybe_const<Const, adjacent_transform_view>;  // exposition only
        using Base = maybe_const<Const, V>;  // exposition only
        Parent* parent_ = nullptr;  // exposition only
        inner_iterator<Const> inner_;  // exposition only

        constexpr iterator(Parent& parent, inner_iterator<Const> inner);  // exposition only

    public:
        using iterator_category = see below;
        using iterator_concept = typename inner_iterator<Const>::iterator_concept;
        using value_type = remove_cvref_t<invoke_result_t<
            maybe_const<Const, F&,
                REPEAT(range_reference_t<Base>, N)...>>;
        using difference_type = range_difference_t<Base>;

        iterator() = default;
        constexpr iterator(iterator<!Const> i)
            requires Const && convertible_to<inner_iterator<false>, inner_iterator<Const>>;

        constexpr decltype(auto) operator[](difference_type n) const
            requires random_access_range<Base>;

        friend constexpr bool operator==(const iterator x, const iterator y);
        friend constexpr bool operator<(const iterator x, const iterator y)
            requires random_access_range<Base>;
        friend constexpr bool operator!=(const iterator x, const iterator y)
            requires random_access_range<Base>;
        friend constexpr bool operator>=(const iterator x, const iterator y)
            requires random_access_range<Base>;
        friend constexpr bool operator<=(const iterator x, const iterator y)
            requires random_access_range<Base>;
    }

    friend constexpr bool operator==(const iterator x, const iterator y);
    friend constexpr bool operator<(const iterator x, const iterator y)
        requires random_access_range<Base>;
    friend constexpr bool operator<=(const iterator x, const iterator y)
        requires random_access_range<Base>;
    friend constexpr bool operator>=(const iterator x, const iterator y)
        requires random_access_range<Base>;
    friend constexpr bool operator>=(const iterator x, const iterator y)
        requires random_access_range<Base> & & three_way_comparable<inner_iterator<Const>>;

    friend constexpr iterator operator+(const iterator x, difference_type n)
        requires random_access_range<Base>;
    friend constexpr iterator operator+(difference_type n, const iterator x)
        requires random_access_range<Base>;
}

§ 26.7.28.3 © ISO/IEC 1308
friend constexpr iterator operator-(const iterator& i, difference_type n) requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<inner_iterator< Const>, inner_iterator< Const>>;
};

The member typedef-name iterator::iterator_category is defined as follows:

- If invoke_result_t<maybe-const<Const, F>&, \texttt{REPEAT}(range_reference_t<Base>, N)\ldots> is not a reference, iterator_category denotes input_iterator_tag.
- Otherwise, let C denote the type \texttt{iterator_traits<iterator_t<Base>>:iterator_category}.
  - If derived_from<C, random_access_iterator_tag> is true, iterator_category denotes random_access_iterator_tag.
  - Otherwise, if derived_from<C, bidirectional_iterator_tag> is true, iterator_category denotes bidirectional_iterator_tag.
  - Otherwise, if derived_from<C, forward_iterator_tag> is true, iterator_category denotes forward_iterator_tag.
  - Otherwise, iterator_category denotes input_iterator_tag.

```cpp
constexpr iterator (Parent& parent, inner_iterator<Const> inner);
```
Effects: Initializes parent_ with \texttt{addressof(parent)} and inner_ with \texttt{std::move(inner)}.

```cpp
constexpr iterator (iterator<!Const> i) requires Const && convertible_to<inner_iterator<false>, inner_iterator<Const>>;
```
Effects: Initializes parent_ with i.parent_ and inner_ with \texttt{std::move(i.inner_)}.

```cpp
constexpr decltype(auto) operator*() const noexcept;
```
Effects: Equivalent to:

```cpp
return apply([&](const auto&... iters) -> decltype(auto) {
    return invoke(*parent_->fun_, *iters...);
}, inner_.current_);
```
Remarks: Let Is be the pack 0, 1, \ldots, (N-1). The exception specification is equivalent to:

```cpp
noexcept(invoke(*parent_->fun_, \texttt{std::get<Is>(inner_.current_)}...))
```

```cpp
constexpr iterator& operator++();
```
Effects: Equivalent to:

```cpp
++inner_; return *this;
```

```cpp
constexpr iterator operator++(int);
```
Effects: Equivalent to:

```cpp
auto tmp = *this; +++this; return tmp;
```

```cpp
constexpr iterator& operator--() requires bidirectional_range<Base>;
```
Effects: Equivalent to:

```cpp
--inner_; return *this;
```

```cpp
constexpr iterator operator--(int) requires bidirectional_range<Base>;
```
Effects: Equivalent to:

```cpp
auto tmp = *this; --*this; return tmp;
```
constexpr iterator & operator+=(difference_type x) requires random_access_range<Base>;

Effects: Equivalent to:

inner_ += x;
return *this;

constexpr iterator & operator-=(difference_type x) requires random_access_range<Base>;

Effects: Equivalent to:

inner_ -= x;
return *this;

constexpr decltype(auto) operator[](difference_type n) const requires random_access_range<Base>;

Effects: Equivalent to:

return apply([&](const auto&... iters) -> decltype(auto) {
    return invoke(*parent_->fun_, iters[n]...);
}, inner_.current_);

friend constexpr bool operator==(const iterator & x, const iterator & y) requires random_access_range<Base>;
friend constexpr bool operator<(const iterator & x, const iterator & y) requires random_access_range<Base>;
friend constexpr bool operator>(const iterator & x, const iterator & y) requires random_access_range<Base>;
friend constexpr bool operator<=(const iterator & x, const iterator & y) requires random_access_range<Base>;
friend constexpr bool operator>=(const iterator & x, const iterator & y) requires random_access_range<Base> && three_way_comparable<inner-iterator<Const>>;

Let op be the operator.

friend constexpr iterator operator+(const iterator & i, difference_type n) requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator & i) requires random_access_range<Base>;

Effects: Equivalent to: return iterator(*i.parent_, i.inner_ + n);

friend constexpr iterator operator-(const iterator & i, difference_type n) requires random_access_range<Base>;

Effects: Equivalent to: return iterator(*i.parent_, i.inner_ - n);

friend constexpr difference_type operator-(const iterator & x, const iterator & y) requires sized_sentinel_for<inner-iterator<Const>, inner-iterator<Const>>;

Effects: Equivalent to: return x.inner_ - y.inner_;

26.7.28.4 Class template adjacent_transform_view::sentinel
[range.adjacent.transform.sentinel]

namespace std::ranges {
    template<forward_range V, move_constructible F, size_t N>
    requires view<V> && (N > 0) && is_object_v<F> &&
    regular_invocable<F&, REPEAT(range_reference_t<V>, N)...> &&
    can-reference<invoke_result_t<F&>, REPEAT(range_reference_t<V>, N)...>
    template<bool Const>
    class adjacent_transform_view<V, F, N>::sentinel {
        inner-sentinel<Const> inner_; // exposition only
        constexpr explicit sentinel(inner-sentinel<Const> inner); // exposition only

    public:
        sentinel() = default;
    
```
constexpr explicit sentinel(inner-sentinel<Const> inner);

1 Effects: Initializes inner_ with inner.

constexpr sentinel(sentinel<!Const> i)
    requires Const && convertible_to<inner-sentinel<false>, inner-sentinel<Const>>;

template<bool OtherConst>
    requires sentinel_for<inner-sentinel<Const>, inner-iterator<OtherConst>>
friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);

template<bool OtherConst>
    requires sized_sentinel_for<inner-sentinel<Const>, inner-iterator<OtherConst>>
friend constexpr range_difference_t<maybe-const<OtherConst, InnerView>>
    operator-(const iterator<OtherConst>& x, const sentinel& y);

template<bool OtherConst>
    requires sized_sentinel_for<inner-sentinel<Const>, inner-iterator<OtherConst>>
friend constexpr range_difference_t<maybe-const<OtherConst, InnerView>>
    operator-(const sentinel& x, const iterator<OtherConst>& y);

2 Effects: Equivalent to: return x.inner_ == y.inner_

26.7.29 Chunk view

26.7.29.1 Overview

chunk_view takes a view and a number N and produces a range of views that are N-sized non-overlapping successive chunks of the elements of the original view, in order. The last view in the range can have fewer than N elements.

The name views::chunk denotes a range adaptor object (26.7.2). Given subexpressions E and N, the expression views::chunk(E, N) is expression-equivalent to chunk_view(E, N).

[Example 1:

```
vector v = {1, 2, 3, 4, 5};

for (auto r : v | views::chunk(2)) {
    cout << '[';
    auto sep = "";
    for (auto i : r) {
        cout << sep << i;
        sep = ", ";
    }
    cout << ']
```

There is no 1311 at the bottom of the page.
cout << "] " ;
}
// The above prints [1, 2] [3, 4] [5]
— end example
26.7.29.2 Class template chunk_view for input ranges

namespace std::ranges {
  template<class I>
  constexpr I div_ceil(I num, I denom) { // exposition only
    I r = num / denom;
    if (num % denom)
      ++r;
    return r;
  }
  template<view V>
  requires input_range<V>
  class chunk_view : public view_interface<chunk_view<V>> {
    V base_; // exposition only
    range_difference_t<V> n_; // exposition only
    range_difference_t<V> remainder_ = 0; // exposition only
    non-propagating-cache_iterator_t<V> current_; // exposition only

    // 26.7.29.3, class chunk_view::outer-iterator
    class outer_iterator;
  // 26.7.29.5, class chunk_view::inner-iterator
    class inner_iterator;
    // exposition only

public:
  constexpr explicit chunk_view(V base, range_difference_t<V> n);
  constexpr V base() const & requires copy_constructible<V> { return base_; }
  constexpr V base() && { return std::move(base_); }
  constexpr outer_iterator begin();
  constexpr default_sentinel_t end() const noexcept;
  constexpr auto size() requires sized_range<V>;
  constexpr auto size() const requires sized_range<const V>;
};

template<class R>
chunk_view(R&&, range_difference_t<R>) -> chunk_view<views::all_t<R>>;

constexpr explicit chunk_view(V base, range_difference_t<V> n);

1 Preconditions: n > 0 is true.
2 Effects: Initializes base_ with std::move(base) and n_ with n.
constexpr outer_iterator begin();

3 Effects: Equivalent to:
    current_ = ranges::begin(base_);
    remainder_ = n;
    return outer_iterator(*this);

castexpr default_sentinel_t end() const noexcept;

4 Returns: default_sentinel.
constexpr auto size() requires sized_range<V>;
constexpr auto size() const requires sized_range<const V>;

Effects: Equivalent to:

\[
\text{return to-unsigned-like}(\text{div-ceil}(\text{ranges::distance}(\text{base}_1, n_1)));
\]

26.7.29.3 Class chunk_view::outer-iterator

namespace std::ranges {
    template<view V>
        requires input_range<V>
    class chunk_view<V>::outer-iterator {
        chunk_view* parent_;          // exposition only

        constexpr explicit outer-iterator(chunk_view& parent);  // exposition only

        public:
            using iterator_concept = input_iterator_tag;
            using difference_type = range_difference_t<V>;

            // 26.7.29.4, class chunk_view::outer-iterator::value_type
            struct value_type;

            outer-iterator(outer-iterator&&) = default;
            outer-iterator& operator=(outer-iterator&&) = default;

            constexpr value_type operator*() const;
            constexpr outer-iterator& operator++();
            constexpr void operator++(int);

            friend constexpr bool operator==(const outer-iterator& x, default_sentinel_t);
            friend constexpr difference_type operator-(default_sentinel_t y, const outer-iterator& x) requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
            friend constexpr difference_type operator-(const outer-iterator& x, default_sentinel_t y) requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
    };
}

constexpr explicit outer-iterator(chunk_view& parent);

Effects: Initializes parent_ with addressof(parent).

constexpr value_type operator*() const;

Preconditions: *this == default_sentinel is false.

Returns: value_type(*parent_).

constexpr outer-iterator& operator++();

Preconditions: *this == default_sentinel is false.

Effects: Equivalent to:

\[
\text{ranges::advance}(*\text{parent}_1->\text{current}_1, \text{parent}_1->\text{remainder}_1, \text{ranges::end}(\text{parent}_1->\text{base}_1));
\text{parent}_1->\text{remainder}_1 = \text{parent}_1->n_1;
\text{return }*\text{this};
\]

constexpr void operator++(int);

Effects: Equivalent to +++this.

friend constexpr bool operator==(const outer-iterator& x, default_sentinel_t);

Effects: Equivalent to:

\[
\text{return }*x.\text{parent}_1->\text{current}_1 = \text{ranges::end}(x.\text{parent}_1->\text{base}_1) \&\& x.\text{parent}_1->\text{remainder}_1 != 0;
\]
friend constexpr difference_type operator-(default_sentinel_t y, const outer-iterator & x) requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;

Effects: Equivalent to:
const auto dist = ranges::end(x.parent_→base_→) - *x.parent_→current_;
if (dist < x.parent_→remainder_) {
    return dist == 0 ? 0 : 1;
}
return div-ceil(dist - x.parent_→remainder_, x.parent_→n_) + 1;

friend constexpr difference_type operator-(const outer-iterator & x, default_sentinel_t y) requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;

Effects: Equivalent to: return -(y - x);

26.7.29.4 Class chunk_view::outer-iterator::value_type

namespace std::ranges {
    template<view V>
    requires input_range<V>
    struct chunk_view<V>::outer-iterator::value_type : view_interface<value_type> {
        private:
            chunk_view* parent_; // exposition only
        constexpr explicit value_type(chunk_view& parent); // exposition only
        public:
            constexpr inner-iterator begin() const noexcept;
            constexpr default_sentinel_t end() const noexcept;
            
            constexpr auto size() const requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
        }
    }

    constexpr explicit value_type(chunk_view& parent);
    Effects: Initializes parent_ with addressof(parent).

    constexpr inner-iterator begin() const noexcept;
    Returns: inner-iterator(*parent_).

    constexpr default_sentinel_t end() const noexcept;
    Returns: default_sentinel.

    constexpr auto size() const requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
    Effects: Equivalent to:
    return to-unsigned-like(ranges::min(parent_→remainder_, ranges::end(parent_→base_→) - *parent_→current_));

26.7.29.5 Class chunk_view::inner-iterator

namespace std::ranges {
    template<view V>
    requires input_range<V>
    class chunk_view<V>::inner-iterator {
        chunk_view* parent_; // exposition only
        constexpr explicit inner-iterator(chunk_view& parent) noexcept; // exposition only
        public:
            using iterator_concept = input_iterator_tag;
            using difference_type = range_difference_t<V>;
            using value_type = range_value_t<V>;
    }
}

§ 26.7.29.5 © ISO/IEC 1314
INNER_ITERATOR(inner_iterator&&) = default;
INNER_ITERATOR& operator=(inner_iterator&&) = default;

constexpr const iterator_t<V>& base() const &;
constexpr range_reference_t<V> operator*() const;
constexpr inner_iterator& operator++();
constexpr void operator++(int);

friend constexpr bool operator==(const inner_iterator& x, default_sentinel_t);
friend constexpr difference_type operator-(default_sentinel_t y, const inner_iterator& x)
  requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
friend constexpr difference_type operator-(const inner_iterator& x, default_sentinel_t y)
  requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;

friend constexpr range_rvalue_reference_t<V> iter_move(const inner_iterator& i)
  noexcept(noexcept(ranges::iter_move(*i.parent_->current_)));
friend constexpr void iter_swap(const inner_iterator& x, const inner_iterator& y)
  noexcept(noexcept(ranges::iter_swap(*x.parent_->current_, *y.parent_->current_)))
  requires indirectly_swappable<iterator_t<V>>;

constexpr explicit inner_iterator(chunk_view& parent) noexcept;
  // Effects: Initializes parent_ with addressof(parent).

constexpr const iterator_t<V>& base() const &;
  // Effects: Equivalent to: return *parent_->current_;

constexpr range_reference_t<V> operator*() const;
  // Preconditions: *this == default_sentinel is false.
  // Effects: Equivalent to: return **parent_->current_;

constexpr inner_iterator& operator++();
  // Preconditions: *this == default_sentinel is false.
  // Effects: Equivalent to: 
  //   ***parent_->current_;
  //   if (*parent_->current_ == ranges::end(parent_->base_))
  //     parent_->remainder_ = 0;
  //   else
  //     --parent_->remainder_;
  //   return *this;

constexpr void operator++(int);
  // Effects: Equivalent to +++this.

friend constexpr bool operator==(const inner_iterator& x, default_sentinel_t);
  // Returns: x.parent_->remainder_ == 0.

friend constexpr difference_type operator-(default_sentinel_t y, const inner_iterator& x)
  requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
  // Effects: Equivalent to:
  //   return ranges::min(x.parent_->remainder_,
  //                       ranges::end(x.parent_->base_) - *x.parent_->current_);

friend constexpr difference_type operator-(const inner_iterator& x, default_sentinel_t y)
  requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;
  // Effects: Equivalent to: return -(y - x);
friend constexpr range_rvalue_reference_t<V> iter_move(const inner_iterator& i)
noexcept(noexcept(ranges::iter_move(*i.parent_->current_)));  
11
Effects: Equivalent to: return ranges::iter_move(*i.parent_->current_);

friend constexpr void iter_swap(const inner_iterator& x, const inner_iterator& y)
noexcept(noexcept(ranges::iter_swap(*x.parent_->current_, *y.parent_->current_)))
requires indirectly_swappable<iterator_t<V>>;
12
Effects: Equivalent to: ranges::iter_swap(*x.parent_->current_, *y.parent_->current_);

26.7.29.6 Class template chunk_view for forward ranges [range.chunk.view.fwd]

namespace std::ranges {
  template<view V>
  requires forward_range<V>
class chunk_view<V> : public view_interface<chunk_view<V>> {
    V base_; // exposition only
    range_difference_t<V> n_; // exposition only

    // 26.7.29.7, class template chunk_view::iterator
template<bool> class iterator; // exposition only

public:
  constexpr explicit chunk_view(V base, range_difference_t<V> n);

  constexpr V base() const & requires copy_constructible<V> { return base_; }
  constexpr V base() && { return std::move(base_); }

  constexpr auto begin() requires (!simple_view<V>) {
    return iterator<false>(this, ranges::begin(base_));
  }

  constexpr auto begin() const requires forward_range<const V> {
    return iterator<true>(this, ranges::begin(base_));
  }

  constexpr auto end() requires (!simple_view<V>) {
    if constexpr (common_range<V> && sized_range<V>) {
      auto missing = (n_ - ranges::distance(base_) % n_) % n_;
      return iterator<false>(this, ranges::end(base_), missing);
    } else if constexpr (common_range<V> && !bidirectional_range<V>) {
      return iterator<false>(this, ranges::end(base_));
    } else {
      return default_sentinel;
    }
  }

  constexpr auto end() const requires forward_range<const V> {
    if constexpr (common_range<const V> && sized_range<const V>) {
      auto missing = (n_ - ranges::distance(base_) % n_) % n_;
      return iterator<true>(this, ranges::end(base_), missing);
    } else if constexpr (common_range<const V> && !bidirectional_range<const V>) {
      return iterator<true>(this, ranges::end(base_));
    } else {
      return default_sentinel;
    }
  }

  constexpr auto size() requires sized_range<V>;  
  constexpr auto size() const requires sized_range<const V>;
};

constexpr explicit chunk_view(V base, range_difference_t<V> n);

1 Preconditions: n > 0 is true.
Effects: Initializes `base_` with `std::move(base)` and `n_` with `n`.

```
constexpr auto size() requires sized_range<V>;
constexpr auto size() const requires sized_range<const V>;
```

 Equivalent to:
```
return to-unsigned-like(div-ceil(ranges::distance(base_, n_));
```

### 26.7.29.7 Class template `chunk_view::iterator` for forward ranges

```
namespace std::ranges {
    template<view V>
    requires forward_range<V>
    template<bool Const>
    class chunk_view<V>::iterator {
        using Parent = maybe-const<Const, chunk_view>; // exposition only
        using Base = maybe-const<Const, V>; // exposition only
        iterator_t<Base> current_ = iterator_t<Base>(); // exposition only
        sentinel_t<Base> end_ = sentinel_t<Base>(); // exposition only
        range_difference_t<Base> n_ = 0; // exposition only
        range_difference_t<Base> missing_ = 0; // exposition only
        constexpr iterator(Parent* parent, iterator_t<Base> current,
            range_difference_t<Base> missing = 0); // exposition only
    }

    public:
        using iterator_category = input_iterator_tag;
        using iterator_concept = see below;
        using value_type = decltype(views::take(subrange(current_, end_), n_));
        using difference_type = range_difference_t<Base>;
        iterator() = default;
        constexpr iterator(iterator<!Const> i)
            requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>,
            iterator_t<Base>& operator++();
        constexpr iterator operator++(int);
        constexpr iterator& operator--() requires bidirectional_range<Base>;
        constexpr iterator& operator--(int) requires bidirectional_range<Base>;
        constexpr iterator& operator+=(difference_type x)
            requires random_access_range<Base>;
        constexpr iterator& operator-=(difference_type x)
            requires random_access_range<Base>;
        constexpr value_type operator[](difference_type n) const
            requires random_access_range<Base>;
        friend constexpr bool operator==(const iterator& x, const iterator& y);
        friend constexpr bool operator==(const iterator& x, default_sentinel_t);
        friend constexpr bool operator<(const iterator& x, const iterator& y)
            requires random_access_range<Base>;
        friend constexpr bool operator<(const iterator& x, default_sentinel_t);
        friend constexpr bool operator<=(const iterator& x, const iterator& y)
            requires random_access_range<Base>;
        friend constexpr bool operator<=(const iterator& x, default_sentinel_t);
        friend constexpr bool operator>(const iterator& x, const iterator& y)
            requires random_access_range<Base>;
        friend constexpr bool operator>(const iterator& x, default_sentinel_t);
        friend constexpr bool operator>=(const iterator& x, const iterator& y)
            requires random_access_range<Base>;
        friend constexpr bool operator>=(const iterator& x, default_sentinel_t);
    }
```
friend constexpr auto operator<=>(const iterator& x, const iterator& y) 
  requires random_access_range<Base> && 
  three_way_comparable<iterator_t<Base>>;

friend constexpr iterator operator+(const iterator& i, difference_type n) 
  requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator& i) 
  requires random_access_range<Base>;
friend constexpr iterator operator-(const iterator& i, difference_type n) 
  requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y) 
  requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;
friend constexpr difference_type operator-(default_sentinel_t y, const iterator& x) 
  requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Base>>;
friend constexpr difference_type operator-(const iterator& x, default_sentinel_t y) 
  requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Base>>;
};

1 iterator::iterator_concept is defined as follows:
(1.1) — If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
(1.2) — Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
(1.3) — Otherwise, iterator_concept denotes forward_iterator_tag.

constexpr iterator(Parent* parent, iterator_t<Base> current, 
  range_difference_t<Base> missing = 0);
Effects: Initializes current_ with current, end_ with ranges::end(parent->base_), n_ with parent->n_, and missing_ with missing.

constexpr iterator(iterator<const> i) 
  requires Const && convertible_to<iterator_t<V>, iterator_t<Base>> 
  && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
Effects: Initializes current_ with std::move(i.current_), end_ with std::move(i.end_), n_ with i.n_, and missing_ with i.missing_.

constexpr iterator_t<Base> base() const;
Returns: current_.

constexpr value_type operator*() const; 
Preconditions: current_ != end_ is true.
Returns: views::take(subrange(current_, end_), n_).

constexpr iterator& operator++();
Preconditions: current_ != end_ is true.
Effects: Equivalent to:
  missing_ = ranges::advance(current_, n_, end_); 
  return *this;

constexpr iterator& operator++(int);
Effects: Equivalent to:
  auto tmp = *this; 
  ***this; 
  return tmp;

constexpr iterator& operator--() requires bidirectional_range<Base>;
Effects: Equivalent to:

§ 26.7.29.7


ranges::advance(current_, missing_ - n_);
missing_ = 0;
return *this;

constexpr iterator operator--(int) requires bidirectional_range<Base>;

Effects: Equivalent to:
auto tmp = *this;
--*this;
return tmp;

constexpr iterator& operator+=(difference_type x) requires random_access_range<Base>;

Effects: Equivalent to:
if (x > 0) {
  ranges::advance(current_, n_ * (x - 1));
  missing_ = ranges::advance(current_, n_, end_);
} else if (x < 0) {
  ranges::advance(current_, n_ * x + missing_);
  missing_ = 0;
}
return *this;

constexpr iterator& operator=(difference_type x) requires random_access_range<Base>;

Preconditions: If x is positive, ranges::distance(current_, end_) > n_ * (x - 1) is true.

[Note 1: If x is negative, the Effects paragraph implies a precondition. — end note]

Effects: Equivalent to:

constexpr value_type operator[](difference_type n) const requires random_access_range<Base>;

Returns: *(this + n);

friend constexpr bool operator==(const iterator& x, const iterator& y);

Returns: x.current_ == y.current_;

friend constexpr bool operator==(const iterator& x, default_sentinel_t);

Returns: x.current_ == x.end_;

friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;

Returns: x.current_ < y.current_;

friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;

Effects: Equivalent to: return y < x;

friend constexpr bool operator==(const iterator& x, const iterator& y) requires random_access_range<Base>;

Effects: Equivalent to: return !(y < x);

friend constexpr bool operator>(const iterator& x, const iterator& y) requires random_access_range<Base>;

Effects: Equivalent to: return !(x < y);

friend constexpr auto operator<>(const iterator& x, const iterator& y) requires random_access_range<Base> 
  && three_way_comparable<iterator_t<Base>>;

Returns: x.current_ <= y.current_.
N4986

friend constexpr iterator operator+(const iterator & i, difference_type n)
requires random_access_range<Base >;
friend constexpr iterator operator+(difference_type n, const iterator & i)
requires random_access_range<Base >;
23

Effects: Equivalent to:
auto r = i;
r += n;
return r;
friend constexpr iterator operator-(const iterator & i, difference_type n)
requires random_access_range<Base >;

24

Effects: Equivalent to:
auto r = i;
r -= n;
return r;
friend constexpr difference_type operator-(const iterator & x, const iterator & y)
requires sized_sentinel_for<iterator_t<Base >, iterator_t<Base >>;

25

Returns: (x.current_ - y.current_ + x.missing_ - y.missing_) / x.n_.
friend constexpr difference_type operator-(default_sentinel_t y, const iterator & x)
requires sized_sentinel_for<sentinel_t<Base >, iterator_t<Base >>;

26

Returns: div-ceil (x.end_ - x.current_, x.n_).
friend constexpr difference_type operator-(const iterator & x, default_sentinel_t y)
requires sized_sentinel_for<sentinel_t<Base >, iterator_t<Base >>;

27

Effects: Equivalent to: return -(y - x);

26.7.30

Slide view

26.7.30.1

Overview

[range.slide]
[range.slide.overview]

1

slide_view takes a view and a number N and produces a view whose M element is a view over the M th
through (M + N − 1)th elements of the original view. If the original view has fewer than N elements, the
resulting view is empty.

2

The name views::slide denotes a range adaptor object (26.7.2). Given subexpressions E and N, the
expression views::slide(E, N) is expression-equivalent to slide_view(E, N).

th

[Example 1 :
vector v = {1, 2, 3, 4};
for (auto i : v | views::slide(2)) {
cout << '[' << i[0] << ", " << i[1] << "] ";
}

// prints [1, 2] [2, 3] [3, 4]

— end example]

26.7.30.2

Class template slide_view

[range.slide.view]

namespace std::ranges {
template<class V>
concept slide-caches-nothing = random_access_range<V> && sized_range<V>;

// exposition only

template<class V>
concept slide-caches-last =
// exposition only
!slide-caches-nothing <V> && bidirectional_range<V> && common_range<V>;
template<class V>
concept slide-caches-first =
!slide-caches-nothing <V> && !slide-caches-last <V>;

§ 26.7.30.2

// exposition only

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1320


template<forward_range V>
requires view<V>
class slide_view : public view_interface<slide_view<V>> {
  V base_;  // exposition only
  range_difference_t<V> n_;  // exposition only

  // 26.7.30.3, class template slide_view::iterator
  template<bool> class iterator;  // exposition only

  // 26.7.30.4, class slide_view::sentinel
  class sentinel;  // exposition only

public:
  constexpr explicit slide_view(V base, range_difference_t<V> n);

  constexpr V base() const & requires copy_constructible<V> { return base_; }
  constexpr V base() && { return std::move(base_); }

  constexpr auto begin()
  requires (!
    (simple-view<V> && slide-caches-nothing<const V>));
  constexpr auto begin() const requires slide-caches-nothing<const V>;

  constexpr auto end()
  requires (!
    (simple-view<V> && slide-caches-nothing<const V>));
  constexpr auto end() const requires slide-caches-nothing<const V>;

  constexpr auto size() requires sized_range<V>;
  constexpr auto size() const requires sized_range<const V>;
};

template<class R>
slide_view(R&&, range_difference_t<R>) -> slide_view<views::all_t<R>>;

constexpr explicit slide_view(V base, range_difference_t<V> n);

§ 26.7.30.2
iterator<false>(ranges::prev(ranges::end(base_), n_ - 1, ranges::begin(base_)), n_)

— Otherwise, if \(V\) models common_range,

iterator<false>(ranges::end(base_), ranges::end(base_), n_)

— Otherwise, sentinel(ranges::end(base_)).

7 Remarks: In order to provide the amortized constant-time complexity required by the range concept, this function caches the result within the slide_view for use on subsequent calls when \(V\) models slide-caches-last.

constexpr auto end() const requires slide-caches-nothing<\!\const V>;

Returns: \(\text{begin()} + \text{range_difference_t<\!\const V>(size())}\).

constexpr auto size() requires sized_range<\!\const V>;

constexpr auto size() const requires sized_range<\const V>;

9 Effects: Equivalent to:

auto sz = ranges::distance(base_) - n_ + 1;
if (sz < 0) sz = 0;
return to_unsigned_like(sz);

26.7.30.3 Class template slide_view::iterator

namespace std::ranges {
  template<forward_range V>
  requires view<V>
  template<bool Const>
  class slide_view<V>::iterator {
    using Base = maybe-const<Const, V>;
    // exposition only
    iterator_t<Base> current_ = iterator_t<Base>();
    // exposition only
    iterator_t<Base> last_ele_ = iterator_t<Base>();
    // exposition only,
    // present only if \(\text{Base}\) models slide-caches-first
    range_difference_t<Base> n_ = 0;
    // exposition only
    constexpr iterator(iterator_t<Base> current, range_difference_t<Base> n) // exposition only
    requires (!slide-caches-first<\!\Base>);
    
    constexpr iterator(iterator_t<Base> current, iterator_t<Base> last_ele, // exposition only
      range_difference_t<Base> n)
    requires slide-caches-first<\!\Base>;
    
public:
  using iterator_category = input_iterator_tag;
  using iterator_concept = see below;
  using value_type = decltype(views::counted(current_, n_));
  using difference_type = range_difference_t<Base>;
  
  iterator() = default;
  constexpr iterator(iterator<!\const V> i)
    requires Const \&\& convertible_to<iterator_t<\!V>, iterator_t<\const Base>>;
    
  constexpr auto operator*() const;
  constexpr iterator& operator++();
  constexpr iterator operator++(int);
  
  constexpr iterator& operator--() requires bidirectional_range<\!Base>;
  constexpr iterator operator--(int) requires bidirectional_range<\!Base>;
    
  constexpr iterator& operator+=(difference_type x)
    requires random_access_range<\!Base>;
  constexpr iterator operator+=(difference_type x)
    requires random_access_range<\!Base>
    
  constexpr auto operator[](difference_type n) const
    requires random_access_range<\!Base>;
  
  § 26.7.30.3 © ISO/IEC 1322
friend constexpr bool operator==(const iterator& x, const iterator& y);
friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator>(const iterator& x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator>=(const iterator& x, const iterator& y) requires random_access_range<Base>;
friend constexpr bool operator<=>(const iterator& x, const iterator& y) requires random_access_range<Base> && three_wayComparable<iterator_t<Base>>;
friend constexpr iterator operator+(const iterator& i, difference_type n) requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator& i) requires random_access_range<Base>;
friend constexpr iterator operator-(const iterator& i, difference_type n) requires random_access_range<Base>;
friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;
}

1 iterator::iterator_concept is defined as follows:

(1.1) — If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
(1.2) — Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
(1.3) — Otherwise, iterator_concept denotes forward_iterator_tag.

2 If the invocation of any non-const member function of iterator exits via an exception, the iterator acquires a singular value.

constexpr iterator (iterator_t<Base> current, range_difference_t<Base> n) requires (!slide-caches-first<Base>);

Effects: Initializes current_ with current and n_ with n.

constexpr iterator (iterator_t<Base> current, iterator_t<Base> last_ele, range_difference_t<Base> n) requires slide-caches-first<Base>;

Effects: Initializes current_ with current, last_ele_ with last_ele, and n_ with n.

constexpr iterator (iterator<!Const> i) requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;

Effects: Initializes current_ with std::move(i.current_) and n_ with i.n_.

[Note 1: iterator<true> can only be formed when Base models slide-caches-nothing, in which case last_ele_ is not present. — end note]

constexpr auto operator*() const;

Returns: views::counted(current_, n_).

constexpr iterator& operator++();

Preconditions: current_ and last_ele_ (if present) are incrementable.

Postconditions: current_ and last_ele_ (if present) are each equal to ranges::next(i), where i is the value of that data member before the call.

Returns: *this.
constexpr iterator operator++(int);
\hspace{1em} Effects: Equivalent to:
\hspace{2em} auto tmp = *this;
\hspace{2em} ++*this;
\hspace{2em} return tmp;

constexpr iterator& operator--() requires bidirectional_range<Base>;
\hspace{1em} Preconditions: current_ and last_ele_ (if present) are decrementable.
\hspace{1em} Postconditions: current_ and last_ele_ (if present) are each equal to ranges::prev(i), where i is the value of that data member before the call.
\hspace{1em} Returns: *this.

constexpr iterator operator--(int) requires bidirectional_range<Base>;
\hspace{1em} Effects: Equivalent to:
\hspace{2em} auto tmp = *this;
\hspace{2em} --*this;
\hspace{2em} return tmp;

constexpr iterator& operator+=(difference_type x) requires random_access_range<Base>;
\hspace{1em} Preconditions: current_ + x and last_ele_ + x (if last_ele_ is present) have well-defined behavior.
\hspace{1em} Postconditions: current_ and last_ele_ (if present) are each equal to i + x, where i is the value of that data member before the call.
\hspace{1em} Returns: *this.

constexpr iterator& operator-=(difference_type x) requires random_access_range<Base>;
\hspace{1em} Preconditions: current_ - x and last_ele_ - x (if last_ele_ is present) have well-defined behavior.
\hspace{1em} Postconditions: current_ and last_ele_ (if present) are each equal to i - x, where i is the value of that data member before the call.
\hspace{1em} Returns: *this.

constexpr auto operator[](difference_type n) const
\hspace{1em} requires random_access_range<Base>;
\hspace{1em} Effects: Equivalent to: return views::counted(current_ + n, n_);

friend constexpr bool operator==(const iterator& x, const iterator& y);
\hspace{1em} Returns: If last_ele_ is present, x.last_ele_ == y.last_ele_; otherwise, x.current_ == y.current_.

friend constexpr bool operator==(const iterator& x, const iterator& y) requires random_access_range<Base>;
\hspace{1em} Returns: x.current_ < y.current_.

friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;
\hspace{1em} Effects: Equivalent to: return y < x;

friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;
\hspace{1em} Effects: Equivalent to: return !y < x;

friend constexpr bool operator>(const iterator& x, const iterator& y) requires random_access_range<Base>;
\hspace{1em} Effects: Equivalent to: return !(x < y);

friend constexpr bool operator>=(const iterator& x, const iterator& y) requires random_access_range<Base>;
\hspace{1em} Effects: Equivalent to: return !(x < y);
friend constexpr auto operator<=>(const iterator& x, const iterator& y)
  requires random_access_range<Base> &&
          three_way_comparable<iterator_t<Base>>;

Returns: x.current_ <=> y.current_.

friend constexpr iterator operator+(const iterator& i, difference_type n)
  requires random_access_range<Base>;
friend constexpr iterator operator+(difference_type n, const iterator& i)
  requires random_access_range<Base>;

Effects: Equivalent to:
  auto r = i;
  r += n;
  return r;

friend constexpr iterator operator-(const iterator& i, difference_type n)
  requires random_access_range<Base>;

Effects: Equivalent to:
  auto r = i;
  r -= n;
  return r;

friend constexpr difference_type operator-(const iterator& x, const iterator& y)
  requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

Returns: If last_ele_ is present, x.last_ele_ - y.last_ele_; otherwise, x.current_ - y.current_.

26.7.30.4 Class slide_view::sentinel

namespace std::ranges {
  template<forward_range V>
  requires view<V>
  class slide_view<V>::sentinel {
    sentinel_t<V> end_ = sentinel_t<V>();  // exposition only
    constexpr explicit sentinel(sentinel_t<V> end);  // exposition only
  public:
    sentinel() = default;

    friend constexpr bool operator==(const iterator<false>& x, const sentinel& y);

    friend constexpr range_difference_t<V> operator-(const iterator<false>& x, const sentinel& y)
      requires sized_sentinel_for<iterator_t<V>, iterator_t<V>>;

    friend constexpr range_difference_t<V> operator-(const sentinel& y, const iterator<false>& x)
      requires sized_sentinel_for<iterator_t<V>, iterator_t<V>>;
  };
}

1 [Note 1: sentinel is used only when slide-caches-first<V> is true. — end note]

constexpr explicit sentinel(sentinel_t<V> end);

Effects: Initializes end_ with end.

friend constexpr bool operator==(const iterator<false>& x, const sentinel& y);

Returns: x.last_ele_ == y.end_.

friend constexpr range_difference_t<V> operator-(const iterator<false>& x, const sentinel& y)
  requires sized_sentinel_for<iterator_t<V>, iterator_t<V>>;

Returns: x.last_ele_ - y.end_.
friend constexpr range_difference_t<V>
    operator-(const sentinel& y, const iterator<false>& x)
    requires sized_sentinel_for<sentinel_t<V>, iterator_t<V>>;

Returns: y.end_ - x.last_ele_.

26.7.31 Chunk by view

26.7.31.1 Overview

chunk_by_view takes a view and a predicate, and splits the view into subrange(s) between each pair of adjacent elements for which the predicate returns false.

The name views::chunk_by denotes a range adaptor object (26.7.2). Given subexpressions E and F, the expression views::chunk_by(E, F) is expression-equivalent to chunk_by_view(E, F).

[Example 1:]

    vector v = {1, 2, 2, 3, 0, 4, 5, 2};
    for (auto r : v | views::chunk_by(ranges::less_equal{})) {
        cout << '[';
        auto sep = "";
        for (auto i : r) {
            cout << sep << i;
            sep = ", ";
        }
        cout << "] ";
    }
    // The above prints [1, 2, 2, 3] [0, 4, 5] [2]

26.7.31.2 Class template chunk_by_view

namespace std::ranges {
    template<forward_range V, indirect_binary_predicate<iterator_t<V>, iterator_t<V>> Pred>
    requires view<V> && is_object_v<Pred>
    class chunk_by_view : public view_interface<chunk_by_view<V, Pred>> {
        // exposition only
        V base_ = V();
        movable_box<Pred> pred_; // exposition only

    // 26.7.31.3, class chunk_by_view::iterator
    class iterator; // exposition only

    public:
        chunk_by_view() requires default_initializable<V> && default_initializable<Pred> = default;
        constexpr explicit chunk_by_view(V base, Pred pred);
        constexpr V base() const & requires copy_constructible<V> { return base_; } // exposition only
        constexpr V base() && { return std::move(base_); } // exposition only
        constexpr const Pred& pred() const;

        constexpr iterator begin();
        constexpr auto end();

        constexpr iterator_t<V> find_next(iterator_t<V>); // exposition only
        constexpr iterator_t<V> find_prev(iterator_t<V>) // exposition only
        requires bidirectional_range<V>;
    };

    template<class R, class Pred>
    chunk_by_view(R&&, Pred) -> chunk_by_view<views::all_t<R>, Pred>;
}

constexpr explicit chunk_by_view(V base, Pred pred);

Effects: Initializes base_ with std::move(base) and pred_ with std::move(pred).
constexpr const Pred& pred() const;

Effects: Equivalent to: return *pred_

constexpr iterator begin();

Preconditions: pred_.has_value() is true.

Returns: iterator(*this, ranges::begin(base_), find-next(ranges::begin(base_))).

Remarks: In order to provide the amortized constant-time complexity required by the range concept, this function caches the result within the chunk_by_view for use on subsequent calls.

constexpr auto end();

Effects: Equivalent to:
if constexpr (common_range<V>) {
  return iterator(*this, ranges::end(base_), ranges::end(base_));
} else {
  return default_sentinel;
}

constexpr iterator_t<V> find-next(iterator_t<V> current);

Preconditions: pred_.has_value() is true.

Returns:
  ranges::next(ranges::adjacent_find(current, ranges::end(base_), not_fn(ref(*pred_))),
  1, ranges::end(base_))

constexpr iterator_t<V> find-prev(iterator_t<V> current) requires bidirectional_range<V>;

Preconditions:
(9.1) current is not equal to ranges::begin(base_).
(9.2) pred_.has_value() is true.

Returns: An iterator i in the range [ranges::begin(base_),current) such that:
(10.1) ranges::adjacent_find(i, current, not_fn(ref(*pred_))) is equal to current; and
(10.2) if i is not equal to ranges::begin(base_), then bool(invoke(*pred_, *ranges::prev(i), *i)) is false.

26.7.31.3 Class chunk_by_view::iterator

namespace std::ranges {
  template<forward_range V, indirect_binary_predicate<iterator_t<V>, iterator_t<V>> Pred>
  requires view<V> && is_object_v<Pred>
  class chunk_by_view<V, Pred>::iterator {
    chunk_by_view* parent_ = nullptr;
    iterator_t<V> current_ = iterator_t<V>();
    iterator_t<V> next_ = iterator_t<V>();
    constexpr iterator(chunk_by_view& parent, iterator_t<V> current, // exposition only
                        iterator_t<V> next);  // exposition only

    public:
      using value_type = subrange<iterator_t<V>>;
      using difference_type = range_difference_t<V>;
      using iterator_category = input_iterator_tag;
      using iterator_concept = see below;

      iterator() = default;

      constexpr value_type operator*() const;
      constexpr iterator& operator++();
      constexpr iterator operator++(int);

    } // class chunk_by_view::iterator

} // namespace std::ranges

§ 26.7.31.3
constexpr iterator& operator--() requires bidirectional_range<V>;
constexpr iterator operator--(int) requires bidirectional_range<V>;

friend constexpr bool operator==(const iterator& x, const iterator& y);
friend constexpr bool operator==(const iterator& x, default_sentinel_t);
}

1 iterator::iterator_concept is defined as follows:

(1.1) — If V models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
(1.2) — Otherwise, iterator_concept denotes forward_iterator_tag.

constexpr iterator(chunk_by_view& parent, iterator_t<V> current, iterator_t<V> next);

Effects: Initializes parent_ with addressof(parent), current_ with current, and next_ with next.

constexpr value_type operator*() const;

Preconditions: current_ is not equal to next_.

Returns: subrange(current_, next_).

constexpr iterator& operator++();

Preconditions: current_ is not equal to next_.

Effects: Equivalent to:
    current_ = next_;    
    next_ = parent_->find-next(current_);
    return *this;

constexpr iterator operator++(int);

Effects: Equivalent to:
    auto tmp = *this;
    +++this;
    return tmp;

constexpr iterator& operator--() requires bidirectional_range<V>;

Effects: Equivalent to:
    next_ = current_;    
    current_ = parent_->find-prev(next_);
    return *this;

constexpr iterator operator--(int) requires bidirectional_range<V>;

Effects: Equivalent to:
    auto tmp = *this;
    --*this;
    return tmp;

friend constexpr bool operator==(const iterator& x, const iterator& y);

Returns: x.current_ == y.current_.

friend constexpr bool operator==(const iterator& x, default_sentinel_t);

Returns: x.current_ == x.next_.

26.7.32 Stride view

26.7.32.1 Overview

stride_view presents a view of an underlying sequence, advancing over n elements at a time, as opposed to the usual single-step succession.

The name views::stride denotes a range adaptor object (26.7.2). Given subexpressions E and N, the expression views::stride(E, N) is expression-equivalent to stride_view(E, N).
Example 1:

```cpp
auto input = views::iota(0, 12) | views::stride(3);
ranges::copy(input, ostream_iterator<int>(cout, " ")); // prints 0 3 6 9
ranges::copy(input | views::reverse, ostream_iterator<int>(cout, " ")); // prints 9 6 3 0
```

--- end example

26.7.32.2 Class template stride_view

```cpp
namespace std::ranges {
    template<input_range V>
    requires view<V>
    class stride_view : public view_interface<stride_view<V>> {
        V base_; // exposition only
        range_difference_t<V> stride_; // exposition only
        // 26.7.32.3, class template stride_view::iterator
        template<bool>
        class iterator;
        // exposition only
    public:
        constexpr explicit stride_view(V base, range_difference_t<V> stride);
        constexpr V base() const & requires copy_constructible<V> { return base_; }
        constexpr V base() && { return std::move(base_); }
        constexpr range_difference_t<V> stride() const noexcept;
        constexpr auto begin() requires (!simple_view<V>) {
            return iterator<false>(this, ranges::begin(base_));
        }
        constexpr auto begin() const requires range<const V> {
            return iterator<true>(this, ranges::begin(base_));
        }
        constexpr auto end() requires (!simple_view<V>) {
            if constexpr (common_range<V> && sized_range<V> && forward_range<V>) {
                auto missing = (stride_ - ranges::distance(base_) % stride_) % stride_;
                return iterator<false>(this, ranges::end(base_), missing);
            } else if constexpr (common_range<V> && !bidirectional_range<V>) {
                return iterator<false>(this, ranges::end(base_));
            } else {
                return default_sentinel;
            }
        }
        constexpr auto end() const requires range<const V> {
            if constexpr (common_range<const V> && sized_range<const V> && forward_range<const V>) {
                auto missing = (stride_ - ranges::distance(base_) % stride_) % stride_;
                return iterator<true>(this, ranges::end(base_), missing);
            } else if constexpr (common_range<const V> && !bidirectional_range<const V>) {
                return iterator<true>(this, ranges::end(base_));
            } else {
                return default_sentinel;
            }
        }
        constexpr auto size() requires sized_range<V>;
        constexpr auto size() const requires sized_range<const V>;
    };

    template<class R>
    stride_view(R&&, range_difference_t<R>) -> stride_view<views::all_t<R>>;
}
constexpr stride_view(V base, range_difference_t<V> stride);
```

Preconditions: 

- `stride > 0` is true.
**Effects**: Initializes `base_` with `std::move(base)` and `stride_` with `stride`.

```cpp
constexpr range_difference_t<V> stride() const noexcept;
```

**Returns**: `stride_`.

```cpp
constexpr auto size() requires sized_range<V>;
constexpr auto size() const requires sized_range<const V>;
```

**Effects**: Equivalent to:

```cpp
return to_unsigned-like(div-ceil(ranges::distance(base_, stride_));
```

### 26.7.32.3 Class template stride_view::iterator

```cpp
namespace std::ranges {
  template<input_range V>
  requires view<V>
  template<bool Const>
  class stride_view<V>::iterator {
    using Parent = maybe-const<Const, stride_view>;
    using Base = maybe-const<Const, V>;
    iterator_t<Base> current_ = iterator_t<Base>();
    sentinel_t<Base> end_ = sentinel_t<Base>();
    range_difference_t<Base> stride_ = 0;
    range_difference_t<Base> missing_ = 0;
    constexpr iterator(Parent* parent, iterator_t<Base> current,
      range_difference_t<Base> missing = 0);
    public:
      using difference_type = range_difference_t<Base>;
      using value_type = range_value_t<Base>;
      using iterator_concept = see below;
      using iterator_category = see below;
      iterator() requires default_initializable<iterator_t<Base>> = default;
      constructor iterator(const iterator& other)
        requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>
        && convertible_to<sentinel_t<V>, sentinel_t<Base>>;
      constructor iterator_t<Base> base() &&;
      constexpr const iterator_t<Base>& base() const & noexcept;
      constexpr decltype(auto) operator*() const { return *current_; }
      constructor iterator& operator++();
      constructor void operator++(int);
      constructor iterator operator++(int) requires forward_range<Base>;
      constructor iterator& operator--() requires bidirectional_range<Base>;
      constructor iterator operator--(int) requires bidirectional_range<Base>;
      constructor iterator& operator+=(difference_type n) requires random_access_range<Base>;
      constructor iterator& operator-=(difference_type n) requires random_access_range<Base>;
      constructor decltype(auto) operator[](difference_type n) const
        requires random_access_range<Base>
        { return *(this + n); }
      friend constexpr bool operator==(const iterator& x, default_sentinel_t);
      friend constexpr bool operator==(const iterator& x, const iterator& y)
        requires equality_comparable<iterator_t<Base>>;
  }
}
```

§ 26.7.32.3 © ISO/IEC 1330
friend constexpr bool operator<(const iterator& x, const iterator& y)  
requires random_access_range<Base>;

friend constexpr bool operator>(const iterator& x, const iterator& y)  
requires random_access_range<Base>;

friend constexpr bool operator<=(const iterator& x, const iterator& y)  
requires random_access_range<Base>;

friend constexpr bool operator>=(const iterator& x, const iterator& y)  
requires random_access_range<Base>;

friend constexpr auto operator<=>(const iterator& x, const iterator& y)  
requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;

friend constexpr iterator operator+(const iterator& x, difference_type n)  
requires random_access_range<Base>;

friend constexpr iterator operator+(difference_type n, const iterator& x)  
requires random_access_range<Base>;

friend constexpr iterator operator-(const iterator& x, difference_type n)  
requires random_access_range<Base>;

friend constexpr difference_type operator-(const iterator& x, const iterator& y)  
requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

friend constexpr difference_type operator-(default_sentinel_t y, const iterator& x)  
requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Base>>;

friend constexpr difference_type operator-(const iterator& x, default_sentinel_t y)  
requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Base>>;

friend constexpr range_rvalue_reference_t<Base> iter_move(const iterator& i)  
noexcept(noexcept(ranges::iter_move(i.current_)));

friend constexpr void iter_swap(const iterator& x, const iterator& y)  
noexcept(noexcept(ranges::iter_swap(x.current_, y.current_)))  
requires indirectly_swappable<iterator_t<Base>>;

\[
\text{iterator::iterator_concept} \text{ is defined as follows:}
\]

(1.1) — If \textit{Base} models \textit{random_access_range}, then \textit{iterator_concept} denotes \textit{random_access_iterator_tag}.

(1.2) — Otherwise, if \textit{Base} models \textit{bidirectional_range}, then \textit{iterator_concept} denotes \textit{bidirectional_iterator_tag}.

(1.3) — Otherwise, if \textit{Base} models \textit{forward_range}, then \textit{iterator_concept} denotes \textit{forward_iterator_tag}.

(1.4) — Otherwise, \textit{iterator_concept} denotes \textit{input_iterator_tag}.

\[
\text{The member typedef-name} \textit{iterator_category} \text{ is defined if and only if \textit{Base} models \textit{forward_range}. In that case,} \textit{iterator::iterator_category} \text{ is defined as follows:}
\]

(2.1) — Let \textit{C} denote the type iterator_traits<iterator_t<Base>>::iterator_category.

(2.2) — If \textit{C} models derived_from<random_access_iterator_tag>, then \textit{iterator_category} denotes random_access_iterator_tag.

(2.3) — Otherwise, \textit{iterator_category} denotes \textit{C}.

\[
\text{constexpr iterator}(\text{Parent}^* \text{parent}, \text{iterator_t<Base>} \text{current},  
\begin{align*}
\text{range_difference_t<Base>} \text{missing} &= 0;
\end{align*}
\]

\text{Effects:} \text{Initializes} \text{current} \text{ with std::move(current), end} \text{ with ranges::end(parent->base), stride_ with parent->stride_, and missing_ with missing.}

\[
\text{constexpr iterator}(\text{iterator<!Const}^\text{>i})  
\text{requires Const \&\& convertible_to<iterator_t<V>, iterator_t<Base>>}
\]
& convert_to<sentinel_t<V>, sentinel_t<Base>>;

Effects: Initializes \( \text{current} \) with std::move(\( \text{current} \)), \( \text{end} \) with std::move(\( \text{end} \)), \( \text{stride} \) with \( \text{i.stride} \), and \( \text{missing} \) with \( \text{i.missing} \).

constexpr iterator_t<Base> base() &&;

Returns: std::move(\( \text{current} \)).

constexpr const iterator_t<Base>& base() const & noexcept;

Returns: \( \text{current} \).

constexpr iterator& operator++();

Preconditions: \( \text{current} \neq \text{end} \) is true.

Effects: Equivalent to:
\[
\text{missing} = \text{ranges::advance(\( \text{current} \), \( \text{stride} \), \( \text{end} \));
\]
return *this;

constexpr void operator++(int);

Effects: Equivalent to: \( \text{++this} \).

constexpr iterator operator++(int) requires forward_range<Base>;

Effects: Equivalent to:
\[
\text{auto tmp = *this;}
\text{++this;}
\text{return tmp;}
\]

constexpr iterator& operator--() requires bidirectional_range<Base>;

Effects: Equivalent to:
\[
\text{ranges::advance(\( \text{current} \), \( \text{missing} - \text{stride} \));
\text{missing} = 0;
\text{return *this;}
\]

constexpr iterator operator--(int) requires bidirectional_range<Base>;

Effects: Equivalent to:
\[
\text{auto tmp = *this;}
\text{--this;}
\text{return tmp;}
\]

constexpr iterator& operator+=(difference_type n) requires random_access_range<Base>;

Preconditions: If \( n \) is positive, \( \text{ranges::distance(\( \text{current} \), \( \text{end} \)) > \text{stride} * (n - 1) \) is true.

[Note 1: If \( n \) is negative, the Effects paragraph implies a precondition. — end note]

Effects: Equivalent to:
\[
\text{if (n > 0) {}
\text{ranges::advance(\( \text{current} \), \( \text{stride} * (n - 1) \));
\text{missing} = \text{ranges::advance(\( \text{current} \), \( \text{stride} \), \( \text{end} \));
\text{else if (n < 0) {}
\text{ranges::advance(\( \text{current} \), \( \text{stride} * n + \text{missing} \));
\text{missing} = 0;
\text{}}
\text{return *this;}
\}
\]

constexpr iterator& operator-=(difference_type x)
requires random_access_range<Base>;

Effects: Equivalent to: return *this += -x;

friend constexpr bool operator==(const iterator& x, default_sentinel_t);

Returns: \( x.\text{current} == x.\text{end} \).
friend constexpr bool operator==(const iterator& x, const iterator& y) requires equality_comparable<iterator_t<Base>>;

Returns: \( x.\text{current}_- == y.\text{current}_- \).

friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;

Returns: \( x.\text{current}_- < y.\text{current}_- \).

Effects: Equivalent to: return y < x;

friend constexpr bool operator<=(const iterator& x, const iterator& y) requires random_access_range<Base>;

Effects: Equivalent to: return !(y < x);

friend constexpr bool operator>(const iterator& x, const iterator& y) requires random_access_range<Base>;

Effects: Equivalent to: return !(x < y);

friend constexpr bool operator>=(const iterator& x, const iterator& y) requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;

Returns: \( x.\text{current}_- \leq y.\text{current}_- \).

friend constexpr auto operator<=>(const iterator& x, const iterator& y) requires random_access_range<Base> && three_way_comparable<iterator_t<Base>>;

Returns: \( x.\text{current}_- \leftrightarrow y.\text{current}_- \).

friend constexpr iterator operator+(const iterator& i, difference_type n) requires random_access_range<Base>;

friend constexpr iterator operator+(difference_type n, const iterator& i) requires random_access_range<Base>;

Effects: Equivalent to:

\[
\text{auto } r = i; \\
r += n; \\
return r;
\]

friend constexpr iterator operator-(const iterator& i, difference_type n) requires random_access_range<Base>;

Effects: Equivalent to:

\[
\text{auto } r = i; \\
r -= n; \\
return r;
\]

friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

Returns: \( \text{Let } N \text{ be } (x.\text{current}_- - y.\text{current}_-). \)

\begin{enumerate}
\item If \( \text{Base} \) models \( \text{forward\_range} \), \( (N + x.\text{missing}_- - y.\text{missing}_-) / x.\text{stride}_- \).
\item Otherwise, if \( N \) is negative, \( -\text{div\_ceil}(-N, x.\text{stride}_-) \).
\item Otherwise, \( \text{div\_ceil}(N, x.\text{stride}_-) \).
\end{enumerate}

friend constexpr difference_type operator-(default_sentinel_t y, const iterator& x) requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Base>>;

Effects: Equivalent to: return \( -(y - x) \);

friend constexpr difference_type operator-(const iterator& x, default_sentinel_t y) requires sized_sentinel_for<sentinel_t<Base>, iterator_t<Base>>;

Effects: Equivalent to: return \( -(y - x) \);

friend constexpr range_rvalue_reference_t<Base> iter_move(const iterator& i) noexcept(noexcept(ranges::iter_move(i.\text{current}_-)));
friend constexpr void iter_swap(const iterator& x, const iterator& y)
    noexcept(noexcept(ranges::iter_swap(x.current_, y.current_)))
requires indirectly_swappable<iterator_t<Base>>;

Effects: Equivalent to: ranges::iter_swap(x.current_, y.current_);

26.7.33 Cartesian product view

26.7.33.1 Overview

cartesian_product_view takes any non-zero number of ranges \( n \) and produces a view of tuples calculated by the \( n \)-ary cartesian product of the provided ranges.

The name views::cartesian_product denotes a customization point object (16.3.3.3.5). Given a pack of subexpressions \( E_s \), the expression views::cartesian_product\((E_s)\) is expression-equivalent to

\[(2.1)\] views::single\((\text{tuple}())\) if \( E_s \) is an empty pack,

\[(2.2)\] otherwise, cartesian_product_view\(\langle \text{views::all_t<\text{decltype}(E_s)>},\ldots\rangle\)(Es...).

[Example 1:

```cpp
to int v { 0, 1, 2 }
for (auto&& [a, b, c] : views::cartesian_product(v, v, v)) {
    cout << a << ' ' << b << ' ' << c << 'n';
}
// The above prints
// 0 0 0
// 0 0 1
// 0 0 2
// 0 1 0
// 0 1 1
// ...
// end example]
```

26.7.33.2 Class template cartesian_product_view

namespace std::ranges {

template<bool Const, class First, class... Vs>
concept cartesian-product-is-random-access = // exposition only
    (random_access_range<maybe-const<Const, First>> & & \ldots & &
    (random_access_range<maybe-const<Const, Vs>>
    & & sized_range<maybe-const<Const, Vs>>));

template<class R>
concept cartesian-product-common-arg = // exposition only
    common_range<R> || (sized_range<R> & & random_access_range<R>);

template<bool Const, class First, class... Vs>
concept cartesian-product-is-bidirectional = // exposition only
    (bidirectional_range<maybe-const<Const, First>> & & \ldots & &
    (bidirectional_range<maybe-const<Const, Vs>>
    & & cartesian_product_common_arg<maybe-const<Const, Vs>>));

template<class First, class...>
concept cartesian-product-is-common = // exposition only
cartesian_product_common_arg<First>;

template<class... Vs>
concept cartesian-product-is-sized = // exposition only
    (sized_range<Vs> & & \ldots);

template<bool Const, template<class> class FirstSent, class First, class... Vs>
concept cartesian-product-is-sized-sentinel = // exposition only
    (sized_sentinel_for<FirstSent<maybe-const<Const, First>>>,
    iterator_t<maybe-const<Const, First>> & & \ldots & &
    (sized_range<maybe-const<Const, Vs>>
    & & sized_sentinel_for<iterator_t<maybe-const<Const, Vs>>>,
    iterator_t<maybe-const<Const, Vs>>));
template<cartesian-product-common-arg R>
constexpr auto cartesian-common-arg-end(R& r) { // exposition only
    if constexpr (common_range<R>) {
        return ranges::end(r);
    } else {
        return ranges::begin(r) + ranges::distance(r);
    }
}

template<input_range First, forward_range... Vs>
requires (view<First> && ... && view<Vs>)
class cartesian_product_view : public view_interface<cartesian_product_view<First, Vs...>> { // exposition only
private:
    tuple<First, Vs...> bases_; // exposition only
    // 26.7.33.3, class template cartesian_product_view::iterator
    template<bool Const> class iterator; // exposition only
public:
    constexpr cartesian_product_view() = default;
    constexpr explicit cartesian_product_view(First first_base, Vs... bases);
    constexpr iterator<false> begin() requires (! simple-view<First> || ... || ! simple-view<Vs>);
    constexpr iterator<true> begin() const requires (range<const First> && ... && range<const Vs>);
    constexpr iterator<false> end() requires (! simple-view<First> || ... || ! simple-view<Vs>) && cartesian-product-is-common<First, Vs...>);
    constexpr iterator<true> end() const requires cartesian-product-is-common<const First, const Vs...>;
    constexpr default_sentinel_t end() const noexcept;
    constexpr see below size() requires cartesian-product-is-sized<First, Vs...>;
    constexpr see below size() const requires cartesian-product-is-sized<const First, const Vs...>;
};
template<class... Vs>
cartesian_product_view(Vs&&...) -> cartesian_product_view<views::all_t<Vs>...>;

1 Effects: Initializes bases_ with std::move(first_base), std::move(bases)....

constexpr iterator<false> begin()
    requires (! simple-view<First> || ... || ! simple-view<Vs>);
2 Effects: Equivalent to:
    return iterator<false>(*this, tuple-transform(ranges::begin, bases_));

constexpr iterator<true> begin() const
    requires (range<const First> && ... && range<const Vs>);
3 Effects: Equivalent to:
    return iterator<true>(*this, tuple-transform(ranges::begin, bases_));

constexpr iterator<false> end()
    requires (!simple-view<First> || ... || !simple-view<Vs>)
    && cartesian-product-is-common<First, Vs...>);
4 Let:
— is-const be true for the const-qualified overload, and false otherwise;

— is-empty be true if the expression ranges::empty(rng) is true for any rng among the underlying ranges except the first one and false otherwise; and

— begin-or-first-end(rng) be expression-equivalent to is-empty ? ranges::begin(rng) : cartesian-common-arg-end(rng) if rng is the first underlying range and ranges::begin(rng) otherwise.

Effects: Equivalent to:

```cpp
iterator<is-const> it(*this, tuple-transform(
    [](auto& rng){ return begin-or-first-end(rng); }, bases_));
return it;
```

constexpr default_sentinel_t end() const noexcept;

Returns: default_sentinel.

```cpp
constexpr see below size();
```

constexpr see below size() const

The return type is an implementation-defined unsigned-integer-like type.

Recommended practice: The return type should be the smallest unsigned-integer-like type that is sufficiently wide to store the product of the maximum sizes of all the underlying ranges, if such a type exists.

Let p be the product of the sizes of all the ranges in bases_.

Preconditions: p can be represented by the return type.

Returns: p.

§ 26.7.33.3 Class template cartesian_product_view::iterator

```cpp
namespace std::ranges {
    template<input_range First, forward_range... Vs>
        requires (view<First> && ... && view<Vs>)
    template<bool Const>
        class cartesian_product_view<First, Vs...>::iterator { public:
            using iterator_category = input_iterator_tag;
            using iterator_concept = see below;
            using value_type = tuple<range_value_t<
                maybe-const<Const, First>>,
                range_value_t<
                    maybe-const<Const, Vs>>...>;
            using reference = tuple<range_reference_t<
                maybe-const<Const, First>>,
                range_reference_t<
                    maybe-const<Const, Vs>>...>;
            using difference_type = see below;

            iterator() = default;

            constexpr iterator(iterator<!Const> i) requires Const &&
                (convertible_to<iterator_t<First>, iterator_t<const First>> &&
                ... && convertible_to<iterator_t<Vs>, iterator_t<const Vs>>);

            constexpr auto operator*() const;
            constexpr iterator& operator++();
            constexpr void operator++(int);
            constexpr iterator operator++(int) requires forward_range<
                maybe-const<Const, First>>;

            constexpr iterator& operator--();
            requires cartesian-product-is-bidirectional<Const, First, Vs...>;
            constexpr iterator operator--(int)
                requires cartesian-product-is-bidirectional<Const, First, Vs...>;

            constexpr iterator& operator+=(difference_type x)
                requires cartesian-product-is-random-access<Const, First, Vs...>;
```
constexpr iterator& operator-=(difference_type x)
       requires cartesian-product-is-random-access<Const, First, Vs...>;

castexpr reference operator[](difference_type n) const
       requires cartesian-product-is-random-access<Const, First, Vs...>;

friend constexpr bool operator==(const iterator& x, const iterator& y)
       requires equality_comparable<iterator_t<maybe-const<Const, First>>>;

friend constexpr bool operator==(const iterator& x, default_sentinel_t);

friend constexpr auto operator<=>(const iterator& x, const iterator& y)
       requires all-random-access<Const, First, Vs...>;

friend constexpr iterator operator+(const iterator& x, difference_type y)
       requires cartesian-product-is-random-access<Const, First, Vs...>;

friend constexpr iterator operator+(difference_type x, const iterator& y)
       requires cartesian-product-is-random-access<Const, First, Vs...>;

friend constexpr iterator operator-(const iterator& x, difference_type y)
       requires cartesian-product-is-random-access<Const, First, Vs...>;

friend constexpr difference_type operator-(const iterator& x, const iterator& y)
       requires cartesian-is-sized-sentinel<Const, iterator_t, First, Vs...>;

friend constexpr difference_type operator-(const iterator& i, default_sentinel_t)
       requires cartesian-is-sized-sentinel<Const, sentinel_t, First, Vs...>;

friend constexpr difference_type operator-(default_sentinel_t, const iterator& i)
       requires cartesian-is-sized-sentinel<Const, sentinel_t, First, Vs...>;

friend constexpr auto iter_move(const iterator& i) noexcept(see below);

friend constexpr void iter_swap(const iterator& l, const iterator& r) noexcept(see below)
       requires (indirectly_swappable<iterator_t<maybe-const<Const, First>>> && ...
       && indirectly_swappable<iterator_t<maybe-const<Const, Vs>>>);

private:

using Parent = maybe-const<Const, cartesian_product_view>;  // exposition only
Parent* parent_ = nullptr;  // exposition only
tuple<iterator_t<maybe-const<Const, First>>,
     iterator_t<maybe-const<Const, Vs>>...> current_;  // exposition only

template<size_t N = sizeof...(Vs)>
   castexpr void next();  // exposition only

template<size_t N = sizeof...(Vs)>
   castexpr void prev();  // exposition only

template<class Tuple>
   castexpr difference_type distance-from(const Tuple& t) const;  // exposition only

castexpr iterator(Parent& parent, tuple<iterator_t<maybe-const<Const, First>>,
     iterator_t<maybe-const<Const, Vs>>...> current);  // exposition only
};

1 iterator::iterator_concept is defined as follows:
   
   (1.1) — If cartesian-product-is-random-access<Const, First, Vs...> is modeled, then iterator_concept denotes random_access_iterator_tag.
   
   (1.2) — Otherwise, if cartesian-product-is-bidirectional<Const, First, Vs...> is modeled, then iterator_concept denotes bidirectional_iterator_tag.
   
   (1.3) — Otherwise, if maybe-const<Const, First> models forward_range, then iterator_concept denotes forward_iterator_tag.
   
   (1.4) — Otherwise, iterator_concept denotes input_iterator_tag.
2 `iterator::difference_type` is an implementation-defined signed-integer-like type.

3 **Recommended practice:** `iterator::difference_type` should be the smallest signed-integer-like type that is sufficiently wide to store the product of the maximum sizes of all underlying ranges if such a type exists.

4 template<size_t N = sizeof...(Vs)>
   constexpr void next();

   **Effects:** Equivalent to:
   auto& it = std::get<N>(current_);
   ++it;
   if constexpr (N > 0) {
     if (it == ranges::end(std::get<N>(parent_->bases_))) {
       it = ranges::begin(std::get<N>(parent_->bases_));
       next<N - 1>();
     }
   }

5 template<size_t N = sizeof...(Vs)>
   constexpr void prev();

   **Effects:** Equivalent to:
   auto& it = std::get<N>(current_);
   if constexpr (N > 0) {
     if (it == ranges::begin(std::get<N>(parent_->bases_))) {
       it = cartesian_common_arg_end(std::get<N>(parent_->bases_));
       prev<N - 1>();
     }
   }
   --it;

6 template<class Tuple>
   constexpr difference_type distance_from(const Tuple& t) const;

   **Let:**

   (7.1) — `scaled-size(N)` be the product of static_cast<difference_type>( ranges::size(std::get<N>(parent_->bases_))) and `scaled-size(N + 1)` if `N <= sizeof...(Vs)`, otherwise static_cast<difference_type>(1);

   (7.2) — `scaled-distance(N)` be the product of static_cast<difference_type>( current_ - std::get<N>(t)) and `scaled-size(N + 1)`; and

   (7.3) — `scaled-sum` be the sum of `scaled-distance(N)` for every integer `0 <= N <= sizeof...(Vs).

   **Preconditions:** `scaled-sum` can be represented by `difference_type`.

   **Returns:** `scaled-sum`.

7 constexpr iterator(Parent& parent, tuple<iterator_t<maybe-const<Const, First>>, iterator_t<maybe-const<Const, Vs>>... current);

   **Effects:** Initializes `parent_` with addressof(parent) and `current_` with std::move(current).

8 constexpr iterator(iterator<Const> i) requires Const && (convertible_to<iterator_t<First>, iterator_t<const First>> && ... && convertible_to<iterator_t<Vs>, iterator_t<const Vs>>);

   **Effects:** Initializes `parent_` with `i.parent_` and `current_` with std::move(i.current_).

9 constexpr auto operator*() const;

   **Effects:** Equivalent to:
   return tuple_transform([](auto& i) -> decltype(auto) { return *i; }, current_);

10 constexpr iterator& operator++();

   **Effects:** Equivalent to:
   next();
   return *this;
constexpr void operator++(int);

**Effects:** Equivalent to `++*this`.

constexpr iterator operator++(int) requires forward_range<maybe-const<Const, First>>;

**Effects:** Equivalent to:

```cpp
auto tmp = *this;
++*this;
return tmp;
```

constexpr iterator& operator--() requires cartesian_product_is_bidirectional<Const, First, Vs...>;

**Effects:** Equivalent to:

```cpp
prev();
return *this;
```

constexpr iterator operator--(int) requires cartesian_product_is_bidirectional<Const, First, Vs...>;

**Effects:** Equivalent to:

```cpp
auto tmp = *this;
--*this;
return tmp;
```

constexpr iterator& operator+=(difference_type x) requires cartesian_product_is_random_access<Const, First, Vs...>;

**Effects:** Equivalent to:

Let `orig` be the value of `*this` before the call.

Let `ret` be:

- If `x > 0`, the value of `*this` had `next` been called `x` times.
- Otherwise, if `x < 0`, the value of `*this` had `prev` been called `-x` times.
- Otherwise, `orig`.

**Preconditions:** `x` is in the range `[ranges::distance(*this, ranges::begin(*parent_)), ranges::distance(*this, ranges::end(*parent_))]`.

**Effects:** Sets the value of `*this` to `ret`.

**Returns:** `*this`.

**Complexity:** Constant.

constexpr iterator& operator+=(difference_type x) requires cartesian_product_is_random_access<Const, First, Vs...>;

**Effects:** Equivalent to:

```cpp
*this += -x;
return *this;
```

constexpr reference operator[](difference_type n) const requires cartesian_product_is_random_access<Const, First, Vs...>;

**Effects:** Equivalent to: return `*(this) + n`;

friend constexpr bool operator==(const iterator& x, const iterator& y) requires equality_comparable<iterator_t<maybe-const<Const, First>>>;

**Effects:** Equivalent to: return `x.current_ == y.current_`;

friend constexpr bool operator==(const iterator& x, default_sentinel_t);

**Returns:** `true` if `std::get<i>(x.current_) == ranges::end(std::get<i>(x.parent_)->bases_)` is `true` for any integer `0 ≤ i ≤ sizeof...(Vs)`; otherwise, `false`.

§ 26.7.33.3 © ISO/IEC 1339
friend constexpr auto operator<=>(const iterator& x, const iterator& y) requires all-random-access<Const, First, Vs...>;

Effects: Equivalent to: return x.current_ <=> y.current_

friend constexpr iterator operator+(const iterator& x, difference_type y) requires cartesian-product-is-random-access<Const, First, Vs...>;

Effects: Equivalent to: return iterator(x) += y;

friend constexpr iterator operator+(difference_type x, const iterator& y) requires cartesian-product-is-random-access<Const, First, Vs...>;

Effects: Equivalent to: return y + x;

friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires cartesian-is-sized-sentinel<Const, iterator_t, First, Vs...>;

Effects: Equivalent to: return x.distance-from(y.current_);

friend constexpr difference_type operator-(default_sentinel_t s, const iterator& i) requires cartesian-is-sized-sentinel<Const, sentinel_t, First, Vs...>;

Effects: Equivalent to: return -(i - s);

friend constexpr auto iter_move(const iterator& i) noexcept(see below);

Effects: Equivalent to: return tuple_transform(ranges::iter_move, i.current_);

Remarks: The exception specification is equivalent to the logical AND of the following expressions:

(36.1) noexcept(ranges::iter_move(std::get<i>(i.current_), i.current_)) for every integer 0 ≤ i ≤ sizeof...(Vs),

(36.2) is_nothrow_move_constructible_v<range_rvalue_reference_t<maybe-const<Const, T>>> for every type T in First, Vs....

friend constexpr void iter_swap(const iterator& l, const iterator& r) noexcept(see below) requires (indirectly_swappable<iterator_t<maybe-const<Const, First>>> && ... && indirectly_swappable<iterator_t<maybe-const<Const, Vs>>>);

Effects: For every integer 0 ≤ i ≤ sizeof...(Vs), performs:

ranges::iter_swap(std::get<i>(l.current_), std::get<i>(r.current_))

Remarks: The exception specification is equivalent to the logical AND of the following expressions:

(38.1) noexcept(ranges::iter_swap(std::get<i>(l.current_), std::get<i>(r.current_))) for every integer 0 ≤ i ≤ sizeof...(Vs).

26.8 Range generators

26.8.1 Overview

Class template generator presents a view of the elements yielded by the evaluation of a coroutine.

A generator generates a sequence of elements by repeatedly resuming the coroutine from which it was returned. Elements of the sequence are produced by the coroutine each time a co_yield statement is
evaluated. When the co_yield statement is of the form co_yield elements_of(r), each element of the range r is successively produced as an element of the sequence.

Example 1:

```cpp
generator<int> ints(int start = 0) {
    while (true)
        co_yield start++;
}

t void f() {
    for (auto i : ints() | views::take(3))
        cout << i << ' '; // prints 0 1 2
}
```

— end example |

26.8.2 Header <generator> synopsis

```cpp
namespace std {
    // 26.8.3, class template generator
    template<class Ref, class V = void, class Allocator = void>
    class generator;

    namespace pmr {
        template<class R, class V = void>
        using generator = std::generator<R, V, polymorphic_allocator<>;}
}
```

26.8.3 Class template generator

```cpp
namespace std {
    template<class Ref, class V = void, class Allocator = void>
    class generator : public ranges::view_interface<generator<Ref, V, Allocator>> { 
    private:
        using value = conditional_t<is_void_v<V>, remove_cvref_t<Ref>, V>; // exposition only
        using reference = conditional_t<is_void_v<V>, Ref&&, Ref>; // exposition only

    // 26.8.6, class generator::iterator
    class iterator; // exposition only

    public:
        using yielded = conditional_t<is_reference_v<reference>, reference, const reference&>;

    // 26.8.5, class generator::promise_type
    class promise_type;

    generator(const generator&) = delete;
    generator(generator&& other) noexcept;

    ~generator();

    generator& operator=(generator other) noexcept;

    iterator begin();
    default_sentinel_t end() const noexcept;

    private:
        coroutine_handle<promise_type> coroutine_ = nullptr; // exposition only
        unique_ptr<stack<coroutine_handle<>>> active_; // exposition only
});
```

Mandates:

(1.1) — If Allocator is not void, allocator_traits<Allocator>::pointer is a pointer type.
— value is a cv-unqualified object type.

— reference is either a reference type, or a cv-unqualified object type that models copy_constructible.

— Let RRef denote remove_reference_t<reference>&& if reference is a reference type, and reference otherwise. Each of:

— common_reference_with<reference&&, value&>,
— common_reference_with<reference&&, RRef&&>, and
— common_reference_with<RRef&&, const value&>

is modeled.

[Note 1: These requirements ensure the exposition-only iterator type can model indirectly_readable and thus input_iterator. — end note]

2 If Allocator is not void, it shall meet the Cpp17Allocator requirements.

Specializations of generator model view and input_range.

4 The behavior of a program that adds a specialization for generator is undefined.

26.8.4 Members

generator(generator&& other) noexcept;

Effects: Initializes coroutine_ with exchange(other.coroutine_, { }) and active_ with exchange(other.active_, nullptr).

[Note 1: Iterators previously obtained from other are not invalidated; they become iterators into *this. — end note]

~generator();

Effects: Equivalent to:

if (coroutine_) {
  coroutine_.destroy();
}

[Note 2: Ownership of recursively yielded generators is held in awaitable objects in the coroutine frame of the yielding generator, so destroying the root generator effectively destroys the entire stack of yielded generators. — end note]

generator& operator=(generator other) noexcept;

Effects: Equivalent to:

swap(coroutine_, other.coroutine_);
swap(active_, other.active_);

Returns: *this.

[Note 3: Iterators previously obtained from other are not invalidated; they become iterators into *this. — end note]

iterator begin();

Preconditions: coroutine_ refers to a coroutine suspended at its initial suspend point (9.5.4).

Effects: Pushes coroutine_ into *active_, then evaluates coroutine_.resume().

Returns: An iterator object whose member coroutine_ refers to the same coroutine as does coroutine_.

[Note 4: A program that calls begin more than once on the same generator has undefined behavior. — end note]

default_sentinel_t end() const noexcept;

Returns: default_sentinel.

26.8.5 Class generator::promise_type

coro.generator.promise]
namespace std {
    template<class Ref, class V, class Allocator>
    class generator<Ref, V, Allocator>::promise_type {
    public:
        generator get_return_object() noexcept;

        suspend_always initial_suspend() const noexcept { return {}; }
        auto final_suspend() noexcept;

        suspend_always yield_value(yielded val) noexcept;
    
auto yield_value(const remove_reference_t<yielded>& lval) noexcept;
    requires is_rvalue_reference_v<yielded> &&
          constructible_from<remove_cvref_t<yielded>, const remove_reference_t<yielded>&>;

        template<class R2, class V2, class Alloc2, class Unused>
        requires same_as<typename generator<R2, V2, Alloc2>::yielded, yielded>
        auto yield_value(ranges::elements_of<generator<R2, V2, Alloc2>&&, Unused> g) noexcept;

        template<ranges::input_range R, class Alloc>
        requires convertible_to<ranges::range_reference_t<R>, yielded>
        auto yield_value(ranges::elements_of<R, Alloc> r);

        void await_transform() = delete;

        void return_void() const noexcept {}
        void unhandled_exception();

    void* operator new(size_t size) noexcept;
    requires same_as<Allocator, void> || default_initializable<Allocator>;

    template<class Alloc, class... Args>
    requires convertible_to<const Alloc&, Allocator>
    void* operator new(size_t size, allocator_arg_t, const Alloc& alloc, const Args&...);

    template<class This, class Alloc, class... Args>
    requires convertible_to<const Alloc&, Allocator>
    void* operator new(size_t size, const This&, allocator_arg_t, const Alloc& alloc,
                       const Args&...);

    void operator delete(void* pointer, size_t size) noexcept;

private:
    add_pointer_t<yielded> value_ = nullptr; // exposition only
    exception_ptr except_; // exposition only
    }

    generator get_return_object() noexcept;

    Returns: A generator object whose member coroutine_ is coroutine_handle<promise_type>::
    from_promise(*this), and whose member active_ points to an empty stack.

    auto final_suspend() noexcept;
    Preconditions: A handle referring to the coroutine whose promise object is *this is at the top of
    *active_ of some generator object x. This function is called by that coroutine upon reaching its final
    suspend point (9.5.4).

    Returns: An awaitable object of unspecified type (7.6.2.4) whose member functions arrange for the
    calling coroutine to be suspended, pop the coroutine handle from the top of *x.active_, and resume
    execution of the coroutine referred to by x.active_->top() if *x.active_ is not empty. If it is empty,
    control flow returns to the current coroutine caller or resumer (9.5.4).
suspend_always yield_value(yielded val) noexcept;

Effects: Equivalent to value_ = addressof(val).

Returns: {}.

auto yield_value(const remove_reference_t<yielded>& lval)
requires is_rvalue_reference_v<yielded> &&
constructible_from<remove_cvref_t<yielded>, const remove_reference_t<yielded>&>;

Preconditions: A handle referring to the coroutine whose promise object is *this is at the top of
*active_ of some generator object.

Returns: An awaitable object of an unspecified type (7.6.2.4) that stores an object of type remove_cvref_t<yielded> direct-non-list-initialized with lval, whose member functions arrange for value_ to point to that stored object and then suspend the coroutine.

Throws: Any exception thrown by the initialization of the stored object.

Remarks: Any exception thrown by the initialization of the stored object.

template<class R2, class V2, class Alloc2, class Unused>
requires same_as<typename generator<R2, V2, Alloc2>::yielded, yielded>
auto yield_value(ranges::elements_of<generator<R2, V2, Alloc2>&&, Unused> g) noexcept;

Preconditions: A handle referring to the coroutine whose promise object is *this is at the top of
*active_ of some generator object x. The coroutine referred to by g.range.coroutine_ is suspended at its initial suspend point.

Returns: An awaitable object of an unspecified type (7.6.2.4) into which g.range is moved, whose
member await_ready returns false, whose member await_suspend pushes g.range.coroutine_ into *x.active_ and resumes execution of the coroutine referred to by g.range.coroutine_, and whose member await_resume evaluates rethrow_exception(except_) if bool(except_) is true. If bool(except_) is false, the await_resume member has no effects.

Remarks: A yield-expression that calls this function has type void (7.6.17).

template<ranges::input_range R, class Alloc>
requires convertible_to<ranges::range_reference_t<R>, yielded>
auto yield_value(ranges::elements_of<R, Alloc> r);

Effects: Equivalent to:

auto nested = [](allocator_arg_t, Alloc, ranges::iterator_t<R> i, ranges::sentinel_t<R> s)
-> generator<yielded, ranges::range_value_t<R>, Alloc> {
  for (; i != s; ++i) {
    co_yield static_cast<yielded>(*i);
  }
};

return yield_value(ranges::elements_of(nested(
  allocator_arg, r.allocator, ranges::begin(r.range), ranges::end(r.range))));

[Note 1: A yield-expression that calls this function has type void (7.6.17). — end note]

void unhandled_exception();

Preconditions: A handle referring to the coroutine whose promise object is *this is at the top of
*active_ of some generator object x.

Effects: If the handle referring to the coroutine whose promise object is *this is the sole element of
*x.active_, equivalent to throw, otherwise, assigns current_exception() to except_.

void* operator new(size_t size)
requires same_as<Allocator, void> || default_initializable<Allocator>;

template<class Alloc, class... Args>
requires same_as<Allocator, void> || convertible_to<const Alloc&, Allocator>
void* operator new(size_t size, allocator_arg_t, const Alloc& alloc, const Args&...);
template<class This, class Alloc, class... Args>
requires same_as<Allocator, void> || convertible_to<const Alloc&, Allocator>
void* operator new(size_t size, const This&, allocator_arg_t, const Alloc& alloc,
    const Args&...);

Let A be
— Allocator, if it is not void,
— Alloc for the overloads with a template parameter Alloc, or
— allocator<void> otherwise.

Let B be allocator_traits<A>::template rebind_alloc<U> where U is an unspecified type whose size and alignment are both __STDCPP_DEFAULT_NEW_ALIGNMENT__.

Mandates: allocator_traits<B>::pointer is a pointer type.

Effects: Initializes an allocator b of type B with A(alloc), for the overloads with a function parameter alloc, and with A() otherwise. Uses b to allocate storage for the smallest array of U sufficient to provide storage for a coroutine state of size size, and unspecified additional state necessary to ensure that operator delete can later deallocate this memory block with an allocator equal to b.

Returns: A pointer to the allocated storage.

void operator delete(void* pointer, size_t size) noexcept;

Preconditions: pointer was returned from an invocation of one of the above overloads of operator new with a size argument equal to size.

Effects: Deallocates the storage pointed to by pointer using an allocator equivalent to that used to allocate it.

26.8.6 Class generator::iterator

namespace std {
    template<class Ref, class V, class Allocator>
    class generator<Ref, V, Allocator>::iterator {
        public:
            using value_type = value;
            using difference_type = ptrdiff_t;

            iterator(iterator&& other) noexcept;
            iterator& operator=(iterator&& other) noexcept;

            reference operator*() const noexcept(is_nothrow_copy_constructible_v<reference>);
            iterator& operator++();
            void operator++(int);

            friend bool operator==(const iterator& i, default_sentinel_t);

        private:
            coroutine_handle<promise_type> coroutine_; // exposition only
        }
    }

    iterator(iterator&& other) noexcept;

    Effects: Initializes coroutine_ with exchange(other.coroutine_, {}).

    iterator& operator=(iterator&& other) noexcept;

    Effects: Equivalent to coroutine_ = exchange(other.coroutine_, {}).

    Returns: *this.

    reference operator*() const noexcept(is_nothrow_copy_constructible_v<reference>);

    Preconditions: For some generator object x, coroutine_ is in *x.active_ and x.active_->top() refers to a suspended coroutine with promise object p.

    Effects: Equivalent to: return static_cast<reference>(*p.value_);
iterator& operator++();

   Preconditions: For some generator object x, coroutine_ is in *x.active_.
   Effects: Equivalent to x.active_->top().resume().
   Returns: *this.

void operator++(int);

   Effects: Equivalent to +++this.

friend bool operator==(const iterator& i, default_sentinel_t);

   Effects: Equivalent to: return i.coroutine_.done();
27 Algorithms library

27.1 General

This Clause describes components that C++ programs may use to perform algorithmic operations on containers (Clause 24) and other sequences.

The following subclauses describe components for non-modifying sequence operations, mutating sequence operations, sorting and related operations, and algorithms from the C library, as summarized in Table 96.

Table 96 — Algorithms library summary

<table>
<thead>
<tr>
<th>Subclause Header</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.2 Algorithms requirements</td>
<td>&lt;algorithm&gt;</td>
</tr>
<tr>
<td>27.3 Parallel algorithms</td>
<td></td>
</tr>
<tr>
<td>27.5 Algorithm result types</td>
<td></td>
</tr>
<tr>
<td>27.6 Non-modifying sequence operations</td>
<td></td>
</tr>
<tr>
<td>27.7 Mutating sequence operations</td>
<td></td>
</tr>
<tr>
<td>27.8 Sorting and related operations</td>
<td></td>
</tr>
<tr>
<td>27.10 Generalized numeric operations</td>
<td>&lt;numeric&gt;</td>
</tr>
<tr>
<td>27.11 Specialized &lt;memory&gt; algorithms</td>
<td>&lt;memory&gt;</td>
</tr>
<tr>
<td>27.12 Specialized &lt;random&gt; algorithms</td>
<td>&lt;random&gt;</td>
</tr>
<tr>
<td>27.13 C library algorithms</td>
<td>&lt;cstdlib&gt;</td>
</tr>
</tbody>
</table>

27.2 Algorithms requirements

All of the algorithms are separated from the particular implementations of data structures and are parameterized by iterator types. Because of this, they can work with program-defined data structures, as long as these data structures have iterator types satisfying the assumptions on the algorithms.

The entities defined in the `std::ranges` namespace in this Clause are not found by argument-dependent name lookup (6.5.4). When found by unqualified (6.5.3) name lookup for the postfix-expression in a function call (7.6.1.3), they inhibit argument-dependent name lookup.

```plaintext
Example 1:
void foo() {
    using namespace std::ranges;
    std::vector<int> vec{1,2,3};
    find(begin(vec), end(vec), 2);       // #1
}
```

The function call expression at #1 invokes `std::ranges::find`, not `std::find`, despite that (a) the iterator type returned from `begin(vec)` and `end(vec)` may be associated with namespace `std` and (b) `std::find` is more specialized (13.7.7.3) than `std::ranges::find` since the former requires its first two parameters to have the same type. — end example

For purposes of determining the existence of data races, algorithms shall not modify objects referenced through an iterator argument unless the specification requires such modification.

Throughout this Clause, where the template parameters are not constrained, the names of template parameters are used to express type requirements.

(4.1) — If an algorithm’s `Effects` element specifies that a value pointed to by any iterator passed as an argument is modified, then the type of that argument shall meet the requirements of a mutable iterator (25.3).

(4.2) — If an algorithm’s template parameter is named `InputIterator`, `InputIterator1`, or `InputIterator2`, the template argument shall meet the `Cpp17InputIterator` requirements (25.3.5.3).

(4.3) — If an algorithm’s template parameter is named `OutputIterator`, `OutputIterator1`, or `OutputIterator2`, the template argument shall meet the `Cpp17OutputIterator` requirements (25.3.5.4).
If an algorithm's template parameter is named `ForwardIterator`, `ForwardIterator1`, `ForwardIterator2`, or `NoThrowForwardIterator`, the template argument shall meet the `Cpp17ForwardIterator` requirements (25.3.5.5) if it is required to be a mutable iterator, or model `forward_iterator` (25.3.4.11) otherwise.

If an algorithm's template parameter is named `NoThrowForwardIterator`, the template argument is also required to have the property that no exceptions are thrown from increment, assignment, or comparison of, or indirectation through, valid iterators.

If an algorithm's template parameter is named `BidirectionalIterator`, `BidirectionalIterator1`, or `BidirectionalIterator2`, the template argument shall meet the `Cpp17BidirectionalIterator` requirements (25.3.5.6) if it is required to be a mutable iterator, or model `bidirectional_iterator` (25.3.4.12) otherwise.

If an algorithm's template parameter is named `RandomAccessIterator`, `RandomAccessIterator1`, or `RandomAccessIterator2`, the template argument shall meet the `Cpp17RandomAccessIterator` requirements (25.3.5.7) if it is required to be a mutable iterator, or model `random_access_iterator` (25.3.4.13) otherwise.

[Note 1: These requirements do not affect iterator arguments that are constrained, for which iterator category and mutability requirements are expressed explicitly. — end note]

Both in-place and copying versions are provided for certain algorithms. When such a version is provided for `algorithm` it is called `algorithm_copy`. Algorithms that take predicates end with the suffix `_if` (which follows the suffix `_copy`).

When not otherwise constrained, the `Predicate` parameter is used whenever an algorithm expects a function object (22.10) that, when applied to the result of dereferencing the corresponding iterator, returns a value testable as `true`. If an algorithm takes `Predicate` as its argument and `first` as its iterator argument with value type `T`, the expression `pred(*first)` shall be well-formed and the type `decltype(pred(*first))` shall model `boolean-testable` (18.5.2). The function object `pred` shall not apply any non-constant function through its argument. Given a glvalue `u` of type (possibly const) `T` that designates the same object as `first`, `pred(u)` shall be a valid expression that is equal to `pred(*first)`. When not otherwise constrained, the `BinaryPredicate` parameter is used whenever an algorithm expects a function object that, when applied to the result of dereferencing two corresponding iterators or to dereferencing an iterator and type `T` when `T` is part of the signature, returns a value testable as `true`. If an algorithm takes `BinaryPredicate` as its argument and `first1` and `first2` as its iterator arguments with respective value types `T1` and `T2`, the expression `binary_pred(*first1, *first2)` shall be well-formed and the type `decltype(binary_pred(*first1, *first2))` shall model `boolean-testable`. Unless otherwise specified, `BinaryPredicate` always takes the first iterator’s `value_type` as its first argument, that is, in those cases when `T ` value is part of the signature, the expression `binary_pred(*first1, value)` shall be well-formed and the type `decltype(binary_pred(*first1, value))` shall model `boolean-testable`. `binary_pred` shall not apply any non-constant function through any of its arguments. Given a glvalue `u` of type (possibly const) `T1` that designates the same object as `first1`, and a glvalue `v` of type (possibly const) `T2` that designates the same object as `first2`, `binary_pred(u, *first2)`, `binary_pred(*first1, v)`, and `binary_pred(u, v)` shall each be a valid expression that is equal to `binary_pred(*first1, *first2)`, and `binary_pred(u, value)` shall be a valid expression that is equal to `binary_pred(*first1, value)`. The parameters `UnaryOperation`, `BinaryOperation`, `BinaryOperation1`, and `BinaryOperation2` are used whenever an algorithm expects a function object (22.10).

[Note 2: Unless otherwise specified, algorithms that take function objects as arguments can copy those function objects freely. If object identity is important, a wrapper class that points to a non-copied implementation object such as `reference_wrapper<T>` (22.10.6), or some equivalent solution, can be used. — end note]

When the description of an algorithm gives an expression such as `*first == value` for a condition, the expression shall evaluate to either `true` or `false` in boolean contexts.

In the description of the algorithms, operator `+` is used for some of the iterator categories for which it does not have to be defined. In these cases the semantics of `a + n` are the same as those of

```c
auto tmp = a;
for (; n < 0; ++n) --tmp;
```

The decision whether to include a copying version was usually based on complexity considerations. When the cost of doing the operation dominates the cost of copy, the copying version is not included. For example, `sort_copy` is not included because the cost of sorting is much more significant, and users can invoke `copy` followed by `sort`.

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§ 27.2
Similarly, operator - is used for some combinations of iterators and sentinel types for which it does not have to be defined. If \([a, b)\) denotes a range, the semantics of \(b - a\) in these cases are the same as those of

\[
\text{iter_difference_t<typename(a)> n = 0; for (auto tmp = a; tmp != b; ++tmp) ++n; return n;}
\]

and if \([b, a)\) denotes a range, the same as those of

\[
\text{iter_difference_t<typename(b)> n = 0; for (auto tmp = b; tmp != a; ++tmp) --n; return n;}
\]

12 In the description of the algorithms, given an iterator \(a\) whose difference type is \(D\), and an expression \(n\) of integer-like type other than \(cv\) \(D\), the semantics of \(a + n\) and \(a - n\) are, respectively, those of \(a + D(n)\) and \(a - D(n)\).

13 In the description of algorithm return values, a sentinel value \(s\) denoting the end of a range \([i, s)\) is sometimes returned where an iterator is expected. In these cases, the semantics are as if the sentinel is converted into an iterator using \(\text{ranges::next}(i, s)\).

14 Overloads of algorithms that take \textit{range} arguments (26.4.2) behave as if they are implemented by calling \texttt{ranges::begin} and \texttt{ranges::end} on the \textit{range}(s) and dispatching to the overload in namespace \texttt{ranges} that takes separate iterator and sentinel arguments.

15 The well-formedness and behavior of a call to an algorithm with an explicitly-specified template argument list is unspecified, except where explicitly stated otherwise.

\[\text{Note 3: Consequently, an implementation can declare an algorithm with different template parameters than those presented. —end note}\]

27.3 Parallel algorithms

27.3.1 Preamble

Subclause 27.3 describes components that C++ programs may use to perform operations on containers and other sequences in parallel.

A \textbf{parallel algorithm} is a function template listed in this document with a template parameter named \texttt{ExecutionPolicy}.

Parallel algorithms access objects indirectly accessible via their arguments by invoking the following functions:

\[(3.1)\] All operations of the categories of the iterators or \texttt{mdspan} types that the algorithm is instantiated with.

\[(3.2)\] Operations on those sequence elements that are required by its specification.

\[(3.3)\] User-provided function objects to be applied during the execution of the algorithm, if required by the specification.

\[(3.4)\] Operations on those function objects required by the specification.

\[\text{[Note 1: See 27.2. —end note]}\]

These functions are herein called \textit{element access functions}.

\[\text{[Example 1: The sort function may invoke the following element access functions:}\]

\[(4.1)\] Operations of the random-access iterator of the actual template argument (as per 25.3.5.7), as implied by the name of the template parameter \texttt{RandomAccessIterator}.

\[(4.2)\] The \texttt{swap} function on the elements of the sequence (as per the preconditions specified in 27.8.2.1).

\[(4.3)\] The user-provided \texttt{Compare} function object.

\[\text{—end example}\]

A standard library function is \textit{vectorization-unsafe} if it is specified to synchronize with another function invocation, or another function invocation is specified to synchronize with it, and if it is not a memory allocation or deallocation function.

\[\text{[Note 2: Implementations must ensure that internal synchronization inside standard library functions does not prevent forward progress when those functions are executed by threads of execution with weakly parallel forward progress guarantees. —end note]}\]
Example 2:

```cpp
int x = 0;
std::mutex m;
void f() {
    int a[2] = {1, 2};
    std::for_each(std::execution::par_unseq, std::begin(a), std::end(a), [&] (int) {
        std::lock_guard<mutex> guard(m); // incorrect: lock_guard constructor calls m.lock()
        ++x;
    });
}
```

The above program may result in two consecutive calls to `m.lock()` on the same thread of execution (which may deadlock), because the applications of the function object are not guaranteed to run on different threads of execution. — end example

27.3.2 Requirements on user-provided function objects [algorithms.parallel.user]

Unless otherwise specified, function objects passed into parallel algorithms as objects of type `Predicate`, `BinaryPredicate`, `Compare`, `UnaryOperation`, `BinaryOperation1`, `BinaryOperation2`, `BinaryDivideOp`, and the operators used by the analogous overloads to these parallel algorithms that are formed by an invocation with the specified default predicate or operation (where applicable) shall not directly or indirectly modify objects via their arguments, nor shall they rely on the identity of the provided objects.

27.3.3 Effect of execution policies on algorithm execution [algorithms.parallel.exec]

Parallel algorithms have template parameters named `ExecutionPolicy` (22.12) which describe the manner in which the execution of these algorithms may be parallelized and the manner in which they apply the element access functions.

1. If an object is modified by an element access function, the algorithm will perform no other unsynchronized accesses to that object. The modifying element access functions are those which are specified as modifying the object.

   [Note 1: For example, `swap`, `++`, `--`, `@=`, and assignments modify the object. For the assignment and `@=` operators, only the left argument is modified. — end note]

2. Unless otherwise stated, implementations may make arbitrary copies of elements (with type `T`) from sequences where `is_trivially_copy_constructible_v<T>` and `is_trivially_destructible_v<T>` are `true`.

   [Note 2: This implies that user-supplied function objects cannot rely on object identity of arguments for such input sequences. If object identity of the arguments to these function objects is important, a wrapping iterator that returns a non-copied implementation object such as `reference_wrapper<T>` (22.10.6), or some equivalent solution, can be used. — end note]

3. The invocations of element access functions in parallel algorithms invoked with an execution policy object of type `execution::sequenced_policy` all occur in the calling thread of execution.

   [Note 3: The invocations are not interleaved; see 6.9.1. — end note]

4. The invocations of element access functions in parallel algorithms invoked with an execution policy object of type `execution::unsequenced_policy` are permitted to execute in an unordered fashion in the calling thread of execution, unsequenced with respect to one another in the calling thread of execution.

   [Note 4: This means that multiple function object invocations can be interleaved on a single thread of execution, which overrides the usual guarantee from 6.9.1 that function executions do not overlap with one another. — end note]

   The behavior of a program is undefined if it invokes a vectorization-unsafe standard library function from user code called from an `execution::unsequenced_policy` algorithm.

   [Note 5: Because `execution::unsequenced_policy` allows the execution of element access functions to be interleaved on a single thread of execution, blocking synchronization, including the use of mutexes, risks deadlock. — end note]

5. The invocations of element access functions in parallel algorithms invoked with an execution policy object of type `execution::parallel_policy` are permitted to execute either in the invoking thread of execution or in a thread of execution implicitly created by the library to support parallel algorithm execution. If the threads of execution created by `thread` (33.4.3) or `jthread` (33.4.4) provide concurrent forward progress guarantees (6.9.2.3), then a thread of execution implicitly created by the library will provide parallel forward progress guarantees; otherwise, the provided forward progress guarantee is implementation-defined. Any such invocations executing in the same thread of execution are indeterminately sequenced with respect to each other.
[Note 6: It is the caller’s responsibility to ensure that the invocation does not introduce data races or deadlocks. — end note]

[Example 1:]
```cpp
int a[] = {0,1};
std::vector<int> v;
std::for_each(std::execution::par, std::begin(a), std::end(a), [&](int i) {
  v.push_back(i*2+1);  // incorrect: data race
});
```
The program above has a data race because of the unsynchronized access to the container `v`. — end example]

[Example 2:]
```cpp
std::atomic<int> x{0};
int a[] = {1,2};
std::for_each(std::execution::par, std::begin(a), std::end(a), [&](int) {
  x.fetch_add(1, std::memory_order::relaxed);
  // spin wait for another iteration to change the value of x
  while (x.load(std::memory_order::relaxed) == 1) { }  // incorrect: assumes execution order
});
```
The above example depends on the order of execution of the iterations, and will not terminate if both iterations are executed sequentially on the same thread of execution. — end example]

[Example 3:]
```cpp
int x = 0;
std::mutex m;
int a[] = {1,2};
std::for_each(std::execution::par, std::begin(a), std::end(a), [&](int) {
  std::lock_guard<mutex> guard(m);
  ++x;
});
```
The above example synchronizes access to object `x` ensuring that it is incremented correctly. — end example]

The invocations of element access functions in parallel algorithms invoked with an execution policy object of type `execution::parallel_unsequenced_policy` are permitted to execute in an unordered fashion in unspecified threads of execution, and unsequenced with respect to one another within each thread of execution. These threads of execution are either the invoking thread of execution or threads of execution implicitly created by the library; the latter will provide weakly parallel forward progress guarantees.

[Note 7: This means that multiple function object invocations can be interleaved on a single thread of execution, which overrides the usual guarantee from 6.9.1 that function executions do not overlap with one another. — end note]

The behavior of a program is undefined if it invokes a vectorization-unsafe standard library function from user code called from an `execution::parallel_unsequenced_policy` algorithm.

[Note 8: Because `execution::parallel_unsequenced_policy` allows the execution of element access functions to be interleaved on a single thread of execution, blocking synchronization, including the use of mutexes, risks deadlock. — end note]

[Note 9: The semantics of invocation with `execution::unsequenced_policy`, `execution::parallel_policy`, or `execution::parallel_unsequenced_policy` allow the implementation to fall back to sequential execution if the system cannot parallelize an algorithm invocation, e.g., due to lack of resources. — end note]

If an invocation of a parallel algorithm uses threads of execution implicitly created by the library, then the invoking thread of execution will either

1. temporarily block with forward progress guarantee delegation (6.9.2.3) on the completion of these library-managed threads of execution, or
2. eventually execute an element access function;

the thread of execution will continue to do so until the algorithm is finished.

[Note 10: In blocking with forward progress guarantee delegation in this context, a thread of execution created by the library is considered to have finished execution as soon as it has finished the execution of the particular element access function that the invoking thread of execution logically depends on. — end note]

The semantics of parallel algorithms invoked with an execution policy object of implementation-defined type are implementation-defined.
27.3.4 Parallel algorithm exceptions

During the execution of a parallel algorithm, if temporary memory resources are required for parallelization and none are available, the algorithm throws a `bad_alloc` exception.

During the execution of a parallel algorithm, if the invocation of an element access function exits via an uncaught exception, the behavior is determined by the `ExecutionPolicy`.

27.3.5 ExecutionPolicy algorithm overloads

Parallel algorithms are algorithm overloads. Each parallel algorithm overload has an additional template type parameter named `ExecutionPolicy`, which is the first template parameter. Additionally, each parallel algorithm overload has an additional function parameter of type `ExecutionPolicy&&`, which is the first function parameter.

[Note 1: Not all algorithms have parallel algorithm overloads. — end note]

Unless otherwise specified, the semantics of `ExecutionPolicy` algorithm overloads are identical to their overloads without.

Unless otherwise specified, the complexity requirements of `ExecutionPolicy` algorithm overloads are relaxed from the complexity requirements of the overloads without as follows: when the guarantee says “at most expr” or “exactly expr” and does not specify the number of assignments or swaps, and expr is not already expressed with \(O()\) notation, the complexity of the algorithm shall be \(O(expr)\).

Parallel algorithms shall not participate in overload resolution unless `is_execution_policy_v<remove_cvref_t<ExecutionPolicy>>` is true.

27.4 Header `<algorithm>` synopsis

```cpp
#include <initializer_list> // see 17.10.2

namespace std {
    namespace ranges {
        // 27.5, algorithm result types
        template<class I, class F>
            struct in_fun_result;
        template<class I1, class I2>
            struct in_in_result;
        template<class I, class O>
            struct in_out_result;
        template<class I1, class I2, class O>
            struct in_in_out_result;
        template<class I, class O1, class O2>
            struct in_out_out_result;
        template<class T>
            struct min_max_result;
        template<class I>
            struct in_found_result;
        template<class I, class T>
            struct in_value_result;
        template<class O, class T>
            struct out_value_result;
    }

    // 27.6, non-modifying sequence operations
    // 27.6.1, all of
    template<class InputIterator, class Predicate>
        constexpr bool all_of(InputIterator first, InputIterator last, Predicate pred);
```
template<class ExecutionPolicy, class ForwardIterator, class Predicate>
bool all_of(ExecutionPolicy&& exec,  // see 27.3.5
    ForwardIterator first, ForwardIterator last, Predicate pred);

namespace ranges {
    template<input_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_unary_predicate<projected<I, Proj>> Pred>
        constexpr bool all_of(I first, S last, Pred pred, Proj proj = {});
    template<input_range R, class Proj = identity,
        indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
        constexpr bool all_of(R&& r, Pred pred, Proj proj = {});
}

// 27.6.2, any_of
template<class InputIterator, class Predicate>
    constexpr bool any_of(InputIterator first, InputIterator last, Predicate pred);

namespace ranges {
    template<input_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_unary_predicate<projected<I, Proj>> Pred>
        constexpr bool any_of(I first, S last, Pred pred, Proj proj = {});
    template<input_range R, class Proj = identity,
        indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
        constexpr bool any_of(R&& r, Pred pred, Proj proj = {});
}

// 27.6.3, none_of
template<class InputIterator, class Predicate>
    constexpr bool none_of(InputIterator first, InputIterator last, Predicate pred);

namespace ranges {
    template<input_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_unary_predicate<projected<I, Proj>> Pred>
        constexpr bool none_of(I first, S last, Pred pred, Proj proj = {});
    template<input_range R, class Proj = identity,
        indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
        constexpr bool none_of(R&& r, Pred pred, Proj proj = {});
}

// 27.6.4, contains
namespace ranges {
    template<input_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_unary_predicate<projected<I, Proj>> Pred>
        constexpr bool contains(I first, S last, const T * value, Proj proj = {});
    template<input_range R, class Proj = identity,
        indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
        constexpr bool contains(R&& r, const T * value, Proj proj = {});
    template<forward_iterator I1, sentinel_for<I1> S1,
            forward_iterator I2, sentinel_for<I2> S2,
            class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
        requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
        constexpr bool contains_subrange(I1 first1, S1 last1, I2 first2, S2 last2,
            Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
template<forward_range R1, forward_range R2, 
class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires indirectly_comparable<iterator_t<R1>, iterator_t<R2>, Pred, Proj1, Proj2>
constexpr bool contains_subrange(R1&& r1, R2&& r2,
   Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

// 27.6.5, for each
template<class InputIterator, class Function>
constexpr Function for_each(InputIterator first, InputIterator last, Function f);
template<class ExecutionPolicy, class ForwardIterator, class Function>
void for_each(ExecutionPolicy&& exec,
   // see 27.3.5
   ForwardIterator first, ForwardIterator last, Function f);

namespace ranges {
  template<class I, class F>
  using for_each_result = in_fun_result<I, F>;

template<input_iterator I, sentinel_for<I> S, class Proj = identity,
   indirectly_unary_invocable<projected<I, Proj>> Fun>
constexpr for_each_result<I, Fun>
for_each(I first, S last, Fun f, Proj proj = {});

template<input_range R, class Proj = identity,
   indirectly_unary_invocable<projected<iterator_t<R>, Proj>> Fun>
constexpr for_each_result<borrowed_iterator_t<R>, Fun>
for_each(R&& r, Fun f, Proj proj = {});
}

namespace ranges {
  template<class InputIterator, class Size, class Function>
  constexpr InputIterator for_each_n(InputIterator first, Size n, Function f);
  template<class ExecutionPolicy, class ForwardIterator, class Size, class Function>
  ForwardIterator for_each_n(ExecutionPolicy&& exec,
   // see 27.3.5
   ForwardIterator first, Size n, Function f);
}

template<class InputIterator, class T = iterator_traits<InputIterator>::value_type>
constexpr InputIterator find(InputIterator first, InputIterator last, 
   const T& value);

template<class ExecutionPolicy, class ForwardIterator, 
   class T = iterator_traits<ForwardIterator>::value_type>
ForwardIterator find(ExecutionPolicy&& exec,
   // see 27.3.5
   ForwardIterator first, ForwardIterator last, 
   const T& value);

// 27.6.6, find
template<class InputIterator, class Predicate>
constexpr InputIterator find_if(InputIterator first, InputIterator last, 
   Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator find_if(ExecutionPolicy&& exec,
   // see 27.3.5
   ForwardIterator first, ForwardIterator last, 
   Predicate pred);

template<class InputIterator, class Predicate>
constexpr InputIterator find_if_not(InputIterator first, InputIterator last, 
   Predicate pred);
template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator find_if_not(ExecutionPolicy&& exec, // see 27.3.5
   ForwardIterator first, ForwardIterator last, 
   Predicate pred);

namespace ranges {
  template<input_iterator I, sentinel_for<I> S, class Proj = identity,
    class T = projected_value_t<I, Proj>>
    requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*> 
  constexpr I find(I first, S last, const T& value, Proj proj = {});
  template<input_range R, class Proj = identity, 
    class T = projected_value_t<iterator_t<R>, Proj>>
    requires indirect_binary_predicate<ranges::equal_to, 
                                    projected<iterator_t<R>, Proj>, const T*> 
  constexpr borrowed_iterator_t<R> find(R&& r, const T& value, Proj proj = {});

  template<input_iterator I, sentinel_for<I> S, class Proj = identity, 
    indirect_unary_predicate<projected<I, Proj>> Pred>
    constexpr I find_if(I first, S last, Pred pred, Proj proj = {});
  template<input_range R, class Proj = identity, 
    indirect_unary_predicate<projected_iterator_t<R>, Proj>>
    requires indirect_unary_predicate<ranges::equal_to, 
                                   projected<iterator_t<R>, Proj>, const T*> 
  constexpr borrowed_iterator_t<R> find_if(R&& r, Pred pred, Proj proj = {});

  // 27.6.7, find last
  namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity>
      requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*> 
    constexpr subrange<I> find_last(I first, S last, const T& value, Proj proj = {});
    template<forward_range R, class T, class Proj = identity> 
      requires indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T*> 
    constexpr borrowed_subrange_t<R> find_last(R&& r, const T& value, Proj proj = {});

    template<forward_iterator I, sentinel_for<I> S, class Proj = identity, 
      indirect_unary_predicate<projected_iterator_t<R>, Proj>>
      requires indirect_unary_predicate<ranges::equal_to, 
                                       projected<iterator_t<R>, Proj>, const T*> 
    constexpr subrange<I> find_last_if(I first, S last, Pred pred, Proj proj = {});
    template<forward_range R, class Proj = identity, 
      indirect_unary_predicate<projected_iterator_t<R>, Proj>>
      requires indirect_unary_predicate<ranges::equal_to, 
                                       projected<iterator_t<R>, Proj>, const T*> 
    constexpr borrowed_subrange_t<R> find_last_if(R&& r, Pred pred, Proj proj = {});

    // 27.6.8, find end
    template<class ForwardIterator1, class ForwardIterator2>
      constexpr ForwardIterator1 find_end(ForwardIterator1 first1, ForwardIterator1 last1,
                                            ForwardIterator2 first2, ForwardIterator2 last2);
    template<class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
      constexpr ForwardIterator1 find_end(ForwardIterator1 first1, ForwardIterator1 last1,
                                            ForwardIterator2 first2, ForwardIterator2 last2,§ 27.4
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator1
find_end(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2, ForwardIterator2 last2);

namespace ranges {
    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
    ForwardIterator1
    find_end(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first1, ForwardIterator1 last1,
        ForwardIterator2 first2, ForwardIterator2 last2,
        BinaryPredicate pred);
}

namespace ranges {
    template<forward_iterator I1, sentinel_for<I1> S1, forward_iterator I2, sentinel_for<I2> S2,
            class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
    requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
    constexpr subrange<I1>
    find_end(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
             Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.9, find first
namespace ranges {
    template<input_iterator I1, sentinel_for<I1> S1, forward_iterator I2, sentinel_for<I2> S2,
            class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
    requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
    constexpr I1
    find_first_of(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
                  Proj1 proj1 = {}, Proj2 proj2 = {});
}

§ 27.4 © ISO/IEC 1356
template<class ForwardIterator>
constexpr ForwardIterator
adjacent_find(ForwardIterator first, ForwardIterator last);

template<class ForwardIterator, class BinaryPredicate>
constexpr ForwardIterator
adjacent_find(ForwardIterator first, ForwardIterator last, BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
adjacent_find(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator, class BinaryPredicate>
ForwardIterator
adjacent_find(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last, BinaryPredicate pred);

namespace ranges {
  template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
            indirect_binary_predicate<projected<I, Proj>,
                                    projected<I, Proj>> Pred = ranges::equal_to>
  constexpr I adjacent_find(I first, S last, Pred pred = {}, Proj proj = {});

  template<forward_range R, class Proj = identity,
            indirect_binary_predicate<projected<iterator_t<R>, Proj>,
                                   projected<iterator_t<R>, Proj>> Pred = ranges::equal_to>
  constexpr borrowed_iterator_t<R>
  adjacent_find(R&& r, Pred pred = {}, Proj proj = {});
}

template<class InputIterator, class T = iterator_traits<InputIterator>::value_type>
constexpr typename iterator_traits<InputIterator>::difference_type
count(InputIterator first, InputIterator last, const T& value);

template<class ExecutionPolicy, class ForwardIterator,
         class T = iterator_traits<InputIterator>::value_type>
typename iterator_traits<ForwardIterator>::difference_type
count(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last, const T& value);

template<class InputIterator, class Predicate>
constexpr typename iterator_traits<InputIterator>::difference_type
count_if(InputIterator first, InputIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
typename iterator_traits<ForwardIterator>::difference_type
count_if(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last, Predicate pred);

namespace ranges {
  template<input_iterator I, sentinel_for<I> S, class Proj = identity,
            class T = projected_value_t<I, Proj>>
  requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*>.
  constexpr iter_difference_t<I>
  count(I first, S last, const T* value, Proj proj = {});

  template<input_range R, class Proj = identity,
            class T = projected_value_t<iterator_t<R>, Proj>>
  requires indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T*>
  constexpr range_difference_t<R>
  count(R&& r, const T* value, Proj proj = {});
}
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_unary_predicate<projected<I, Proj>> Pred>
        constexpr iter_difference_t<I>
count_if(I first, S last, Pred pred, Proj proj = {});
template<input_range R, class Proj = identity,
        indirect_unary_predicate<iterator_t<R>, Proj>> Pred>
        constexpr range_difference_t<R>
count_if(R&& r, Pred pred, Proj proj = {});
}

// 27.6.12, mismatch
template<class InputIterator1, class InputIterator2>
            constexpr pair<InputIterator1, InputIterator2>
mismatch(InputIterator1 first1, InputIterator1 last1,
            InputIterator2 first2);
template<class InputIterator1, class InputIterator2, class BinaryPredicate>
            constexpr pair<InputIterator1, InputIterator2>
mismatch(InputIterator1 first1, InputIterator1 last1,
            InputIterator2 first2, BinaryPredicate pred);
template<class InputIterator1, class InputIterator2>
            constexpr pair<InputIterator1, InputIterator2>
mismatch(InputIterator1 first1, InputIterator1 last1,
            InputIterator2 first2, InputIterator2 last2);
template<class InputIterator1, class InputIterator2, class BinaryPredicate>
            constexpr pair<InputIterator1, InputIterator2>
mismatch(InputIterator1 first1, InputIterator1 last1,
            InputIterator2 first2, InputIterator2 last2,
            BinaryPredicate pred);

namespace ranges {
    template<class I1, class I2>
        using mismatch_result = in_in_result<I1, I2>;

    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
            class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
        requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
        constexpr mismatch_result<I1, I2>
mismatch(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
            Proj1 proj1 = {}, Proj2 proj2 = {});
template<input_range R1, input_range R2,  
class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>  
requires indirectly_comparable<iterator_t<R1>, iterator_t<R2>>, Pred, Proj1, Proj2>  
constexpr mismatch_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>  
mismatch(R1&& r1, R2&& r2, Pred pred = {},  
        Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.13, equal  
template<class InputIterator1, class InputIterator2>  
constexpr bool equal(InputIterator1 first1, InputIterator1 last1,  
                     InputIterator2 first2);  

template<class InputIterator1, class InputIterator2, class BinaryPredicate>  
constexpr bool equal(InputIterator1 first1, InputIterator1 last1,  
                     InputIterator2 first2, BinaryPredicate pred);

template<class InputIterator1, class InputIterator2>  
constexpr bool equal(InputIterator1 first1, InputIterator1 last1,  
                     InputIterator2 first2, InputIterator2 last2);  

template<class InputIterator1, class InputIterator2, class BinaryPredicate>  
constexpr bool equal(InputIterator1 first1, InputIterator1 last1,  
                     InputIterator2 first2, InputIterator2 last2,  
                     BinaryPredicate pred);

namespace ranges {  
    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,  
             class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>  
    requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>  
    constexpr bool equal(I1 first1, S1 last1, I2 first2, S2 last2,  
                          Pred pred = {},  
                          Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.14, is permutation  
template<class ForwardIterator1, class ForwardIterator2>  
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,  
                               ForwardIterator2 first2, ForwardIterator2 last2);  

template<class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>  
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,  
                               ForwardIterator2 first2, ForwardIterator2 last2,  
                               BinaryPredicate pred);
template<class ForwardIterator1, class ForwardIterator2>
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,
                               ForwardIterator2 first2, ForwardIterator2 last2);

namespace ranges {

    template<class ForwardIterator I1, sentinel_for<I1> S1, forward_iterator I2,
             sentinel_for<I2> S2, class Proj1 = identity, class Proj2 = identity,
             indirect_equivalence_relation<projected<I1, Proj1>,
                                         projected<I2, Proj2>> Pred = ranges::equal_to>
    constexpr bool is_permutation(I1 first1, S1 last1, I2 first2, S2 last2,
                                   Pred pred = {},
                                   Proj1 proj1 = {}, Proj2 proj2 = {});

    template<class forward_range R1, forward_range R2,
             class Proj1 = identity, class Proj2 = identity,
             indirect_equivalence_relation<iterator_t<R1>, Proj1>,
             projected<iterator_t<R2>, Proj2>> Pred = ranges::equal_to>
    constexpr bool is_permutation(R1&& r1, R2&& r2, Pred pred = {},
                                   Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.15, search

namespace ranges {

    template<class ForwardIterator1, class ForwardIterator2>
    constexpr ForwardIterator1
    search(ForwardIterator1 first1, ForwardIterator1 last1,
           ForwardIterator2 first2, ForwardIterator2 last2);

    template<class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
    constexpr ForwardIterator1
    search(ForwardIterator1 first1, ForwardIterator1 last1,
           ForwardIterator2 first2, ForwardIterator2 last2,
           BinaryPredicate pred);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
    ForwardIterator1
    search(ExecutionPolicy&& exec,
            // see 27.3.5
            ForwardIterator1 first1, ForwardIterator1 last1,
            ForwardIterator2 first2, ForwardIterator2 last2);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
             class BinaryPredicate>
    ForwardIterator1
    search(ExecutionPolicy&& exec,
            // see 27.3.5
            ForwardIterator1 first1, ForwardIterator1 last1,
            ForwardIterator2 first2, ForwardIterator2 last2,
            BinaryPredicate pred);
}

namespace ranges {

    template<class forward_iterator I1, sentinel_for<I1> S1, forward_iterator I2,
             sentinel_for<I2> S2, class Pred = ranges::equal_to,
             class Proj1 = identity, class Proj2 = identity>
    requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
    constexpr subrange<I1>
    search(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
           Proj1 proj1 = {}, Proj2 proj2 = {});

    template<class forward_range R1, forward_range R2, class Pred = ranges::equal_to,
             class Proj1 = identity, class Proj2 = identity>
    requires indirectly_comparable<iterator_t<R1>, iterator_t<R2>, Pred, Proj1, Proj2>
    constexpr borrowed_subrange_t<R1>
    search(R1&& r1, R2&& r2, Pred pred = {},
           Proj1 proj1 = {}, Proj2 proj2 = {});
}

§ 27.4
template<class ForwardIterator, class Size,
class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator
search_n(ForwardIterator first, ForwardIterator last,
Size count, const T& value);

template<class ForwardIterator, class Size,
class T = iterator_traits<ForwardIterator>::value_type, class BinaryPredicate>
constexpr ForwardIterator
search_n(ForwardIterator first, ForwardIterator last,
Size count, const T& value, BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Size,
class T = iterator_traits<ForwardIterator>::value_type>
ForwardIterator
search_n(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last,
Size count, const T& value);

template<class ExecutionPolicy, class ForwardIterator, class Size,
class T = iterator_traits<ForwardIterator>::value_type, class BinaryPredicate>
ForwardIterator
search_n(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last,
Size count, const T& value, BinaryPredicate pred);

namespace ranges {

template<forward_iterator I, sentinel_for<I> S,
class Pred = ranges::equal_to, class Proj = identity,
class T = projected_value_t<I, Proj>>
requires indirectly_comparable<I, const T*, Pred, Proj>
constexpr subrange<I>
search_n(I first, S last, iter_difference_t<I> count,
const T& value, Pred pred = {}, Proj proj = {});

template<input_iterator I, sentinel_for<I> S1, input_iterator I2, sentinel_for<I2> S2,
class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
constexpr bool starts_with(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
Proj1 proj1 = {}, Proj2 proj2 = {});

namespace ranges {

// 27.6.16, starts with

// 27.6.17, ends with

template<input_range R1, input_range R2, class Pred = ranges::equal_to,
class Proj1 = identity, class Proj2 = identity>
requires (forward_range<R1> || sized_range<R1>) &&
(forward_range<R2> || sized_range<R2>) &&
indirectly_comparable<iterator_t<R1>, iterator_t<R2>>, Pred, Proj1, Proj2>
constexpr bool ends_with(R1&& r1, R2&& r2, Pred pred = {},
Proj1 proj1 = {}, Proj2 proj2 = {});

// 27.6.18, fold
template<class F>
class flipped {
  // exposition only
  F f;
  // exposition only
public:
  template<class T, class U> requires invocable<F&, U, T>
  invoke_result_t<F&, U, T> operator()(T&&, U&&);
};

template<class F, class T, class I, class U>
concept indirectly-binary-left-foldable-impl = // exposition only
  movable<T> && movable<U> &&
  convertible_to<T, U> && invocable<F&, U, iter_reference_t<I>> &&
  assignable_from<U, invoke_result_t<F&, U, iter_reference_t<I>>>;

template<class F, class T, class I>
concept indirectly-binary-left-foldable = // exposition only
  indirectly-binary-left-foldable-impl<F, T, I>;

template<input_iterator I, sentinel_for<I> S, class T = iter_value_t<I>,
  indirectly-binary-left-foldable<T, I> F>
constexpr auto fold_left(I first, S last, T init, F f);

template<input_range R, class T = range_value_t<R>,
  indirectly-binary-left-foldable<T, iterator_t<R>> F>
constexpr auto fold_left(R&& r, T init, F f);

template<input_iterator I, sentinel_for<I> S,
  indirectly-binary-right-foldable<iter_value_t<I>, I> F>
requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
constexpr auto fold_left_first(I first, S last, T init, F f);

template<input_range R, indirectly-binary-left-foldable<range_value_t<R>, iterator_t<R>> F>
requires constructible_from<range_value_t<R>, range_reference_t<R>>
constexpr auto fold_left_first(R&& r, F f);

template<bidirectional_iterator I, sentinel_for<I> S, class T = iter_value_t<I>,
  indirectly-binary-right-foldable<T, I> F>
constexpr auto fold_right(I first, S last, T init, F f);

template<bidirectional_range R, class T = range_value_t<R>,
  indirectly-binary-right-foldable<T, iterator_t<R>> F>
constexpr auto fold_right(R&& r, T init, F f);
template<bidirectional_iterator I, sentinel_for<I> S, 
  indirectly-binary-right-foldable<iter_value_t<I>, I> F> 
  requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
  constexpr auto fold_right_last(I first, S last, F f);

template<bidirectional_range R, 
  indirectly-binary-right-foldable<range_value_t<R>, iterator_t<R>> F> 
  requires constructible_from<range_value_t<R>, range_reference_t<R>>
  constexpr auto fold_right_last(R&& r, F f);

template<class I, class T> 
  using fold_left_with_iter_result = in_value_result<I, T>;

template<class I, class T> 
  using fold_left_first_with_iter_result = in_value_result<I, T>;

template<input_iterator I, sentinel_for<I> S, class T = iter_value_t<I>, 
  indirectly-binary-left-foldable<T, I> F> 
  requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
  constexpr 
  see below fold_left_with_iter(I first, S last, T init, F f);

template<input_range R, class T = range_value_t<R>, 
  indirectly-binary-left-foldable<T, iterator_t<R>> F> 
  requires constructible_from<range_value_t<R>, range_reference_t<R>>
  constexpr 
  see below fold_left_with_iter(R&& r, T init, F f);

template<input_iterator I, sentinel_for<I> S, 
  indirectly-binary-left-foldable<iter_value_t<I>, I> F> 
  requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
  constexpr 
  see below fold_left_first_with_iter(I first, S last, F f);

template<input_range R, 
  indirectly-binary-left-foldable<range_value_t<R>, iterator_t<R>> F> 
  requires constructible_from<range_value_t<R>, range_reference_t<R>>
  constexpr 
  see below fold_left_first_with_iter(R&& r, F f);

// 27.7, mutating sequence operations 
// 27.7.1, copy 
template<class InputIterator, class OutputIterator> 
  constexpr OutputIterator copy(InputIterator first, InputIterator last, 
  OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2> 
  ForwardIterator2 copy(ExecutionPolicy&& exec, 
  // see 27.3.5 
  ForwardIterator1 first, ForwardIterator1 last, 
  ForwardIterator2 result);

namespace ranges {
  template<class I, class O> 
  using copy_result = in_out_result<I, O>;

  template<input_iterator I, sentinel_for<I> S, weakly_incrementable O> 
  requires indirectly_copyable<I, O> 
  constexpr copy_result<I, O> 
  copy(I first, S last, O result); 

  template<input_range R, weakly_incrementable O> 
  requires indirectly_copyable<iterator_t<R>, O> 
  constexpr copy_result<borrowed_iterator_t<R>, O> 
  copy(R&& r, O result);
}

template<class InputIterator, class Size, class OutputIterator> 
  constexpr OutputIterator copy_n(InputIterator first, Size n, 
  OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class Size, 
  class ForwardIterator2> 
  ForwardIterator2 copy_n(ExecutionPolicy&& exec, 
  // see 27.3.5
  // 27.4
namespace ranges {
    template<class I, class O>
    using copy_n_result = in_out_result<I, O>;

template<input_iterator I, weakly_incrementable O>
    requires indirectly_copyable<I, O>
    constexpr copy_n_result<I, O> copy_n(I first, iter_difference_t<I> n, O result);
}

namespace ranges {
    template<class InputIterator, class OutputIterator, class Predicate>
    constexpr OutputIterator copy_if(InputIterator first, InputIterator last,
        OutputIterator result, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class Predicate>
    ForwardIterator2 copy_if(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first, ForwardIterator1 last,
        ForwardIterator2 result, Predicate pred);
}

namespace ranges {
    template<class I1, class I2>
    using copy_backward_result = in_out_result<I1, I2>;

template<bidirectional_iterator I1, sentinel_for<I1> S1, bidirectional_iterator I2>
    requires indirectly_copyable<I1, I2>
    constexpr copy_backward_result<I1, I2> copy_backward(I1 first, S1 last, I2 result);

template<bidirectional_range R, bidirectional_iterator I>
    requires indirectly_copyable<iterator_t<R>, I>
    constexpr copy_backward_result<borrowed_iterator_t<R>, I> copy_backward(R&& r, I result);
}

// 27.7.2, move
namespace ranges {
    template<class InputIterator, class OutputIterator>
    constexpr OutputIterator move(InputIterator first, InputIterator last,
        OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
    ForwardIterator2 move(ExecutionPolicy&& exec, // see 27.3.5
namespace ranges {
    template<class I, class O>
    using move_result = in_out_result<I, O>;

    template<input_iterator I, sentinel_for<I> S, weakly_incrementable O>
    requires indirectly_movable<I, O>
    constexpr move_result<I, O> move(I first, S last, O result);

    template<input_range R, weakly_incrementable O>
    requires indirectly_movable<input_iterator_t<R>, O>
    constexpr move_result<borrowed_iterator_t<R>, O> move(R&& r, O result);
}

namespace ranges {
    template<class BidirectionalIterator1, class BidirectionalIterator2>
    constexpr BidirectionalIterator2 move_backward(BidirectionalIterator1 first, BidirectionalIterator1 last, BidirectionalIterator2 result);

    template<class I1, class I2>
    using move_backward_result = in_out_result<I1, I2>;

    template<bidirectional_iterator I1, sentinel_for<I1> S1, bidirectional_iterator I2>
    requires indirectly_movable<I1, I2>
    constexpr move_backward_result<I1, I2> move_backward(I1 first, S1 last, I2 result);

    template<bidirectional_range R, bidirectional_iterator I>
    requires indirectly_movable<iterator_t<R>, I>
    constexpr move_backward_result<borrowed_iterator_t<R>, I> move_backward(R&& r, I result);
}

// 27.7.3, swap
namespace ranges {
    template<class ForwardIterator1, class ForwardIterator2>
    constexpr ForwardIterator2 swap_ranges(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 result);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
    ForwardIterator2 swap_ranges(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 result);
}

namespace ranges {
    template<class I1, class I2>
    using swap_ranges_result = in_in_result<I1, I2>;

    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2>
    requires indirectly_swappable<I1, I2>
    constexpr swap_ranges_result<I1, I2> swap_ranges(I1 first1, S1 last1, I2 first2, S2 last2);

    template<input_range R1, input_range R2>
    requires indirectly_swappable<input_iterator_t<R1>, iterator_t<R2>>
    constexpr swap_ranges_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>> swap_ranges(R1&& r1, R2&& r2);
}

namespace ranges {
    template<class ForwardIterator1, class ForwardIterator2>
    constexpr void iter_swap(ForwardIterator1 a, ForwardIterator2 b);
}

§ 27.4
template<class InputIterator1, class InputIterator2, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
transform(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, OutputIterator result, BinaryOperation binary_op);

namespace ranges {
    template<class I, class O>
    using unary_transform_result = in_out_result<I, O>;

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, copy_constructible F, class Proj = identity>
requires indirectly_writable<O, indirect_result_t<F&, projected<I, Proj>>
constexpr unary_transform_result<I, O>
transform(I first1, S last1, O result, F op, Proj proj = {});

template<input_range R, weakly_incrementable O, copy_constructible F, class Proj1 = identity, class Proj2 = identity>
requires indirectly_writable<O, indirect_result_t<F&, projected<iterator_t<R1>, Proj1>, projected<iterator_t<R2>, Proj2>>
constexpr binary_transform_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
transform(R&& r1, R&& r2, O result, F binary_op, Proj1 proj1 = {}, Proj2 proj2 = {});

// 27.7.5, replace
template<class ForwardIterator, class T>
constexpr void replace(ForwardIterator first, ForwardIterator last, const T& old_value, const T& new_value);

§ 27.4
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template<class ExecutionPolicy, class ForwardIterator,  
class T = iterator_traits<ForwardIterator>::value_type>  
void replace(ExecutionPolicy&& exec,  
    ForwardIterator first, ForwardIterator last,  
    const T& old_value, const T& new_value);  

template<class ForwardIterator, class Predicate,  
class T = iterator_traits<ForwardIterator>::value_type>  
constexpr void replace_if(ForwardIterator first, ForwardIterator last,  
    Predicate pred, const T& new_value);  

namespace ranges {  
    template<input_iterator I, sentinel_for<I> S, class Proj = identity,  
        class T1 = projected_value_t<I, Proj>, class T2 = T1>  
    requires indirectly_writable<I, const T2&> &&  
        indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T1*>  
    constexpr I replace(I first, S last, const T1& old_value, const T2& new_value, Proj proj = {});  

    template<input_range R, class Proj = identity,  
        class T1 = projected_value_t<iterator_t<R>, Proj>, class T2 = T1>  
    requires indirectly_writable<iterator_t<R>, const T2&> &&  
        indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T1*>  
    constexpr borrowed_iterator_t<R> replace(R&& r, const T1& old_value, const T2& new_value, Proj proj = {});  

    template<input_iterator I, sentinel_for<I> S, class Proj = identity,  
        class T = projected_value_t<I, Proj>,  
        indirect_unary_predicate<projected<I, Proj>> Pred>  
    requires indirectly_writable<I, const T&>  
    constexpr I replace_if(I first, S last, Pred pred, const T& new_value, Proj proj = {});  

    template<input_range R, class Proj = identity, class T = projected_value_t<I, Proj>,  
        indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>  
    requires indirectly_writable<iterator_t<R>, const T&>  
    constexpr borrowed_iterator_t<R> replace_if(R&& r, Pred pred, const T& new_value, Proj proj = {});  
}  

template<class InputIterator, class OutputIterator, class T>  
constexpr OutputIterator replace_copy(InputIterator first, InputIterator last,  
    OutputIterator result,  
    const T& old_value, const T& new_value);  

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class T>  
ForwardIterator2 replace_copy(ExecutionPolicy&& exec,  
    ForwardIterator1 first, ForwardIterator1 last,  
    ForwardIterator2 result,  
    const T& old_value, const T& new_value);  

template<class InputIterator, class OutputIterator, class Predicate,  
    class T = iterator_traits<OutputIterator>::value_type>  
constexpr OutputIterator replace_copy_if(InputIterator first, InputIterator last,  
    OutputIterator result,  
    Predicate pred, const T& new_value);  

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,  
    class Predicate, class T = iterator_traits<ForwardIterator2>::value_type>  
ForwardIterator2 replace_copy_if(ExecutionPolicy&& exec,  
    ForwardIterator1 first, ForwardIterator1 last,  
    ForwardIterator2 result,  
    Predicate pred, const T& new_value);
namespace ranges {
    template<class I, class O>
    using replace_copy_result = in_out_result<I, O>;

    template<input_iterator I, sentinel_for<I> S, class O, 
    class Proj = identity, 
    class T1 = projected_value_t<I, Proj>, class T2 = iter_value_t<O>>
    requires indirectly_copyable<I, O> && 
    indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T1*>& &
    output_iterator<O, const T2&>
    constexpr replace_copy_result<I, O>
    replace_copy(I first, S last, O result, const T1& old_value, const T2& new_value,
                  Proj proj = {});

    template<input_range R, class O, 
    class Proj = identity, 
    class T1 = projected_value_t<iterator_t<R>, Proj>, class T2 = iter_value_t<O>>
    requires indirectly_copyable<iterator_t<R>, O> && 
    indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T1*>& &
    output_iterator<O, const T2&>
    constexpr replace_copy_result<borrowed_iterator_t<R>, O>
    replace_copy(R&& r, O result, const T1& old_value, const T2& new_value,
                  Proj proj = {});

    template<class I, class O>
    using replace_copy_if_result = in_out_result<I, O>;

    template<input_iterator I, sentinel_for<I> S, class O, class T = iter_value_t<O>, 
    class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
    requires indirectly_copyable<I, O> && output_iterator<O, const T&>
    constexpr replace_copy_if_result<I, O>
    replace_copy_if(I first, S last, O result, Pred pred, const T& new_value,
                    Proj proj = {});

    template<input_range R, class O, class T = iter_value_t<O>, class Proj = identity, 
    indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
    requires indirectly_copyable<iterator_t<R>, O> && output_iterator<O, const T&>
    constexpr replace_copy_if_result<borrowed_iterator_t<R>, O>
    replace_copy_if(R&& r, O result, Pred pred, const T& new_value,
                    Proj proj = {});
)

// 27.7.6, fill
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr void fill(ForwardIterator first, ForwardIterator last, const T& value);

template<class ExecutionPolicy, class ForwardIterator, 
class T = iterator_traits<ForwardIterator>::value_type>
void fill(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator first, ForwardIterator last, const T& value);

template<class OutputIterator, class Size, 
class T = iterator_traits<OutputIterator>::value_type>
constexpr OutputIterator fill_n(OutputIterator first, Size n, const T& value); // freestanding

template<class ExecutionPolicy, class ForwardIterator, 
class Size, class T = iterator_traits<ForwardIterator>::value_type>
ForwardIterator fill_n(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator first, Size n, const T& value);

namespace ranges {
    template<class O, sentinel_for<O> S, class T = iter_value_t<O>>
    requires output_iterator<O, const T&>
    constexpr O fill(O first, S last, const T& value);

    template<class R, class T = range_value_t<R>>
    requires output_range<R, const T&>
    constexpr borrowed_iterator_t<R> fill(R&& r, const T& value);

}}
template<class O, class T = iter_value_t<O>>

requires output_iterator<O, const T&>

constexpr O fill_n(O first, iter_difference_t<O> n, const T& value);

// 27.7.7, generate

template<class ForwardIterator, class Generator>
constexpr void generate(ForwardIterator first, ForwardIterator last,
                        Generator gen);

template<class ExecutionPolicy, class ForwardIterator, class Generator>
void generate(ExecutionPolicy&& exec,
              ForwardIterator first, ForwardIterator last,
              Generator gen); // see 27.3.5

template<class OutputIterator, class Size, class Generator>
constexpr OutputIterator generate_n(OutputIterator first, Size n, Generator gen);

template<class ExecutionPolicy, class ForwardIterator, class Size, class Generator>
ForwardIterator generate_n(ExecutionPolicy&& exec,
                           ForwardIterator first, Size n, Generator gen);

namespace ranges {

template<input_or_output_iterator O, sentinel_for<O> S, copy_constructible F>
requires invocable<F&> && indirectly_writable<O, invoke_result_t<F&>>
constexpr O generate(O first, S last, F gen);

template<class R, copy_constructible F>
requires invocable<F&> && output_range<R, invoke_result_t<F&>>
constexpr borrowed_iterator_t<R> generate(R&& r, F gen);

template<input_or_output_iterator O, copy_constructible F>
requires invocable<F&> && indirectly_writable<O, invoke_result_t<F&>>
constexpr O generate_n(O first, iter_difference_t<O> n, F gen);

// 27.7.8, remove

template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator remove(ForwardIterator first, ForwardIterator last,
                                const T& value);

template<class ExecutionPolicy, class ForwardIterator,
         class T = iterator_traits<ForwardIterator>::value_type>
ForwardIterator remove(ExecutionPolicy&& exec,
                       ForwardIterator first, ForwardIterator last,
                       const T& value); // see 27.3.5

template<class ForwardIterator, class Predicate>
constexpr ForwardIterator remove_if(ForwardIterator first, ForwardIterator last,
                                    Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator remove_if(ExecutionPolicy&& exec,
                         ForwardIterator first, ForwardIterator last,
                         Predicate pred); // see 27.3.5

namespace ranges {

template<permutable I, sentinel_for<I> S, class Proj = identity,
         class T = projected_value_t<I, Proj>>
requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*>
constexpr subrange<I> remove(I first, S last, const T& value, Proj proj = {});

template<forward_range R, class Proj = identity,
         class T = projected_value_t<iterator_t<R>, Proj>>
requires permutable<iterator_t<R>> &&
indirect_binary_predicate<ranges::equal_to,
                         projected<iterator_t<R>, Proj>, const T*>
constexpr borrowed_subrange_t<R> remove(R&& r, const T& value, Proj proj = {});

template<permutable I, sentinel_for<I> S, class Proj = identity,
         indirect_unary_predicate<projected<I, Proj>> Pred>
constexpr subrange<I> remove_if(I first, S last, Pred pred, Proj proj = {});

§ 27.4
template<forward_range R, class Proj = identity,
    indirect_unary_predicate<projected<iterator_t<R>>, Proj>>
requires permutable<iterator_t<R>>
constexpr borrowed subrange_t<R>
    remove_if(R&& r, Pred pred, Proj proj = {});
}

template<class InputIterator, class OutputIterator,
    class T = iterator_traits<InputIterator>::value_type
constexpr OutputIterator
    remove_copy(InputIterator first, InputIterator last,
        OutputIterator result, const T& value);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class T = iterator_traits<ForwardIterator1>::value_type
ForwardIterator2
    remove_copy(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first, ForwardIterator1 last,
        ForwardIterator2 result, const T& value);

template<class InputIterator, class OutputIterator, class Predicate
constexpr OutputIterator
    remove_copy_if(InputIterator first, InputIterator last,
        OutputIterator result, Predicate pred);

namespace ranges {
    template<class I, class O>
    using remove_copy_result = in_out_result<I, O>;

    template<input_iterator I, sentinel_for<I> S, weakly_incremenatable O,
        class Proj = identity, class T = projected_value_t<I, Proj>>
requires indirectly_copyable<I, O> &&
    indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*>
constexpr remove_copy_result<I, O>
    remove_copy(I first, S last, O result, const T& value, Proj proj = {});

    template<input_range R, weakly_incremenatable O, class Proj = identity,
        indirect_unary_predicate<projected<iterator_t<R>>, Proj>>
requires indirectly_copyable<iterator_t<R>, O> &&
    indirect_binary_predicate<ranges::equal_to,
        projected<iterator_t<R>, Proj>, const T*>
constexpr remove_copy_result<borrowed_iterator_t<R>, O>
    remove_copy(R&& r, O result, const T& value, Proj proj = {});

    template<class I, class O>
    using remove_copy_if_result = in_out_result<I, O>;

    template<input_iterator I, sentinel_for<I> S, weakly_incremenatable O,
        class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
requires indirectly_copyable<I, O>
constexpr remove_copy_if_result<I, O>
    remove_copy_if(I first, S last, O result, Pred pred, Proj proj = {});

    template<input_range R, weakly_incremenatable O,
        indirect_unary_predicate<projected<iterator_t<R>>, Proj>> Pred>
requires indirectly_copyable<iterator_t<R>, O>
constexpr remove_copy_if_result<borrowed_iterator_t<R>, O>
    remove_copy_if(R&& r, O result, Pred pred, Proj proj = {});
}
// 27.7.9, unique

template<class ForwardIterator>
constexpr ForwardIterator unique(ForwardIterator first, ForwardIterator last);

template<class ForwardIterator, class BinaryPredicate>
constexpr ForwardIterator unique(ForwardIterator first, ForwardIterator last,
    BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator unique(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator, class BinaryPredicate>
ForwardIterator unique(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator first, ForwardIterator last,
    BinaryPredicate pred);

namespace ranges {
    template<permutable I, sentinel_for<I> S, class Proj = identity,
        indirect_equivalence_relation<projected<I, Proj>> C = ranges::equal_to>
    constexpr subrange<I> unique(I first, S last, C comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity,
        indirect_equivalence_relation<iterator_t<R>, Proj>> C = ranges::equal_to>
    requires permutable<iterator_t<R>>
    constexpr borrowed_subrange_t<R>
    unique(R&& r, C comp = {}, Proj proj = {});
}

template<class InputIterator, class OutputIterator>
constexpr OutputIterator
unique_copy(InputIterator first, InputIterator last,
    OutputIterator result);

template<class InputIterator, class OutputIterator, class BinaryPredicate>
constexpr OutputIterator
unique_copy(InputIterator first, InputIterator last,
    OutputIterator result, BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
unique_copy(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class BinaryPredicate>
ForwardIterator2
unique_copy(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, BinaryPredicate pred);

namespace ranges {
    template<class I, class O>
    using unique_copy_result = in_out_result<I, O>;

    template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, class Proj = identity,
        indirect_equivalence_relation<projected<I, Proj>> C = ranges::equal_to>
    requires indirectly_copyable<I, O> &&
    (forward_iterator<I> ||
    (input_iterator<O> && same_as<range_value_t<I>, iter_value_t<O>>) ||
    indirectly_copyable_storable<I, O>)
    constexpr unique_copy_result<I, O>
    unique_copy(I first, S last, O result, C comp = {}, Proj proj = {});
    template<input_range R, weakly_incrementable O, class Proj = identity,
        indirect_equivalence_relation<iterator_t<R>, Proj>> C = ranges::equal_to>
    requires indirectly_copyable<iterator_t<R>, O> &&
    (forward_iterator<iterator_t<R>> ||
    (input_iterator<O> && same_as<range_value_t<R>, iter_value_t<O>>) ||
    indirectly_copyable_storable<iterator_t<R>, O>)
    constexpr unique_copy_result<borrowed_iterator_t<R>, O>
unique_copy(R&& r, O result, C comp = {}, Proj proj = {});
}

// 27.7.10, reverse

namespace ranges {
    template<bidirectional_iterator I, sentinel_for<I> S>
    requires permutable<I>
    constexpr I reverse(I first, S last);
    template<bidirectional_range R>
    requires permutable<iterator_t<R>>
    constexpr borrowed_iterator_t<R> reverse(R&& r);
}

namespace ranges {
    template<class I, class O>
    using reverse_copy_result = in_out_result<I, O>;
    template<bidirectional_iterator I, sentinel_for<I> S, weakly_incrementable O>
    requires indirectly_copyable<I, O>
    constexpr reverse_copy_result<I, O> reverse_copy(I first, I middle, S last, O result);
    template<bidirectional_range R, weakly_incrementable O>
    requires indirectly_copyable<iterator_t<R>, O>
    constexpr reverse_copy_result<borrowed_iterator_t<R>, O> reverse_copy(R&& r, O result);
}

// 27.7.11, rotate

namespace ranges {
    template<class ForwardIterator>
    constexpr ForwardIterator rotate(ForwardIterator first,
                                     ForwardIterator middle,
                                     ForwardIterator last);
    template<class ExecutionPolicy, class ForwardIterator>
    ForwardIterator rotate(ExecutionPolicy&& exec, // see 27.3.5
                           ForwardIterator first,
                           ForwardIterator middle,
                           ForwardIterator last);
}

§ 27.4
template<
class ForwardIterator, class OutputIterator>
constexpr OutputIterator
rotate_copy(ForwardIterator first, ForwardIterator middle,
 ForwardIterator last, OutputIterator result);

template<
class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
rotate_copy(ExecutionPolicy&& exec,
 ForwardIterator1 first, ForwardIterator1 middle,
 ForwardIterator1 last, ForwardIterator2 result);

namespace ranges {
 template<class I, class O>
 using rotate_copy_result = in_out_result<I, O>;

template<forward_iterator I, sentinel_for<I> S, weakly_incrementable O>
 requires indirectly_copyable<I, O>
 constexpr rotate_copy_result<I, O>
 rotate_copy(I first, I middle, S last, O result);

template<forward_range R, weakly_incrementable O>
 requires indirectly_copyable<iterator_t<R>, O>
 constexpr rotate_copy_result<borrowed_iterator_t<R>, O>
 rotate_copy(R&& r, iterator_t<R> middle, O result);
}

// 27.7.12, sample

template<class PopulationIterator, class SampleIterator,
 class Distance, class UniformRandomBitGenerator>
 SampleIterator sample(PopulationIterator first, PopulationIterator last,
 SampleIterator out, Distance n,
 UniformRandomBitGenerator&& g);

namespace ranges {
 template<input_iterator I, sentinel_for<I> S,
 weakly_incrementable O, class Gen>
 requires (forward_iterator<I> || random_access_iterator<O>) &&
 indirectly_copyable<I, O> &&
 uniform_random_bit_generator<remove_reference_t<Gen>>
 O sample(I first, S last, O out, iter_difference_t<I> n, Gen&& g);

template<input_range R, weakly_incrementable O, class Gen>
 requires (forward_range<R> || random_access_iterator<O>) &&
 indirectly_copyable<iterator_t<R>, O> &&
 uniform_random_bit_generator<remove_reference_t<Gen>>
 O sample(R&& r, O out, range_difference_t<R> n, Gen&& g);
}

// 27.7.13, shuffle

template<class RandomAccessIterator, class UniformRandomBitGenerator>
 void shuffle(RandomAccessIterator first,
 RandomAccessIterator last,
 UniformRandomBitGenerator&& g);

namespace ranges {
 template<random_access_iterator I, sentinel_for<I> S, class Gen>
 requires permutable<I> &&
 uniform_random_bit_generator<remove_reference_t<Gen>>
 I shuffle(I first, S last, Gen&& g);

template<random_access_range R, class Gen>
 requires permutable<iterator_t<R>> &&
 uniform_random_bit_generator<remove_reference_t<Gen>>
 borrowed_iterator_t<R> shuffle(R&& r, Gen&& g);
}
template<class ForwardIterator>
constexpr ForwardIterator
shift_left(ForwardIterator first, ForwardIterator last,
   typename iterator_traits<ForwardIterator>::difference_type n);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
shift_left(ExecutionPolicy&& exec,
   ForwardIterator first, ForwardIterator last,
   typename iterator_traits<ForwardIterator>::difference_type n);

namespace ranges {
    template<permutable I, sentinel_for<I> S>
        constexpr subrange<I> shift_left(I first, S last, iter_difference_t<I> n);
    template<forward_range R>
        requires permutable<iterator_t<R>>
        constexpr borrowed_subrange_t<R> shift_left(R&& r, range_difference_t<R> n);
}

template<class ForwardIterator>
constexpr ForwardIterator
shift_right(ForwardIterator first, ForwardIterator last,
   typename iterator_traits<ForwardIterator>::difference_type n);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
shift_right(ExecutionPolicy&& exec,
   ForwardIterator first, ForwardIterator last,
   typename iterator_traits<ForwardIterator>::difference_type n);

namespace ranges {
    template<permutable I, sentinel_for<I> S>
        constexpr subrange<I> shift_right(I first, S last, iter_difference_t<I> n);
    template<forward_range R>
        requires permutable<iterator_t<R>>
        constexpr borrowed_subrange_t<R> shift_right(R&& r, range_difference_t<R> n);
}

// 27.8.2, sorting
template<class RandomAccessIterator>
constexpr void sort(RandomAccessIterator first, RandomAccessIterator last);

namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
                class Proj = identity>
        requires sortable<I, Comp, Proj>
        constexpr I sort(I first, S last, Comp comp = {}, Proj proj = {});
    template<random_access_range R, class Comp = ranges::less, class Proj = identity>
        requires sortable<iterator_t<R>, Comp, Proj>
        constexpr borrowed_iterator_t<R> sort(R&& r, Comp comp = {}, Proj proj = {});
}
template<class RandomAccessIterator>
constexpr void stable_sort(RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void stable_sort(RandomAccessIterator first, RandomAccessIterator last, Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator>
void stable_sort(ExecutionPolicy&& exec,
  // see 27.3.5
RandomAccessIterator first, RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void stable_sort(ExecutionPolicy&& exec,
  // see 27.3.5
RandomAccessIterator first, RandomAccessIterator last, Compare comp);

namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
      class Proj = identity>
    requires sortable<I, Comp, Proj>
    constexpr I stable_sort(I first, S last, Comp comp = {}, Proj proj = {});

    template<random_access_range R, class Comp = ranges::less, class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
    constexpr borrowed_iterator_t<R>
    stable_sort(R&& r, Comp comp = {}, Proj proj = {});
}

template<class RandomAccessIterator>
constexpr void partial_sort(RandomAccessIterator first, RandomAccessIterator middle,
RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void partial_sort(RandomAccessIterator first, RandomAccessIterator middle,
RandomAccessIterator last, Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator>
void partial_sort(ExecutionPolicy&& exec,
// see 27.3.5
RandomAccessIterator first, RandomAccessIterator middle,
RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void partial_sort(ExecutionPolicy&& exec,
// see 27.3.5
RandomAccessIterator first, RandomAccessIterator middle,
RandomAccessIterator last, Compare comp);

namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
      class Proj = identity>
    requires sortable<I, Comp, Proj>
    constexpr I partial_sort(I first, I middle, S last, Comp comp = {}, Proj proj = {});

    template<random_access_range R, class Comp = ranges::less, class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
    constexpr borrowed_iterator_t<R>
    partial_sort(R&& r, iterator_t<R> middle, Comp comp = {}, Proj proj = {});
}

template<class InputIterator, class RandomAccessIterator>
constexpr RandomAccessIterator
partial_sort_copy(InputIterator first, InputIterator last,
RandomAccessIterator result_first,
RandomAccessIterator result_last);

template<class InputIterator, class RandomAccessIterator, class Compare>
constexpr RandomAccessIterator
partial_sort_copy(InputIterator first, InputIterator last,
RandomAccessIterator result_first,
RandomAccessIterator result_last, Compare comp);
template<
class ExecutionPolicy, class ForwardIterator, class RandomAccessIterator>
RandomAccessIterator
partial_sort_copy(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last,
RandomAccessIterator result_first,
RandomAccessIterator result_last);

template<
class ExecutionPolicy, class ForwardIterator, class RandomAccessIterator,
class Compare>
RandomAccessIterator
partial_sort_copy(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last,
RandomAccessIterator result_first,
RandomAccessIterator result_last,
Compare comp);

namespace ranges {

template<class I, class O>
using partial_sort_copy_result = in_out_result<I, O>;

template<input_iterator I1, sentinel_for<I1> S1,
random_access_iterator I2, sentinel_for<I2> S2,
class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
requires indirectly_copyable<I1, I2> && sortable<I2, Comp, Proj2> &&
indirect_strict_weak_order<Comp, projected<I1, Proj1>, projected<I2, Proj2>>
constexpr partial_sort_copy_result<I1, I2>
partial_sort_copy(I1 first, S1 last, I2 result_first, S2 result_last,
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, random_access_range R2, class Comp = ranges::less,
class Proj1 = identity, class Proj2 = identity>
requires indirectly_copyable<iterator_t<R1>, iterator_t<R2>> &
sortable<iterator_t<R2>, Comp, Proj2> &
indirect_strict_weak_order<Comp, projected<iterator_t<R1>, Proj1>,
projected<iterator_t<R2>, Proj2>>
constexpr partial_sort_copy_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
partial_sort_copy(R1&& r, R2&& result_r, Comp comp = {},
Proj1 proj1 = {}, Proj2 proj2 = {});
}

template<class ForwardIterator>
constexpr bool is_sorted(ForwardIterator first, ForwardIterator last);

namespace ranges {

template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr bool is_sorted(I first, S last, Comp comp = {}, Proj proj = {});

template<forman_range R, class Proj = identity,
indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr bool is_sorted(R&& r, Comp comp = {}, Proj proj = {});
}

template<class ForwardIterator>
constexpr ForwardIterator
is_sorted_until(ForwardIterator first, ForwardIterator last);
// 27.4, Binary search
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator
lower_bound(ForwardIterator first, ForwardIterator last, const T& value);

// 27.4, Binary search
namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
    requires sortable<I, Comp, Proj>
   constexpr I
    nth_element(I first, I nth, S last, Comp comp = {}, Proj proj = {});
    template<random_access_range R, class Comp = ranges::less, class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
   constexpr borrowed_iterator_t<R>
    nth_element(R&& r, iterator_t<R> nth, Comp comp = {}, Proj proj = {});
}

// 27.8.4, Binary search
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator
lower_bound(ForwardIterator first, ForwardIterator last, const T& value);

// 27.8.4, Binary search
namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
    requires sortable<I, Comp, Proj>
   constexpr I
    nth_element(I first, I nth, S last, Comp comp = {}, Proj proj = {});
    template<random_access_range R, class Comp = ranges::less, class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
   constexpr borrowed_iterator_t<R>
    nth_element(R&& r, iterator_t<R> nth, Comp comp = {}, Proj proj = {});
}
namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
    class T = projected_value_t<I, Proj>,
    indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
    constexpr I lower_bound(I first, S last, const T& value, Comp comp = {},
    Proj proj = {});
    template<forward_range R, class Proj = identity,
    class T = projected_value_t<iterator_t<R>, Proj>,
    indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp =
    ranges::less>
    constexpr borrowed_iterator_t<R> lower_bound(R&& r, const T& value, Comp comp = {}, Proj proj = {});
}

template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last,
const T& value);

namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
    class T = projected_value_t<I, Proj, indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
    constexpr subrange<I> upper_bound(I first, S last, const T& value, Comp comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity,
    class T = projected_value_t<iterator_t<R>, Proj, indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr borrowed_subrange_t<R> upper_bound(R&& r, const T& value, Comp comp = {}, Proj proj = {});
}

namespace ranges {
    template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
    constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, ForwardIterator last,
const T& value);
    template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type,
    class Compare>
    constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, ForwardIterator last,
const T& value, Compare comp);
}

namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
    class T = projected_value_t<I, Proj, indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
    constexpr subrange<I> equal_range(I first, S last, const T& value, Comp comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity,
    class T = projected_value_t<iterator_t<R>, Proj, indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr borrowed_subrange_t<R> equal_range(R&& r, const T& value, Comp comp = {}, Proj proj = {});
}
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr bool
binary_search(ForwardIterator first, ForwardIterator last, const T& value);

template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type, class Compare>
constexpr bool
binary_search(ForwardIterator first, ForwardIterator last, const T& value, Compare comp);

namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class Proj = identity, class T = projected_value_t<I, Proj>, indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
    constexpr bool binary_search(I first, S last, const T& value, Comp comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity, class T = projected_value_t<iterator_t<R>, Proj>, indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr bool binary_search(R&& r, const T& value, Comp comp = {}, Proj proj = {});
}

// 27.8.5, partitions
template<class InputIterator, class Predicate>
constexpr bool is_partitioned(InputIterator first, InputIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
bool is_partitioned(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Predicate pred);

namespace ranges {
    template<input_iterator I, sentinel_for<I> S, class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
    constexpr bool is_partitioned(I first, S last, Pred pred, Proj proj = {});
    template<input_range R, class Proj = identity, indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
    constexpr bool is_partitioned(R&& r, Pred pred, Proj proj = {});
}

template<class ForwardIterator, class Predicate>
constexpr ForwardIterator partition(ForwardIterator first, ForwardIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator partition(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Predicate pred);

namespace ranges {
    template<permutable I, sentinel_for<I> S, class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
    constexpr subrange<I> partition(I first, S last, Pred pred, Proj proj = {});
    template<forward_range R, class Proj = identity, indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
    requires permutable<iterator_t<R>>
    constexpr borrowed_subrange_t<R> partition(R&& r, Pred pred, Proj proj = {});
}

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template<class BidirectionalIterator, class Predicate>
constexpr BidirectionalIterator stable_partition(BidirectionalIterator first, 
        BidirectionalIterator last, 
        Predicate pred);

template<class ExecutionPolicy, class BidirectionalIterator, class Predicate>
BidirectionalIterator stable_partition(ExecutionPolicy&& exec, // see 27.3.5 
        BidirectionalIterator first, 
        BidirectionalIterator last, 
        Predicate pred);

namespace ranges {
    template<bidirectional_iterator I, sentinel_for<I> S, class Proj = identity, 
        indirect_unary_predicate<projected<I, Proj>> Pred>
    requires permutable<I>
    constexpr subrange<I> stable_partition(I first, S last, Pred pred, Proj proj = {});

template<bidirectional_range R, class Proj = identity, 
        indirect_unary_predicate<iterator_t<R>, Proj>> Pred>
    requires permutable<iterator_t<R>>
    constexpr borrowed_subrange_t<R> stable_partition(R&& r, Pred pred, Proj proj = {});
}

template<class InputIterator, class OutputIterator1, 
        class OutputIterator2, class Predicate>
constexpr pair<OutputIterator1, OutputIterator2> 
    partition_copy(InputIterator first, InputIterator last, 
        OutputIterator1 out_true, OutputIterator2 out_false, 
        Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class ForwardIterator1, 
        class ForwardIterator2, class Predicate>
pair<ForwardIterator1, ForwardIterator2> 
    partition_copy(ExecutionPolicy&& exec, // see 27.3.5 
        ForwardIterator first, ForwardIterator last, 
        ForwardIterator1 out_true, ForwardIterator2 out_false, 
        Predicate pred);

namespace ranges {
    template<class I, class O1, class O2>
    using partition_copy_result = in_out_out_result<I, O1, O2>;

    template<input_iterator I, sentinel_for<I> S, 
            weakly_incrementable O1, weakly_incrementable O2, 
            class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
    requires indirectly_copyable<I, O1> && indirectly_copyable<I, O2>
    constexpr partition_copy_result<I, O1, O2> 
        partition_copy(I first, S last, O1 out_true, O2 out_false, Pred pred, 
            Proj proj = {});

    template<input_range R, weakly_incrementable O1, weakly_incrementable O2, 
            class Proj = identity, 
            indirect_unary_predicate<iterator_t<R>, Proj>> Pred>
    requires indirectly_copyable<iterator_t<R>, O1> && 
            indirectly_copyable<iterator_t<R>, O2>
    constexpr partition_copy_result<borrowed_iterator_t<R>, O1, O2> 
        partition_copy(R&& r, O1 out_true, O2 out_false, Pred pred, Proj proj = {});
}

template<class ForwardIterator, class Predicate>
constexpr ForwardIterator 
    partition_point(ForwardIterator first, ForwardIterator last, 
        Predicate pred);

namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, 
            weakly_incrementable O1, weakly_incrementable O2, 
            class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
    constexpr I partition_point(I first, S last, Pred pred, Proj proj = {});
}
template<forward_range R, class Proj = identity,
    indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
constexpr borrowed_iterator_t<R>
    partition_point(R&& r, Pred pred, Proj proj = {});

// 27.8.6, merge
template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
    merge(InputIterator1 first1, InputIterator1 last1,
         InputIterator2 first2, InputIterator2 last2,
         OutputIterator result);
template<class InputIterator1, class InputIterator2, class OutputIterator,
    class Compare>
constexpr OutputIterator
    merge(InputIterator1 first1, InputIterator1 last1,
         InputIterator2 first2, InputIterator2 last2,
         OutputIterator result, Compare comp);
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class Compare>
ForwardIterator
    merge(ExecutionPolicy&& exec,
         ForwardIterator1 first1, ForwardIterator1 last1,
         ForwardIterator2 first2, ForwardIterator2 last2,
         ForwardIterator result, Compare comp);

namespace ranges {
    template<class I1, class I2, class O>
    using merge_result = in_in_out_result<I1, I2, O>;
    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
        weakly_incrementable O, class Comp = ranges::less, class Proj1 = identity,
        class Proj2 = identity>
    requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
    constexpr merge_result<I1, I2, O>
    merge(I1 first1, S1 last1, I2 first2, S2 last2, O result,
          Comp comp = {}, Proj1 proji = {}, Proj2 proj2 = {});
    template<input_range R1, input_range R2, weakly_incrementable O, class Comp = ranges::less,
        class Proj1 = identity, class Proj2 = identity>
    requires mergeable<iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
    constexpr merge_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
    merge(R1&& r1, R2&& r2, O result,
          Comp comp = {}, Proj1 proji = {}, Proj2 proj2 = {});
}

template<class BidirectionalIterator>
constexpr void inplace_merge(BidirectionalIterator first,
      BidirectionalIterator middle,
      BidirectionalIterator last);

template<class ExecutionPolicy, class BidirectionalIterator>
void inplace_merge(ExecutionPolicy&& exec,
      BidirectionalIterator first,
      BidirectionalIterator middle,
      BidirectionalIterator last);
BidirectionalIterator last);

// see 27.3.5
template<class ExecutionPolicy, class BidirectionalIterator, class Compare>
void inplace_merge(ExecutionPolicy&& exec,

BidirectionalIterator first,
BidirectionalIterator middle,
BidirectionalIterator last, Compare comp);

namespace ranges {

template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less,

class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I inplace_merge(I first, I middle, S last, Comp comp = {}, Proj proj = {});

template<bidirectional_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>

inplace_merge(R&& r, iterator_t<R> middle, Comp comp = {},

Proj proj = {});

// 27.8.7, set operations

template<class InputIterator1, class InputIterator2>
constexpr bool includes(InputIterator1 first1, InputIterator1 last1,

InputIterator2 first2, InputIterator2 last2);

template<class InputIterator1, class InputIterator2, class Compare>
constexpr bool includes(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
Compare comp);
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class ForwardIterator>
ForwardIterator
set_union(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2, ForwardIterator2 last2,
    ForwardIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class Compare>
ForwardIterator
set_union(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2, ForwardIterator2 last2,
    ForwardIterator result, Compare comp);

namespace ranges {
    template<class I1, class I2, class O>
    using set_union_result = in_in_out_result<I1, I2, O>;

    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
        weakly_incrementable O, class Comp = ranges::less,
        class Proj1 = identity, class Proj2 = identity>
    requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
    constexpr set_union_result<I1, I2, O>
    set_union(I1 first1, S1 last1, I2 first2, S2 last2, O result, Comp comp = {},
        Proj1 proj1 = {}, Proj2 proj2 = {});

    template<input_range R1, input_range R2, weakly_incrementable O,
        class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
    requires mergeable<input_iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
    constexpr set_union_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
    set_union(R1&& r1, R2&& r2, O result, Comp comp = {},
        Proj1 proj1 = {}, Proj2 proj2 = {});
}

template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
set_intersection(InputIterator1 first1, InputIterator1 last1,
    InputIterator2 first2, InputIterator2 last2,
    OutputIterator result);

template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
set_intersection(InputIterator1 first1, InputIterator1 last1,
    InputIterator2 first2, InputIterator2 last2,
    OutputIterator result, Compare comp);

namespace ranges {
    template<class I1, class I2, class O>
    using set_intersection_result = in_in_out_result<I1, I2, O>;

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class ForwardIterator>
    set_intersection(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first1, ForwardIterator1 last1,
        ForwardIterator2 first2, ForwardIterator2 last2,
        ForwardIterator result);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class Compare>
    set_intersection(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first1, ForwardIterator1 last1,
        ForwardIterator2 first2, ForwardIterator2 last2,
        ForwardIterator result, Compare comp);
}

§ 27.4

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1383
template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
weakly_incrementable O, class Comp = ranges::less,
class Proj1 = identity, class Proj2 = identity>
requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
constexpr set_intersection_result<I1, I2, O>
set_intersection(I1 first1, S1 last1, I2 first2, S2 last2, O result,
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
template<input_range R1, input_range R2, weakly_incrementable O,
class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
requires mergeable<iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
constexpr set_intersection_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
set_intersection(R1&& r1, R2&& r2, O result,
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
}

namespace ranges {

template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
set_difference(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result);
template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
set_difference(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result, Compare comp);

namespace ranges {

namespace ranges {

template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
set_symmetric_difference(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result);
}

§ 27.4
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1384
template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
set_symmetric_difference(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result, Compare comp);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
class ForwardIterator>
ForwardIterator
set_symmetric_difference(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
ForwardIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
class ForwardIterator, class Compare>
ForwardIterator
set_symmetric_difference(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
ForwardIterator result, Compare comp);

namespace ranges {
    template<class I1, class I2, class O>
    using set_symmetric_difference_result = in_in_out_result<I1, I2, O>;

    namespace {
        template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
        weakly_incrementable O, class Comp = ranges::less,
        class Proj1 = identity, class Proj2 = identity>
        requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
        constexpr set_symmetric_difference_result<I1, I2, O>
        set_symmetric_difference(I1 first1, S1 last1, I2 first2, S2 last2, O result,
        Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

        template<input_range R1, input_range R2, weakly_incrementable O,
        class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
        requires mergeable<iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
        constexpr set_symmetric_difference_result< borrowed_iterator_t<R1>,
        borrowed_iterator_t<R2>, O>
        set_symmetric_difference(R1&& r1, R2&& r2, O result, Comp comp = {},
        Proj1 proj1 = {}, Proj2 proj2 = {});
    }
}

// 27.8.8, heap operations
namespace {template<class RandomAccessIterator>
    constexpr void push_heap(RandomAccessIterator first, RandomAccessIterator last);
    template<class RandomAccessIterator, class Compare>
    constexpr void push_heap(RandomAccessIterator first, RandomAccessIterator last,
    Compare comp);
}

namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
    class Proj = identity>
    requires sortable<I, Comp, Proj>
    constexpr I
    push_heap(I first, S last, Comp comp = {}, Proj proj = {});

    template<random_access_range R, class Comp = ranges::less, class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
    constexpr borrowed_iterator_t<R>
    push_heap(R&& r, Comp comp = {}, Proj proj = {});
}

template<class RandomAccessIterator>
constexpr void pop_heap(RandomAccessIterator first, RandomAccessIterator last);
template<class RandomAccessIterator, class Compare>
constexpr void pop_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);

namespace ranges {
  template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
  requires sortable<I, Comp, Proj>
  constexpr I pop_heap(I first, S last, Comp comp = {}, Proj proj = {});
  template<random_access_range R, class Comp = ranges::less, class Proj = identity>
  requires sortable<iterator_t<R>, Comp, Proj>
  constexpr borrowed_iterator_t<R> pop_heap(R&& r, Comp comp = {}, Proj proj = {});
}

template<class RandomAccessIterator>
constexpr void make_heap(RandomAccessIterator first, RandomAccessIterator last);

namespace ranges {
  template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
  requires sortable<I, Comp, Proj>
  constexpr I make_heap(I first, S last, Comp comp = {}, Proj proj = {});
  template<random_access_range R, class Comp = ranges::less, class Proj = identity>
  requires sortable<iterator_t<R>, Comp, Proj>
  constexpr borrowed_iterator_t<R> make_heap(R&& r, Comp comp = {}, Proj proj = {});
}

template<class RandomAccessIterator>
constexpr void sort_heap(RandomAccessIterator first, RandomAccessIterator last);

namespace ranges {
  template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
  requires sortable<I, Comp, Proj>
  constexpr I sort_heap(I first, S last, Comp comp = {}, Proj proj = {});
  template<random_access_range R, class Comp = ranges::less, class Proj = identity>
  requires sortable<iterator_t<R>, Comp, Proj>
  constexpr borrowed_iterator_t<R> sort_heap(R&& r, Comp comp = {}, Proj proj = {});
}

template<class RandomAccessIterator>
constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last);

namespace ranges {
  template<class ExecutionPolicy, class RandomAccessIterator>
  bool is_heap(ExecutionPolicy&& exec, RandomAccessIterator first, RandomAccessIterator last);
  template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
  bool is_heap(ExecutionPolicy&& exec, RandomAccessIterator first, RandomAccessIterator last, Compare comp);
}
namespace ranges {
    template<random_access_iterator I, sentinel_for<I> S, class Proj = identity,
             indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
    constexpr bool is_heap(I first, S last, Comp comp = {}, Proj proj = {});
    template<random_access_range R, class Proj = identity,
             indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr bool is_heap(R&& r, Comp comp = {}, Proj proj = {});
}

template<class RandomAccessIterator>
constexpr RandomAccessIterator
is_heap_until(RandomAccessIterator first, RandomAccessIterator last);

namespace ranges {
    template<class RandomAccessIterator, class Compare>
    constexpr RandomAccessIterator
    is_heap_until(RandomAccessIterator first, RandomAccessIterator last,
                  Compare comp);
    template<class ExecutionPolicy, class RandomAccessIterator>
    RandomAccessIterator
    is_heap_until(ExecutionPolicy&& exec,
                  RandomAccessIterator first, RandomAccessIterator last);
    template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
    RandomAccessIterator
    is_heap_until(ExecutionPolicy&& exec,
                  RandomAccessIterator first, RandomAccessIterator last,
                  Compare comp);
}

// 27.8.9, minimum and maximum
template<class T>
constexpr const T& min(const T& a, const T& b);

namespace ranges {
    template<class T, class Proj = identity,
             indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr const T& min(const T& a, const T& b, Comp comp = {}, Proj proj = {});
    template<copyable T, class Proj = identity,
             indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr T min(initializer_list<T> r, Comp comp = {}, Proj proj = {});
    template<input_range R, class Proj = identity,
             indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
    requires indirectly_copyable_storable<iterator_t<R>, range_value_t<R>>
    constexpr range_value_t<R>
    min(R&& r, Comp comp = {}, Proj proj = {});
}

template<class T>
constexpr const T& max(const T& a, const T& b);

namespace ranges {
    template<class T, class Proj = identity,
             indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr const T& max(const T& a, const T& b, Comp comp = {}, Proj proj = {});
    template<class T, class Compare>
    constexpr const T& max(const T& a, const T& b, Compare comp);
    template<class T>
    constexpr T max(initializer_list<T> t);
    template<class T, class Compare>
    constexpr T max(initializer_list<T> t, Compare comp);
}
template<class T, class Compare>
constexpr T max(initializer_list<T> t, Compare comp);

namespace ranges {
    template<class T, class Proj = identity,
        indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr const T& max(const T& a, const T& b, Comp comp = {}, Proj proj = {});
    template<copyable T, class Proj = identity,
        indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr T max(initializer_list<T> r, Comp comp = {}, Proj proj = {});
    template<input_range R, class Proj = identity,
        indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
    requires indirectly_copyable_storable<iterator_t<R>, range_value_t<R>>
    constexpr range_value_t<R> max(R&& r, Comp comp = {}, Proj proj = {});
}

template<class T> constexpr pair<const T&, const T&> minmax(const T& a, const T& b);

template<class T, class Compare>
constexpr pair<const T&, const T&> minmax(const T& a, const T& b, Compare comp);

template<class T>
constexpr pair<T, T> minmax(initializer_list<T> t);

template<class T, class Compare>
constexpr pair<T, T> minmax(initializer_list<T> t, Compare comp);

namespace ranges {
    template<class T>
    using minmax_result = min_max_result<T>;
    
    template<class T, class Proj = identity,
        indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr minmax_result<const T&> minmax(const T& a, const T& b, Comp comp = {}, Proj proj = {});
    template<copyable T, class Proj = identity,
        indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr minmax_result<T> minmax(initializer_list<T> r, Comp comp = {}, Proj proj = {});
    template<input_range R, class Proj = identity,
        indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
    requires indirectly_copyable_storable<iterator_t<R>, range_value_t<R>>
    constexpr minmax_result<range_value_t<R>> minmax(R&& r, Comp comp = {}, Proj proj = {});
}

template<class ForwardIterator>
constexpr ForwardIterator min_element(ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator min_element(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator min_element(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,
    Compare comp);

namespace ranges {
    template<forward_iterator I, sentinel_for<forward_iterator> S, class Proj = identity,
        indirect_strict_weak_order<projected<forward_iterator, Proj>> Comp = ranges::less>
    constexpr I min_element(I first, S last, Comp comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity,
        indirect_strict_weak_order<projected<iterator_t<forward_range>, Proj>> Comp = ranges::less>
    constexpr borrowed_iterator_t<forward_range> min_element(R&& r, Proj comp = {}, Proj proj = {});

§ 27.4 https://www.iso.org/standard/1388.html
min_element(R&& r, Comp comp = {}, Proj proj = {});
}

template<class ForwardIterator>
constexpr ForwardIterator max_element(ForwardIterator first, ForwardIterator last);
template<class ForwardIterator, class Compare>
constexpr ForwardIterator max_element(ForwardIterator first, ForwardIterator last, Compare comp);
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator max_element(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last);
template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator max_element(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator first, ForwardIterator last, Compare comp);

namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
    constexpr I max_element(I first, S last, Comp comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity,
        indirect_strict_weak_order<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr borrowed_iterator_t<R>
    max_element(R&& r, Comp comp = {}, Proj proj = {});
}

namespace ranges {
    template<class ForwardIterator>
    constexpr pair<ForwardIterator, ForwardIterator>
    minmax_element(ForwardIterator first, ForwardIterator last);
    template<class ForwardIterator, class Compare>
    constexpr pair<ForwardIterator, ForwardIterator>
    minmax_element(ForwardIterator first, ForwardIterator last, Compare comp);
    template<class ExecutionPolicy, class ForwardIterator>
    pair<ForwardIterator, ForwardIterator>
    minmax_element(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator first, ForwardIterator last);
    template<class ExecutionPolicy, class ForwardIterator, class Compare>
    pair<ForwardIterator, ForwardIterator>
    minmax_element(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator first, ForwardIterator last, Compare comp);
}

namespace ranges {
    template<class I>
    using minmax_element_result = min_max_result<I>;
    template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
        indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
    constexpr minmax_element_result<I>
    minmax_element(I first, S last, Comp comp = {}, Proj proj = {});
    template<forward_range R, class Proj = identity,
        indirect_strict_weak_order<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr minmax_element_result<borrowed_iterator_t<R>>
    minmax_element(R&& r, Comp comp = {}, Proj proj = {});
}

// 27.8.10, bounded value
template<class T>
constexpr const T& clamp(const T& v, const T& lo, const T& hi);
template<class T, class Compare>
constexpr const T& clamp(const T& v, const T& lo, const T& hi, Compare comp);
```cpp
namespace ranges {
    template<class T, class Proj = identity,
             indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr const T&
        clamp(const T& v, const T& lo, const T& hi, Comp comp = {}, Proj proj = {});
}

// 27.8.11, lexicographical comparison
template<class InputIterator1, class InputIterator2>
constexpr bool
    lexicographical_compare(InputIterator1 first1, InputIterator1 last1,
                             InputIterator2 first2, InputIterator2 last2);

template<class InputIterator1, class InputIterator2, class Compare>
constexpr bool
    lexicographical_compare(InputIterator1 first1, InputIterator1 last1,
                             InputIterator2 first2, InputIterator2 last2,
                             Compare comp);

namespace ranges {
    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
             class Proj1 = identity, class Proj2 = identity,
             indirect_strict_weak_order<projected<I1, Proj1>, projected<I2, Proj2>> Comp =
             ranges::less>
    constexpr bool
        lexicographical_compare(I1 first1, S1 last1, I2 first2, S2 last2,
                                Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
    template<input_range R1, input_range R2, class Proj1 = identity,
              class Proj2 = identity,
              indirect_strict_weak_order<projected<iterator_t<R1>, Proj1>,
                                      projected<iterator_t<R2>, Proj2>> Comp = ranges::less>
    constexpr bool
        lexicographical_compare(R1&& r1, R2&& r2, Comp comp = {},
                                 Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.8.12, three-way comparison algorithms
template<class InputIterator1, class InputIterator2, class Cmp>
constexpr auto
    lexicographical_compare_three_way(InputIterator1 b1, InputIterator1 e1,
                                        InputIterator2 b2, InputIterator2 e2,
                                        Cmp comp)
-> decltype(comp(*b1, *b2));

template<class InputIterator1, class InputIterator2>
constexpr auto
    lexicographical_compare_three_way(InputIterator1 b1, InputIterator1 e1,
                                        InputIterator2 b2, InputIterator2 e2);

// 27.8.13, permutations
template<class BidirectionalIterator>
constexpr bool
    next_permutation(BidirectionalIterator first, BidirectionalIterator last);
```


```cpp
template<class BidirectionalIterator, class Compare>
constexpr bool next_permutation(BidirectionalIterator first,
                                BidirectionalIterator last, Compare comp);

namespace ranges {
    template<class I>
    using next_permutation_result = in_found_result<I>;

    template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less,
             class Proj = identity>
    requires sortable<I, Comp, Proj>
    constexpr next_permutation_result<I>
    next_permutation(I first, S last, Comp comp = {}, Proj proj = {});

    template<bidirectional_range R, class Comp = ranges::less,
             class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
    constexpr next_permutation_result<borrowed_iterator_t<R>>
    next_permutation(R&& r, Comp comp = {}, Proj proj = {});
}

template<class BidirectionalIterator>
constexpr bool prev_permutation(BidirectionalIterator first,
                                 BidirectionalIterator last);

namespace ranges {
    template<class I>
    using prev_permutation_result = in_found_result<I>;

    template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less,
             class Proj = identity>
    requires sortable<I, Comp, Proj>
    constexpr prev_permutation_result<I>
    prev_permutation(I first, S last, Comp comp = {}, Proj proj = {});

    template<bidirectional_range R, class Comp = ranges::less,
             class Proj = identity>
    requires sortable<iterator_t<R>, Comp, Proj>
    constexpr prev_permutation_result<borrowed_iterator_t<R>>
    prev_permutation(R&& r, Comp comp = {}, Proj proj = {});
}

27.5 Algorithm result types

Each of the class templates specified in this subclause has the template parameters, data members, and special members specified below, and has no base classes or members other than those specified.

```
template<class I1, class I2>
struct in_in_result {
    [[no_unique_address]] I1 in1;
    [[no_unique_address]] I2 in2;

template<class II1, class II2>
    requires convertible_to<const I1&, II1> && convertible_to<const I2&, II2>
constexpr operator in_in_result<II1, II2>() const & {
    return {in1, in2};
}
template<class II1, class II2>
    requires convertible_to<const I1, II1> && convertible_to<const I2, II2>
constexpr operator in_in_result<II1, II2>() && {
    return {std::move(in1), std::move(in2)};
};

template<class I, class O>
struct in_out_result {
    [[no_unique_address]] I in;
    [[no_unique_address]] O out;

template<class I2, class O2>
    requires convertible_to<const I&, I2> && convertible_to<const O&, O2>
constexpr operator in_out_result<I2, O2>() const & {
    return {in, out};
}
template<class I2, class O2>
    requires convertible_to<I, I2> && convertible_to<O, O2>
constexpr operator in_out_result<I2, O2>() && {
    return {std::move(in), std::move(out)};
};

template<class I1, class I2, class O>
struct in_in_out_result {
    [[no_unique_address]] I1 in1;
    [[no_unique_address]] I2 in2;
    [[no_unique_address]] O out;

template<class II1, class II2, class OO>
    requires convertible_to<const I1&, II1> &&
    convertible_to<const I2&, II2> &&
    convertible_to<const O&, OO>
constexpr operator in_in_out_result<II1, II2, OO>() const & {
    return {in1, in2, out};
}
template<class II1, class II2, class OO>
    requires convertible_to<I1, II1> &&
    convertible_to<I2, II2> &&
    convertible_to<O, OO>
constexpr operator in_in_out_result<II1, II2, OO>() && {
    return {std::move(in1), std::move(in2), std::move(out)};
};
template<class I, class O1, class O2>
struct in_out_out_result {
    [[no_unique_address]] I in;
    [[no_unique_address]] O1 out1;
    [[no_unique_address]] O2 out2;
}

template<class II, class OO1, class OO2>
requires convertible_to<const I&, II> &&
    convertible_to<const O1&, OO1> &&
    convertible_to<const O2&, OO2>
constexpr operator in_out_out_result<II, OO1, OO2>() const & {
    return {in, out1, out2};
}

template<class II, class OO1, class OO2>
requires convertible_to<const I&, II> &&
    convertible_to<const O1&, OO1> &&
    convertible_to<const O2&, OO2>
constexpr operator in_out_out_result<II, OO1, OO2>() && {
    return {std::move(in), std::move(out1), std::move(out2)};
}

template<class T>
struct min_max_result {
    [[no_unique_address]] T min;
    [[no_unique_address]] T max;
}

template<class T2>
requires convertible_to<const T&, T2>
constexpr operator min_max_result<T2>() const & {
    return {min, max};
}

template<class T2>
requires convertible_to<const T&, T2>
constexpr operator min_max_result<T2>() && {
    return {std::move(min), std::move(max)};
}

template<class I>
struct in_found_result {
    [[no_unique_address]] I in;
    bool found;
}

template<class I2>
requires convertible_to<const I&, I2>
constexpr operator in_found_result<I2>() const & {
    return {in, found};
}

template<class I2>
requires convertible_to<const I&, I2>
constexpr operator in_found_result<I2>() && {
    return {std::move(in), found};
}

template<class I, class T>
struct in_value_result {
    [[no_unique_address]] I in;
    [[no_unique_address]] T value;
}
27.6 Non-modifying sequence operations [alg.nonmodifying]

27.6.1 All of [alg.all.of]

template<class InputIterator, class Predicate>
constexpr bool all_of(InputIterator first, InputIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
bool all_of(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, 
            Predicate pred);

template<input_iterator I, sentinel_for<I> S, class Proj = identity, 
          indirect_unary_predicate<projected<I, Proj>> Pred>
constexpr bool ranges::all_of(I first, S last, Pred pred, Proj proj = {});

template<input_range R, class Proj = identity, 
          indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
constexpr bool ranges::all_of(R&& r, Pred pred, Proj proj = {});

Let E be:

1. 
   \[ \text{pred}(*i) \] for the overloads in namespace std;
2. 
   \[ \text{invoke(pred, invoke(proj, \ast i))} \] for the overloads in namespace ranges.

Returns: false if E is false for some iterator \( i \) in the range \([\text{first}, \text{last})\), and true otherwise.

Complexity: At most \( \text{last} - \text{first} \) applications of the predicate and any projection.

27.6.2 Any of [alg.any.of]

template<class InputIterator, class Predicate>
constexpr bool any_of(InputIterator first, InputIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
bool any_of(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, 
            Predicate pred);
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
  indirect_unary_predicate<projected<I>, Proj>> Pred>
constexpr bool ranges::any_of(I first, S last, Pred pred, Proj proj = {});

template<input_range R, class Proj = identity,
  indirect_unary_predicate<projected<iterator_t<R>>, Proj>> Pred>
constexpr bool ranges::any_of(R&& r, Pred pred, Proj proj = {});

Let $E$ be:

1. (1.1) $\textit{pred}(*i)$ for the overloads in namespace \texttt{std};
2. (1.2) $\textit{invoke}(\textit{pred}, \textit{invoke}(\textit{proj}, *i))$ for the overloads in namespace \texttt{ranges}.

\textit{Returns}: true if $E$ is true for some iterator $i$ in the range \texttt{[first, last)}, and false otherwise.

\textit{Complexity}: At most last - first applications of the predicate and any projection.

27.6.3 None of

$\texttt{ranges::none\_of}()$

template<class InputIterator, class Predicate>
constexpr bool none_of(InputIterator first, InputIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
bool none_of(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,
  Predicate pred);

Let $E$ be:

1. (1.1) $\textit{pred}(*i)$ for the overloads in namespace \texttt{std};
2. (1.2) $\textit{invoke}(\textit{pred}, \textit{invoke}(\textit{proj}, *i))$ for the overloads in namespace \texttt{ranges}.

\textit{Returns}: false if $E$ is true for some iterator $i$ in the range \texttt{[first, last)}, and true otherwise.

\textit{Complexity}: At most last - first applications of the predicate and any projection.

27.6.4 Contains

$\texttt{ranges::contains}()$

template<input_iterator I, sentinel_for<I> S, class Proj = identity,
  class T = projected_value_t<I, Proj>>
requires indirect_binary_predicate<ranges::equal_to, projected<I>, Proj>, const T*>
constexpr bool ranges::contains(I first, S last, const T& value, Proj proj = {});

template<input_range R, class Proj = identity, class T = projected_value_t<iterator_t<R>, Proj>>
requires indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>>, Proj>, const T*>
constexpr bool ranges::contains(R&& r, const T& value, Proj proj = {});

Returns: $\texttt{ranges::find}() = \texttt{last}$.

template<forward_iterator I1, sentinel_for<I1> S1,
  forward_iterator I2, sentinel_for<I2> S2,
  class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
constexpr bool ranges::contains_subrange(I1 first1, S1 last1, I2 first2, S2 last2,
  Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<forward_range R1, forward_range R2,
  class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires indirectly_comparable<iterator_t<R1>, iterator_t<R2>, Pred, Proj1, Proj2>
constexpr bool ranges::contains_subrange(R1&& r1, R2&& r2, Pred pred = {},
  Proj1 proj1 = {}, Proj2 proj2 = {});

Returns: first2 == last2 || !ranges::search(first1, last1, first2, last2, pred, proj1,
  proj2).empty().

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### 27.6.5 For each

**template<class InputIterator, class Function>**

```cpp
constexpr Function for_each(InputIterator first, InputIterator last, Function f);
```

1. **Preconditions:** Function meets the Cpp17MoveConstructible requirements (Table 31).
   
   [Note 1: Function need not meet the requirements of Cpp17CopyConstructible (Table 32). — end note]

2. **Effects:** Applies f to the result of dereferencing every iterator in the range [first, last), starting from first and proceeding to last - 1.
   
   [Note 2: If the type of first meets the requirements of a mutable iterator, f can apply non-constant functions through the dereferenced iterator. — end note]

3. **Returns:** f.

4. **Complexity:** Applies f exactly last - first times.

5. **Remarks:** If f returns a result, the result is ignored.

**template<class ExecutionPolicy, class ForwardIterator, class Function>**

```cpp
void for_each(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Function f);
```

6. **Preconditions:** Function meets the Cpp17CopyConstructible requirements.

7. **Effects:** Applies f to the result of dereferencing every iterator in the range [first, last).

8. **Complexity:** Applies f exactly last - first times.

9. **Remarks:** If f returns a result, the result is ignored. Implementations do not have the freedom granted under 27.3.3 to make arbitrary copies of elements from the input sequence.

   [Note 4: Does not return a copy of its Function parameter, since parallelization often does not permit efficient state accumulation. — end note]

**template<input_iterator I, sentinel_for<I> S, class Proj = identity, indirectly_unary_invocable<projected<I, Proj>> Fun>**

```cpp
constexpr ranges::for_each_result<I, Fun> ranges::for_each(I first, S last, Fun f, Proj proj = {});
```

10. **Effects:** Calls `invoke(f, invoke(proj, *i))` for every iterator i in the range [first, last), starting from first and proceeding to last - 1.

   [Note 5: If the result of invoke(proj, *i) is a mutable reference, f can apply non-constant functions. — end note]

11. **Returns:** `{last, std::move(f)}`.

12. **Complexity:** Applies f and proj exactly last - first times.

13. **Remarks:** If f returns a result, the result is ignored.

   [Note 6: The overloads in namespace `ranges` require Fun to model `copy_constructible`. — end note]

**template<class InputIterator, class Size, class Function>**

```cpp
constexpr InputIterator for_each_n(InputIterator first, Size n, Function f);
```

14. **Mandates:** The type Size is convertible to an integral type (7.3.9, 11.4.8).

15. **Preconditions:** n >= 0 is true. Function meets the Cpp17MoveConstructible requirements.

   [Note 7: Function need not meet the requirements of Cpp17CopyConstructible. — end note]

16. **Effects:** Applies f to the result of dereferencing every iterator in the range [first.first + n) in order.

   [Note 8: If the type of first meets the requirements of a mutable iterator, f can apply non-constant functions through the dereferenced iterator. — end note]
template<class ExecutionPolicy, class ForwardIterator, class Size, class Function>
ForwardIterator for_each_n(ExecutionPolicy&& exec, ForwardIterator first, Size n,
Function f);

Mandates: The type Size is convertible to an integral type (7.3.9, 11.4.8).

Preconditions: n >= 0 is true. Function meets the Cpp17CopyConstructible requirements.

Effects: Applies f to the result of dereferencing every iterator in the range [first,first + n).  
[Note 9: If the type of first meets the requirements of a mutable iterator, f can apply non-constant functions 
through the dereferenced iterator. — end note]

Returns: first + n.

Remarks: If f returns a result, the result is ignored. Implementations do not have the freedom granted 
under 27.3.3 to make arbitrary copies of elements from the input sequence.

template<input_iterator I, class Proj = identity, 
indirectly_unary_invocable<projected<I, Proj>>> Fun
constexpr ranges::for_each_n_result<I, Fun>
ranges::for_each_n(I first, iter_difference_t<I> n, Fun f, Proj proj = {});

Preconditions: n >= 0 is true.

Effects: Calls invoke(f, invoke(proj, *i)) for every iterator i in the range [first,first + n) in 
order.
[Note 10: If the result of invoke(proj, *i) is a mutable reference, f can apply non-constant functions. — end 
note]

Returns: {first + n, std::move(f)}.

Remarks: If f returns a result, the result is ignored.

[Note 11: The overload in namespace ranges requires Fun to model copy_constructible. — end note]

§ 27.6.6 Find

template<class InputIterator, class T = iterator_traits<InputIterator>::value_type>
constexpr InputIterator find(InputIterator first, InputIterator last,  
const T& value);

template<class ExecutionPolicy, class ForwardIterator, 
class T = iterator_traits<ForwardIterator>::value_type>
ForwardIterator find(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,  
const T& value);

template<class InputIterator, class Predicate>
constexpr InputIterator find_if(InputIterator first, InputIterator last,  
Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator find_if(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, 
Predicate pred);

template<class InputIterator, class Predicate>
constexpr InputIterator find_if_not(InputIterator first, InputIterator last, 
Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator find_if_not(ExecutionPolicy&& exec, 
ForwardIterator first, ForwardIterator last, 
Predicate pred);

template<input_iterator I, sentinel_for<I> S, class Proj = identity, 
class T = projected_value_t<I, Proj>>
requires indirect_binary_predicate ranges::equal_to, projected<I, Proj>, const T*>  
constexpr I ranges::find(I first, S last, const T& value, Proj proj = {});
template<input_range R, class Proj = identity, class T = projected_value_t<iterator_t<R>, Proj>>
requires indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T*>constexpr borrowed_iterator_t<R>
ranges::find(R&& r, const T& value, Proj proj = {});

1 Let $E$ be:
2
(1.1) $\ast i == \text{value for find}$;
(1.2) $\text{pred}(\ast i) != \text{false for find_if}$;
(1.3) $\text{pred}(\ast i) == \text{false for find_if_not}$;
(1.4) $\text{bool(invoke(proj, } \ast i) == \text{value for ranges::find}$;
(1.5) $\text{bool(invoke(pred, invoke(proj, } \ast i)))$ for ranges::find_if;
(1.6) $\text{bool(!invoke(pred, invoke(proj, } \ast i)))$ for ranges::find_if_not.

2 Returns: The first iterator $i$ in the range [first, last) for which $E$ is true. Returns last if no such iterator is found.

3 Complexity: At most last - first applications of the corresponding predicate and any projection.

27.6.7 Find last

template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
class T = projected_value_t<I, Proj>>
requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*>constexpr subrange<I> ranges::find_last(I first, S last, const T& value, Proj proj = {});

1 Let $E$ be:

(1.1) $\text{bool(invoke(proj, } \ast i) == \text{value for ranges::find_last}$;
(1.2) $\text{bool(invoke(pred, invoke(proj, } \ast i)))$ for ranges::find_last_if;
(1.3) $\text{bool(!invoke(pred, invoke(proj, } \ast i)))$ for ranges::find_last_if_not.
Returns: Let \( i \) be the last iterator in the range \([\text{first}, \text{last})\) for which \( E \) is true. Returns \( \{i, \text{last}\} \), or \( \{\text{last}, \text{last}\} \) if no such iterator is found.

Complexity: At most \( \text{last} - \text{first} \) applications of the corresponding predicate and projection.

### 27.6.8 Find end

```cpp
template<class ForwardIterator1, class ForwardIterator2>
constexpr ForwardIterator1 find_end(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator1 find_end(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);

template<class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
constexpr ForwardIterator1 find_end(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2, BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
ForwardIterator1 find_end(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2, BinaryPredicate pred);

template<forward_iterator I1, sentinel_for<I1> S1, forward_iterator I2, sentinel_for<I2> S2, class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
constexpr subrange<I1> ranges::find_end(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<forward_range R1, forward_range R2, class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires indirectly_comparable<iterator_t<R1>, iterator_t<R2>, Pred, Proj1, Proj2>
constexpr borrowed_subrange_t<R1> ranges::find_end(R1&& r1, R2&& r2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
```

1. Let:
   - \( \text{pred} \) be \( \text{equal}_\text{to}{} \) for the overloads with no parameter \( \text{pred} \);
   - \( E \) be:
     1. \( \text{pred}(*(i + n), *(\text{first2} + n)) \) for the overloads in namespace \( \text{std} \);
     2. \( \text{invoke} (\text{pred}, \text{invoke} (\text{proj1}, *(i + n)), \text{invoke} (\text{proj2}, *(\text{first2} + n))) \) for the overloads in namespace \( \text{ranges} \);
     3. \( i \) be \( \text{last1} \) if \([\text{first2}, \text{last2})\) is empty, or if \((\text{last2} - \text{first2}) > (\text{last1} - \text{first1})\) is true, or if there is no iterator in the range \([\text{first1}, \text{last1} - (\text{last2} - \text{first2}))\) such that for every non-negative integer \( n < (\text{last2} - \text{first2}) \), \( E \) is true. Otherwise \( i \) is the last such iterator in \([\text{first1}, \text{last1} - (\text{last2} - \text{first2}))\).

2. Returns:
   - \( \{i, i + (i == \text{last1} ? 0 : \text{last2} - \text{first2})\} \) for the overloads in namespace \( \text{ranges} \).

3. Complexity: At most \((\text{last2} - \text{first2}) * (\text{last1} - \text{first1} - (\text{last2} - \text{first2}) + 1)\) applications of the corresponding predicate and any projections.
27.6.9 Find first

Let $E$ be:

- $(1.1)\ *i == *j$ for the overloads with no parameter $\text{pred}$;
- $(1.2)\ \text{pred}(*i, *j) \neq \text{false}$ for the overloads with a parameter $\text{pred}$ and no parameter $\text{proj}$;
- $(1.3)\ \text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj1}, *i), \text{invoke}(\text{proj2}, *j)))$ for the overloads with parameters $\text{pred}$ and $\text{proj}$.

**Effects:** Finds an element that matches one of a set of values.

**Returns:** The first iterator $i$ in the range $[\text{first1}, \text{last1})$ such that for some iterator $j$ in the range $[\text{first2}, \text{last2})$ $E$ holds. Returns $\text{last1}$ if $[\text{first2}, \text{last2})$ is empty or if no such iterator is found.

**Complexity:** At most $(\text{last1}-\text{first1}) \times (\text{last2}-\text{first2})$ applications of the corresponding predicate and any projections.

27.6.10 Adjacent find

**Effects:** Finds an element that matches one of a set of values.

**Returns:** The first iterator $i$ in the range $[\text{first1}, \text{last1})$ such that for some iterator $j$ in the range $[\text{first2}, \text{last2})$ $E$ holds. Returns $\text{last1}$ if $[\text{first2}, \text{last2})$ is empty or if no such iterator is found.

**Complexity:** At most $(\text{last1}-\text{first1}) \times (\text{last2}-\text{first2})$ applications of the corresponding predicate and any projections.
template<class ForwardIterator, class BinaryPredicate>
constexpr ForwardIterator
adjacent_find(ForwardIterator first, ForwardIterator last,
BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator, class BinaryPredicate>
ForwardIterator
adjacent_find(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last,
BinaryPredicate pred);

Let $E$ be:

1. $i == *(i + 1)$ for the overloads with no parameter $\text{pred}$;
2. $\text{pred}(i, *(i + 1)) \neq \text{false}$ for the overloads with a parameter $\text{pred}$ and no parameter $\text{proj}$;
3. $\text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, i), \text{invoke}(\text{proj}, *(i + 1))))$ for the overloads with both parameters $\text{pred}$ and $\text{proj}$.

2. $\text{Returns}$: The first iterator $i$ such that both $i$ and $i + 1$ are in the range $[\text{first}, \text{last})$ for which $E$ holds. Returns $\text{last}$ if no such iterator is found.

3. $\text{Complexity}$: For the overloads with no $\text{ExecutionPolicy}$, exactly

\[
\min((i - \text{first}) + 1, (\text{last} - \text{first}) - 1)
\]

applications of the corresponding predicate, where $i$ is $\text{adjacent}\_\text{find}$'s return value. For the overloads with an $\text{ExecutionPolicy}$, $O(\text{last} - \text{first})$ applications of the corresponding predicate, and no more than twice as many applications of any projection.

27.6.11 Count [alg.count]

template<class InputIterator, class T = iterator_traits<InputIterator>::value_type>
constexpr typename iterator_traits<InputIterator>::difference_type
count(InputIterator first, InputIterator last, const T& value);

template<class ExecutionPolicy, class ForwardIterator,
class T = iterator_traits<ForwardIterator>::value_type>
typename iterator_traits<ForwardIterator>::difference_type
count(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last, const T& value);

template<class InputIterator, class Predicate>
constexpr typename iterator_traits<InputIterator>::difference_type
count_if(InputIterator first, InputIterator last, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class Predicate>
typename iterator_traits<ForwardIterator>::difference_type
count_if(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last, Predicate pred);

constexpr iter_difference_t<I>
ranges::count(I first, sentinel_for<I> S last, const T& value, Proj proj = {});

constexpr range_difference_t<R>
ranges::count(R&& r, const T& value, Proj proj = {});
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
    indirect_unary_predicate<projected<I, Proj>> Pred>
constexpr iter_difference_t<I>
ranges::count_if(I first, S last, Pred pred, Proj proj = {});

template<input_range R, class Proj = identity,
    indirect_unary_predicate<iterator_t<R>, Proj>> Pred>
constexpr range_difference_t<R>
ranges::count_if(R&& r, Pred pred, Proj proj = {});

Let $E$ be:

1. $i == \text{value}$ for the overloads with no parameter $\text{pred}$ or $\text{proj}$;
2. $\text{pred}(i) \neq \text{false}$ for the overloads with a parameter $\text{pred}$ but no parameter $\text{proj}$;
3. $\text{invoke}(\text{proj}, i) == \text{value}$ for the overloads with a parameter $\text{proj}$ but no parameter $\text{pred}$;
4. $\text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, i)))$ for the overloads with both parameters $\text{proj}$ and $\text{pred}$.

**Effects**: Returns the number of iterators $i$ in the range $[\text{first}, \text{last})$ for which $E$ holds.

**Complexity**: Exactly $\text{last} - \text{first}$ applications of the corresponding predicate and any projection.

§ 27.6.12 Mismatch

```cpp
template<class InputIterator1, class InputIterator2>
constexpr pair<InputIterator1, InputIterator2>
mismatch(InputIterator1 first1, InputIterator1 last1,
    InputIterator2 first2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
pair<ForwardIterator1, ForwardIterator2>
mismatch(ExecutionPolicy&& exec,
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2);

template<class InputIterator1, class InputIterator2,
    class BinaryPredicate>
constexpr pair<InputIterator1, InputIterator2>
mismatch(InputIterator1 first1, InputIterator1 last1,
    InputIterator2 first2, BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class BinaryPredicate>
pair<ForwardIterator1, ForwardIterator2>
mismatch(ExecutionPolicy&& exec,
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2, BinaryPredicate pred);

// Remaining templates...
```
Let last2 be first2 + (last1 - first1) for the overloads with no parameter last2 or r2.

Let E be:

1. !(*((first1 + n) == *(first2 + n))) for the overloads with no parameter pred:

2. pred(*((first1 + n), *(first2 + n)) == false for the overloads with a parameter pred and no parameter proj1;

3. !invoke(pred, invoke(proj1, *(first1 + n)), invoke(proj2, *(first2 + n))) for the overloads with both parameters pred and proj1.

Let N be min(last1 - first1, last2 - first2).

Returns: { first1 + n, first2 + n }, where n is the smallest integer in [0, N) such that E holds, or N if no such integer exists.

Complexity: At most N applications of the corresponding predicate and any projections.

27.6.13 Equal

```cpp
template<class InputIterator1, class InputIterator2>
constexpr bool equal(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
bool equal(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2);

template<class InputIterator1, class InputIterator2, class BinaryPredicate>
constexpr bool equal(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
bool equal(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, BinaryPredicate pred);

template<class InputIterator1, class InputIterator2>
constexpr bool equal(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
bool equal(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);

template<class InputIterator1, class InputIterator2, class BinaryPredicate>
constexpr bool equal(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2);
```
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,  
class BinaryPredicate>
bool equal(ExecutionPolicy&& exec,  
ForwardIterator1 first1, ForwardIterator1 last1,  
ForwardIterator2 first2, ForwardIterator2 last2,  
BinaryPredicate pred);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,  
class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>  
requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>  
constexpr bool ranges::equal(I1 first1, S1 last1, I2 first2, S2 last2,  
Pred pred = {},  
Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, class Pred = ranges::equal_to,  
class Proj1 = identity, class Proj2 = identity>  
requires indirectly_comparable<iterator_t<R1>, iterator_t<R2>, Pred, Proj1, Proj2>  
constexpr bool ranges::equal(R1&& r1, R2&& r2, Pred pred = {},  
Proj1 proj1 = {}, Proj2 proj2 = {});

1 Let:
   — last2 be first2 + (last1 - first1) for the overloads with no parameter last2 or r2;
   — pred be equal_to{} for the overloads with no parameter pred;
   — E be:
     (1.3.1) pred(*i, *(first2 + (i - first1))) for the overloads with no parameter proj1;
     (1.3.2) invoke(pred, invoke(proj1, *i), invoke(proj2, *(first2 + (i - first1)))) for  
     the overloads with parameter proj1.

2 Returns: If last1 - first1 != last2 - first2, return false. Otherwise return true if E holds  
for every iterator i in the range [first1, last1). Otherwise, returns false.

3 Complexity: If
   (3.1) the types of first1, last1, first2, and last2 meet the Cpp17RandomAccessIterator require-  
mements (25.3.5.7) and last1 - first1 != last2 - first2 for the overloads in namespace std;
   (3.2) the types of first1, last1, first2, and last2 pairwise model sized_sentinel_for (25.3.4.8)  
and last1 - first1 != last2 - first2 for the first overload in namespace ranges,
   (3.3) R1 and R2 each model sized_range and ranges::distance(r1) != ranges::distance(r2) for  
the second overload in namespace ranges,
   then no applications of the corresponding predicate and each projection; otherwise,
   (3.4) For the overloads with no ExecutionPolicy, at most min(last1 - first1, last2 - first2)  
applications of the corresponding predicate and any projections.
   (3.5) For the overloads with an ExecutionPolicy, \(O(\min(last1 - first1, last2 - first2))\) appli-  
cations of the corresponding predicate.

27.6.14 Is permutation

[alg.is.permutation]
template<forward_iterator I1, sentinel_for<I1> S1, forward_iterator I2, sentinel_for<I2> S2, class Proj1 = identity, class Proj2 = identity, indirect_equivalence_relation<projected<I1, Proj1>, projected<I2, Proj2>> Pred = ranges::equal_to>
constexpr bool ranges::is_permutation(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<forward_range R1, forward_range R2, class Proj1 = identity, class Proj2 = identity, indirect_equivalence_relation<projected<iterator_t<R1>, Proj1>, projected<iterator_t<R2>, Proj2>> Pred = ranges::equal_to>
constexpr bool ranges::is_permutation(R1&& r1, R2&& r2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

§ 27.6.15 Search

template<class ForwardIterator1, class ForwardIterator2>
constexpr ForwardIterator1 search(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator1 search(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);
template<class ForwardIterator1, class ForwardIterator2, 
class BinaryPredicate>
constexpr ForwardIterator1
search(ForwardIterator1 first1, ForwardIterator1 last1, 
ForwardIterator2 first2, ForwardIterator2 last2, 
BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
class BinaryPredicate>
ForwardIterator1
search(ExecutionPolicy&& exec, 
ForwardIterator1 first1, ForwardIterator1 last1, 
ForwardIterator2 first2, ForwardIterator2 last2, 
BinaryPredicate pred);

1 Returns: The first iterator i in the range \([\text{first1}, \text{last1} - (\text{last2}-\text{first2}))\) such that for every non-negative integer n less than \(\text{last2} - \text{first2}\) the following corresponding conditions hold: \((i + n) == *(\text{first2} + n), \text{pred}(*(i + n), *(\text{first2} + n)) != false\). Returns \text{first1} if \([\text{first2}, \text{last2})\) is empty, otherwise returns \text{last1} if no such iterator is found.

2 Complexity: At most \((\text{last1} - \text{first1}) \times (\text{last2} - \text{first2})\) applications of the corresponding predicate.

template<forward_iterator I1, sentinel_for<I1> S1, forward_iterator I2, sentinel_for<I2> S2, class Pred = ranges::equal_to, 
class Proj1 = identity, class Proj2 = identity>
constexpr subrange<I1>
ranges::search(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {}, 
Proj1 proj1 = {}, Proj2 proj2 = {});

template<forward_range R1, forward_range R2, class Pred = ranges::equal_to, 
class Proj1 = identity, class Proj2 = identity>
constexpr borrowed_subrange_t<R1>
ranges::search(R1&& r1, R2&& r2, Pred pred = {}, 
Proj1 proj1 = {}, Proj2 proj2 = {});

3 Returns:

\((3.1)\) \{i, i + (\text{last2} - \text{first2})\}, where i is the first iterator in the range \([\text{first1}, \text{last1} - (\text{last2} - \text{first2}))\) such that for every non-negative integer n less than \(\text{last2} - \text{first2}\) the condition
\[
\text{bool}(\text{invoke(pred, invoke(proj1, *(i + n)), invoke(proj2, *(\text{first2} + n)))})
\]
is true.

\((3.2)\) Returns \{last1, last1\} if no such iterator exists.

4 Complexity: At most \((\text{last1} - \text{first1}) \times (\text{last2} - \text{first2})\) applications of the corresponding predicate and projections.
template<class ExecutionPolicy, class ForwardIterator, class Size,
class T = iterator_traits<ForwardIterator>::value_type,
class BinaryPredicate>
ForwardIterator
search_n(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last,
Size count, const T& value,
BinaryPredicate pred);

*Mandates:* The type Size is convertible to an integral type (7.3.9, 11.4.8).

*Returns:* The first iterator i in the range [first, last-count) such that for every non-negative integer n less than count the following corresponding conditions hold: *(i + n) == value, pred(*(i + n), value) != false. Returns last if no such iterator is found.

*Complexity:* At most last - first applications of the corresponding predicate.

```cpp
template<forward_iterator I, sentinel_for<I> S,
class Pred = ranges::equal_to, class Proj = identity,
class T = projected_value_t<I, Proj>>
constexpr subrange<I>
ranges::search_n(I first, S last, iter_difference_t<I> count,
const T& value, Pred pred = {}, Proj proj = {});
```

*Returns:* {i, i + count} where i is the first iterator in the range [first, last - count) such that for every non-negative integer n less than count, the following condition holds: invoke(pred, invoke(proj, *(i + n)), value). Returns {last, last} if no such iterator is found.

*Complexity:* At most last - first applications of the corresponding predicate and projection.

```cpp
template<class ForwardIterator, class Searcher>
constexpr ForwardIterator
search(ForwardIterator first, ForwardIterator last, const Searcher& searcher);
```

*Effects:* Equivalent to: return searcher(first, last).first;

*Remarks:* Searcher need not meet the Cpp17CopyConstructible requirements.

### § 27.6.16 Starts with

```cpp
template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
constexpr bool ranges::starts_with(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
Proj1 proj1 = {}, Proj2 proj2 = {});
```

*Returns:* ranges::mismatch(std::move(first1), last1, std::move(first2), last2,
pred, proj1, proj2).in2 == last2

### § 27.6.17 Ends with

```cpp
template<input_range R1, input_range R2, class Pred = ranges::equal_to, class Proj1 = identity,
class Proj2 = identity>
constexpr bool ranges::starts_with(R1&& r1, R2&& r2, Pred pred = {},
Proj1 proj1 = {}, Proj2 proj2 = {});
```
template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2, class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires (forward_iterator<I1> || sized_sentinel_for<S1, I1>) &&
(forward_iterator<I2> || sized_sentinel_for<S2, I2>) &&
indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
constexpr bool ranges::ends_with(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

Let $N_1$ be $last_1 - first_1$ and $N_2$ be $last_2 - first_2$.

Returns: false if $N_1 < N_2$, otherwise
ranges::equal(std::move(first1) + (N1 - N2), last1, std::move(first2), last2, pred, proj1, proj2)

template<input_range R1, input_range R2, class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity>
requires (forward_range<R1> || sized_range<R1>) &&
(forward_range<R2> || sized_range<R2>) &&
indirectly_comparable<iterator_t<R1>, iterator_t<R2>, Pred, Proj1, Proj2>
constexpr bool ranges::ends_with(R1&& r1, R2&& r2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

Let $N_1$ be ranges::distance(r1) and $N_2$ be ranges::distance(r2).

Returns: false if $N_1 < N_2$, otherwise
ranges::equal(views::drop(ranges::ref_view(r1), N1 - static_cast<decltype(N1)>(N2)), r2, pred, proj1, proj2)

27.6.18 Fold

template<input_iterator I, sentinel_for<I> S, class T = iter_value_t<I>, indirectly-binary-left-foldable<T, I> F>
constexpr auto ranges::fold_left(I first, S last, T init, F f);
template<input_range R, class T = range_value_t<R>, indirectly-binary-left-foldable<T, iterator_t<R>> F>
constexpr auto ranges::fold_left(R&& r, T init, F f);

1 Returns:
ranges::fold_left_with_iter(std::move(first), last, std::move(init), f).value

template<input_iterator I, sentinel_for<I> S, indirectly-binary-left-foldable<iter_value_t<I>, I> F>
requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
constexpr auto ranges::fold_left_first(I first, S last, F f);
template<input_range R, indirectly-binary-left-foldable<range_value_t<R>, iterator_t<R>> F>
requires constructible_from<range_value_t<R>, range_reference_t<R>>
constexpr auto ranges::fold_left_first(R&& r, F f);

2 Returns:
ranges::fold_left_first_with_iter(std::move(first), last, f).value

template<bidirectional_iterator I, sentinel_for<I> S, class T = iter_value_t<I>, indirectly-binary-right-foldable<T, I> F>
constexpr auto ranges::fold_right(I first, S last, T init, F f);
template<bidirectional_range R, class T = range_value_t<R>, indirectly-binary-right-foldable<T, iterator_t<R>> F>
constexpr auto ranges::fold_right(R&& r, T init, F f);

3 Effects: Equivalent to:
using U = decay_t<invoke_result_t<F&, iter_reference_t<I>, T>>;
if (first == last)
    return U(std::move(init));
I tail = ranges::next(first, last);
U accum = invoke(f, --tail, std::move(init));
while (first != tail)
    accum = invoke(f, --tail, std::move(accum));
return accum;

template<bidirectional_iterator I, sentinel_for<I> S,
  indirectly-binary-right-foldable<iter_value_t<I>, I> F>
requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
constexpr auto ranges::fold_right_last(I first, S last, F f);

template<bidirectional_range R,
  indirectly-binary-right-foldable<range_value_t<R>, iterator_t<R>> F>
requires constructible_from<range_value_t<R>, range_reference_t<R>>
constexpr auto ranges::fold_right_last(R&& r, F f);

Let U be decltype(ranges::fold_right(first, last, iter_value_t<I>(*first), f)).

Effects: Equivalent to:
    if (first == last)
      return optional<U>();
    I tail = ranges::prev(ranges::next(first, std::move(last)));
    return optional<U>(in_place,
      ranges::fold_right(std::move(first), tail, iter_value_t<I>(*tail), std::move(f)));

template<input_iterator I, sentinel_for<I> S, class T = iter_value_t<I>,
  indirectly-binary-left-foldable<T, I> F>
constexpr see below ranges::fold_left_with_iter(I first, S last, T init, F f);

template<input_range R, class T = range_value_t<R>,
  indirectly-binary-left-foldable<T, iterator_t<R>> F>
constexpr see below ranges::fold_left_with_iter(R&& r, T init, F f);

Let U be decay_t<invoke_result_t<F&, T, iter_reference_t<I>>>.

Effects: Equivalent to:
    if (first == last)
      return {std::move(first), U(std::move(init))};
    U accum = invoke(f, std::move(init), *first);
    for (++first; first != last; ++first)
      accum = invoke(f, std::move(accum), *first);
    return {std::move(first), std::move(accum)};

Remarks: The return type is fold_left_with_iter_result<I, U> for the first overload and fold_left_with_iter_result<borrowed_iterator_t<R>, U> for the second overload.

template<input_iterator I, sentinel_for<I> S,
  indirectly-binary-left-foldable<iter_value_t<I>, I> F>
requires constructible_from<iter_value_t<I>, iter_reference_t<I>>
constexpr see below ranges::fold_left_first_with_iter(I first, S last, F f);

template<input_range R, indirectly-binary-left-foldable<range_value_t<R>, iterator_t<R>> F>
requires constructible_from<range_value_t<R>, range_reference_t<R>>
constexpr see below ranges::fold_left_first_with_iter(R&& r, F f);

Let U be
decay_t<invoke_result_t<F&, borrowed_iterator_t_t<R>, T, iter_reference_t<I>>>.

Effects: Equivalent to:
    if (first == last)
      return {std::move(first), optional<U>()};
    optional<U> init(in_place, *first);
    for (++first; first != last; ++first)
      *init = invoke(f, std::move(*init), *first);
    return {std::move(first), std::move(init)};

Remarks: The return type is fold_left_first_with_iter_result<I, optional<U>> for the first overload and fold_left_first_with_iter_result<borrowed_iterator_t_t<R>, optional<U>> for the second overload.

27.7 Mutating sequence operations

27.7.1 Copy
template<class InputIterator, class OutputIterator>
constexpr OutputIterator copy(InputIterator first, InputIterator last,
OutputIterator result);

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O>
requires indirectly_copyable<I, O>
constexpr ranges::copy_result<I, O> ranges::copy(I first, S last, O result);

template<input_range R, weakly_incrementable O>
requires indirectly_copyable<iterator_t<R>, O>
constexpr ranges::copy_result<borrowed_iterator_t<R>, O> ranges::copy(R&& r, O result);

Let \( N \) be \( \text{last} - \text{first} \).

**Preconditions:** result is not in the range \([\text{first}, \text{last})\).

**Effects:** Copies elements in the range \([\text{first}, \text{last})\) into the range \([\text{result}, \text{result} + N)\) starting from \text{first} and proceeding to \text{last}. For each non-negative integer \( n < N \), performs \(*(\text{result} + n) = *(\text{first} + n)\).

**Returns:**
- \( \text{result} + N \) for the overload in namespace std.
- \{\text{last}, \text{result} + N\} for the overloads in namespace ranges.

**Complexity:** Exactly \( N \) assignments.

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2 copy(ExecutionPolicy&& policy,
ForwardIterator1 first, ForwardIterator1 last,
ForwardIterator2 result);

**Preconditions:** The ranges \([\text{first}, \text{last})\) and \([\text{result.result} + (\text{last} - \text{first}))\) do not overlap.

**Effects:** Copies elements in the range \([\text{first}, \text{last})\) into the range \([\text{result.result} + (\text{last} - \text{first}))\). For each non-negative integer \( n < (\text{last} - \text{first}) \), performs \(*(\text{result} + n) = *(\text{first} + n)\).

**Returns:** \( \text{result} + (\text{last} - \text{first}) \).

**Complexity:** Exactly \( \text{last} - \text{first} \) assignments.

template<class InputIterator, class Size, class OutputIterator>
constexpr OutputIterator copy_n(InputIterator first, Size n,
OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class Size, class ForwardIterator2>
ForwardIterator2 copy_n(ExecutionPolicy&& exec,
ForwardIterator1 first, Size n,
ForwardIterator2 result);

**Mandates:** The type \( \text{Size} \) is convertible to an integral type (7.3.9, 11.4.8).

**Effects:** For each non-negative integer \( i < N \), performs \(*(\text{result} + i) = *(\text{first} + i)\).

**Returns:**
- \( \text{result} + N \) for the overloads in namespace std.
- \{\text{first} + N, \text{result} + N\} for the overload in namespace ranges.

**Complexity:** Exactly \( N \) assignments.

template<class InputIterator, class OutputIterator, class Predicate>
constexpr OutputIterator copy_if(InputIterator first, InputIterator last,
OutputIterator result, Predicate pred);
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
class Predicate>
  ForwardIterator2 copy_if(ExecutionPolicy&& exec, 
  ForwardIterator1 first, ForwardIterator1 last, 
  ForwardIterator2 result, Predicate pred);

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, 
class Proj = identity, 
indirect_unary_predicate<projected<I, Proj>> Pred>
  requires indirectly_copyable<I, O>
  ranges::copy_if_result<I, O>
  ranges::copy_if(I first, S last, O result, Pred pred, Proj proj = {});

template<input_range R, weakly_incrementable O, 
class Proj = identity, 
indirect_unary_predicate<iterator_t<R>, Proj>> Pred>
  requires indirectly_copyable<iterator_t<R>, O>
  ranges::copy_if_result<borrowed_iterator_t<R>, O>
  ranges::copy_if(R&& r, O result, Pred pred, Proj proj = {});

15
Let $E$ be:

(15.1) \[ \begin{align*}
  & \text{— } \text{bool}(\text{pred}(*i)) \text{ for the overloads in namespace } \text{std}; \\
  & \text{— } \text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, *i))) \text{ for the overloads in namespace } \text{ranges}, \\
\end{align*} \]

and $N$ be the number of iterators $i$ in the range $[\text{first}, \text{last})$ for which the condition $E$ holds.

16
Preconditions: The ranges $[\text{first}, \text{last})$ and $[\text{result.result + (last - first)}]$ do not overlap.

[Note 1: For the overload with an ExecutionPolicy, there might be a performance cost if \text{iterator_traits<ForwardIterator1>::value_type is not Cpp17MoveConstructible (Table 31).} — end note]

Effects: Copies all of the elements referred to by the iterator $i$ in the range $[\text{first}, \text{last})$ for which $E$ is true.

18
Returns:

(18.1) \[ \text{— } \text{result} + N \text{ for the overloads in namespace } \text{std}. \]

(18.2) \[ \text{— } \{\text{last}, \text{result} + N\} \text{ for the overloads in namespace } \text{ranges}. \]

19
Complexity: Exactly $\text{last - first}$ applications of the corresponding predicate and any projection.

20
Remarks: Stable (16.4.6.8).

template<class BidirectionalIterator1, class BidirectionalIterator2>
  constexpr BidirectionalIterator2
  copy_backward(BidirectionalIterator1 first, 
  BidirectionalIterator1 last, 
  BidirectionalIterator2 result);

21
Let $N$ be $\text{last} - \text{first}$.

22
Preconditions: result is not in the range $[\text{first}, \text{last}]$.

23
Effects: Copies elements in the range $[\text{first}, \text{last})$ into the range $[\text{result} - N, \text{result})$ starting from $\text{last} - 1$ and proceeding to $\text{first}$.\cite{10} For each positive integer $n \leq N$, performs $\ast(\text{result} - n) = \ast(\text{last} - n)$.

24
Returns:

(24.1) \[ \text{— } \text{result} - N \text{ for the overload in namespace } \text{std}. \]

(24.2) \[ \text{— } \{\text{last}, \text{result} - N\} \text{ for the overloads in namespace } \text{ranges}. \]

\cite{10} \texttt{copy_backward} can be used instead of \texttt{copy} when \texttt{last} is in the range $[\text{result} - N, \text{result})$. 

§ 27.7.1 ©ISO/IEC 1411
**27.7.2 Move**

```cpp
template<class InputIterator, class OutputIterator>
constexpr OutputIterator move(InputIterator first, InputIterator last, OutputIterator result);
```

```cpp
template<input_iterator I, sentinel_for<I> S, weakly_incrementable O>
requires indirectly_movable<I, O>
constexpr ranges::move_result<I, O>
ranges::move(I first, S last, O result);
```

```cpp
template<input_range R, weakly_incrementable O>
requires indirectly_movable<iterator_t<R>, O>
constexpr ranges::move_result<borrowed_iterator_t<R>, O>
ranges::move(R&& r, O result);
```

Let \( E \) be

- \( \text{std::move(*\( \text{first} + n \))} \) for the overload in namespace `std`;
- \( \text{ranges::iter_move(\( \text{first} + n \))} \) for the overloads in namespace `ranges`.

Let \( N \) be \( \text{last} - \text{first} \).

**Preconditions**: `result` is not in the range \([\text{first}, \text{last})\).

**Effects**: Moves elements in the range \([\text{first}, \text{last})\) into the range \([\text{result}, \text{result} + N)\) starting from `first` and proceeding to `last`. For each non-negative integer \( n < N \), performs \( *(\text{result} + n) = E \).

**Returns**:
- \( \text{result} + N \) for the overload in namespace `std`.
- \( \{\text{last}, \text{result} + N\} \) for the overloads in namespace `ranges`.

**Complexity**: Exactly \( N \) assignments.

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2 move(ExecutionPolicy&& policy, ForwardIterator1 first, ForwardIterator1 last, ForwardIterator2 result);
```

```cpp
template<bidirectional_iterator I1, sentinel_for<I1> S1, bidirectional_iterator I2>
requires indirectly_movable<I1, I2>
constexpr ranges::move_backward_result<borrowed_iterator_t<I1>, I2>
ranges::move_backward(I1 first, S1 last, I2 result);
```

```cpp
template<bidirectional_range R, bidirectional_iterator I>
requires indirectly_movable<iterator_t<R>, I>
constexpr ranges::move_backward_result<borrowed_iterator_t<R>, I>
ranges::move_backward(R&& r, I result);
```

Let \( E \) be

- \( \text{std::move(*\( \text{last} - n \))} \) for the overload in namespace `std`;
- \( \text{ranges::iter_move(\( \text{last} - n \))} \) for the overloads in namespace `ranges`.

**Complexity**: Exactly \( N \) assignments.
Let \( N \) be \( \text{last} - \text{first} \).

**Preconditions:** \( \text{result} \) is not in the range \([\text{first}, \text{last}]\).

**Effects:** Moves elements in the range \([\text{first}, \text{last}]\) into the range \([\text{result} - N, \text{result}]\) starting from \( \text{last} - 1 \) and proceeding to \( \text{first} \).

For each positive integer \( n \leq N \), performs \(*(\text{result} - n) = E.*

**Returns:**

- \( \text{result} - N \) for the overload in namespace \( \text{std} \).
- \{last, \( \text{result} - N \)\} for the overloads in namespace \( \text{ranges} \).

**Complexity:** Exactly \( N \) assignments.

### 27.7.3 Swap

**Template:**

```cpp
template<class ForwardIterator1, class ForwardIterator2>
constexpr ForwardIterator2
swap_ranges(ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2); // freestanding
```

**Template:**

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
swap_ranges(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2);
```

**Template:**

```cpp
template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2>
requires indirectly_swappable<I1, I2>
constexpr ranges::swap_ranges_result<I1, I2>
ranges::swap_ranges(I1 first1, S1 last1, I2 first2, S2 last2);
```

**Template:**

```cpp
template<input_range R1, input_range R2>
requires indirectly_swappable<iterator_t<R1>, iterator_t<R2>>
constexpr ranges::swap_ranges_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
ranges::swap_ranges(R1&& r1, R2&& r2);
```

**Let:**

1. \( \text{last2} \) be \( \text{first2} + (\text{last} - \text{first1}) \) for the overloads with no parameter named \( \text{last2} \);
2. \( M \) be \( \min(\text{last} - \text{first1}, \text{last2} - \text{first2}) \).

**Preconditions:** The two ranges \([\text{first1}, \text{last1}]\) and \([\text{first2}, \text{last2}]\) do not overlap. For the overloads in namespace \( \text{std} \), \(*(\text{first1} + n)\) is swappable with \((16.4.4.3) \ast(\text{first2} + n)\).

**Effects:** For each non-negative integer \( n < M \) performs:

1. \( \text{swap}(\ast(\text{first1} + n), \ast(\text{first2} + n)) \) for the overloads in namespace \( \text{std} \);
2. \( \text{ranges}::\text{iter_swap}(\text{first1} + n, \text{first2} + n) \) for the overloads in namespace \( \text{ranges} \).

**Returns:**

1. \( \text{last2} \) for the overloads in namespace \( \text{std} \).
2. \{\text{first1} + \text{M}, \text{first2} + \text{M}\} for the overloads in namespace \( \text{ranges} \).

**Complexity:** Exactly \( M \) swaps.

**Template:**

```cpp
constexpr void iter_swap(ForwardIterator1 a, ForwardIterator2 b);
```

**Preconditions:** \( a \) and \( b \) are dereferenceable. \( \ast a \) is swappable with \((16.4.4.3) \ast b\).

**Effects:** As if by \( \text{swap}(\ast a, \ast b) \).

### 27.7.4 Transform

**Template:**

```cpp
move_backward can be used instead of move when last is in the range \([\text{result} - N, \text{result}]\).
```
template<class InputIterator, class OutputIterator, 
    class UnaryOperation>
constexpr OutputIterator
transform(InputIterator first1, InputIterator last1, 
    OutputIterator result, UnaryOperation op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
    class UnaryOperation>
ForwardIterator2
transform(ExecutionPolicy&& exec, 
    ForwardIterator1 first1, ForwardIterator1 last1, 
    ForwardIterator2 result, UnaryOperation op);

template<class InputIterator1, class InputIterator2, 
    class OutputIterator, class BinaryOperation>
constexpr OutputIterator
transform(InputIterator1 first1, InputIterator1 last1, 
    InputIterator2 first2, OutputIterator result, 
    BinaryOperation binary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
    class ForwardIterator, class BinaryOperation>
ForwardIterator
transform(ExecutionPolicy&& exec, 
    ForwardIterator1 first1, ForwardIterator1 last1, 
    ForwardIterator2 first2, ForwardIterator result, 
    BinaryOperation binary_op);

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, 
    copy_constructible F, class Proj = identity>
requires indirectly_writable<O, indirect_result_t<F&, projected<I, Proj>>
constexpr ranges::unary_transform_result<I, O>
ranges::transform(I first1, S last1, O result, F op, Proj proj = {});

template<input_range R, weakly_incrementable O, copy_constructible F, 
    class Proj = identity>
requires indirectly_writable<O, indirect_result_t<F&, projected<iterator_t<R>, Proj>>
constexpr ranges::unary_transform_result<borrowed_iterator_t<R>, O>
ranges::transform(R&& r, O result, F op, Proj proj = {});

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2, 
    weakly_incrementable O, copy_constructible F, class Proj1 = identity, 
    class Proj2 = identity>
requires indirectly_writable<O, indirect_result_t<F&, projected<I1, Proj1>, 
    projected<I2, Proj2>>
constexpr ranges::binary_transform_result<I1, I2, O>
ranges::transform(I1 first1, S1 last1, I2 first2, S2 last2, O result, 
    F binary_op, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, weakly_incrementable O, 
    copy_constructible F, class Proj1 = identity, class Proj2 = identity>
requires indirectly_writable<O, indirect_result_t<F&, projected<iterator_t<R1>, Proj1>, 
    projected<iterator_t<R2>, Proj2>>
constexpr ranges::binary_transform_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
ranges::transform(R1&& r1, R2&& r2, O result, 
    F binary_op, Proj1 proj1 = {}, Proj2 proj2 = {});

Let:

1. last2 be first2 + (last1 - first1) for the overloads with parameter first2 but no parameter last2;
2. N be last1 - first1 for unary transforms, or min(last1 - first1, last2 - first2) for binary transforms;
3. E be
    1.1. op(*(first1 + (i - result))) for unary transforms defined in namespace std;
    1.3.1. binary_op(*(first1 + (i - result)), *(first2 + (i - result))) for binary transforms defined in namespace std;

§ 27.7.4 ©ISO/IEC 14141
invoke(op, invoke(proj, *(first1 + (i - result)))) for unary transforms defined in namespace ranges;

invoke(binary_op, invoke(proj1, *(first1 + (i - result))), invoke(proj2, *(first2 + (i - result)))) for binary transforms defined in namespace ranges.

Preconditions: op and binary_op do not invalidate iterators or subranges, nor modify elements in the ranges

— [first1,first1 + N],
— [first2,first2 + N], and
— [result,result + N].

Effects: Assigns through every iterator i in the range [result,result + N) a new corresponding value equal to E.

Returns:
— result + N for the overloads defined in namespace std.
— {first1 + N, result + N} for unary transforms defined in namespace ranges.
— {first1 + N, first2 + N, result + N} for binary transforms defined in namespace ranges.

Complexity: Exactly N applications of op or binary_op, and any projections. This requirement also applies to the overload with an ExecutionPolicy.

Remarks: result may be equal to first1 or first2.

27.7.5 Replace

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr void replace(ForwardIterator first, ForwardIterator last, const T& old_value, const T& new_value);

template<class ExecutionPolicy, class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
void replace(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, const T& old_value, const T& new_value);

template<class ForwardIterator, class Predicate, class T = iterator_traits<ForwardIterator>::value_type>
constexpr void replace_if(ForwardIterator first, ForwardIterator last, Predicate pred, const T& new_value);

template<class ExecutionPolicy, class ForwardIterator, class Predicate, class T = iterator_traits<ForwardIterator>::value_type>
void replace_if(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Predicate pred, const T& new_value);

template<input_iterator I, sentinel_for<I> S, class Proj = identity, class T1 = projected_value_t<I, Proj>, class T2 = T1>
requires indirectly_writable<I, const T2&> && indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T1*>constexpr I
ranges::replace(I first, S last, const T1& old_value, const T2& new_value, Proj proj = {});

template<input_range R, class Proj = identity, class T1 = projected_value_t<iterator_t<R>, Proj>, class T2 = T1>
requires indirectly_writable<iterator_t<R>, const T2&> && indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T1*>constexpr borrowed_iterator_t<R>
ranges::replace(R&& r, const T1& old_value, const T2& new_value, Proj proj = {});
```

212) The use of fully closed ranges is intentional.
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
  class T = projected_value_t<I, Proj>,
  indirect_unary_predicate<projected<I, Proj>> Pred>
requires indirectly_writable<I, const T &>
constexpr I ranges::replace_if(I first, S last, Pred pred, const T & new_value, Proj proj = {});

template<input_range R, class Proj = identity, class T = projected_value_t<iterator_t<R>, Proj>,
  indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
requires indirectly_writable<iterator_t<R>, const T &>
constexpr borrowed_iterator_t<R>
ranges::replace_if(R&& r, Pred pred, const T & new_value, Proj proj = {});

Let $E$ be

\begin{align}
(1.1) & \quad \text{bool}(\ast i == \text{old\_value}) \text{ for replace;} \\
(1.2) & \quad \text{bool(pred}(\ast i)) \text{ for replace\_if;} \\
(1.3) & \quad \text{bool}(	ext{invoke(proj, } \ast i) == \text{old\_value}) \text{ for ranges::replace;} \\
(1.4) & \quad \text{bool}(	ext{invoke(pred, invoke(proj, } \ast i))) \text{ for ranges::replace\_if.}
\end{align}

\textbf{Mandates:} new\_value is writable (25.3.1) to first.

\textbf{Effects:} Substitutes elements referred by the iterator $i$ in the range $[\text{first, last})$ with new\_value, when $E$ is true.

\textbf{Returns:} last for the overloads in namespace ranges.

\textbf{Complexity:} Exactly last - first applications of the corresponding predicate and any projection.
Let $E$ be

\[ \text{(6.1)} \] \quad \text{bool}(*(\text{first} + (i - \text{result})) == \text{old_value}) \text{ for replace_copy;}

\[ \text{(6.2)} \] \quad \text{bool(pred(*(\text{first} + (i - \text{result}))))) \text{ for replace_copy_if;}

\[ \text{(6.3)} \] \quad \text{bool(invoke(proj, *(\text{first} + (i - \text{result})))) == \text{old_value}) \text{ for ranges::replace_copy;}

\[ \text{(6.4)} \] \quad \text{bool(invoke(pred, invoke(proj, *(\text{first} + (i - \text{result}))))}) \text{ for ranges::replace_copy_if.}

\begin{itemize}
  \item [[Mandates]]: The results of the expressions *first and new_value are writable (25.3.1) to result.
  \item [[Preconditions]]: The ranges [first, last) and [result, result + (last - first)) do not overlap.
  \item [[Effects]]: Assigns through every iterator $i$ in the range [result, result + (last - first)) a new corresponding value
    \[ \text{(9.1)} \] \quad \text{new_value if } E \text{ is true or}
    \[ \text{(9.2)} \] \quad *(\text{first} + (i - \text{result})) \text{ otherwise.}
  \item [[Returns]]:
    \[ \text{(10.1)} \] \quad \text{result + (last - first) for the overloads in namespace std.}
    \[ \text{(10.2)} \] \quad {\text{last, result + (last - first)}} \text{ for the overloads in namespace ranges.}
\end{itemize}

\section{27.7.6 Fill}

\label{alg.fill}

\begin{itemize}
  \item \text{template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>}
  \begin{verbatim}
  constexpr void fill(ForwardIterator first, ForwardIterator last, const T& value);
  \end{verbatim}
  \item \text{template<class ExecutionPolicy, class ForwardIterator,}
    \begin{verbatim}
  class T = iterator_traits<ForwardIterator>::value_type>
  \end{verbatim}
    \begin{verbatim}
  void fill(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, const T& value);
  \end{verbatim}
  \item \text{template<class OutputIterator, class Size, class T = iterator_traits<OutputIterator>::value_type>}
  \begin{verbatim}
  constexpr OutputIterator fill_n(OutputIterator first, Size n, const T& value);
  \end{verbatim}
  \item \text{template<class ExecutionPolicy, class ForwardIterator, class Size,}
    \begin{verbatim}
  class T = iterator_traits<ForwardIterator>::value_type>
  \end{verbatim}
    \begin{verbatim}
  ForwardIterator fill_n(ExecutionPolicy&& exec, ForwardIterator first, Size n, const T& value);
  \end{verbatim}
  \item \text{template<class O, sentinel_for<O> S, class T = iter_value_t<O>}
    \begin{verbatim}
  requires output_iterator<O, const T&> \begin{verbatim}
  constexpr O ranges::fill(O first, S last, const T& value);
  \end{verbatim}
  \item \text{template<class R, class T = range_value_t<R>}
    \begin{verbatim}
  requires output_range<R, const T&> \begin{verbatim}
  constexpr borrowed_iterator_t<R> ranges::fill(R&& r, const T& value);
  \end{verbatim}
\end{itemize}
template<class O, class T = iter_value_t<O>>
   requires output_iterator<O, const T&>
constexpr O ranges::fill_n(O first, iter_difference_t<O> n, const T& value);

Let \( N \) be \( \max(0, n) \) for the \texttt{fill_n} algorithms, and \( \text{last} - \text{first} \) for the \texttt{fill} algorithms.

\textit{Mandates:} The expression \texttt{value} is writable (25.3.1) to the output iterator. The type \texttt{Size} is convertible to an integral type (7.3.9, 11.4.8).

\textit{Effects:} Assigns \texttt{value} through all the iterators in the range \([\text{first}, \text{first} + N)\).

\textit{Returns:} \texttt{first} + \( N \).

\textit{Complexity:} Exactly \( N \) assignments.

### 27.7.7 Generate

\[\text{[alg.generate]}\]

template<class ForwardIterator, class Generator>
   constexpr void generate(ForwardIterator first, ForwardIterator last, Generator gen);

template<class ExecutionPolicy, class ForwardIterator, class Generator>
   void generate(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Generator gen);

template<class OutputIterator, class Size, class Generator>
   constexpr OutputIterator generate_n(OutputIterator first, Size n, Generator gen);

template<class ExecutionPolicy, class ForwardIterator, class Size, class Generator>
   ForwardIterator generate_n(ExecutionPolicy&& exec, ForwardIterator first, Size n, Generator gen);

template<input_or_output_iterator O, sentinel_for<O> S, copy_constructible F>
   requires invocable<F&&> & & indirectly_writable<O, invoke_result_t<F&&>>
   constexpr O ranges::generate(O first, S last, F gen);

template<class R, copy_constructible F>
   requires invocable<F&&> & & output_range<R, invoke_result_t<F&&>>
   constexpr borrowed_iterator_t<R> ranges::generate(R&& r, F gen);

template<input_or_output_iterator O, copy_constructible F>
   requires invocable<F&&> & & indirectly_writable<O, invoke_result_t<F&&>>
   constexpr O ranges::generate_n(O first, iter_difference_t<O> n, F gen);

Let \( N \) be \( \max(0, n) \) for the \texttt{generate_n} algorithms, and \( \text{last} - \text{first} \) for the \texttt{generate} algorithms.

\textit{Mandates:} \texttt{Size} is convertible to an integral type (7.3.9, 11.4.8).

\textit{Effects:} Assigns the result of successive evaluations of \texttt{gen()} through each iterator in the range \([\text{first}, \text{first} + N)\).

\textit{Returns:} \texttt{first} + \( N \).

\textit{Complexity:} Exactly \( N \) evaluations of \texttt{gen()} and assignments.

### 27.7.8 Remove

\[\text{[alg.remove]}\]

template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
   constexpr ForwardIterator remove(ForwardIterator first, ForwardIterator last, const T& value);

template<class ExecutionPolicy, class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
   ForwardIterator remove(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, const T& value);

template<class ForwardIterator, class Predicate>
   constexpr ForwardIterator remove_if(ForwardIterator first, ForwardIterator last, Predicate pred);
template<class ExecutionPolicy, class ForwardIterator, class Predicate>
ForwardIterator remove_if(ExecutionPolicy&& exec,
                     ForwardIterator first, ForwardIterator last,
                     Predicate pred);

template<permutable I, sentinel_for<I> S, class Proj = identity,
         indirect_unary_predicate<projected<I, Proj>> Pred>
constexpr subrange<I> ranges::remove(I first, S last, Pred pred, Proj proj = {});

template<class InputIterator, class OutputIterator, class T = iterator_traits<InputIterator>::value_type>
constexpr OutputIterator
remove_copy(InputIterator first, InputIterator last,
            OutputIterator result, const T& value);

template<class ExecutionPolicy, class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
ForwardIterator2
remove_copy(ExecutionPolicy&& exec,
            ForwardIterator1 first, ForwardIterator1 last,
            ForwardIterator2 result, const T& value);

template<class InputIterator, class OutputIterator, class Predicate>
constexpr OutputIterator
remove_copy_if(InputIterator first, InputIterator last,
                OutputIterator result, Predicate pred);

Let \( E \) be

\begin{align*}
(1.1) & \quad \text{bool}(\*i == \text{value}) \text{ for remove;} \\
(1.2) & \quad \text{bool}(\text{pred}(\*i)) \text{ for remove_if;} \\
(1.3) & \quad \text{bool}(\text{invoke}(\text{proj}, \*i) == \text{value}) \text{ for ranges::remove;} \\
(1.4) & \quad \text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, \*i))) \text{ for ranges::remove_if.}
\end{align*}

Preconditions: For the algorithms in namespace std, the type of \(*\text{first}\) meets the Cpp17MoveAssignable requirements (Table 33).

Effects: Eliminates all the elements referred to by iterator \( i \) in the range \([\text{first}, \text{last})\) for which \( E \) holds.

Returns: Let \( j \) be the end of the resulting range. Returns:

\begin{align*}
(4.1) & \quad j \text{ for the overloads in namespace std.} \\
(4.2) & \quad \{j, \text{last}\} \text{ for the overloads in namespace ranges.}
\end{align*}

Complexity: Exactly \( \text{last} - \text{first} \) applications of the corresponding predicate and any projection.

Remarks: Stable (16.4.6.8).

\[ \text{Note 1: Each element in the range} \{\text{ret, last}\}, \text{where ret is the returned value, has a valid but unspecified state, because the algorithms can eliminate elements by moving from elements that were originally in that range.} \text{— end note} \]
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class Predicate>
ForwardIterator2
remove_copy_if(ExecutionPolicy&& exec,
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, Predicate pred);

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O,
    class Proj = identity, class T = projected_value_t<I, Proj>>
requires indirectly_copyable<I, O> &&
    indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*>
constexpr ranges::remove_copy_result<I, O>
ranges::remove_copy(I first, S last, O result, const T& value, Proj proj = {});

template<input_range R, weakly_incrementable O, class Proj = identity,
    class T = projected_value_t<iterator_t<R>, Proj>>
requires indirectly_copyable<iterator_t<R>, O> &&
    indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T*>
constexpr ranges::remove_copy_result<borrowed_iterator_t<R>, O>
ranges::remove_copy(R&& r, O result, const T& value, Proj proj = {});

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O,
    class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
requires indirectly_copyable<I, O>
constexpr ranges::remove_copy_if_result<I, O>
ranges::remove_copy_if(I first, S last, O result, Pred pred, Proj proj = {});

template<input_range R, weakly_incrementable O, class Proj = identity,
    indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
requires indirectly_copyable<iterator_t<R>, O>
constexpr ranges::remove_copy_if_result<borrowed_iterator_t<R>, O>
ranges::remove_copy_if(R&& r, O result, Pred pred, Proj proj = {});

Let $E$ be

- $\text{bool}(\*i == \text{value})$ for remove_copy;
- $\text{bool}(\text{pred}(\*i))$ for remove_copy_if;
- $\text{bool}(\text{invoke}(\text{proj}, \*i) == \text{value})$ for ranges::remove_copy;
- $\text{bool}(\text{invoke}(\text{proj}, \text{invoke}(\text{proj}, \*i)))$ for ranges::remove_copy_if.

Let $N$ be the number of elements in [first, last) for which $E$ is false.

**Mandates:** first is writable (25.3.1) to result.

**Preconditions:** The ranges [first, last] and [result, result + (last - first)) do not overlap.

[Note 2: For the overloads with an ExecutionPolicy, there might be a performance cost if iterator_traits<ForwardIterator1>::value_type does not meet the Cpp17MoveConstructible (Table 31) requirements.

--- end note]

**Effects:** Copies all the elements referred to by the iterator $i$ in the range [first, last) for which $E$ is false.

**Returns:**

- result + $N$, for the algorithms in namespace std.
- {last, result + $N$}, for the algorithms in namespace ranges.

**Complexity:** Exactly last - first applications of the corresponding predicate and any projection.

**Remarks:** Stable (16.4.6.8).

### 27.7.9 Unique [alg.unique]

```cpp
template<class ForwardIterator>
constexpr ForwardIterator unique(ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator unique(ExecutionPolicy&& exec,
    ForwardIterator first, ForwardIterator last);
```
template<class ForwardIterator, class BinaryPredicate>
constexpr ForwardIterator unique(ForwardIterator first, ForwardIterator last,
        BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator, class BinaryPredicate>
ForwardIterator unique(ExecutionPolicy&& exec,
        ForwardIterator first, ForwardIterator last,
        BinaryPredicate pred);

template<permutable I, sentinel_for<I> S, class Proj = identity,
        indirect_equivalence_relation<projected<I, Proj>> C = ranges::equal_to>
constexpr subrange<I> ranges::unique(I first, S last, C comp = {}, Proj proj = {});

template<forward_range R, class Proj = identity,
        indirect_equivalence_relation<projected<iterator_t<R>, Proj>> C = ranges::equal_to>
requires permutable<iterator_t<R>>
constexpr borrowed_subrange_t<R>
ranges::unique(R&& r, C comp = {}, Proj proj = {});

Let \( \text{pred} \) be \( \text{equal}_\text{to} \{ \} \) for the overloads with no parameter \( \text{pred} \), and let \( \mathcal{E} \) be

\begin{align}
\text{(1.1)} & \quad \text{bool}(\text{pred}(\ast(i - 1), \ast i)) \quad \text{for the overloads in namespace std}; \\
\text{(1.2)} & \quad \text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \ast(i - 1)), \text{invoke}(\text{proj}, \ast i))) \quad \text{for the overloads in} \\
& \quad \text{namespace ranges}.
\end{align}

**Preconditions:** For the overloads in namespace std, \( \text{pred} \) is an equivalence relation and the type of
\*first meets the Cpp17MoveAssignable requirements (Table 33).

**Effects:** For a nonempty range, eliminates all but the first element from every consecutive group of
equivalent elements referred to by the iterator \( i \) in the range \([\text{first} + 1, \text{last})\) for which \( \mathcal{E} \) is \true.

**Returns:** Let \( j \) be the end of the resulting range. Returns:

\begin{align}
\text{(4.1)} & \quad j \quad \text{for the overloads in namespace std} \\
\text{(4.2)} & \quad \{ j, \text{last} \} \quad \text{for the overloads in namespace ranges}.
\end{align}

**Complexity:** For nonempty ranges, exactly \( (\text{last} - \text{first}) - 1 \) applications of the corresponding
predicate and no more than twice as many applications of any projection.
ranges::unique_copy(I first, S last, O result, C comp = {}, Proj proj = {});

template<input_range R, weakly_incrementable O, class Proj = identity,
   indirect_equivalence_relation<projected<iterator_t<R>>, Proj>> C = ranges::equal_to
requires indirectly_copyable<iterator_t<R>, O> &&
   (forward_iterator<iterator_t<R>> ||
    indirectly_copyable_storable<iterator_t<R>, O>)
constexpr ranges::unique_copy_result<borrowed_iterator_t<R>, O>
ranges::unique_copy(R&& r, O result, C comp = {}, Proj proj = {});

Let pred be equal_to{} for the overloads in namespace std with no parameter pred, and let E be
— bool(pred(*i, *(i - 1))) for the overloads in namespace std;
— bool(invoke(comp, invoke(proj, *i), invoke(proj, *(i - 1)))) for the overloads in
namespace ranges.

Mandates: *first is writable (25.3.1) to result.

Preconditions:
— The ranges [first, last) and [result.result+(last-first)) do not overlap.
— For the overloads in namespace std:
   — The comparison function is an equivalence relation.
   — For the overloads with no ExecutionPolicy, let T be the value type of InputIterator. If
     InputIterator models forward_iterator (25.3.4.11), then there are no additional require-
     ments for T. Otherwise, if OutputIterator meets the Cpp17ForwardIterator requirements and
     its value type is the same as T, then T meets the Cpp17CopyAssignable (Table 34) requirements.
     Otherwise, T meets both the Cpp17CopyConstructible (Table 32) and Cpp17CopyAssignable
     requirements.

[Note 1: For the overloads with an ExecutionPolicy, there might be a performance cost if the value
   type of ForwardIterator1 does not meet both the Cpp17CopyConstructible and Cpp17CopyAssignable
   requirements. — end note]

Effects: Copies only the first element from every consecutive group of equal elements referred to by the
iterator i in the range [first, last) for which E holds.

Returns:
— result + N for the overloads in namespace std.
— {last, result + N} for the overloads in namespace ranges.

Complexity: Exactly last - first - 1 applications of the corresponding predicate and no more than
twice as many applications of any projection.

27.7.10 Reverse [alg.reverse]

template<class BidirectionalIterator>
constexpr void reverse(BidirectionalIterator first, BidirectionalIterator last);

template<class ExecutionPolicy, class BidirectionalIterator>
void reverse(ExecutionPolicy&& exec, BidirectionalIterator first, BidirectionalIterator last);

template<bidirectional_iterator I, sentinel_for<I> S>
requires permutable<I>
constexpr I ranges::reverse(I first, S last);

template<bidirectional_range R>
requires permutable<iterator_t<R>>
constexpr borrowed_iterator_t<R> ranges::reverse(R&& r);

Preconditions: For the overloads in namespace std, BidirectionalIterator meets the Cpp17Value-
Swappabble requirements (16.4.4.3).

Effects: For each non-negative integer i < (last - first) / 2, applies std::iter_swap, or ranges::
iter_swap for the overloads in namespace ranges, to all pairs of iterators first + i, (last - i) - 1.

Returns: last for the overloads in namespace ranges.
Complexity: Exactly \((\text{last} - \text{first})/2\) swaps.

\[
\begin{align*}
\text{template}<\text{class BidirectionalIterator, class OutputIterator} & > \\
\text{constexpr OutputIterator} & \text{reverse_copy(BidirectionalIterator first, BidirectionalIterator last,} \\
& \text{OutputIterator result);} \\
\text{template<class ExecutionPolicy, class BidirectionalIterator, class ForwardIterator} & > \\
\text{ForwardIterator} & \text{reverse_copy(ExecutionPolicy\&\& exec,} \\
& \text{BidirectionalIterator first, BidirectionalIterator last,} \\
& \text{ForwardIterator result);} \\
\text{template<bidirectional_iterator I, sentinel_for<I> S, weakly_incrementable O} & > \\
\text{requires indirectly_copyable<I, O>} \\
\text{constexpr ranges::reverse_copy_result<I, O>} & \text{ranges::reverse_copy(I first, S last, O result);} \\
\text{template<bidirectional_range R, weakly_incrementable O} & > \\
\text{requires indirectly_copyable<iterator_t<R>, O>} \\
\text{constexpr ranges::reverse_copy_result<borrowed_iterator_t<R>, O>} & \text{ranges::reverse_copy(R\&\& r, O result);} \\
\end{align*}
\]

Let \(N\) be \(\text{last} - \text{first}\).

Preconditions: The ranges \([\text{first}, \text{last})\) and \([\text{result.result + N})\) do not overlap.

Effects: Copies the range \([\text{first}, \text{last})\) to the range \([\text{result.result + N})\) such that for every non-negative integer \(i < N\) the following assignment takes place: \(*\text{result + N - 1 - i} = *(\text{first} + i\).

Returns:

(8.1) \(\text{result + N}\) for the overloads in namespace \text{std.}

(8.2) \{\text{last, result + N}\} for the overloads in namespace \text{ranges.}

Complexity: Exactly \(N\) assignments.

27.7.11 Rotate

\[
\begin{align*}
\text{template<class ForwardIterator} & > \\
\text{constexpr ForwardIterator} & \text{rotate(ForwardIterator first, ForwardIterator middle, ForwardIterator last);} \\
\text{template<class ExecutionPolicy, class ForwardIterator} & > \\
\text{ForwardIterator} & \text{rotate(ExecutionPolicy\&\& exec,} \\
& \text{ForwardIterator first, ForwardIterator middle, ForwardIterator last);} \\
\text{template<permutable I, sentinel_for<I> S} & > \\
\text{constexpr subrange<I> ranges::rotate(I first, I middle, S last);} \\
\end{align*}
\]

Preconditions: \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\) are valid ranges. For the overloads in namespaces \text{std.} \text{ForwardIterator}\ meets the \text{Cpp17ValueSwappable} requirements (16.4.4.3), and the type of \(*\text{first}\) meets the \text{Cpp17MoveConstructible} (Table 31) and \text{Cpp17MoveAssignable} (Table 33) requirements.

Effects: For each non-negative integer \(i < (\text{last} - \text{first})\), places the element from the position \(\text{first} + i\) into position \(\text{first} + (i + (\text{last} - \text{middle})) \% (\text{last} - \text{first})\).

[Note 1: This is a left rotate. — end note]

Returns:

(3.1) \(\text{first} + (\text{last} - \text{middle})\) for the overloads in namespace \text{std.}

(3.2) \{\text{first} + (\text{last} - \text{middle}), \text{last}\} for the overload in namespace \text{ranges.}

Complexity: At most \(\text{last} - \text{first}\) swaps.

\[
\begin{align*}
\text{template<forward_range R} & > \\
\text{requires permutable<iterator_t<R>>} \\
\text{constexpr borrowed_subrange_t<R> ranges::rotate(R\&\& r, iterator_t<R> middle);} \\
\end{align*}
\]

Effects: Equivalent to: \text{return ranges::rotate(ranges::begin(r), middle, ranges::end(r));}
template<class ForwardIterator, class OutputIterator>
constexpr OutputIterator
rotate_copy(ForwardIterator first, ForwardIterator middle, ForwardIterator last,
OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
rotate_copy(ExecutionPolicy&& exec,
ForwardIterator1 first, ForwardIterator1 middle, ForwardIterator1 last,
ForwardIterator2 result);

template<forward_iterator I, sentinel_for<I> S, weakly_incrementable O>
requires indirectly_copyable<I, O>
constexpr ranges::rotate_copy_result<I, O>
ranges::rotate_copy(I first, I middle, S last, O result);

Let \( N \) be \( \text{last} - \text{first} \).

Preconditions: \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\) are valid ranges. The ranges \([\text{first}, \text{last})\) and \([\text{result}, \text{result} + N)\) do not overlap.

Effects: Copies the range \([\text{first}, \text{last})\) to the range \([\text{result}, \text{result} + N)\) such that for each non-negative integer \( i < N \) the following assignment takes place: \( *(\text{result} + i) = *(\text{first} + (i + (\text{middle} - \text{first})) \% N) \).

Returns:

- \( \text{result} + N \) for the overloads in namespace \( \text{std} \).
- \( \{\text{last}, \text{result} + N\} \) for the overload in namespace \( \text{ranges} \).

Complexity: Exactly \( N \) assignments.

template<forward_range R, weakly_incrementable O>
requires indirectly_copyable<iterator_t<R>, O>
constexpr ranges::rotate_copy_result<borrowed_iterator_t<R>, O>
ranges::rotate_copy(R&& r, iterator_t<R> middle, O result);

Effects: Equivalent to:

\[
\text{return ranges::rotate_copy(ranges::begin(r), middle, ranges::end(r), std::move(result));}
\]

27.7.12 Sample

[alg.random.sample]

template<class PopulationIterator, class SampleIterator,
class Distance, class UniformRandomBitGenerator>
SampleIterator sample(PopulationIterator first, PopulationIterator last,
SampleIterator out, Distance n,
UniformRandomBitGenerator&& g);

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, class Gen>
requires (forward_iterator<I> || random_access_iterator<O>) &&
indirectly_copyable<I, O> &&
uniform_random_bit_generator<remove_reference_t<Gen>>
O ranges::sample(I first, S last, O out, iter_difference_t<I> n, Gen& g);

template<input_range R, weakly_incrementable O, class Gen>
requires (forward_range<R> || random_access_iterator<O>) &&
indirectly_copyable<iterator_t<R>, O> &&
uniform_random_bit_generator<remove_reference_t<Gen>>
O ranges::sample(R&& r, O out, range_difference_t<R> n, Gen& g);

Mandates: For the overload in namespace \( \text{std} \), \( \text{Distance} \) is an integer type and \(*\text{first} \) is writable (25.3.1) to out.

Preconditions: \( \text{out} \) is not in the range \([\text{first}, \text{last})\). For the overload in namespace \( \text{std} \):

(2.1) \( \text{PopulationIterator} \) meets the \( \text{Cpp17InputIterator} \) requirements (25.3.5.3).

(2.2) \( \text{SampleIterator} \) meets the \( \text{Cpp17OutputIterator} \) requirements (25.3.5.4).

(2.3) \( \text{SampleIterator} \) meets the \( \text{Cpp17RandomAccessIterator} \) requirements (25.3.5.7) unless \( \text{PopulationIterator} \) models \( \text{forward_iterator} \) (25.3.4.11).
---
remove_reference_t<UniformRandomBitGenerator> meets the requirements of a uniform random bit generator type (28.5.3.3).

**Effects:** Copies \( \min(\text{last} - \text{first}, n) \) elements (the *sample*) from \([\text{first},\text{last})\) (the *population*) to out such that each possible sample has equal probability of appearance.

[Note 1: Algorithms that obtain such effects include *selection sampling* and *reservoir sampling*. — end note]

**Returns:** The end of the resulting sample range.

**Complexity:** \( \Theta(\text{last} - \text{first}) \).

**Remarks:**

---
For the overload in namespace *std*, stable if and only if *PopulationIterator* models *forward_iterator*. For the first overload in namespace *ranges*, stable if and only if *I* models *forward_iterator*.

---
To the extent that the implementation of this function makes use of random numbers, the object \( g \) serves as the implementation’s source of randomness.

### 27.7.13 Shuffle

```
template<class RandomAccessIterator, class UniformRandomBitGenerator>
void shuffle(RandomAccessIterator first, RandomAccessIterator last, UniformRandomBitGenerator&& g);
```

```
template<random_access_iterator I, sentinel_for<I> S, class Gen>
requires permutable<I> && uniform_random_bit_generator<remove_reference_t<Gen>>
I ranges::shuffle(I first, S last, Gen&& g);
```

```
template<random_access_range R, class Gen>
requires permutable<iterator_t<R>> && uniform_random_bit_generator<remove_reference_t<Gen>>
borrowed_iterator_t<R> ranges::shuffle(R&& r, Gen&& g);
```

---
**Preconditions:** For the overload in namespace *std*:

---
**Effects:** Permutes the elements in the range \([\text{first},\text{last})\) such that each possible permutation of those elements has equal probability of appearance.

---
**Returns:** \( \text{last} \) for the overloads in namespace *ranges*.

---
**Complexity:** Exactly \( \text{last} - \text{first} \) - 1 swaps.

---
**Remarks:** To the extent that the implementation of this function makes use of random numbers, the object referenced by \( g \) shall serve as the implementation’s source of randomness.

### 27.7.14 Shift

```
template<class ForwardIterator>
constexpr ForwardIterator shift_left(ForwardIterator first, ForwardIterator last,
typename iterator_traits<ForwardIterator>::difference_type n);
```

```
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
shift_left(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,
typename iterator_traits<ForwardIterator>::difference_type n);
```

```
template<permutable I, sentinel_for<I> S>
constexpr subrange<I> ranges::shift_left(I first, S last, iter_difference_t<I> n);
```
template<forward_range R>
requires permutable<iterator_t<R>>
constexpr borrowed_subrange_t<R> ranges::shift_left(R&& r, range_difference_t<R> n)

1 Preconditions: n >= 0 is true. For the overloads in namespace std, the type of *first meets the Cpp17MoveAssignable requirements.

2 Effects: If n == 0 or n >= last - first, does nothing. Otherwise, moves the element from position first + i into position first + i for each non-negative integer i < (last - first) - n. For the overloads without an ExecutionPolicy template parameter, does so in order starting from i = 0 and proceeding to i = (last - first) - n - 1.

3 Returns: Let NEW_LAST be first + (last - first - n) if n < last - first, otherwise first.

   — NEW_LAST for the overloads in namespace std.

   — {first, NEW_LAST} for the overloads in namespace ranges.

4 Complexity: At most (last - first) - n assignments.

template<class ForwardIterator>
constexpr ForwardIterator
shift_right(ForwardIterator first, ForwardIterator last,
typeid iterator_traits<ForwardIterator>::difference_type n);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
shift_right(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,
typeid iterator_traits<ForwardIterator>::difference_type n);

template<permutable I, sentinel_for<I> S>
constexpr subrange<I> ranges::shift_right(I first, S last, iter_difference_t<I> n);

template<forward_range R>
requires permutable<iterator_t<R>>
constexpr borrowed_subrange_t<R> ranges::shift_right(R&& r, range_difference_t<R> n)

5 Preconditions: n >= 0 is true. For the overloads in namespace std, the type of *first meets the Cpp17MoveAssignable requirements, and ForwardIterator meets the Cpp17BidirectionalIterator requirements (25.3.5.6) or the Cpp17ValueSwappable requirements.

6 Effects: If n == 0 or n >= last - first, does nothing. Otherwise, moves the element from position first + i into position first + n + i for each non-negative integer i < (last - first) - n. Does so in order starting from i = (last - first) - n - 1 and proceeding to i = 0 if

   — for the overload in namespace std without an ExecutionPolicy template parameter, ForwardIterator meets the Cpp17BidirectionalIterator requirements,

   — for the overloads in namespace ranges, I models bidirectional_iterator.

7 Returns: Let NEW_FIRST be first + n if n < last - first, otherwise last.

   — NEW_FIRST for the overloads in namespace std.

   — {NEW_FIRST, last} for the overloads in namespace ranges.

8 Complexity: At most (last - first) - n assignments or swaps.

27.8 Sorting and related operations

27.8.1 General

The operations in 27.8 defined directly in namespace std have two versions: one that takes a function object of type Compare and one that uses an operator<.

Compare is a function object type (22.10) that meets the requirements for a template parameter named BinaryPredicate (27.2). The return value of the function call operation applied to an object of type Compare, when converted to bool, yields true if the first argument of the call is less than the second, and false otherwise. Compare comp is used throughout for algorithms assuming an ordering relation.

For all algorithms that take Compare, there is a version that uses operator< instead. That is, comp(*i, *j) != false defaults to *i < *j != false. For algorithms other than those described in 27.8.4, comp shall induce a strict weak ordering on the values.
The term *strict* refers to the requirement of an irreflexive relation \(!\text{comp}(x, x)\) for all \(x\), and the term *weak* to requirements that are not as strong as those for a total ordering, but stronger than those for a partial ordering. If we define \(\text{equiv}(a, b)\) as \(!\text{comp}(a, b) \&\& !\text{comp}(b, a)\), then the requirements are that \(\text{comp}\) and \(\text{equiv}\) both be transitive relations:

\[(4.1) \quad \text{comp}(a, b) \&\& \text{comp}(b, c) \text{ implies } \text{comp}(a, c)\]

\[(4.2) \quad \text{equiv}(a, b) \&\& \text{equiv}(b, c) \text{ implies equiv}(a, c)\]

[Note 1: Under these conditions, it can be shown that]

\[(4.3) \quad \text{equiv} \text{ is an equivalence relation,}\]

\[(4.4) \quad \text{comp} \text{ induces a well-defined relation on the equivalence classes determined by equiv, and}\]

\[(4.5) \quad \text{the induced relation is a strict total ordering.}\]

—end note]

A sequence is *sorted with respect to a comp and proj* for a comparator and projection \(\text{comp}\) and \(\text{proj}\) if for every iterator \(i\) pointing to the sequence and every non-negative integer \(n\) such that \(i + n\) is a valid iterator pointing to an element of the sequence,

\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *(i + n)), \text{invoke}(\text{proj}, *i)))
\]

is false.

A sequence is *sorted with respect to a comparator comp* for a comparator \(\text{comp}\) if it is sorted with respect to \(\text{comp}\) and \(\text{identity}\) (the identity projection).

A sequence \([\text{start}, \text{finish})\] is *partitioned with respect to an expression f(e)* if there exists an integer \(n\) such that for all \(0 \leq i < (\text{finish} - \text{start})\), \(f(*(\text{start} + i))\) is true if and only if \(i < n\).

In the descriptions of the functions that deal with ordering relationships we frequently use a notion of equivalence to describe concepts such as stability. The equivalence to which we refer is not necessarily an \(\text{operator\_eq}\), but an equivalence relation induced by the strict weak ordering. That is, two elements \(a\) and \(b\) are considered equivalent if and only if \(!((a < b) \&\& ! (b < a))\).

### 27.8.2 Sorting

#### 27.8.2.1 sort

```cpp
template<class RandomAccessIterator>
constexpr void sort(RandomAccessIterator first, RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator>
void sort(ExecutionPolicy&& exec,
          RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void sort(RandomAccessIterator first, RandomAccessIterator last,
                      Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void sort(ExecutionPolicy&& exec,
          RandomAccessIterator first, RandomAccessIterator last,
          Compare comp);

template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
          class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::sort(I first, S last, Comp comp = {}, Proj proj = {});

template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::sort(R&& r, Comp comp = {}, Proj proj = {});
```

1. Let \(\text{comp}\) be \(\text{less}\{\}\) and \(\text{proj}\) be \(\text{identity}\{\}\) for the overloads with no parameters by those names.

2. **Preconditions:** For the overloads in namespace \(\text{std}\), \(\text{RandomAccessIterator}\) meets the \(\text{Cpp17Value-Swappable}\) requirements (16.4.4.3) and the type of \(*\text{first}\) meets the \(\text{Cpp17MoveConstructible}\) (Table 31) and \(\text{Cpp17MoveAssignable}\) (Table 33) requirements.
**Effects:** Sorts the elements in the range \([\text{first, last})\) with respect to \text{comp} and \text{proj}.

**Returns:** \text{last} for the overloads in namespace \text{ranges}.

**Complexity:** Let \(N\) be \text{last} - \text{first}. \(\Theta(N \log N)\) comparisons and projections.

### 27.8.2.2 stable_sort

```
27.8.2.2 stable_sort

template<class RandomAccessIterator>
constexpr void stable_sort(RandomAccessIterator first, RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator>
void stable_sort(ExecutionPolicy&& exec,
RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void stable_sort(RandomAccessIterator first, RandomAccessIterator last,
Compare comp);

template<class RandomAccessRange R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R> ranges::stable_sort(R&& r, Comp comp = {}, Proj proj = {});
```

Let \text{comp} be \text{less{}} and \text{proj} be \text{identity{}} for the overloads with no parameters by those names.

**Preconditions:** For the overloads in namespace \text{std}, \text{RandomAccessIterator} meets the \text{Cpp17Value-Swappable} requirements (16.4.4.3) and the type of \*\text{first} meets the \text{Cpp17MoveConstructible} (Table 31) and \text{Cpp17MoveAssignable} (Table 33) requirements.

**Effects:** Sorts the elements in the range \([\text{first, last})\) with respect to \text{comp} and \text{proj}.

**Returns:** \text{last} for the overloads in namespace \text{ranges}.

**Complexity:** Let \(N\) be \text{last} - \text{first}. If enough extra memory is available, \(N \log(N)\) comparisons. Otherwise, at most \(N \log^2(N)\) comparisons. In either case, twice as many projections as the number of comparisons.

**Remarks:** Stable (16.4.6.8).

### 27.8.2.3 partial_sort

```
27.8.2.3 partial_sort

template<class RandomAccessIterator>
constexpr void partial_sort(RandomAccessIterator first,
RandomAccessIterator middle,
RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator>
void partial_sort(ExecutionPolicy&& exec,
RandomAccessIterator first, RandomAccessIterator middle,
RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void partial_sort(RandomAccessIterator first,
RandomAccessIterator middle,
RandomAccessIterator last,
Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void partial_sort(ExecutionPolicy&& exec,
RandomAccessIterator first, RandomAccessIterator middle,
```
RandomAccessIterator last,
  Compare comp);

template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
  class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::partial_sort(I first, I middle, S last, Comp comp = {}, Proj proj = {});

Let comp be less{} and proj be identity{} for the overloads with no parameters by those names.

Preconditions: [first, middle) and [middle, last) are valid ranges. For the overloads in namespace std,
RandomAccessIterator meets the Cpp17ValueSwappable requirements (16.4.4.3) and the type of *first
meets the Cpp17MoveConstructible (Table 31) and Cpp17MoveAssignable (Table 33) requirements.

Effects: Places the first middle - first elements from the range [first, last) as sorted with respect
to comp and proj into the range [first, middle). The rest of the elements in the range [middle, last)
are placed in an unspecified order.

Returns: last for the overload in namespace ranges.

Complexity: Approximately (last - first) * log(middle - first) comparisons, and twice as
many projections.

template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::partial_sort(R&& r, iterator_t<R> middle, Comp comp = {}, Proj proj = {});

Effects: Equivalent to:
return ranges::partial_sort(ranges::begin(r), middle, ranges::end(r), comp, proj);

27.8.2.4 partial_sort_copy

template<class InputIterator, class RandomAccessIterator>
constexpr RandomAccessIterator
partial_sort_copy(InputIterator first, InputIterator last,
  RandomAccessIterator result_first,
  RandomAccessIterator result_last);

template<class ExecutionPolicy, class ForwardIterator, class RandomAccessIterator>
RandomAccessIterator
partial_sort_copy(ExecutionPolicy&& exec,
  ForwardIterator first, ForwardIterator last,
  RandomAccessIterator result_first,
  RandomAccessIterator result_last);

template<class InputIterator, class RandomAccessIterator,
  class Compare>
constexpr RandomAccessIterator
partial_sort_copy(InputIterator first, InputIterator last,
  RandomAccessIterator result_first,
  RandomAccessIterator result_last,
  Compare comp);

template<class ExecutionPolicy, class ForwardIterator, class RandomAccessIterator,
  class Compare>
RandomAccessIterator
partial_sort_copy(ExecutionPolicy&& exec,
  ForwardIterator first, ForwardIterator last,
  RandomAccessIterator result_first,
  RandomAccessIterator result_last,
  Compare comp);

template<input_iterator I1, sentinel_for<I1> S1, random_access_iterator I2, sentinel_for<I2> S2,
  class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
requires indirectly_copyable<I1, I2> && sortable<I2, Comp, Proj2> &&
  indirect_strict_weak_order<Comp, projected<I1, Proj1>, projected<I2, Proj2>>
constexpr ranges::partial_sort_copy_result<I1, I2>
ranges::partial_sort_copy(I1 first, S1 last, I2 result_first, S2 result_last, 
    Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, random_access_range R2, class Comp = ranges::less, 
    class Proj1 = identity, class Proj2 = identity>
requires indirectly_copyable<iterator_t<R1>, iterator_t<R2>> && 
    sortable<iterator_t<R2>, Comp, Proj2> && 
    indirect_strict_weak_order<Comp, projected<iterator_t<R1>, Proj1>, 
    projected<iterator_t<R2>, Proj2>>
constexpr ranges::partial_sort_copy_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
ranges::partial_sort_copy(R1&& r, R2&& result_r, Comp comp = {}, 
    Proj1 proj1 = {}, Proj2 proj2 = {});

1 Let N be min(last - first, result_last - result_first). Let comp be less{}, and proj1 and 
    proj2 be identity{} for the overloads with no parameters by those names.

2 Mandates: For the overloads in namespace std, the expression *first is writable (25.3.1) to result_- 
    first.

3 Preconditions: For the overloads in namespace std, RandomAccessIterator meets the Cpp17Value- 
    Swappable requirements (16.4.4.3), the type of *result_first meets the Cpp17MoveConstructible 
    (Table 31) and Cpp17MoveAssignable (Table 33) requirements.

4 For iterators a1 and b1 in [first, last), and iterators x2 and y2 in [result_first, result_last), 
    after evaluating the assignment *y2 = *b1, let E be the value of
    bool(invoke(comp, invoke(proj1, *a1), invoke(proj2, *y2))).

    Then, after evaluating the assignment *x2 = *a1, E is equal to
    bool(invoke(comp, invoke(proj2, *x2), invoke(proj2, *y2))).

    [Note 1: Writing a value from the input range into the output range does not affect how it is ordered by comp 
    and proj1 or proj2. — end note]

5 Effects: Places the first N elements as sorted with respect to comp and proj2 into the range [result_- 
    first, result_first + N).

6 Returns:

(6.1) result_first + N for the overloads in namespace std.

(6.2) {last, result_first + N} for the overloads in namespace ranges.

7 Complexity: Approximately (last - first) * log N comparisons, and twice as many projections.

27.8.2.5 is_sorted

[is.sorted] template<class ForwardIterator>
constexpr bool is_sorted(ForwardIterator first, ForwardIterator last);

1 Effects: Equivalent to: return is_sorted_until(first, last) == last;

template<class ExecutionPolicy, class ForwardIterator>
bool is_sorted(ExecutionPolicy&& exec, 
    ForwardIterator first, ForwardIterator last);

2 Effects: Equivalent to: return is_sorted_until(std::forward<ExecutionPolicy>(exec), first, last) == last;

template<class ForwardIterator, class Compare>
constexpr bool is_sorted(ForwardIterator first, ForwardIterator last, 
    Compare comp);

3 Effects: Equivalent to: return is_sorted_until(first, last, comp) == last;

template<class ExecutionPolicy, class ForwardIterator, class Compare>
bool is_sorted(ExecutionPolicy&& exec, 
    ForwardIterator first, ForwardIterator last, 
    Compare comp);

4 Effects: Equivalent to: return is_sorted_until(std::forward<ExecutionPolicy>(exec), first, last, comp) == last;
template<forward_iterator I, sentinel_for<I> S, class Proj = identity, 
    indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr bool ranges::is_sorted(I first, S last, Comp comp = {}, Proj proj = {});

template<forward_range R, class Proj = identity, 
    indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr bool ranges::is_sorted(R&& r, Comp comp = {}, Proj proj = {});

**Effects:** Equivalent to: return ranges::is_sorted_until(first, last, comp, proj) == last;

template<class ForwardIterator>
constexpr ForwardIterator
is_sorted_until(ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
is_sorted_until(ExecutionPolicy&& exec, 
    ForwardIterator first, ForwardIterator last);

template<class ForwardIterator, class Compare>
constexpr ForwardIterator
is_sorted_until(ForwardIterator first, ForwardIterator last, 
    Compare comp);

template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator
is_sorted_until(ExecutionPolicy&& exec, 
    ForwardIterator first, ForwardIterator last, 
    Compare comp);

template<forward_iterator I, sentinel_for<I> S, class Proj = identity, 
    indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr I ranges::is_sorted_until(I first, I nth, S last, Comp comp = {}, Proj proj = {});

template<forward_range R, class Proj = identity, 
    indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr borrowed_iterator_t<R>
ranges::is_sorted_until(R&& r, Comp comp = {}, Proj proj = {});

Let **comp** be less{} and **proj** be identity{} for the overloads with no parameters by those names.

**Returns:** The last iterator `i` in `[first, last]` for which the range `[first, i)` is sorted with respect to `comp` and `proj`.

**Complexity:** Linear.

### 27.8.3 Nth element

```cpp
template<class RandomAccessIterator>
constexpr void nth_element(RandomAccessIterator first, RandomAccessIterator nth, 
    RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator>
void nth_element(ExecutionPolicy&& exec, 
    RandomAccessIterator first, RandomAccessIterator nth, 
    RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void nth_element(RandomAccessIterator first, RandomAccessIterator nth, 
    RandomAccessIterator last, Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void nth_element(ExecutionPolicy&& exec, 
    RandomAccessIterator first, RandomAccessIterator nth, 
    RandomAccessIterator last, Compare comp);

template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, 
    class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::nth_element(I first, I nth, S last, Comp comp = {}, Proj proj = {});
```

Let `comp` be less{} and `proj` be identity{} for the overloads with no parameters by those names.
**Preconditions:** `[first, nth)` and `[nth, last)` are valid ranges. For the overloads in namespace `std`, `RandomAccessIterator` meets the `Cpp17ValueSwappable` requirements (16.4.4.3), and the type of `*first` meets the `Cpp17MoveConstructible` (Table 31) and `Cpp17MoveAssignable` (Table 33) requirements.

**Effects:** After `nth_element` the element in the position pointed to by `nth` is the element that would be in that position if the whole range were sorted with respect to `comp` and `proj`, unless `nth == last`. Also for every iterator `i` in the range `[first, nth)` and every iterator `j` in the range `[nth, last)` it holds that: bool(`invoke(comp, invoke(proj, *j), invoke(proj, *i)))` is false.

**Returns:** `last` for the overload in namespace `ranges`.

**Complexity:** For the overloads with no `ExecutionPolicy`, linear on average. For the overloads with an `ExecutionPolicy`, \( O(N) \) applications of the predicate, and \( O(N \log N) \) swaps, where \( N = \text{last} - \text{first} \).

```cpp
template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::nth_element(R&& r, iterator_t<R> nth, Comp comp = {}, Proj proj = {});
```

**Effects:** Equivalent to:

```
return ranges::nth_element(ranges::begin(r), nth, ranges::end(r), comp, proj);
```

### 27.8.4 Binary search

**General**

All of the algorithms in 27.8.4 are versions of binary search and assume that the sequence being searched is partitioned with respect to an expression formed by binding the search key to an argument of the comparison function. They work on non-random access iterators minimizing the number of comparisons, which will be logarithmic for all types of iterators. They are especially appropriate for random access iterators, because these algorithms do a logarithmic number of steps through the data structure. For non-random access iterators they execute a linear number of steps.

#### 27.8.4.2 lower_bound

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator
lower_bound(ForwardIterator first, ForwardIterator last, const T& value);
```

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type, class Compare>
constexpr ForwardIterator
lower_bound(ForwardIterator first, ForwardIterator last, const T& value, Compare comp);
```

```cpp
template<forward_iterator I, sentinel_for<I> S, class Proj = identity, 
class T = projected_value_t<I, Proj>, 
indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
constexpr I ranges::lower_bound(I first, S last, const T& value, Comp comp = {},
Proj proj = {});
```

```cpp
template<forward_range R, class Proj = identity, 
class T = projected_value_t<iterator_t<R>, Proj>, 
indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr borrowed_iterator_t<R>
ranges::lower_bound(R&& r, const T& value, Comp comp = {}, Proj proj = {});
```

Let `comp` be `less{}` and `proj` be `identity{}` for overloads with no parameters by those names.

**Preconditions:** The elements `e` of `[first, last)` are partitioned with respect to the expression `bool(``invoke(comp, invoke(proj, e), value))`.

**Returns:** The furthermost iterator `i` in the range `[first, last)` such that for every iterator `j` in the range `[first, i)`, `bool(``invoke(comp, invoke(proj, *j), value))` is true.
Complexity: At most \( \log_2(\text{last} - \text{first}) + \Theta(1) \) comparisons and projections.

### 27.8.4.3 upper_bound

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last,
                                       const T& value);
```

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type,
         class Compare>
constexpr ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last,
                                       const T& value, Compare comp);
```

```cpp
template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
         class T = projected_value_t<I, Proj>,
         indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
constexpr subrange<I> ranges::upper_bound(I first, S last, const T& value, Comp comp = {}, Proj proj = {});
```

```cpp
template<forward_range R, class Proj = identity,
         class T = projected_value_t<iterator_t<R>, Proj>,
         indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr borrowed_iterator_t<R> ranges::upper_bound(R&& r, const T& value, Comp comp = {}, Proj proj = {});
```

Let `comp` be \texttt{less{}} and `proj` be \texttt{identity{}} for overloads with no parameters by those names.

**Preconditions:** The elements \( e \) of \([\text{first}, \text{last})\) are partitioned with respect to the expression
\( \neg \text{bool}(\text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, e))) \).

**Returns:** The furthermost iterator \( i \) in the range \([\text{first}, \text{last})\) such that for every iterator \( j \) in the range \([\text{first}, i)\), \( \neg \text{bool}(\text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, \ast j))) \) is true.

Complexity: At most \( \log_2(\text{last} - \text{first}) + \Theta(1) \) comparisons and projections.

### 27.8.4.4 equal_range

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first,
                                                             ForwardIterator last, const T& value);
```

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type,
         class Compare>
constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first,
                                                             ForwardIterator last, const T& value,
                                                             Compare comp);
```

```cpp
template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
         class T = projected_value_t<I, Proj>,
         indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
constexpr subrange<I> ranges::equal_range(I first, S last, const T& value, Comp comp = {}, Proj proj = {});
```

```cpp
template<forward_range R, class Proj = identity,
         class T = projected_value_t<iterator_t<R>, Proj>,
         indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr borrowed_subrange_t<R> ranges::equal_range(R&& r, const T& value, Comp comp = {}, Proj proj = {});
```

Let `comp` be \texttt{less{}} and `proj` be \texttt{identity{}} for overloads with no parameters by those names.

**Preconditions:** The elements \( e \) of \([\text{first}, \text{last})\) are partitioned with respect to the expressions
\( \text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, e), \text{value})) \) and \( \text{bool}(\text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, \text{value})) \) true.
e)). Also, for all elements e of \([\text{first}, \text{last})\), bool(comp(e, value)) implies !bool(comp(value, e)) for the overloads in namespace std.

**Returns:**

1. For the overloads in namespace std:
   \[
   \{\text{lower_bound(} \text{first, last, value, comp),}
   \text{ upper_bound(} \text{first, last, value, comp)}\}
   \]

2. For the overloads in namespace ranges:
   \[
   \{\text{ranges::lower_bound(} \text{first, last, value, comp, proj),}
   \text{ ranges::upper_bound(} \text{first, last, value, comp, proj)}\}
   \]

**Complexity:** At most \(2 \ast \log_2(\text{last} - \text{first}) + \Theta(1)\) comparisons and projections.

### 27.8.4.5 binary_search

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type>
constexpr bool
binary_search(ForwardIterator first, ForwardIterator last, 
const T& value);
```

```cpp
template<class ForwardIterator, class T = iterator_traits<ForwardIterator>::value_type,
class Compare>
constexpr bool
binary_search(ForwardIterator first, ForwardIterator last, 
const T& value, Compare comp);
```

```cpp
template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
class T = projected_value_t<I, Proj>,
indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
constexpr bool
ranges::binary_search(I first, S last, const T& value, Comp comp = {},
Proj proj = {});
```

```cpp
template<input_range R, class Proj = identity,
indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Pred =
ranges::less>
constexpr bool
ranges::binary_search(R&& r, const T& value, Comp comp = {},
Proj proj = {});
```

1. Let `comp` be `less{}` and `proj` be `identity{}` for overloads with no parameters by those names.

2. **Preconditions:** The elements e of \([\text{first}, \text{last})\) are partitioned with respect to the expressions bool:invoke(comp, invoke(proj, e), value)) and !bool:invoke(comp, value, invoke(proj, e))). Also, for all elements e of \([\text{first}, \text{last})\), bool(comp(e, value)) implies !bool(comp(value, e)) for the overloads in namespace std.

3. **Returns:** true if and only if for some iterator i in the range \([\text{first}, \text{last})\), !bool:invoke(comp, invoke(proj, *i), value)) && !bool:invoke(comp, value, invoke(proj, *i))) is true.

4. **Complexity:** At most \(\log_2(\text{last} - \text{first}) + \Theta(1)\) comparisons and projections.

### 27.8.5 Partitions

```cpp
template<class InputIterator, class Predicate>
constexpr bool
is_partitioned(InputIterator first, InputIterator last, Predicate pred);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator, class Predicate>
bool
is_partitioned(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last, Predicate pred);
```

```cpp
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
indirect_unary_predicate<projected<I, Proj>> Pred =
ranges::less>
constexpr bool
ranges::is_partitioned(I first, S last, Pred pred, Proj proj = {});
```

```cpp
template<input_range R, class Proj = identity,
indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred =
ranges::less>
constexpr bool
ranges::is_partitioned(R&& r, Pred pred, Proj proj = {});
```

1. Let `proj` be `identity{}` for the overloads with no parameter named `proj`.

---

\[ \text{Note: ISO/IEC 14348-2014}\]
Returns: true if and only if the elements $e$ of $[\text{first, last})$ are partitioned with respect to the expression $\text{bool}(\text{invoke}(\text{pred, invoke}(\text{proj, e})))$.

Complexity: Linear. At most last - first applications of pred and proj.

template<class ForwardIterator, class Predicate>
constexpr ForwardIterator
\text{partition}(\text{ForwardIterator first, ForwardIterator last, Predicate pred});
template<class ExecutionPolicy, class ForwardIterator, class Predicate>
\text{ForwardIterator}
\text{partition}(\text{ExecutionPolicy}\&\& \text{exec},
\text{ForwardIterator first, ForwardIterator last, Predicate pred});

template<class permutable I, sentinel_for<I> S, class Proj = identity,
\text{indirect Unary Predicate}<\text{projected<I, Proj>> Pred}>
\text{constexpr subrange}<I>
\text{ranges}::\text{partition}(I \text{ first, S last, Pred pred, Proj proj = {}});
template<class forward_range R, class Proj = identity,
\text{indirect Unary Predicate}<\text{projected<iterator_t<R>, Proj>> Pred}>
\text{requires permutable<iterator_t<R>>}
\text{constexpr borrowed subrange}<R>
\text{ranges}::\text{partition}(R&& r, Pred pred, Proj proj = {});

Let proj be identity{} for the overloads with no parameter named proj and let $E(x)$ be $\text{bool}(\text{invoke( pred, invoke( proj, x)))}.$

Preconditions: For the overloads in namespace std, ForwardIterator meets the Cpp17ValueSwappable requirements (16.4.4.3).

Effects: Places all the elements $e$ in $[\text{first, last})$ that satisfy $E(e)$ before all the elements that do not.

Returns: Let $i$ be an iterator such that $E(*j)$ is true for every iterator $j$ in $[\text{first, i})$ and false for every iterator $j$ in $[i, \text{last})$. Returns:

- $i$ for the overloads in namespace std.
- $\{i, \text{last}\}$ for the overloads in namespace ranges.

Complexity: Let $N = \text{last} - \text{first}$:

- For the overload with no ExecutionPolicy, exactly $N$ applications of the predicate and projection. At most $N/2$ swaps if the type of first meets the Cpp17BidirectionalIterator requirements for the overloads in namespace std or models bidirectional_iterator for the overloads in namespace ranges, and at most $N$ swaps otherwise.
- For the overload with an ExecutionPolicy, $O(N \log N)$ swaps and $O(N)$ applications of the predicate.

§ 27.8.5
Preconditions: For the overloads in namespace std, BidirectionalIterator meets the Cpp17Value-Swappable requirements (16.4.4.3) and the type of *first meets the Cpp17MoveConstructible (Table 31) and Cpp17MoveAssignable (Table 33) requirements.

Effects: Places all the elements e in [first, last) that satisfy E(e) before all the elements that do not. The relative order of the elements in both groups is preserved.

Returns: Let i be an iterator such that for every iterator j in [first, i), E(*j) is true, and for every iterator j in the range [i, last), E(*j) is false. Returns:

- i for the overloads in namespace std.
- {i, last} for the overloads in namespace ranges.

Complexity: Let N = last - first:

- For the overloads with no ExecutionPolicy, at most N log₂ N swaps, but only O(N) swaps if there is enough extra memory. Exactly N applications of the predicate and projection.
- For the overload with an ExecutionPolicy, O(N log N) swaps and O(N) applications of the predicate.

```cpp
template<class InputIterator, class OutputIterator1, class OutputIterator2, class Predicate>
constexpr pair<OutputIterator1, OutputIterator2> partition_copy(InputIterator first, InputIterator last,
OutputIterator1 out_true, OutputIterator2 out_false, Predicate pred);

template<class ExecutionPolicy, class ForwardIterator, class ForwardIterator1,
class ForwardIterator2, class Predicate>
pair<ForwardIterator1, ForwardIterator2> partition_copy(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last,
ForwardIterator1 out_true, ForwardIterator2 out_false, Predicate pred);

template<input_iterator I, sentinel_for<I> S, weakly_incrementable O1, weakly_incrementable O2,
class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
requires indirectly_copyable<I, O1> && indirectly_copyable<I, O2>
constexpr ranges::partition_copy_result<I, O1, O2> ranges::partition_copy(I first, S last, O1 out_true, O2 out_false, Pred pred, Proj proj = {});

template<input_range R, weakly_incrementable O1, weakly_incrementable O2,
class Proj = identity, indirect_unary_predicate<iterator_t<R>, Proj>> Pred>
requires indirectly_copyable<iterator_t<R>, O1> && indirectly_copyable<iterator_t<R>, O2>
constexpr ranges::partition_copy_result<borrowed_iterator_t<R>, O1, O2> ranges::partition_copy(R&& r, O1 out_true, O2 out_false, Pred pred, Proj proj = {});
```

Let proj be identity{} for the overloads with no parameter named proj and let E(x) be bool(invoke(pred, invoke(proj, x))).

Mandates: For the overloads in namespace std, the expression *first is writable (25.3.1) to out_true and out_false.

Preconditions: The input range and output ranges do not overlap.

[Note 1: For the overload with an ExecutionPolicy, there might be a performance cost if first’s value type does not meet the Cpp17CopyConstructible requirements. — end note]

Effects: For each iterator i in [first, last), copies *i to the output range beginning with out_true if E(*i) is true, or to the output range beginning with out_false otherwise.

Returns: Let o1 be the end of the output range beginning at out_true, and o2 the end of the output range beginning at out_false. Returns:

- {o1, o2} for the overloads in namespace std.
- {last, o1, o2} for the overloads in namespace ranges.

Complexity: Exactly last - first applications of pred and proj.

§ 27.8.5 © ISO/IEC 1436
template<class ForwardIterator, class Predicate>
constexpr ForwardIterator
partition_point(ForwardIterator first, ForwardIterator last, Predicate pred);

template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
indirect_unary_predicate<projected<I, Proj>> Pred>
constexpr I
ranges::partition_point(I first, S last, Pred pred, Proj proj = {});

template<forward_range R, class Proj = identity,
indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
constexpr borrowed_iterator_t<R>
ranges::partition_point(R&& r, Pred pred, Proj proj = {});

Let proj be identity{} for the overloads with no parameter named proj and let \( E(x) \) be \( \text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, x))) \).

**Preconditions:** The elements \( e \) of \([\text{first}, \text{last})\) are partitioned with respect to \( E(e) \).

**Returns:** An iterator \( \text{mid} \) such that \( E(\ast i) \) is \text{true} for all iterators \( i \) in \([\text{first}, \text{mid})\), and \text{false} for all iterators \( i \) in \([\text{mid}, \text{last})\).

**Complexity:** \( \Theta(\log(\text{last} - \text{first})) \) applications of \( \text{pred} \) and \( \text{proj} \).

### 27.8.6 Merge

[alg.merge]

#### § 27.8.6 Merge

```cpp
template<class InputIterator1, class InputIterator2,
class OutputIterator>
constexpr OutputIterator
merge(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1,
class ForwardIterator2,
class ForwardIterator>
ForwardIterator
merge(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
ForwardIterator result);

template<class InputIterator1, class InputIterator2,
class OutputIterator, class Compare>
constexpr OutputIterator
merge(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result, Compare comp);

template<class ExecutionPolicy, class ForwardIterator1,
class ForwardIterator2,
class ForwardIterator, class Compare>
ForwardIterator
merge(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
ForwardIterator result, Compare comp);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
weakly_incrementable O, class Comp = ranges::less, class Proj1 = identity,
class Proj2 = identity>
requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
constexpr ranges::merge_result<I1, I2, O>
ranges::merge(I1 first1, S1 last1, I2 first2, S2 last2, O result,
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, weakly_incrementable O, class Comp = ranges::less,
class Proj1 = identity, class Proj2 = identity>
requires mergeable<input_iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
constexpr ranges::merge_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
ranges::merge(R1&& r1, R2&& r2, O result,
```
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {};

Let \( N = (\text{last1} - \text{first1}) + (\text{last2} - \text{first2}) \). Let comp be less\{\}, proj1 be identity\{\}, and proj2 be identity\{\}, for the overloads with no parameters by those names.

**Preconditions:** The ranges \([\text{first1}, \text{last1})\) and \([\text{first2}, \text{last2})\) are sorted with respect to comp and proj1 or proj2, respectively. The resulting range does not overlap with either of the original ranges.

**Effects:** Copies all the elements of the two ranges \([\text{first1}, \text{last1})\) and \([\text{first2}, \text{last2})\) into the range \([\text{result}, \text{result}_\text{last})\), where \(\text{result}_\text{last} = \text{result} + N\). If an element \(a\) precedes \(b\) in an input range, \(a\) is copied into the output range before \(b\). If \(e_1\) is an element of \([\text{first1}, \text{last1})\) and \(e_2\) of \([\text{first2}, \text{last2})\), \(e_2\) is copied into the output range before \(e_1\) if and only if \(\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj2, e2}), \text{invoke}(\text{proj1, e1})))\) is true.

**Returns:**
- result_last for the overloads in namespace std.
- \{last1, last2, result_last\} for the overloads in namespace ranges.

**Complexity:**
- For the overloads with no ExecutionPolicy, at most \(N - 1\) comparisons and applications of each projection.
- For the overloads with an ExecutionPolicy, \(\mathcal{O}(N)\) comparisons.

**Remarks:** Stable (16.4.6.8).

```cpp
template<class BidirectionalIterator>
constexpr void inplace_merge(BidirectionalIterator first,
BidirectionalIterator middle,
BidirectionalIterator last);
```

```cpp
template<class ExecutionPolicy, class BidirectionalIterator>
void inplace_merge(ExecutionPolicy&& exec,
BidirectionalIterator first,
BidirectionalIterator middle,
BidirectionalIterator last);
```

```cpp
template<class BidirectionalIterator, class Compare>
constexpr void inplace_merge(BidirectionalIterator first,
BidirectionalIterator middle,
BidirectionalIterator last, Compare comp);
```

```cpp
template<class ExecutionPolicy, class BidirectionalIterator, class Compare>
void inplace_merge(ExecutionPolicy&& exec,
BidirectionalIterator first,
BidirectionalIterator middle,
BidirectionalIterator last, Compare comp);
```

```cpp
template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less,
class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I ranges::inplace_merge(I first, I middle, S last, Comp comp = {}, Proj proj = {});
```

Let comp be less\{\} and proj be identity\{\} for the overloads with no parameters by those names.

**Preconditions:** \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\) are valid ranges sorted with respect to comp and proj. For the overloads in namespace std, BidirectionalIterator meets the Cpp17ValueSwappable requirements (16.4.4.3) and the type of *first meets the Cpp17MoveConstructible (Table 31) and Cpp17MoveAssignable (Table 33) requirements.

**Effects:** Merges two sorted consecutive ranges \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\), putting the result of the merge into the range \([\text{first}, \text{last})\). The resulting range is sorted with respect to comp and proj.

**Returns:** last for the overload in namespace ranges.

**Complexity:**
- For the overloads with no ExecutionPolicy, and if enough additional memory is available, exactly \(N - 1\) comparisons.
- Otherwise, \(\mathcal{O}(N \log N)\) comparisons.

\(\S\ 27.8.6\)
In either case, twice as many projections as comparisons.

Remarks: Stable (16.4.6.8).

```cpp
template<bidirectional_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::inplace_merge(R&& r, iterator_t<R> middle, Comp comp = {}, Proj proj = {});
```

Effects: Equivalent to:
```
return ranges::inplace_merge(ranges::begin(r), middle, ranges::end(r), comp, proj);
```

27.8.7 Set operations on sorted structures

27.8.7.1 General

Subclause 27.8.7 defines all the basic set operations on sorted structures. They also work with multisets (24.4.7) containing multiple copies of equivalent elements. The semantics of the set operations are generalized to multisets in a standard way by defining `set_union` to contain the maximum number of occurrences of every element, `set_intersection` to contain the minimum, and so on.

27.8.7.2 `includes`

```cpp
template<class InputIterator1, class InputIterator2>
constexpr bool includes(InputIterator1 first1, InputIterator1 last1,
                        InputIterator2 first2, InputIterator2 last2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
bool includes(ExecutionPolicy&& exec,
              ForwardIterator1 first1, ForwardIterator1 last1,
              ForwardIterator2 first2, ForwardIterator2 last2);

template<class InputIterator1, class InputIterator2, class Compare>
constexpr bool includes(InputIterator1 first1, InputIterator1 last1,
                        InputIterator2 first2, InputIterator2 last2,
                        Compare comp);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class Compare>
bool includes(ExecutionPolicy&& exec,
              ForwardIterator1 first1, ForwardIterator1 last1,
              ForwardIterator2 first2, ForwardIterator2 last2,
              Compare comp);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
class Proj1 = identity, class Proj2 = identity,
indirect_strict_weak_order<projected<I1, Proj1>, projected<I2, Proj2>> Comp = ranges::less>
constexpr bool ranges::includes(I1 first1, S1 last1, I2 first2, S2 last2, Comp comp = {},
proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, class Proj1 = identity,
class Proj2 = identity,
indirect_strict_weak_order<projected<iterator_t<R1>, Proj1>,
projected<iterator_t<R2>, Proj2>> Comp = ranges::less>
constexpr bool ranges::includes(R1&& r1, R2&& r2, Comp comp = {},
proj1 proj1 = {}, Proj2 proj2 = {});
```

Let `comp` be `less{}`, `proj1` be `identity{}`, and `proj2` be `identity{}`, for the overloads with no parameters by those names.

**Preconditions**: The ranges `[first1, last1)` and `[first2, last2)` are sorted with respect to `comp` and `proj1` or `proj2`, respectively.

**Returns**: `true` if and only if `[first2, last2)` is a subsequence of `[first1, last1)`.

**Note 1**: A sequence `S` is a subsequence of another sequence `T` if `S` can be obtained from `T` by removing some, all, or none of `T`'s elements and keeping the remaining elements in the same order. — end note

**Complexity**: At most `2 * ((last1 - first1) + (last2 - first2)) - 1` comparisons and applications of each projection.
27.8.7.3 \textit{set\_union} \hfill [set.union]

template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
\begin{verbatim}
set\_union(InputIterator1 first1, InputIterator1 last1,
            InputIterator2 first2, InputIterator2 last2,
            OutputIterator result);
\end{verbatim}

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class ForwardIterator>
ForwardIterator
\begin{verbatim}
set\_union(ExecutionPolicy&& exec,
            ForwardIterator1 first1, ForwardIterator1 last1,
            ForwardIterator2 first2, ForwardIterator2 last2,
            ForwardIterator result);
\end{verbatim}

Let \texttt{comp} be \texttt{less{}}, and \texttt{proj1} and \texttt{proj2} be \texttt{identity{}} for the overloads with no parameters by those names.

\textbf{Preconditions:} The ranges \([\text{first1}, \text{last1})\) and \([\text{first2}, \text{last2})\) are sorted with respect to \texttt{comp} and \texttt{proj1} or \texttt{proj2}, respectively. The resulting range does not overlap with either of the original ranges.

\textbf{Effects:} Constructs a sorted union of the elements from the two ranges; that is, the set of elements that are present in one or both of the ranges.

\textbf{Returns:} Let \texttt{result\_last} be the end of the constructed range. Returns

1. \texttt{result\_last} for the overloads in namespace \texttt{std}.
2. \{\texttt{last1}, \texttt{last2}, \texttt{result\_last}\} for the overloads in namespace \texttt{ranges}.

\textbf{Complexity:} At most \(2 \times ((\text{last1} - \text{first1}) + (\text{last2} - \text{first2})) - 1\) comparisons and applications of each projection.

\textbf{Remarks:} Stable (16.4.6.8). If \([\text{first1}, \text{last1})\) contains \(m\) elements that are equivalent to each other and \([\text{first2}, \text{last2})\) contains \(n\) elements that are equivalent to them, then all \(m\) elements from the first range are copied to the output range, in order, and then the final \(\max(n - m, 0)\) elements from the second range are copied to the output range, in order.

27.8.7.4 \textit{set\_intersection} \hfill [set.intersection]

§ 27.8.7.4 ©ISO/IEC 1440
template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
set_intersection(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class ForwardIterator>
ForwardIterator
set_intersection(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
ForwardIterator result);

template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
set_intersection(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, InputIterator2 last2,
OutputIterator result, Compare comp);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class ForwardIterator, class Compare>
ForwardIterator
set_intersection(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
ForwardIterator result, Compare comp);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2, weakly_incrementable O, class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
constexpr ranges::set_intersection_result<I1, I2, O>
ranges::set_intersection(I1 first1, S1 last1, I2 first2, S2 last2, O result,
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, weakly_incrementable O, class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
requires mergeable<iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
constexpr ranges::set_intersection_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
ranges::set_intersection(R1&& r1, R2&& r2, O result,
Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

Let \texttt{comp} be \texttt{less\{\}}, and \texttt{proj1} and \texttt{proj2} be \texttt{identity\{\}} for the overloads with no parameters by those names.

\textit{Preconditions:} The ranges \([\texttt{first1}, \texttt{last1})\) and \([\texttt{first2}, \texttt{last2})\) are sorted with respect to \texttt{comp} and \texttt{proj1} or \texttt{proj2}, respectively. The resulting range does not overlap with either of the original ranges.

\textit{Effects:} Constructs a sorted intersection of the elements from the two ranges; that is, the set of elements that are present in both of the ranges.

\textit{Returns:} Let \texttt{result\_last} be the end of the constructed range. Returns

\begin{enumerate}
\item \texttt{result\_last} for the overloads in namespace \texttt{std}.
\item \{\texttt{last1}, \texttt{last2}, \texttt{result\_last}\} for the overloads in namespace \texttt{ranges}.
\end{enumerate}

\textit{Complexity:} At most \(2 \ast ((\texttt{last1} - \texttt{first1}) + (\texttt{last2} - \texttt{first2})) - 1\) comparisons and applications of each projection.

\textit{Remarks:} Stable (16.4.6.8). If \([\texttt{first1}, \texttt{last1})\) contains \(m\) elements that are equivalent to each other and \([\texttt{first2}, \texttt{last2})\) contains \(n\) elements that are equivalent to them, the first \(\min(m, n)\) elements are copied from the first range to the output range, in order.
[template<class InputIterator1, class InputIterator2, 
  class OutputIterator> 
  constexpr OutputIterator 
  set_difference(InputIterator1 first1, InputIterator1 last1, 
  InputIterator2 first2, InputIterator2 last2, 
  OutputIterator result);]

[template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
  class ForwardIterator> 
  ForwardIterator 
  set_difference(ExecutionPolicy&& exec, 
  ForwardIterator1 first1, ForwardIterator1 last1, 
  ForwardIterator2 first2, ForwardIterator2 last2, 
  ForwardIterator result);]

[template<class InputIterator1, class InputIterator2, 
  class OutputIterator, class Compare> 
  constexpr OutputIterator 
  set_difference(InputIterator1 first1, InputIterator1 last1, 
  InputIterator2 first2, InputIterator2 last2, 
  OutputIterator result, Compare comp);]

[template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
  class ForwardIterator, class Compare> 
  ForwardIterator 
  set_difference(ExecutionPolicy&& exec, 
  ForwardIterator1 first1, ForwardIterator1 last1, 
  ForwardIterator2 first2, ForwardIterator2 last2, 
  ForwardIterator result, Compare comp);]

[template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2, 
  weakly_incrementable O, class Comp = ranges::less, 
  class Proj1 = identity, class Proj2 = identity> 
  requires mergeable<I1, I2, O, Comp, Proj1, Proj2> 
  constexpr ranges::set_difference_result<I1, O> 
  ranges::set_difference(I1 first1, S1 last1, I2 first2, S2 last2, O result, 
  Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});]

[template<input_range R1, input_range R2, weakly_incrementable O, 
  class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity> 
  requires mergeable<iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2> 
  constexpr ranges::set_difference_result<borrowed_iterator_t<R1>, O> 
  ranges::set_difference(R1&& r1, R2&& r2, O result, 
  Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});]

Let \(\text{comp}\) be \(\text{less}\{}\), and \(\text{proj1}\) and \(\text{proj2}\) be \(\text{identity}\{}\) for the overloads with no parameters by those names.

Preconditions: The ranges \([\text{first1}, \text{last1})\) and \([\text{first2}, \text{last2})\) are sorted with respect to \(\text{comp}\) and \(\text{proj1}\) or \(\text{proj2}\), respectively. The resulting range does not overlap with either of the original ranges.

Effects: Copies the elements of the range \([\text{first1}, \text{last1})\) which are not present in the range \([\text{first2}, \text{last2})\) to the range beginning at \(\text{result}\). The elements in the constructed range are sorted.

Returns: Let \(\text{result}\)_\(\text{last}\) be the end of the constructed range. Returns

\[
\begin{align*}
\text{— } & \text{result}_\text{last} & \text{for the overloads in namespace std.} \\
\text{— } & \{\text{last1}, \text{result}_\text{last}\} & \text{for the overloads in namespace ranges.} \\
\end{align*}
\]

Complexity: At most \(2 \ast ((\text{last1} - \text{first1}) + (\text{last2} - \text{first2})) - 1\) comparisons and applications of each projection.

Remarks: If \([\text{first1}, \text{last1})\) contains \(m\) elements that are equivalent to each other and \([\text{first2}, \text{last2})\) contains \(n\) elements that are equivalent to them, the last \(\max(m - n, 0)\) elements from \([\text{first1}, \text{last1})\) are copied to the output range, in order.
template<class InputIterator1, class InputIterator2,  
    class OutputIterator>
constexpr OutputIterator
    set_symmetric_difference(InputIterator1 first1, InputIterator1 last1,  
    InputIterator2 first2, InputIterator2 last2, 
    OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,  
    class ForwardIterator>
ForwardIterator
    set_symmetric_difference(ExecutionPolicy&& exec, 
    ForwardIterator1 first1, ForwardIterator1 last1, 
    ForwardIterator2 first2, ForwardIterator2 last2, 
    ForwardIterator result);

template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
    set_symmetric_difference(InputIterator1 first1, InputIterator1 last1, 
    InputIterator2 first2, InputIterator2 last2, 
    OutputIterator result, Compare comp);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class ForwardIterator, class Compare>
ForwardIterator
    set_symmetric_difference(ExecutionPolicy&& exec, 
    ForwardIterator1 first1, ForwardIterator1 last1, 
    ForwardIterator2 first2, ForwardIterator2 last2, 
    ForwardIterator result, Compare comp);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,  
    weakly_incrementable O, class Comp = ranges::less,  
    class Proj1 = identity, class Proj2 = identity>
requires mergeable<I1, I2, O, Comp, Proj1, Proj2>
constexpr ranges::set_symmetric_difference_result<I1, I2, O>
    ranges::set_symmetric_difference(I1 first1, S1 last1, I2 first2, S2 last2, 0 result,  
    Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, weakly_incrementable O,  
    class Comp = ranges::less, class Proj1 = identity, class Proj2 = identity>
requires mergeable<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O, Comp, Proj1, Proj2>
constexpr ranges::set_symmetric_difference_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
    ranges::set_symmetric_difference(R1&& r1, R2&& r2, 0 result, Comp comp = {},  
    Proj1 proj1 = {}, Proj2 proj2 = {});

Let comp be less{}, and proj1 and proj2 be identity{} for the overloads with no parameters by those names.

Preconditions: The ranges [first1,last1) and [first2,last2) are sorted with respect to comp and proj1 or proj2, respectively. The resulting range does not overlap with either of the original ranges.

Effects: Copies the elements of the range [first1,last1) that are not present in the range [first2,last2), and the elements of the range [first2,last2) that are not present in the range [first1,last1) to the range beginning at result. The elements in the constructed range are sorted.

Returns: Let result_last be the end of the constructed range. Returns

— result_last for the overloads in namespace std.

(4.1) — {last1, last2, result_last) for the overloads in namespace ranges.

(4.2)

Complexity: At most 2 * ((last1 - first1) + (last2 - first2)) - 1 comparisons and applications of each projection.

Remarks: Stable (16.4.6.8). If [first1,last1) contains m elements that are equivalent to each other and [first2,last2) contains n elements that are equivalent to them, then |m - n| of those elements shall be copied to the output range: the last m - n of these elements from [first1,last1) if m > n,
and the last \(n - m\) of these elements from \([\text{first2}, \text{last2}]\) if \(m < n\). In either case, the elements are copied in order.

### 27.8.8 Heap operations

#### 27.8.8.1 General

A random access range \([a, b)\) is a heap with respect to \(\text{comp}\) and \(\text{proj}\) for a comparator and projection \(\text{comp}\) and \(\text{proj}\) if its elements are organized such that:

1. With \(N = b - a\), for all \(0 < i < N\), bool\(\left(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, a[\left\lfloor \frac{i}{2} \right\rfloor])), \text{invoke}(\text{proj}, a[i]))\right)\) is false.

2. \(*a\) may be removed by \text{pop_heap}, or a new element added by \text{push_heap}, in \(\mathcal{O}(\log N)\) time.

3. \text{make_heap} converts a range into a heap and \text{sort_heap} turns a heap into a sorted sequence.

#### 27.8.8.2 push_heap

```cpp
template<class RandomAccessIterator>
constexpr void push_heap(RandomAccessIterator first, RandomAccessIterator last);
```

```cpp
template<class RandomAccessIterator, class Compare>
constexpr void push_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);
```

```cpp
template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::push_heap(I first, S last, Comp comp = {}, Proj proj = {});
```

```cpp
template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::push_heap(R&& r, Comp comp = {}, Proj proj = {});
```

1. Let \(\text{comp}\) be \text{less\{} and \text{proj} be \text{identity\{}} for the overloads with no parameters by those names.

2. **Preconditions:** The range \([\text{first}, \text{last} - 1)\) is a valid heap with respect to \(\text{comp}\) and \(\text{proj}\). For the overloads in namespace \text{std}, \text{RandomAccessIterator} meets the \text{Cpp17ValueSwappable} requirements (16.4.4.3) and the type of \(*\text{first}\) meets the \text{Cpp17MoveConstructible} requirements (Table 31) and the \text{Cpp17MoveAssignable} requirements (Table 33).

3. **Returns:** Places the value in the location \(\text{last} - 1\) into the resulting heap \([\text{first}, \text{last})\).

4. **Complexity:** At most \(\log(\text{last} - \text{first})\) comparisons and twice as many projections.

#### 27.8.8.3 pop_heap

```cpp
template<class RandomAccessIterator>
constexpr void pop_heap(RandomAccessIterator first, RandomAccessIterator last);
```

```cpp
template<class RandomAccessIterator, class Compare>
constexpr void pop_heap(RandomAccessIterator first, RandomAccessIterator last, Compare comp);
```

```cpp
template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less, class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::pop_heap(I first, S last, Comp comp = {}, Proj proj = {});
```

```cpp
template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::pop_heap(R&& r, Comp comp = {}, Proj proj = {});
```

1. Let \(\text{comp}\) be \text{less\{}} and \text{proj} be \text{identity\{}} for the overloads with no parameters by those names.

§ 27.8.8.3 © ISO/IEC 1444
Preconditions: The range \([\text{first}, \text{last})\) is a valid non-empty heap with respect to \(\text{comp}\) and \(\text{proj}\). For the overloads in namespace \(\text{std}\), \(\text{RandomAccessIterator}\) meets the \(\text{Cpp17ValueSwappable}\) requirements (16.4.4.3) and the type of \(*\text{first}\) meets the \(\text{Cpp17MoveConstructible}\) (Table 31) and \(\text{Cpp17MoveAssignble}\) (Table 33) requirements.

Effects: Swaps the value in the location \(\text{first}\) with the value in the location \(\text{last} - 1\) and makes \([\text{first}, \text{last} - 1)\) into a heap with respect to \(\text{comp}\) and \(\text{proj}\).

Returns: \(\text{last}\) for the overloads in namespace \(\text{ranges}\).

Complexity: At most \(2 \log(\text{last} - \text{first})\) comparisons and twice as many projections.

### 27.8.8.4 \(\text{make_heap}\) [make.heap]

```
template<class RandomAccessIterator>
constexpr void make_heap(RandomAccessIterator first, RandomAccessIterator last);
```

```
template<class RandomAccessIterator, class Compare>
constexpr void make_heap(RandomAccessIterator first, RandomAccessIterator last,
                        Compare comp);
```

```
template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
         class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::make_heap(I first, S last, Comp comp = {}, Proj proj = {});
```

```
template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::make_heap(R&& r, Comp comp = {}, Proj proj = {});
```

Let \(\text{comp}\) be \(\text{less}\) and \(\text{proj}\) be \(\text{identity}\) for the overloads with no parameters by those names.

Preconditions: For the overloads in namespace \(\text{std}\), \(\text{RandomAccessIterator}\) meets the \(\text{Cpp17ValueSwappable}\) requirements (16.4.4.3) and the type of \(*\text{first}\) meets the \(\text{Cpp17MoveConstructible}\) (Table 31) and \(\text{Cpp17MoveAssignble}\) (Table 33) requirements.

Effects: Constructs a heap with respect to \(\text{comp}\) and \(\text{proj}\) out of the range \([\text{first}, \text{last})\).

Returns: \(\text{last}\) for the overloads in namespace \(\text{ranges}\).

Complexity: At most \(3(\text{last} - \text{first})\) comparisons and twice as many projections.

### 27.8.8.5 \(\text{sort_heap}\) [sort.heap]

```
template<class RandomAccessIterator>
constexpr void sort_heap(RandomAccessIterator first, RandomAccessIterator last);
```

```
template<class RandomAccessIterator, class Compare>
constexpr void sort_heap(RandomAccessIterator first, RandomAccessIterator last,
                        Compare comp);
```

```
template<random_access_iterator I, sentinel_for<I> S, class Comp = ranges::less,
         class Proj = identity>
requires sortable<I, Comp, Proj>
constexpr I
ranges::sort_heap(I first, S last, Comp comp = {}, Proj proj = {});
```

```
template<random_access_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr borrowed_iterator_t<R>
ranges::sort_heap(R&& r, Comp comp = {}, Proj proj = {});
```

Let \(\text{comp}\) be \(\text{less}\) and \(\text{proj}\) be \(\text{identity}\) for the overloads with no parameters by those names.

Preconditions: The range \([\text{first}, \text{last})\) is a valid heap with respect to \(\text{comp}\) and \(\text{proj}\). For the overloads in namespace \(\text{std}\), \(\text{RandomAccessIterator}\) meets the \(\text{Cpp17ValueSwappable}\) requirements (16.4.4.3) and the type of \(*\text{first}\) meets the \(\text{Cpp17MoveConstructible}\) (Table 31) and \(\text{Cpp17MoveAssignble}\) (Table 33) requirements.

Effects: Sorts elements in the heap \([\text{first}, \text{last})\) with respect to \(\text{comp}\) and \(\text{proj}\).
Returns: last for the overloads in namespace ranges.

Complexity: At most \(2N \log N\) comparisons, where \(N = \text{last} - \text{first}\), and twice as many projections.

27.8.8.6 is_heap

\[\text{template}<\text{class RandomAccessIterator}>\]
\[\text{constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last);}\]
\[\text{Effects: Equivalent to: return is_heap_until(first, last) == last;};\]

\[\text{template}<\text{class ExecutionPolicy}, \text{class RandomAccessIterator}>\]
\[\text{bool is_heap(ExecutionPolicy&\& exec,}\]
\[\text{RandomAccessIterator first, RandomAccessIterator last);}\]
\[\text{Effects: Equivalent to: return is_heap_until(std::forward<ExecutionPolicy>(exec), first, last) == last;}\]

\[\text{template}<\text{class Compare}>\]
\[\text{constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last,}\]
\[\text{Compare comp);}\]
\[\text{Effects: Equivalent to: return is_heap_until(first, last, comp) == last;}\]

\[\text{template}<\text{class ExecutionPolicy, class RandomAccessIterator, class Compare}>\]
\[\text{bool is_heap(ExecutionPolicy&\& exec,}\]
\[\text{RandomAccessIterator first, RandomAccessIterator last,}\]
\[\text{Compare comp);}\]
\[\text{Effects: Equivalent to: return is_heap_until(std::forward<ExecutionPolicy>(exec), first, last, comp) == last;}\]

\[\text{template}<\text{random_access_iterator I, sentinel_for<I> S, class Proj = identity,}\]
\[\text{indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less}>\]
\[\text{constexpr bool ranges::is_heap(I first, S last, Comp comp = {}, Proj proj = {});}\]
\[\text{template}<\text{random_access_range R, class Proj = identity,}\]
\[\text{indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less}>\]
\[\text{constexpr bool ranges::is_heap(R&& r, Comp comp = {}, Proj proj = {});}\]
\[\text{Effects: Equivalent to: return ranges::is_heap_until(first, last, comp, proj) == last;}\]

\[\text{template}<\text{class RandomAccessIterator}>\]
\[\text{constexpr RandomAccessIterator is_heap_until(RandomAccessIterator first, RandomAccessIterator last);}\]
\[\text{template}<\text{class ExecutionPolicy, class RandomAccessIterator}>\]
\[\text{RandomAccessIterator is_heap_until(ExecutionPolicy&\& exec,}\]
\[\text{RandomAccessIterator first, RandomAccessIterator last);}\]
\[\text{template}<\text{class RandomAccessIterator, class Compare}>\]
\[\text{constexpr RandomAccessIterator is_heap_until(RandomAccessIterator first, RandomAccessIterator last,}\]
\[\text{Compare comp);}\]
\[\text{template}<\text{class ExecutionPolicy, class RandomAccessIterator, class Compare}>\]
\[\text{RandomAccessIterator is_heap_until(ExecutionPolicy&\& exec,}\]
\[\text{RandomAccessIterator first, RandomAccessIterator last,}\]
\[\text{Compare comp);}\]
\[\text{template}<\text{random_access_iterator I, sentinel_for<I> S, class Proj = identity,}\]
\[\text{indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less}>\]
\[\text{constexpr I ranges::is_heap_until(I first, S last, Comp comp = {}, Proj proj = {});}\]
\[\text{template}<\text{random_access_range R, class Proj = identity,}\]
\[\text{indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less}>\]
\[\text{constexpr borrowed_iterator_t<R> ranges::is_heap_until(R&& r, Comp comp = {}, Proj proj = {});}\]
\[\text{Let comp be less\{\} and proj be identity\{\} for the overloads with no parameters by those names.\]
Returns: The last iterator i in [first,last] for which the range [first,i) is a heap with respect to comp and proj.

Complexity: Linear.

27.8.9 Minimum and maximum

```cpp
template<class T>
constexpr T min(const T& a, const T& b);

template<class T, class Compare>
constexpr T min(const T& a, const T& b, Compare comp);
```

Preconditions: For the first form, T meets the Cpp17LessThanComparable requirements (Table 29).

Returns: The smaller value. Returns the first argument when the arguments are equivalent.

Complexity: Exactly one comparison and two applications of the projection, if any.

Remarks: An invocation may explicitly specify an argument for the template parameter T of the overloads in namespace std.

```cpp
template<class T>
constexpr const T& min(const T& a, const T& b, Compare comp);  

template<class T, class Proj = identity,
         indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
constexpr const T& ranges::min(const T& a, const T& b, Comp comp = {}, Proj proj = {});
```

Preconditions: For the first form, T meets the Cpp17LessThanComparable requirements (Table 29).

Returns: The smaller value. Returns the first argument when the arguments are equivalent.

Complexity: Exactly one comparison and two applications of the projection, if any.

Remarks: An invocation may explicitly specify an argument for the template parameter T of the overloads in namespace std.

```cpp
template<class T>
constexpr const T& max(const T& a, const T& b);

template<class T, class Compare>
constexpr const T& max(const T& a, const T& b, Compare comp);
```

Preconditions: For the first form, T meets the Cpp17LessThanComparable requirements (Table 29).

Returns: The larger value. Returns the first argument when the arguments are equivalent.

Complexity: Exactly one comparison and two applications of the projection, if any.

Remarks: An invocation may explicitly specify an argument for the template parameter T of the overloads in namespace std.
template<class T>
    constexpr T max(initializer_list<T> r);

template<class T, class Compare>
    constexpr T max(initializer_list<T> r, Compare comp);

template<copyable T, class Proj = identity,
         indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr T ranges::max(initializer_list<T> r, Comp comp = {}, Proj proj = {});

template<input_range R, class Proj = identity,
          indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
    requires indirectly_copyable_storable<iterator_t<R>, range_value_t<R>>
    constexpr range_value_t<R> ranges::max(R&& r, Comp comp = {}, Proj proj = {});

13 Preconditions: ranges::distance(r) > 0. For the overloads in namespace std, T meets the Cpp17-CopyConstructible requirements. For the first form, T meets the Cpp17LessThanComparable requirements (Table 29).

14 Returns: The largest value in the input range. Returns a copy of the leftmost element when several elements are equivalent to the largest.

15 Complexity: Exactly ranges::distance(r) - 1 comparisons and twice as many applications of the projection, if any.

16 Remarks: An invocation may explicitly specify an argument for the template parameter T of the overloads in namespace std.

template<class T>
    constexpr pair<const T&, const T&> minmax(const T& a, const T& b);

template<class T, class Compare>
    constexpr pair<const T&, const T&> minmax(const T& a, const T& b, Compare comp);

template<class T, class Proj = identity,
         indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr ranges::minmax_result<const T&>
    ranges::minmax(const T& a, const T& b, Comp comp = {}, Proj proj = {});

17 Preconditions: For the first form, T meets the Cpp17LessThanComparable requirements (Table 29).

18 Returns: \{b, a\} if b is smaller than a, and \{a, b\} otherwise.

19 Complexity: Exactly one comparison and two applications of the projection, if any.

20 Remarks: An invocation may explicitly specify an argument for the template parameter T of the overloads in namespace std.

template<class T>
    constexpr pair<T, T> minmax(initializer_list<T> t);

template<class T, class Compare>
    constexpr pair<T, T> minmax(initializer_list<T> t, Compare comp);

template<copyable T, class Proj = identity,
         indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
    constexpr ranges::minmax_result<T>
    ranges::minmax(initializer_list<T> r, Comp comp = {}, Proj proj = {});

21 Preconditions: ranges::distance(r) > 0. For the overloads in namespace std, T meets the Cpp17-CopyConstructible requirements. For the first form, type T meets the Cpp17LessThanComparable requirements (Table 29).

22 Returns: Let X be the return type. Returns \(X\{x, y\}\), where \(x\) is a copy of the leftmost element with the smallest value and \(y\) a copy of the rightmost element with the largest value in the input range.
Complexity: At most \(\frac{3}{2}\) `ranges::distance(r)` applications of the corresponding predicate and twice as many applications of the projection, if any.

Remarks: An invocation may explicitly specify an argument for the template parameter `T` of the overloads in namespace `std`.

```cpp
template<class ForwardIterator>
constexpr ForwardIterator min_element(ForwardIterator first, ForwardIterator last);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator min_element(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last);
```

```cpp
template<class ForwardIterator, class Compare>
constexpr ForwardIterator min_element(ForwardIterator first, ForwardIterator last,
Compare comp);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator min_element(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last, Compare comp);
```

```cpp
template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr I ranges::min_element(I first, S last, Comp comp = {}, Proj proj = {});
```

```cpp
template<forward_range R, class Proj = identity,
indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr borrowed_iterator_t<R> ranges::max_element(R&& r, Comp comp = {}, Proj proj = {});
```

Let `comp` be `less{}` and `proj` be `identity{}` for the overloads with no parameters by those names.

Returns: The first iterator \(i\) in the range \([first, last)\) such that for every iterator \(j\) in the range \([first, last)\),

\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *j), \text{invoke}(\text{proj}, *i)))
\]

is false. Returns `last` if `first == last`.

Complexity: Exactly \(\max(last - first - 1, 0)\) comparisons and twice as many projections.

```cpp
template<class ForwardIterator>
constexpr ForwardIterator max_element(ForwardIterator first, ForwardIterator last);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator max_element(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last);
```

```cpp
template<class ForwardIterator, class Compare>
constexpr ForwardIterator max_element(ForwardIterator first, ForwardIterator last,
Compare comp);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator max_element(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last, Compare comp);
```

```cpp
template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr I ranges::max_element(I first, S last, Comp comp = {}, Proj proj = {});
```

```cpp
template<forward_range R, class Proj = identity,
indirect_strict_weak_order<projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr borrowed_iterator_t<R> ranges::max_element(R&& r, Comp comp = {}, Proj proj = {});
```

Let `comp` be `less{}` and `proj` be `identity{}` for the overloads with no parameters by those names.

Returns: The first iterator \(i\) in the range \([first, last)\) such that for every iterator \(j\) in the range \([first, last)\),

\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *i), \text{invoke}(\text{proj}, *j)))
\]

is false. Returns `last` if `first == last`. 

§ 27.8.9
template<class ForwardIterator>
constexpr pair<ForwardIterator, ForwardIterator>
minmax_element(ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator>
pair<ForwardIterator, ForwardIterator>
minmax_element(ExecutionPolicy&& exec,
                ForwardIterator first, ForwardIterator last);

template<class ForwardIterator, class Compare>
constexpr pair<ForwardIterator, ForwardIterator>
minmax_element(ForwardIterator first, ForwardIterator last, Compare comp);

template<class ExecutionPolicy, class ForwardIterator, class Compare>
pair<ForwardIterator, ForwardIterator>
minmax_element(ExecutionPolicy&& exec,
                ForwardIterator first, ForwardIterator last, Compare comp);

31 Returns: \{first, first\} if \[first, last\) is empty, otherwise \{m, M\}, where m is the first iterator in 
\[first, last\) such that no iterator in the range refers to a smaller element, and where M is the last 
iterator\(^{213}\) in \[first, last\) such that no iterator in the range refers to a larger element.

Complexity: Let \(N\) be last - first. At most max\(\left\lfloor \frac{3}{2}(N - 1) \right\rfloor, 0\) comparisons and twice as many 
applications of the projection, if any.

27.8.10 Bounded value \([\text{alg.clamp}]\)

template<class T>
constexpr const T& clamp(const T& v, const T& lo, const T& hi);

template<class T, class Compare>
constexpr const T& clamp(const T& v, const T& lo, const T& hi, Compare comp);

template<class T, class Proj = identity,
         indirect_strict_weak_order<projected<const T*, Proj>> Comp = ranges::less>
constexpr const T&
ranges::clamp(const T& v, const T& lo, const T& hi, Comp comp = {}, Proj proj = {});

1 Let \text{comp} be \text{less} for the overloads with no parameter \text{comp}, and let \text{proj} be \text{identity} for the 
overloads with no parameter \text{proj}.

2 \textit{Preconditions}: bool\(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \text{hi}), \text{invoke}(\text{proj}, \text{lo}))\) is false. For the first 
form, type \(T\) meets the \textit{Cpp17LessThanComparable} requirements (Table 29).

3 \textit{Returns}: \(\text{lo}\) if bool\(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \text{v}), \text{invoke}(\text{proj}, \text{lo}))\) is true, \(\text{hi}\) if bool\(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \text{hi}), \text{invoke}(\text{proj}, \text{v}))\) is true, otherwise \(v\).

4 \[\text{Note 1: If NaN is avoided, } T \text{ can be a floating-point type. —end note}\]

5 Complexity: At most two comparisons and three applications of the projection.

27.8.11 Lexicographical comparison \([\text{alg.lex.comparison}]\)

template<class InputIterator1, class InputIterator2>
constexpr bool
lexicographical_compare(InputIterator1 first1, InputIterator1 last1, 
                        InputIterator2 first2, InputIterator2 last2);

\(^{213}\) This behavior intentionally differs from \textit{max_element}.
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
bool
lexicographical_compare(ExecutionPolicy&& exec,
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2, ForwardIterator2 last2);

template<class InputIterator1, class InputIterator2, class Compare>
constexpr bool
lexicographical_compare(InputIterator1 first1, InputIterator1 last1,
    InputIterator2 first2, InputIterator2 last2,
    Compare comp);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class Compare>
bool
lexicographical_compare(ExecutionPolicy&& exec,
    ForwardIterator1 first1, ForwardIterator1 last1,
    ForwardIterator2 first2, ForwardIterator2 last2,
    Compare comp);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
    class Proj1 = identity, class Proj2 = identity,
    indirect_strict_weak_order<projected<I1, Proj1>,
    projected<I2, Proj2>> Comp = ranges::less>
constexpr bool
ranges::lexicographical_compare(I1 first1, S1 last1, I2 first2, S2 last2,
    Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, class Proj1 = identity,
    class Proj2 = identity,
    indirect_strict_weak_order<iterator_t<R1>, Proj1>,
    iterator_t<R2>, Proj2>> Comp = ranges::less>
constexpr bool
ranges::lexicographical_compare(R1&& r1, R2&& r2, Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

Returns: true if and only if the sequence of elements defined by the range [first1, last1) is lexicographically less than the sequence of elements defined by the range [first2, last2).

Complexity: At most 2 min(last1 - first1, last2 - first2) applications of the corresponding comparison and each projection, if any.

Remarks: If two sequences have the same number of elements and their corresponding elements (if any) are equivalent, then neither sequence is lexicographically less than the other. If one sequence is a proper prefix of the other, then the shorter sequence is lexicographically less than the longer sequence. Otherwise, the lexicographical comparison of the sequences yields the same result as the comparison of the first corresponding pair of elements that are not equivalent.

[Example 1: ranges::lexicographical_compare(I1, S1, I2, S2, Comp, Proj1, Proj2) can be implemented as:

```cpp
for ( ; first1 != last1 && first2 != last2 ; ++first1, (void) ++first2) {
    if (invoke(comp, invoke(proj1, *first1), invoke(proj2, *first2))) return true;
    if (invoke(comp, invoke(proj2, *first2), invoke(proj1, *first1))) return false;
}
return first1 == last1 && first2 != last2;
```
—end example]

[Note 1: An empty sequence is lexicographically less than any non-empty sequence, but not less than any empty sequence. — end note]
Let $N$ be $\min(e_1 - b_1, e_2 - b_2)$. Let $E(n)$ be $\text{comp}(*b_1 + n, *b_2 + n)$.

**Mandates:** $\text{decltype(comp(*b_1, *b_2))}$ is a comparison category type.

**Returns:** $E(i)$, where $i$ is the smallest integer in $[0, N)$ such that $E(i) \neq 0$ true, or $(e_1 - b_1) <= (e_2 - b_2)$ if no such integer exists.

**Complexity:** At most $N$ applications of $\text{comp}$.

```cpp
decltype(comp(*b1, *b2));
```

Let $N$ be $\min(e_1 - b_1, e_2 - b_2)$. Let $E(n)$ be $\text{comp}(*b_1 + n, *b_2 + n)$.

**Mandates:** $\text{decltype(comp(*b_1, *b_2))}$ is a comparison category type.

**Returns:** $E(i)$, where $i$ is the smallest integer in $[0, N)$ such that $E(i) \neq 0$ true, or $(e_1 - b_1) <= (e_2 - b_2)$ if no such integer exists.

**Complexity:** At most $N$ applications of $\text{comp}$.

```cpp
Let N be min(e1 - b1, e2 - b2). Let E(n) be \text{comp}(*(b1 + n), *(b2 + n)).

Mandates: decltype(comp(*b1, *b2)) is a comparison category type.

Returns: E(i), where i is the smallest integer in [0, N) such that E(i) != 0 is true, or (e1 - b1) <= (e2 - b2) if no such integer exists.

Complexity: At most N applications of \text{comp}.
```
ranges::prev_permutation(I first, S last, Comp comp = {}, Proj proj = {});

template<bidirectional_range R, class Comp = ranges::less,
         class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
constexpr ranges::prev_permutation_result<borrowed_iterator_t<R>>
ranges::prev_permutation(R&& r, Comp comp = {}, Proj proj = {});

Let comp be less{} and proj be identity{} for overloads with no parameters by those names.

Preconditions: For the overloads in namespace std, BidirectionalIterator meets the Cpp17ValueSwappable requirements (16.4.4.3).

Effects: Takes a sequence defined by the range [first, last) and transforms it into the previous permutation. The previous permutation is found by assuming that the set of all permutations is lexicographically sorted with respect to comp and proj. If no such permutation exists, transforms the sequence into the last permutation; that is, the descendingly-sorted one.

Returns: Let B be true if a previous permutation was found and otherwise false. Returns:

- B for the overloads in namespace std.
- { last, B } for the overloads in namespace ranges.

Complexity: At most (last - first) / 2 swaps.

27.9 Header <numeric> synopsis

namespace std {

// 27.10.3, accumulate
template<class InputIterator, class T>
constexpr T accumulate(InputIterator first, InputIterator last, T init);

// 27.10.4, reduce
template<class InputIterator>
constexpr typename iterator_traits<InputIterator>::value_type
reduce(InputIterator first, InputIterator last);  // see 27.3.5

template<class InputIterator, class T>
constexpr T reduce(InputIterator first, InputIterator last, T init);

// see 27.3.5

// 27.10.5, inner product
template<class InputIterator1, class InputIterator2, class T>
constexpr T inner_product(InputIterator1 first1, InputIterator1 last1,
                           InputIterator2 first2, T init);  // see 27.3.5

template<class InputIterator1, class InputIterator2, class T, 
         class BinaryOperation1, class BinaryOperation2>
constexpr T inner_product(InputIterator1 first1, InputIterator1 last1,
                           InputIterator2 first2, T init,
                           BinaryOperation1 binary_op1, BinaryOperation2 binary_op2);

§ 27.9 ©ISO/IEC 1453
// 27.10.6, transform reduce

template<typename InputIterator1, typename InputIterator2, typename T>
constexpr T transform_reduce(InputIterator1 first1, InputIterator1 last1,
                             InputIterator2 first2, T init);

template<typename InputIterator1, typename InputIterator2, typename T,
          BinaryOperation1, BinaryOperation2>
constexpr T transform_reduce(InputIterator1 first1, InputIterator1 last1,
                             InputIterator2 first2, T init,
                             BinaryOperation1 binary_op1, BinaryOperation2 binary_op2);

template<typename InputIterator, typename T,
          BinaryOperation, UnaryOperation>
constexpr T transform_reduce(InputIterator first, InputIterator last, T init,
                              BinaryOperation binary_op, UnaryOperation unary_op);

template<typename ExecutionPolicy,
          ForwardIterator1, ForwardIterator2, T>
T transform_reduce(ExecutionPolicy&& exec,
                   ForwardIterator1 first1, ForwardIterator1 last1,
                   ForwardIterator2 first2, T init);

template<typename ExecutionPolicy,
          ForwardIterator1, ForwardIterator2, T,
          BinaryOperation1, BinaryOperation2>
T transform_reduce(ExecutionPolicy&& exec,
                   ForwardIterator1 first1, ForwardIterator1 last1,
                   ForwardIterator2 first2, T init,
                   BinaryOperation1 binary_op1, BinaryOperation2 binary_op2);

template<typename ExecutionPolicy, ForwardIterator, T,
          BinaryOperation, UnaryOperation>
T transform_reduce(ExecutionPolicy&& exec,
                   ForwardIterator first, ForwardIterator last, T init,
                   BinaryOperation binary_op, UnaryOperation unary_op);

// 27.10.7, partial sum

template<typename InputIterator, typename OutputIterator>
constexpr OutputIterator partial_sum(InputIterator first, InputIterator last,
                                      OutputIterator result);

template<typename InputIterator, typename OutputIterator, BinaryOperation>
constexpr OutputIterator partial_sum(InputIterator first, InputIterator last,
                                      OutputIterator result, BinaryOperation binary_op);

// 27.10.8, exclusive scan

template<typename InputIterator, typename OutputIterator, typename T>
constexpr OutputIterator exclusive_scan(InputIterator first, InputIterator last,
                                        OutputIterator result, T init);

template<typename InputIterator, typename OutputIterator, typename T,
          BinaryOperation>
constexpr OutputIterator exclusive_scan(InputIterator first, InputIterator last,
                                        OutputIterator result, T init, BinaryOperation binary_op);

template<typename ExecutionPolicy, ForwardIterator1, ForwardIterator2, typename T>
ForwardIterator2 exclusive_scan(ExecutionPolicy&& exec,
                                ForwardIterator1 first1, ForwardIterator1 last1,
                                ForwardIterator2 result, T init);

template<typename ExecutionPolicy, ForwardIterator1, ForwardIterator2, typename T,
          BinaryOperation>
ForwardIterator2 exclusive_scan(ExecutionPolicy&& exec,
                                ForwardIterator1 first1, ForwardIterator1 last1,
                                ForwardIterator2 result, T init, BinaryOperation binary_op);
// 27.10.9, inclusive scan
template<class InputIterator, class OutputIterator>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result);

template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result, BinaryOperation binary_op);

template<class InputIterator, class OutputIterator, class BinaryOperation, class T>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result, BinaryOperation binary_op, T init);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
               ForwardIterator1 first, ForwardIterator1 last,
               ForwardIterator2 result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryOperation>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
               ForwardIterator1 first, ForwardIterator1 last,
               ForwardIterator2 result, BinaryOperation binary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryOperation, class T>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
               ForwardIterator1 first, ForwardIterator1 last,
               ForwardIterator2 result, BinaryOperation binary_op, T init);

// 27.10.10, transform exclusive scan
template<class InputIterator, class OutputIterator, class T,
         class BinaryOperation, class UnaryOperation>
constexpr OutputIterator
transform_exclusive_scan(InputIterator first, InputIterator last,
                          OutputIterator result, T init,
                          BinaryOperation binary_op, UnaryOperation unary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class T, class BinaryOperation, class UnaryOperation>
ForwardIterator2
transform_exclusive_scan(ExecutionPolicy&& exec,
                         ForwardIterator1 first, ForwardIterator1 last,
                         ForwardIterator2 result, T init,
                         BinaryOperation binary_op, UnaryOperation unary_op);

// 27.10.11, transform inclusive scan
template<class InputIterator, class OutputIterator,
         class BinaryOperation, class UnaryOperation>
constexpr OutputIterator
transform_inclusive_scan(InputIterator first, InputIterator last,
                         OutputIterator result,
                         BinaryOperation binary_op, UnaryOperation unary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryOperation, class UnaryOperation, class T>
constexpr OutputIterator
transform_inclusive_scan(InputIterator first, InputIterator last,
                         OutputIterator result,
                         BinaryOperation binary_op, UnaryOperation unary_op, T init);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryOperation, class UnaryOperation>
ForwardIterator2
transform_inclusive_scan(ExecutionPolicy&& exec,
                         ForwardIterator1 first, ForwardIterator1 last,
ForwardIterator2 result, BinaryOperation binary_op, UnaryOperation unary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryOperation, class UnaryOperation, class T>
ForwardIterator2
transform_inclusive_scan(ExecutionPolicy&& exec, // see 27.3.5
ForwardIterator1 first, ForwardIterator1 last, ForwardIterator2 result, BinaryOperation binary_op, UnaryOperation unary_op, T init);

// 27.10.12, adjacent difference
template<class InputIterator, class OutputIterator>
constexpr OutputIterator
adjacent_difference(InputIterator first, InputIterator last, OutputIterator result);
template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
adjacent_difference(InputIterator first, InputIterator last, OutputIterator result, BinaryOperation binary_op);

namespace ranges {
  template<class O, class T>
  using iota_result = out_value_result<O, T>;
  template<input_or_output_iterator O, sentinel_for<O> S, weakly_incrementable T>
    requires indirectly_writable<O, const T&>
    constexpr iota_result<O, T> iota(O first, S last, T value);
  template<weakly_incrementable T, output_range<const T&> R>
    constexpr iota_result<borrowed_iterator_t<R>, T> iota(R&& r, T value);
}

// 27.10.14, greatest common divisor
template<class M, class N>
constexpr common_type_t<M, N> gcd(M m, N n);

// 27.10.15, least common multiple
template<class M, class N>
constexpr common_type_t<M, N> lcm(M m, N n);

// 27.10.16, midpoint
template<class T>
constexpr T midpoint(T a, T b) noexcept;

// 27.10.17, saturation arithmetic
template<class T>
constexpr T add_sat(T x, T y) noexcept; // freestanding
template<class T>
constexpr T sub_sat(T x, T y) noexcept; // freestanding

template<class T>
constexpr T mul_sat(T x, T y) noexcept; // freestanding

template<class T>
constexpr T div_sat(T x, T y) noexcept; // freestanding

template<class T, class U>
constexpr T saturate_cast(U x) noexcept; // freestanding

27.10 Generalized numeric operations [numeric.ops]

27.10.1 General [numeric.ops.general]

[Note 1: The use of closed ranges as well as semi-open ranges to specify requirements throughout 27.10 is intentional. —end note]

27.10.2 Definitions [numerics.defns]

1 Define \( \text{GENERALIZED\_NONCOMMUTATIVE\_SUM}(op, a_1, \ldots, a_N) \) as follows:

\[
\begin{align*}
(1.1) & \quad a_1 \text{ when } N = 1, \text{ otherwise} \\
(1.2) & \quad \text{op}(\text{GENERALIZED\_NONCOMMUTATIVE\_SUM}(op, a_1, \ldots, a_K), \\
& \quad \text{GENERALIZED\_NONCOMMUTATIVE\_SUM}(op, a_M, \ldots, a_N)) \text{ for any } K \text{ where } 1 < K + 1 = M \leq N.
\end{align*}
\]

2 Define \( \text{GENERALIZED\_SUM}(op, a_1, \ldots, a_N) \) as \( \text{GENERALIZED\_NONCOMMUTATIVE\_SUM}(op, b_1, \ldots, b_N) \), where \( b_1, \ldots, b_N \) may be any permutation of \( a_1, \ldots, a_N \).

27.10.3 Accumulate [accumulate]

template<class InputIterator, class T>
constexpr T accumulate(InputIterator first, InputIterator last, T init);

template<class InputIterator, class T, class BinaryOperation>
constexpr T accumulate(InputIterator first, InputIterator last, T init, 
BinaryOperation binary_op);

1 Preconditions: \( T \) meets the \text{Cpp17CopyConstructible} (Table 32) and \text{Cpp17CopyAssignable} (Table 34) requirements. In the range \([\text{first}, \text{last}]\), \text{binary\_op} neither modifies elements nor invalidates iterators or subranges.\(^{214}\)

2 Effects: Computes its result by initializing the accumulator \( \text{acc} \) with the initial value \( \text{init} \) and then modifies it with \( \text{acc} = \text{std::move} (\text{acc}) + *i \) or \( \text{acc} = \text{binary\_op}(\text{std::move} (\text{acc}), *i) \) for every iterator \( i \) in the range \([\text{first}, \text{last}]\) in order.\(^{215}\)

27.10.4 Reduce [reduce]

template<class InputIterator>
constexpr typename iterator_traits<InputIterator>::value_type reduce(InputIterator first, InputIterator last);

template<class ExecutionPolicy, class ForwardIterator>
typename iterator_traits<ForwardIterator>::value_type reduce(ExecutionPolicy&& exec, 
ForwardIterator first, ForwardIterator last);

1 Effects: Equivalent to:

\[
\text{return reduce(first, last, 
typename iterator_traits<InputIterator>::value_type());}
\]

2 Effects: Equivalent to:

\[
\text{return reduce(std::forward<ExecutionPolicy>(exec), first, last, 
typename iterator_traits<ForwardIterator>::value_type());}
\]

\(^{214}\) The use of fully closed ranges is intentional.
\(^{215}\) accumulate is similar to the APL reduction operator and Common Lisp reduce function, but it avoids the difficulty of defining the result of reduction on an empty sequence by always requiring an initial value.
template<class InputIterator, class T>
constexpr T reduce(InputIterator first, InputIterator last, T init);

Effects: Equivalent to:
return reduce(first, last, init, plus<>());

Effects: Equivalent to:
return reduce(std::forward<ExecutionPolicy>(exec), first, last, init, plus<>());

Effects: Equivalent to:
return reduce(first, last, init, binary_op);

Mandates: All of
(5.1) — binary_op(init, *first),
(5.2) — binary_op(*first, init),
(5.3) — binary_op(init, init), and
(5.4) — binary_op(*first, *first)
are convertible to T.

Preconditions:
(6.1) — T meets the Cpp17MoveConstructible (Table 31) requirements.
(6.2) — binary_op neither invalidates iterators or subranges, nor modifies elements in the range [first, last].

Returns: GENERALIZED_SUM(binary_op, init, *i, ...) for every i in [first, last).

Complexity: $O(\text{last} - \text{first})$ applications of binary_op.

[Note 1: The difference between reduce and accumulate is that reduce applies binary_op in an unspecified order, which yields a nondeterministic result for non-associative or non-commutative binary_op such as floating-point addition. — end note]

27.10.5 Inner product

[inner.product]

template<class InputIterator1, class InputIterator2, class T>
constexpr T inner_product(InputIterator1 first1, InputIterator1 last1,
InputIterator2 first2, T init);
27.10.6 Transform reduce

```cpp
template<class InputIterator1, class InputIterator2, class T>
constexpr T transform_reduce(InputIterator1 first1, InputIterator1 last1,
                           InputIterator2 first2,
                           T init);
```

**Effects:** Equivalent to:

```
return transform_reduce(first1, last1, first2, init, plus<>(), multiplies<>());
```

```cpp
template<class ExecutionPolicy,
         class ForwardIterator1, class ForwardIterator2, class T>
T transform_reduce(ExecutionPolicy& exec,
                   ForwardIterator1 first1, ForwardIterator1 last1,
                   ForwardIterator2 first2,
                   T init);
```

**Effects:** Equivalent to:

```
return transform_reduce(std::forward<ExecutionPolicy>(exec),
                        first1, last1, first2, init, plus<>(), multiplies<>());
```

```cpp
template<class InputIterator1, class InputIterator2, class T,
         class BinaryOperation1, class BinaryOperation2>
constexpr T transform_reduce(InputIterator1 first1, InputIterator1 last1,
                           InputIterator2 first2,
                           T init,
                           BinaryOperation1 binary_op1,
                           BinaryOperation2 binary_op2);
```

**Effects:** Equivalent to:

```
return transform_reduce(std::forward<ExecutionPolicy>(exec),
                        first1, last1, first2, init, plus<>(), multiplies<>());
```

```cpp
template<class ExecutionPolicy,
         class ForwardIterator1, class ForwardIterator2, class T,
         class BinaryOperation1, class BinaryOperation2>
T transform_reduce(ExecutionPolicy& exec,
                   ForwardIterator1 first1, ForwardIterator1 last1,
                   ForwardIterator2 first2,
                   T init,
                   BinaryOperation1 binary_op1,
                   BinaryOperation2 binary_op2);
```

**Mandates:** All of

- (3.1) `binary_op1(init, init)`,
- (3.2) `binary_op1(init, binary_op2(*first1, *first2))`,
- (3.3) `binary_op1(binary_op2(*first1, *first2), init)`, and
- (3.4) `binary_op1(binary_op2(*first1, *first2), binary_op2(*first1, *first2))` are convertible to T.

**Preconditions:**

- (4.1) T meets the Cpp17MoveConstructible (Table 31) requirements.
- (4.2) Neither `binary_op1` nor `binary_op2` invalidates subranges, nor modifies elements in the ranges `[first1, last1]` and `[first2, first2 + (last1 - first1)]`.

**Returns:**

- (GENERALIZED_SUM) `binary_op1(init, binary_op2(*i, *(first2 + (i - first1))), ...)` for every iterator i in `[first1,last1)`.

**Complexity:** \(O(\text{last1} - \text{first1})\) applications each of `binary_op1` and `binary_op2`.

```cpp
template<class InputIterator, class T,
         class BinaryOperation, class UnaryOperation>
constexpr T transform_reduce(InputIterator first, InputIterator last, T init,
                             BinaryOperation binary_op, UnaryOperation unary_op);
```
template<class ExecutionPolicy, 
    class ForwardIterator, class T, 
    class BinaryOperation, class UnaryOperation>
T transform_reduce(ExecutionPolicy&& exec, 
    ForwardIterator first, ForwardIterator last, 
    T init, BinaryOperation binary_op, UnaryOperation unary_op);

Mandates: All of
(7.1) — binary_op(init, init),
(7.2) — binary_op(init, unary_op(*first)),
(7.3) — binary_op(unary_op(*first), init), and
(7.4) — binary_op(unary_op(*first), unary_op(*first))

are convertible to T.

Preconditions:
(8.1) — T meets the Cpp17MoveConstructible (Table 31) requirements.
(8.2) — Neither unary_op nor binary_op invalidates subranges, nor modifies elements in the range [first, last].

Returns:
GENERALIZED_SUM(binary_op, init, unary_op(*i), ...)
for every iterator i in [first, last).

Complexity: O(last - first) applications each of unary_op and binary_op.

[Note 1: transform_reduce does not apply unary_op to init. — end note]

27.10.7 Partial sum

template<class InputIterator, class OutputIterator> 
constexpr OutputIterator partial_sum(InputIterator first, InputIterator last, 
    OutputIterator result);

Mandates: InputIterator’s value type is constructible from *first. The result of the expression
std::move(acc) + *i or binary_op(std::move(acc), *i) is implicitly convertible to InputIterator-

Preconditions: In the ranges [first, last] and [result, result + (last - first)] binary_op neither
modifies elements nor invalidates iterators or subranges.217

Effects: For a non-empty range, the function creates an accumulator acc whose type is InputIterator’s
value type, initializes it with *first, and assigns the result to *result. For every iterator i in
[first + 1, last) in order, acc is then modified by acc = std::move(acc) + *i or acc = binary_-op(std::move(acc), *i) and the result is assigned to *(result + (i - first)).

Returns: result + (last - first).

Complexity: Exactly (last - first) - 1 applications of the binary operation.

Remarks: result may be equal to first.

27.10.8 Exclusive scan

template<class InputIterator, class OutputIterator, class T> 
constexpr OutputIterator exclusive_scan(InputIterator first, InputIterator last, 
    OutputIterator result, T init);

Effects: Equivalent to:

217) The use of fully closed ranges is intentional.
return exclusive_scan(first, last, result, init, plus<>());

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class T>
ForwardIterator2
exclusive_scan(ExecutionPolicy&& exec,
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, T init);

Effects: Equivalent to:
return exclusive_scan(std::forward<ExecutionPolicy>(exec),
    first, last, result, init, plus<>());

template<class InputIterator, class OutputIterator, class T, class BinaryOperation>
constexpr OutputIterator
exclusive_scan(InputIterator first, InputIterator last,
    OutputIterator result, T init, BinaryOperation binary_op);

Effects: Equivalent to:

template<class ExecutionPolicy,
    class ForwardIterator1, class ForwardIterator2, class T, class BinaryOperation>
ForwardIterator2
exclusive_scan(ExecutionPolicy&& exec,
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, T init, BinaryOperation binary_op);

Mandates: All of
— binary_op(init, init),
— binary_op(init, *first), and
— binary_op(*first, *first)

are convertible to T.

Preconditions:
— T meets the C++17MoveConstructible (Table 31) requirements.
— binary_op neither invalidates iterators or subranges, nor modifies elements in the ranges [first,
    last] or [result, result + (last - first)].

Effects: For each integer K in [0, last - first) assigns through result + K the value of:
GENERALIZED_NONCOMMUTATIVE_SUM
    binary_op, init, *(first + 0), *(first + 1), ..., *(first + K - 1)

Returns: The end of the resulting range beginning at result.

Complexity: Θ(last - first) applications of binary_op.

Remarks: result may be equal to first.

[Note 1: The difference between exclusive_scan and inclusive_scan is that exclusive_scan excludes
the i'th input element from the i'th sum. If binary_op is not mathematically associative, the behavior of exclusive_scan
can be nondeterministic. — end note]

27.10.9 Inclusive scan

template<class InputIterator, class OutputIterator>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
    OutputIterator result);

Effects: Equivalent to:
return inclusive_scan(first, last, result, plus<>());

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result);

Effects: Equivalent to:
```cpp
return inclusive_scan(std::forward<ExecutionPolicy>(exec), first, last, result, plus<>());

template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result, BinaryOperation binary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryOperation>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
               ForwardIterator1 first, ForwardIterator1 last,
               ForwardIterator2 result, BinaryOperation binary_op);

template<class InputIterator, class OutputIterator, class BinaryOperation, class T>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result, BinaryOperation binary_op, T init);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryOperation, class T>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
               ForwardIterator1 first, ForwardIterator1 last,
               ForwardIterator2 result, BinaryOperation binary_op, T init);

Let \( U \) be the value type of decltype(first).

Mandates: If init is provided, all of

(4.1) \( \text{binary\_op}(\text{init}, \text{init}) \),
(4.2) \( \text{binary\_op}(\text{init}, \ast\text{first}), \) and
(4.3) \( \text{binary\_op}(\ast\text{first}, \ast\text{first}) \)

are convertible to \( T \); otherwise, \( \text{binary\_op}(\ast\text{first}, \ast\text{first}) \) is convertible to \( U \).

Preconditions:

(5.1) If init is provided, \( T \) meets the Cpp17MoveConstructible (Table 31) requirements; otherwise, \( U \) meets the Cpp17MoveConstructible requirements.
(5.2) \( \text{binary\_op} \) neither invalidates iterators or subranges, nor modifies elements in the ranges \([\text{first}, \text{last}]\) or \([\text{result}, \text{result} + (\text{last} - \text{first})]\).

Effects: For each integer \( K \) in \([0, \text{last} - \text{first})\) assigns through result + \( K \) the value of

(6.1) \( \text{GENERALIZED\_NONCOMMUTATIVE\_SUM}\)
    \( \text{binary\_op} \), init, \((\text{first} + 0), \ast(\text{first} + 1), \ldots, \ast(\text{first} + K)\)
if init is provided, or
(6.2) \( \text{GENERALIZED\_NONCOMMUTATIVE\_SUM}\)
    \( \text{binary\_op} \), \((\ast(\text{first} + 0), \ast(\text{first} + 1), \ldots, \ast(\text{first} + K))\)
otherwise.

Returns: The end of the resulting range beginning at result.

Complexity: \( O(\text{last} - \text{first}) \) applications of \( \text{binary\_op} \).

Remarks: result may be equal to first.

[Note 1: The difference between exclusive\_scan and inclusive\_scan is that inclusive\_scan includes the \( i^{\text{th}} \) input element in the \( i^{\text{th}} \) sum. If \( \text{binary\_op} \) is not mathematically associative, the behavior of inclusive\_scan can be nondeterministic. — end note]

27.10.10 Transform exclusive scan

```
template<class ExecutionPolicy,  
  class ForwardIterator1, class ForwardIterator2, class T,  
  class BinaryOperation, class UnaryOperation>
ForwardIterator2
transform_exclusive_scan(ExecutionPolicy&& exec,  
  ForwardIterator1 first, ForwardIterator1 last,  
  ForwardIterator2 result, T init,  
  BinaryOperation binary_op, UnaryOperation unary_op);

1
Mandates: All of
(1.1) — binary_op(init, init),
(1.2) — binary_op(init, unary_op(*first)), and
(1.3) — binary_op(unary_op(*first), unary_op(*first))
are convertible to T.

2
Preconditions:
(2.1) — T meets the Cpp17MoveConstructible (Table 31) requirements.
(2.2) — Neither unary_op nor binary_op invalidates iterators or subranges, nor modifies elements in the ranges \([first, last]\) or \([result, result + (last - first)]\).

3
Effects: For each integer \(K\) in \([0, last - first)\) assigns through \(result + K\) the value of:
GENERALIZED_NONCOMMUTATIVE_SUM
  binary_op, init,  
  unary_op(*first + 0), unary_op(*first + 1), ..., unary_op(*first + K - 1))

4
Returns: The end of the resulting range beginning at result.

5
Complexity: \(\Theta(last - first)\) applications each of unary_op and binary_op.

6
Remarks: result may be equal to first.

7
[Note 1: The difference between \(\text{transform\_exclusive\_scan}\) and \(\text{transform\_inclusive\_scan}\) is that \(\text{transform\_exclusive\_scan}\) excludes the \(i\)th input element from the \(i\)th sum. If binary_op is not mathematically associative, the behavior of \(\text{transform\_exclusive\_scan}\) can be nondeterministic. \(\text{transform\_exclusive\_scan}\) does not apply unary_op to init. — end note]
Let $U$ be the value type of `decltype(first)`.

Mandates: If `init` is provided, all of

(2.1) `binary_op(init, init),`
(2.2) `binary_op(init, unary_op(*first)),` and
(2.3) `binary_op(unary_op(*first), unary_op(*first))`

are convertible to $T$; otherwise, `binary_op(unary_op(*first), unary_op(*first))` is convertible to $U$.

Preconditions:

(3.1) If `init` is provided, $T$ meets the Cpp17MoveConstructible (Table 31) requirements; otherwise, $U$ meets the Cpp17MoveConstructible requirements.
(3.2) Neither `unary_op` nor `binary_op` invalidates iterators or subranges, nor modifies elements in the ranges $[\text{first}, \text{last}]$ or $[\text{result}, \text{result} + (\text{last} - \text{first})]$.

Effects: For each integer $K$ in $[0, \text{last} - \text{first})$ assigns through $\text{result} + K$ the value of

(4.1) `GENERALIZED_NONCOMMUTATIVE_SUM`

`binary_op, init,
unary_op(*(first + 0)), unary_op(*(first + 1)), ..., unary_op(*(first + K))`

if `init` is provided, or

(4.2) `GENERALIZED_NONCOMMUTATIVE_SUM`

`binary_op,
unary_op(*(first + 0)), unary_op(*(first + 1)), ..., unary_op(*(first + K))`

otherwise.

Returns: The end of the resulting range beginning at $\text{result}$.

Complexity: $\mathcal{O}((\text{last} - \text{first})$ applications each of `unary_op` and `binary_op`.

Remarks: `result` may be equal to `first`.

[Note 1: The difference between `transform_exclusive_scan` and `transform_inclusive_scan` is that `transform_inclusive_scan` includes the $i$th input element in the $i$th sum. If `binary_op` is not mathematically associative, the behavior of `transform_inclusive_scan` can be nondeterministic. `transform_inclusive_scan` does not apply `unary_op` to `init`. — end note]

### 27.10.12 Adjacent difference

```cpp
template<class InputIterator, class OutputIterator>
constexpr OutputIterator adjacent_difference(InputIterator first, InputIterator last, OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2 adjacent_difference(ExecutionPolicy&& exec, ForwardIterator1 first, ForwardIterator1 last, ForwardIterator2 result);

template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator adjacent_difference(InputIterator first, InputIterator last, OutputIterator result, BinaryOperation binary_op);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryOperation>
ForwardIterator2 adjacent_difference(ExecutionPolicy&& exec, ForwardIterator1 first, ForwardIterator1 last, ForwardIterator2 result);
```
Let $T$ be the value type of `decltype(first)`
For the overloads that do not take an argument `binary_op`, let `binary_op` be an lvalue that denotes an object of type `minus<>`.

**Mandates:**

- For the overloads with no `ExecutionPolicy`, $T$ is constructible from `*first`. `acc` (defined below) is writable (25.3.1) to the `result` output iterator. The result of the expression `binary_op(val, std::move(acc))` is writable to `result`.
- For the overloads with an `ExecutionPolicy`, the result of the expressions `binary_op(*first, *first)` and `*first` are writable to `result`.

**Preconditions:**

- For the overloads with no `ExecutionPolicy`, $T$ meets the `Cpp17MoveAssignable` (Table 33) requirements.
- For all overloads, in the ranges `[first, last]` and `[result, result + (last - first)]`, `binary_op` neither modifies elements nor invalidates iterators or subranges.

**Effects:** For the overloads with no `ExecutionPolicy` and a non-empty range, the function creates an accumulator `acc` of type $T$, initializes it with `*first`, and assigns the result to `*result`. For every iterator $i$ in `[first + 1, last)` in order, creates an object `val` whose type is $T$, initializes it with `*i`, computes `binary_op(val, std::move(acc))`, assigns the result to `*(result + (i - first))`, and move assigns from `val` to `acc`.

For the overloads with an `ExecutionPolicy` and a non-empty range, performs `*result = *first`.

Then, for every $d$ in $[1, \text{last} - \text{first} - 1]$, performs `*(result + d) = binary_op(*(first + d), *(first + (d - 1)))`.

Returns: `result + (last - first)`.

**Complexity:** Exactly $(last - first) - 1$ applications of the binary operation.

**Remarks:** For the overloads with no `ExecutionPolicy`, `result` may be equal to `first`. For the overloads with an `ExecutionPolicy`, the ranges `[first, last)` and `[result, result + (last - first)]` shall not overlap.

### 27.10.13 Iota

**Template:**

```cpp
template<class ForwardIterator, class T>
constexpr void iota(ForwardIterator first, ForwardIterator last, T value);
```

**Mandates:** $T$ is convertible to `ForwardIterator`'s value type. The expression `++val`, where `val` has type $T$, is well-formed.

**Effects:** For each element referred to by the iterator $i$ in the range `[first, last)`, assigns $*i = value$ and increments `value` as if by `++value`.

**Complexity:** Exactly `last - first` increments and assignments.

**Examples:**

```cpp
template<input_or_output_iterator O, sentinel_for<O> S, weakly_incrementable T>
requires indirectly_writable<O, const T&>
constexpr ranges::iota_result<O, T> ranges::iota(O first, S last, T value);
```

**Effects:** Equivalent to:

```cpp
while (first != last) {
    *first = as_const(value);
    ++first;
    ++value;
}
return {std::move(first), std::move(value)};
```

---

218) The use of fully closed ranges is intentional.
27.10.14 Greatest common divisor [numeric.ops.gcd]

```cpp
template<class M, class N>
constexpr common_type_t<M, N> gcd(M m, N n);
```

**Mandates:** M and N both are integer types other than cv bool.

**Preconditions:** |m| and |n| are representable as a value of common_type_t<M, N>.

*Note 1:* These requirements ensure, for example, that gcd(m, m) = |m| is representable as a value of type M.

**Returns:** Zero when m and n are both zero. Otherwise, returns the greatest common divisor of |m| and |n|.

**Throws:** Nothing.

27.10.15 Least common multiple [numeric.ops.lcm]

```cpp
template<class M, class N>
constexpr common_type_t<M, N> lcm(M m, N n);
```

**Mandates:** M and N both are integer types other than cv bool.

**Preconditions:** |m| and |n| are representable as a value of common_type_t<M, N>. The least common multiple of |m| and |n| is representable as a value of type common_type_t<M, N>.

**Returns:** Zero when either m or n is zero. Otherwise, returns the least common multiple of |m| and |n|.

**Throws:** Nothing.

27.10.16 Midpoint [numeric.ops.midpoint]

```cpp
template<class T>
constexpr T midpoint(T a, T b) noexcept;
```

**Constraints:** T is an arithmetic type other than bool.

**Returns:** Half the sum of a and b. If T is an integer type and the sum is odd, the result is rounded towards a.

**Remarks:** No overflow occurs. If T is a floating-point type, at most one inexact operation occurs.

```cpp
template<class T>
constexpr T* midpoint(T* a, T* b);
```

**Constraints:** T is an object type.

**Mandates:** T is a complete type.

**Preconditions:** a and b point to, respectively, elements i and j of the same array object x.

*Note 1:* As specified in 6.8.4, an object that is not an array element is considered to belong to a single-element array for this purpose and a pointer past the last element of an array of n elements is considered to be equivalent to a pointer to a hypothetical array element n for this purpose. — end note

**Returns:** A pointer to array element i + j/2 of x, where the result of the division is truncated towards zero.

27.10.17 Saturation arithmetic [numeric.sat]

27.10.17.1 Arithmetic functions [numeric.sat.func]

In the following descriptions, an arithmetic operation is performed as a mathematical operation with infinite range and then it is determined whether the mathematical result fits into the result type.

```cpp
template<class T>
constexpr T add_sat(T x, T y) noexcept;
```

**Constraints:** T is a signed or unsigned integer type (6.8.2).

**Returns:** If x + y is representable as a value of type T, x + y; otherwise, either the largest or smallest representable value of type T, whichever is closer to the value of x + y.
template<class T>
constexpr T sub_sat(T x, T y) noexcept;

Constraints: T is a signed or unsigned integer type (6.8.2).

Returns: If x − y is representable as a value of type T, x − y; otherwise, either the largest or smallest
representable value of type T, whichever is closer to the value of x − y.

template<class T>
constexpr T mul_sat(T x, T y) noexcept;

Constraints: T is a signed or unsigned integer type (6.8.2).

Returns: If x × y is representable as a value of type T, x × y; otherwise, either the largest or smallest
representable value of type T, whichever is closer to the value of x × y.

template<class T>
constexpr T div_sat(T x, T y) noexcept;

Constraints: T is a signed or unsigned integer type (6.8.2).

Preconditions: y != 0 is true.

Returns: If T is a signed integer type and x == numeric_limits<T>::min() && y == -1 is true,
numeric_limits<T>::max(), otherwise, x / y.

Remarks: A function call expression that violates the precondition in the Preconditions element is not
a core constant expression (7.7).

27.10.17.2 Casting

template<class R, class T>
constexpr R saturate_cast(T x) noexcept;

Constraints: R and T are signed or unsigned integer types (6.8.2).

Returns: If x is representable as a value of type R, x; otherwise, either the largest or smallest representable
value of type R, whichever is closer to the value of x.

27.11 Specialized <memory> algorithms

27.11.1 General

The contents specified in 27.11 are declared in the header <memory> (20.2.2).

Unless otherwise specified, if an exception is thrown in the following algorithms, objects constructed by a
placement new-expression (7.6.2.8) are destroyed in an unspecified order before allowing the exception to
propagate.

Some algorithms specified in 27.11 make use of the exposition-only function template voidify:

```
template<class T>
constexpr void* voidify(T& obj) noexcept {
    return addressof(obj);
}
```

27.11.2 Special memory concepts

Some algorithms in this subclause are constrained with the following exposition-only concepts:

```
template<class I>
concept nothrow-input-iterator = // exposition only
    input_iterator<I> &&
    is_lvalue_reference_v<iter_reference_t<I>> &&
    same_as<remove_cvref_t<iter_reference_t<I>>, iter_value_t<I>>;
```

A type I models nothrow-input-iterator only if no exceptions are thrown from increment, copy
construction, move construction, copy assignment, move assignment, or indirection through valid
iterators.

[Note 1: This concept allows some input_iterator (25.3.4.9) operations to throw exceptions. — end note]
template<class S, class I>
concept noexcept-sentinel-for = sentinel_for<S, I>; // exposition only

Types S and I model noexcept-sentinel-for only if no exceptions are thrown from copy construction, move construction, copy assignment, move assignment, or comparisons between valid values of type I and S.

[Note 2: This concept allows some sentinel_for (25.3.4.7) operations to throw exceptions. — end note]

template<class R>
concept noexcept-input-range = // exposition only
range<R> &&
noexcept-input-iterator<iterator_t<R>> &&
noexcept-sentinel-for<sentinel_t<R>, iterator_t<R>>;

A type R models noexcept-input-range only if no exceptions are thrown from calls to ranges::begin and ranges::end on an object of type R.

template<class I>
concept noexcept-forward-iterator = // exposition only
noexcept-input-iterator<I> &&
forward_iterator<I> &&
noexcept-sentinel-for<I, I>;

[Note 3: This concept allows some forward_iterator (25.3.4.11) operations to throw exceptions. — end note]

template<class R>
concept noexcept-forward-range = // exposition only
noexcept-input-range<R> &&
noexcept-forward-iterator<iterator_t<R>>;

27.11.3 uninitialized_default_construct [uninitialized.construct.default]

namespace ranges {
    template<nothrow-forward-iterator I, noexcept-sentinel-for<I> S>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_default_construct(I first, S last);

    template<nothrow-forward-range R>
    requires default_initializable<range_value_t<R>>
    borrowed_iterator_t<R> uninitialized_default_construct(R&& r);
}

 Effects: Equivalent to:

    for (; first != last; ++first)
        ::new (voidify(*first))
            typename iterator_traits<nothrow-forwardIterator>::value_type;

Effects: Equivalent to:

    for (; first != last; ++first)
        ::new (voidify(*first)) remove_reference_t<iter_reference_t<I>>;
    return first;

template<class NoThrowForwardIterator, class Size>
NoThrowForwardIterator uninitialized_default_construct_n(NoThrowForwardIterator first, Size n);

 Effects: Equivalent to:

    for (; n > 0; (void)+first, --n)
        ::new (voidify(*first))
            typename iterator_traits<nothrow-forwardIterator>::value_type;
    return first;

namespace ranges {
    template<nothrow-forward-iterator I>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_default_construct_n(I first, iter_difference_t<I> n);
}
Effects: Equivalent to:

```cpp
return uninitialized_default_construct(counted_iterator(first, n),
    default_sentinel).base();
```

27.11.4 uninitialized_value_construct

```cpp
template<class NoThrowForwardIterator>
void uninitialized_value_construct(NoThrowForwardIterator first, NoThrowForwardIterator last);
```

Effects: Equivalent to:

```cpp
for (; first != last; ++first)
    ::new (voidify(*first))
        typename iterator_traits<NoThrowForwardIterator>::value_type();
```

namespace ranges {
    template<nothrow-forward-iterator I, nothrow-sentinel-for<I> S>
        requires default_initializable<iter_value_t<I>>
    I uninitialized_value_construct(I first, S last);
    template<nothrow-forward-range R>
        requires default_initializable<range_value_t<R>>
    borrowed_iterator_t<R> uninitialized_value_construct(R&& r);
}

Effects: Equivalent to:

```cpp
for (; first != last; ++first)
    ::new (voidify(*first)) remove_reference_t<iter_reference_t<I>>();
return first;
```

template<class NoThrowForwardIterator, class Size>
NoThrowForwardIterator uninitialized_value_construct_n(NoThrowForwardIterator first, Size n);

Effects: Equivalent to:

```cpp
for (; n > 0; (void)++first, --n)
    ::new (voidify(*first))
        typename iterator_traits<NoThrowForwardIterator>::value_type();
return first;
```

namespace ranges {
    template<nothrow-forward-iterator I>
        requires default_initializable<iter_value_t<I>>
    I uninitialized_value_construct_n(I first, iter_difference_t<I> n);
}

Effects: Equivalent to:

```cpp
return uninitialized_value_construct(counted_iterator(first, n),
    default_sentinel).base();
```

27.11.5 uninitialized_copy

```cpp
template<class InputIterator, class NoThrowForwardIterator>
NoThrowForwardIterator uninitialized_copy(InputIterator first, InputIterator last,
    NoThrowForwardIterator result);
```

Preconditions: result + [0, (last - first)) does not overlap with [first, last).

Effects: Equivalent to:

```cpp
for (; first != last; ++result, (void) ++first)
    ::new (voidify(*result))
        typename iterator_traits<NoThrowForwardIterator>::value_type(*first);
```

Returns: result.
namespace ranges {
    template<input_iterator I, sentinel_for<I> S1,
             nothrow-forward_iterator O, nothrow-sentinel_for<O> S2>
    requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
    uninitialized_copy_result<I, O>
    uninitialized_copy(I ifirst, S1 ilast, O ofirst, S2 olast);
    template<input_range IR, nothrow-forward_range OR>
    requires constructible_from<range_value_t<OR>, range_reference_t<IR>>
    uninitialized_copy_result<borrowed_iterator_t<IR>, borrowed_iterator_t<OR>>
    uninitialized_copy(IR&& in_range, OR&& out_range);
}

Preconditions: \( [\textit{ofirst}, \textit{olast}) \) does not overlap with \( [\textit{ifirst}, \textit{ilast}) \).

Effects: Equivalent to:

\[
\text{for ( ; \textit{ifirst} \neq \textit{ilast} \&\& \textit{ofirst} \neq \textit{olast} ; ++\textit{ofirst}, (\text{void})++\textit{ilast})}
\quad \text{\begin{align*}
\quad &::\text{new (voidify(*\textit{ofirst}) remove_reference_t<iter_reference_t<O>>(*\textit{ifirst});}
\quad &\text{return } \{\text{std::move(\textit{ifirst}), \textit{ofirst}}\};
\end{align*}}
\]

Preconditions: \( \textit{result} + [0, \textit{n}) \) does not overlap with \( \textit{first} + [0, \textit{n}) \).

Effects: Equivalent to:

\[
\text{for ( ; \textit{n} \geq 0 ; ++\textit{result}, (\text{void})++\textit{first}, --\textit{n})}
\quad \text{\begin{align*}
\quad &::\text{new (voidify(*\textit{result})})}
\quad &\text{typename iterator_traits<NoThrowForwardIterator>::value_type(*\textit{first});}
\end{align*}}
\]

Returns: \( \text{result} \).

27.11.6 uninitialized_move

template<class InputIterator, class Size, class NoThrowForwardIterator>
NoThrowForwardIterator uninitialized_move_n(InputIterator first, Size n,
NoThrowForwardIterator result);

Preconditions: \( [\textit{ofirst}, \textit{olast}) \) does not overlap with \( \textit{ifirst} + [0, \textit{n}) \).

Effects: Equivalent to:

\[
\text{auto t = uninitialized_copy(counted_iterator(std::move(\textit{ifirst}), n),}
\quad \text{default_sentinel, \textit{ofirst}, \textit{olast});}
\quad \text{return } \{\text{std::move(t.in).base()}, \text{t.out}}\};
\]

§ 27.11.6 © ISO/IEC 1470
template<input_range IR, nothrow-forward-range OR>
uninitialized_move_result<borrowed_iterator_t<IR>, borrowed_iterator_t<OR>>
uninitialized_move(IR&& in_range, OR&& out_range);

3 Preconditions: \([\text{ofirst}, \text{olast})\) does not overlap with \([\text{ifirst}, \text{ilast})\).

4 Effects: Equivalent to:

\[
\begin{align*}
\text{for} & \quad (: \text{ifirst} != \text{ilast} \&\& \text{ofirst} != \text{olast}; ++\text{ofirst}, (\text{void})++\text{ifirst}) \\
& \quad \text{::new} \ (\text{voidify}(*\text{ofirst})) \\
& \quad \text{remove_reference_t<iter_reference_t<OR>>(ranges::iter_move(\text{ifirst})}); \\
\text{return} & \quad \{\text{std::move(\text{ifirst}), ofirst}\};
\end{align*}
\]

[Note 1: If an exception is thrown, some objects in the range \([\text{ifirst}, \text{ilast})\) are left in a valid, but unspecified state. — end note]

template<class InputIterator, class Size, class NoThrowForwardIterator>
pair<InputIterator, NoThrowForwardIterator>
uninitialized_move_n(InputIterator first, Size n, NoThrowForwardIterator result);

6 Preconditions: \(\text{result} + [0, n)\) does not overlap with \(\text{first} + [0, n)\).

7 Effects: Equivalent to:

\[
\begin{align*}
\text{for} & \quad (: n > 0; ++\text{result}, (\text{void})++\text{first}, --n) \\
& \quad \text{::new} \ (\text{voidify}(*\text{result})) \\
& \quad \text{typename iterator_traits<NoThrowForwardIterator>::value_type(std::move(*\text{first}))}; \\
\text{return} & \quad \{\text{first}, \text{result}\};
\end{align*}
\]

namespace ranges {

template<input_iterator I, nothrow-forward-iterator O, nothrow-sentinel-for<O> S>
uninitialized_move_n_result<I, O>
uninitialized_move_n(I ifirst, iter_difference_t<I> n, O ofirst, S olast);
}

8 Preconditions: \([\text{ofirst}, \text{olast})\) does not overlap with \(\text{ifirst} + [0, n)\).

9 Effects: Equivalent to:

\[
\begin{align*}
\text{auto} & \quad \text{t} = \text{uninitialized_move}(\text{counted_iterator}(\text{std::move(\text{ifirst})), n), \\
& \quad \text{default_sentinel, ofirst, olast}); \\
\text{return} & \quad \{\text{std::move(t.in).base()}, t.out\};
\end{align*}
\]

[Note 2: If an exception is thrown, some objects in the range \(\text{ifirst} + [0, n)\) are left in a valid but unspecified state. — end note]

27.11.7 uninitialized_fill

[uninitialized.fill]

template<class NoThrowForwardIterator, class T>
void uninitialized_fill(NoThrowForwardIterator first, NoThrowForwardIterator last, const T& x);

1 Effects: Equivalent to:

\[
\begin{align*}
\text{for} & \quad (: \text{first} != \text{last}; ++\text{first}) \\
& \quad \text{::new} \ (\text{voidify}(*\text{first})) \\
& \quad \text{typename iterator_traits<NoThrowForwardIterator>::value_type}(x);
\end{align*}
\]

namespace ranges {

template<nothrow-forward-iterator I, nothrow-sentinel-for<I> S, class T>
I uninitialized_fill(I first, S last, const T& x);

template<nothrow-forward-range R, class T>
R&& uninitialized_fill(R&& r, const T& x);
}

2 Effects: Equivalent to:

\[
\begin{align*}
\text{for} & \quad (: \text{first} != \text{last}; ++\text{first}) \\
& \quad \text{::new} \ (\text{voidify}(*\text{first})) \text{remove_reference_t<iter_reference_t<I>>(x);}  \\
\end{align*}
\]
return first;

```c++
template<class NoThrowForwardIterator, class Size, class T>
NoThrowForwardIterator uninitialized_fill_n(NoThrowForwardIterator first, Size n, const T& x);
```

3 Effects: Equivalent to:
   - for (; n--; ++first)
     : new (voidify(*first))
     : typename iterator_traits<NoThrowForwardIterator>::value_type(x);
   return first;

namespace ranges {
  template<nothrow-forward-iterator I, class T>
  requires constructible_from<iter_value_t<I>, const T&>
  I uninitialized_fill_n(I first, iter_difference_t<I> n, const T& x);
}

4 Effects: Equivalent to:
   return uninitialized_fill(counted_iterator(first, n), default_sentinel, x).base();

27.11.8 construct_at

```c++
template<class T, class... Args>
constexpr T* construct_at(T* location, Args&&... args);
```

namespace ranges {
  template<class T, class... Args>
  constexpr T* construct_at(T* location, Args&&... args);
}

1 Constraints: The expression ::new (declval<void*>()) T(declval<Args>()...)
2 Effects: Equivalent to:
   return ::new (voidify(*location)) T(std::forward<Args>(args)...);

27.11.9 destroy

```c++
template<class T>
constexpr void destroy_at(T* location);
```

namespace ranges {
  template<destructible T>
  constexpr void destroy_at(T* location) noexcept;
}

1 Effects:
- If T is an array type, equivalent to destroy(begin(*location), end(*location)).
- Otherwise, equivalent to location->~T().

```c++
template<class NoThrowForwardIterator>
constexpr void destroy(NoThrowForwardIterator first, NoThrowForwardIterator last);
```

2 Effects: Equivalent to:
   - for (; first != last; ++first)
     destroy_at(addressof(*first));

namespace ranges {
  template<nothrow-input-iterator I, nothrow-sentinel_for<I> S>
  requires destructible<iter_value_t<I>>
  constexpr I destroy(I first, S last) noexcept;
  template<nothrow-input-range R>
  requires destructible<range_value_t<R>>
  constexpr borrowed_iterator_t<R> destroy(R&& r) noexcept;
}

3 Effects: Equivalent to:
for (; first != last; ++first)
        destroy_at(addressof(*first));
    return first;

template<class NoThrowForwardIterator, class Size>
constexpr NoThrowForwardIterator destroy_n(NoThrowForwardIterator first, Size n);

Effects: Equivalent to:
for (; n > 0; (void)++first, --n)
        destroy_at(addressof(*first));
    return first;

namespace ranges {
    template<nothrow-input-iterator I>
    requires destructible<iter_value_t<I>>
    constexpr I destroy_n(I first, iter_difference_t<I> n) noexcept;
}

Effects: Equivalent to:
return destroy(counted_iterator(std::move(first), n), default_sentinel).base();

27.12 Specialized <random> algorithms

27.12.1 General

The contents specified in 27.12 are declared in the header <random> (28.5.2).

27.12.2 generate_random

template<class R, class G>
requires output_range<R, invoke_result_t<G&>> && uniform_random_bit_generator<remove_cvref_t<G>>
constexpr borrowed_iterator_t<R> ranges::generate_random(R&& r, G&& g);

Effects:
(1.1) Calls g.generate_random(std::forward<R>(r)) if this expression is well-formed.
(1.2) Otherwise, if R models sized_range, fills r with ranges::size(r) values of type invoke_result_t<G&> by performing an unspecified number of invocations of the form g() or g.generate_random(s), if such an expression is well-formed for a value N and an object s of type span<invoke_result_t<G&>, N>.
    [Note 1: Values of N can differ between invocations. — end note]
(1.3) Otherwise, calls ranges::generate(std::forward<R>(r), ref(g)).

Returns: ranges::end(r).

Remarks: The effects of generate_random(r, g) shall be equivalent to ranges::generate(std::forward<R>(r), ref(g)).
    [Note 2: This implies that g.generate_random(a) fills a with the same values as produced by invocation of g(). — end note]

template<class G, output_iterator<invoke_result_t<G&>> O, sentinel_for<O> S>
requires uniform_random_bit_generator<remove_cvref_t<G>>
constexpr O ranges::generate_random(O first, S last, G&& g);

Effects: Equivalent to:
return generate_random(subrange<O, S>(std::move(first), last), g);

template<class R, class G, class D>
requires output_range<R, invoke_result_t<D&, G&>> && invocable<D&, G&> && uniform_random_bit_generator<remove_cvref_t<G>>
constexpr borrowed_iterator_t<R> ranges::generate_random(R&& r, G&& g, D&& d);

Effects:
(5.1) Calls d.generate_random(std::forward<R>(r), g) if this expression is well-formed.
(5.2) Otherwise, if R models sized_range, fills r with ranges::size(r) values of type invoke_result_t<D&, G&> by performing an unspecified number of invocations of the form invoke(d,
g) or d.generate_random(s, g), if such an expression is well-formed for a value \( N \) and an object \( s \) of type \( \text{span}<\text{invoke_result_t}<\text{D&}, \text{G&}>, \text{N}> \).

[Note 3: Values of \( N \) can differ between invocations. — end note]

\[(5.3)\] Otherwise, calls

\[
\text{ranges::generate(std::forward<R>(r), [\&d, \&g] \{ return invoke(d, g); \})};
\]

Returns: \( \text{ranges::end(r)} \)

Remarks: The effects of \( \text{generate_random(r, g, d)} \) shall be equivalent to

\[
\text{ranges::generate(std::forward<R>(r), [\&d, \&g] \{ return invoke(d, g); \})}
\]

[Note 4: This implies that \( \text{d.generate_random(a, g)} \) fills \( a \) with the values with the same random distribution as produced by invocation of \( \text{invoke(d, g)} \). — end note]

template<class G, class D, output_iterator<invoke_result_t<D&, G&>> O, sentinel_for<O> S>
requires invocable<\text{D&}, \text{G&}> && uniform_random_bit_generator<remove_cvref_t<G>>
constexpr O ranges::generate_random(O first, S last, G&& g, D&& d);

Effects: Equivalent to:

\[
\text{return generate_random(subrange<O, S>(std::move(first), last), g, d);}
\]

27.13 C library algorithms

[Note 1: The header <cstdlib> (17.2.2) declares the functions described in this subclause. — end note]

\[
\text{void* bsearch(const void* key, const void* base, size_t nmemb, size_t size, c-compare-pred* compar)};
\]
\[
\text{void* bsearch(const void* key, const void* base, size_t nmemb, size_t size, compare-pred* compar)};
\]
\[
\text{void qsort(void* base, size_t nmemb, size_t size, c-compare-pred* compar)};
\]
\[
\text{void qsort(void* base, size_t nmemb, size_t size, compare-pred* compar)};
\]

2 Preconditions: For \( \text{qsort} \), the objects in the array pointed to by \( \text{base} \) are of trivially copyable type.
3 Effects: These functions have the semantics specified in the C standard library.
4 Throws: Any exception thrown by \( \text{compar} \) (16.4.6.13).

See also: ISO/IEC 9899:2018, 7.22.5
28  Numerics library

28.1  General

This Clause describes components that C++ programs may use to perform seminumerical operations.

The following subclauses describe components for complex number types, random number generation, numeric (n-at-a-time) arrays, generalized numeric algorithms, and mathematical constants and functions for floating-point types, as summarized in Table 97.

### Table 97 — Numerics library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.2 Requirements</td>
<td><code>&lt;cfenv&gt;</code></td>
</tr>
<tr>
<td>28.3 Floating-point environment</td>
<td><code>&lt;complex&gt;</code></td>
</tr>
<tr>
<td>28.4 Complex numbers</td>
<td><code>&lt;complex&gt;</code></td>
</tr>
<tr>
<td>28.5 Random number generation</td>
<td><code>&lt;random&gt;</code></td>
</tr>
<tr>
<td>28.6 Numeric arrays</td>
<td><code>&lt;valarray&gt;</code></td>
</tr>
<tr>
<td>28.7 Mathematical functions for floating-point types</td>
<td><code>&lt;cmath&gt;</code>, <code>&lt;cstdlib&gt;</code></td>
</tr>
<tr>
<td>28.8 Numbers</td>
<td><code>&lt;numbers&gt;</code></td>
</tr>
<tr>
<td>28.9 Linear algebra</td>
<td><code>&lt;linalg&gt;</code></td>
</tr>
</tbody>
</table>

28.2  Numeric type requirements

The `complex` and `valarray` components are parameterized by the type of information they contain and manipulate. A C++ program shall instantiate these components only with a numeric type. A numeric type is a cv-unqualified object type `T` that meets the `Cpp17DefaultConstructible`, `Cpp17CopyConstructible`, `Cpp17CopyAssignable`, and `Cpp17Destructible` requirements (16.4.4.2).

If any operation on `T` throws an exception the effects are undefined.

In addition, many member and related functions of `valarray<T>` can be successfully instantiated and will exhibit well-defined behavior if and only if `T` meets additional requirements specified for each such member or related function.

[Example 1: It is valid to instantiate `valarray<complex>`, but `operator()` will not be successfully instantiated for `valarray<complex>` operands, since `complex` does not have any ordering operators.
— end example]

28.3  The floating-point environment

28.3.1  Header `<cfenv>`

```cpp
#define FE_ALL_EXCEPT see below
#define FE_DIVBYZERO see below  // optional
#define FE_INEXACT see below     // optional
#define FE_INVALID see below     // optional
#define FE_OVERFLOW see below    // optional
#define FE_UNDERFLOW see below   // optional
#define FE_DOWNWARD see below    // optional
#define FE_TONEAREST see below   // optional
#define FE_TOWARDZERO see below  // optional
#define FE_UPWARD see below      // optional
#define FE_DFL_ENV see below
```

219) In other words, value types. These include arithmetic types, pointers, the library class `complex`, and instantiations of `valarray` for value types.
namespace std {
    // types
    using fenv_t  = object type;
    using fexcept_t = object type;

    // functions
    int feclearexcept(int except);
    int fegetexceptflag(fexcept_t* pflag, int except);
    int feraiseexcept(int except);
    int fetestexcept(int except);
    int fegetround();
    int fesetround(int mode);
    int fegetenv(fenv_t* penv);
    int feholdexcept(fenv_t* penv);
    int fesetenv(const fenv_t* penv);
    int feupdateenv(const fenv_t* penv);
}

The contents and meaning of the header `<cfenv>` are the same as the C standard library header `<fenv.h>`. [Note 1: This document does not require an implementation to support the FENV_ACCESS pragma; it is implementation-defined (15.9) whether the pragma is supported. As a consequence, it is implementation-defined whether these functions can be used to test floating-point status flags, set floating-point control modes, or run under non-default mode settings. If the pragma is used to enable control over the floating-point environment, this document does not specify the effect on floating-point evaluation in constant expressions. — end note]

SEE ALSO: ISO/IEC 9899:2018, 7.6

28.3.2 Threads

The floating-point environment has thread storage duration (6.7.5.3). The initial state for a thread’s floating-point environment is the state of the floating-point environment of the thread that constructs the corresponding thread object (33.4.3) or jthread object (33.4.4) at the time it constructed the object. [Note 1: That is, the child thread gets the floating-point state of the parent thread at the time of the child’s creation. — end note]

2 A separate floating-point environment is maintained for each thread. Each function accesses the environment corresponding to its calling thread.

28.4 Complex numbers

28.4.1 General

The header `<complex>` defines a class template, and numerous functions for representing and manipulating complex numbers.

The effect of instantiating the template `complex` for any type that is not a cv-unqualified floating-point type (6.8.2) is unspecified. Specializations of `complex` for cv-unqualified floating-point types are trivially copyable literal types (6.8.1).

If the result of a function is not mathematically defined or not in the range of representable values for its type, the behavior is undefined.

If z is an lvalue of type cv `complex<T>` then:

(4.1) the expression `reinterpret_cast<cv T(*)[2]>(z)` is well-formed,
(4.2) `reinterpret_cast<cv T(*)[2]>(z)[0]` designates the real part of z, and
(4.3) `reinterpret_cast<cv T(*)[2]>(z)[1]` designates the imaginary part of z.

Moreover, if a is an expression of type cv `complex<T>✶` and the expression a[i] is well-defined for an integer expression i, then:

(4.4) `reinterpret_cast<cv T✶>(a)[2*i]` designates the real part of a[i], and
(4.5) `reinterpret_cast<cv T✶>(a)[2*i + 1]` designates the imaginary part of a[i].
28.4.2 Header <complex> synopsis

namespace std {
    // 28.4.3, class template complex
    template<class T> class complex;

    // 28.4.6, operators
    template<class T> constexpr complex<T> operator+(const complex<T>&, const complex<T>&);
    template<class T> constexpr complex<T> operator+(const complex<T>&, const T&);
    template<class T> constexpr complex<T> operator+(const T&, const complex<T>&);
    template<class T> constexpr complex<T> operator-(const complex<T>&, const complex<T>&);
    template<class T> constexpr complex<T> operator-(const complex<T>&, const T&);
    template<class T> constexpr complex<T> operator-(const T&, const complex<T>&);
    template<class T> constexpr complex<T> operator*(const complex<T>&, const complex<T>&);
    template<class T> constexpr complex<T> operator*(const complex<T>&, const T&);
    template<class T> constexpr complex<T> operator*(const T&, const complex<T>&);
    template<class T> constexpr complex<T> operator/(const complex<T>&, const complex<T>&);
    template<class T> constexpr complex<T> operator/(const complex<T>&, const T&);
    template<class T> constexpr complex<T> operator/(const T&, const complex<T>&);
    template<class T> constexpr complex<T> operator+(const complex<T>&);
    template<class T> constexpr complex<T> operator-(const complex<T>&);
    template<class T, class charT, class traits> basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>&, complex<T>&);
    template<class T, class charT, class traits> basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>&, const complex<T>&);

    // 28.4.7, values
    template<class T> constexpr T real(const complex<T>&);
    template<class T> constexpr T imag(const complex<T>&);
    template<class T> constexpr T abs(const complex<T>&);
    template<class T> constexpr T arg(const complex<T>&);
    template<class T> constexpr T norm(const complex<T>&);
    template<class T> constexpr complex<T> conj(const complex<T>&);
    template<class T> constexpr complex<T> proj(const complex<T>&);
    template<class T> constexpr complex<T> polar(const T&, const T& = T());

    // 28.4.8, transcendentals
    template<class T> constexpr complex<T> acos(const complex<T>&);
    template<class T> constexpr complex<T> asin(const complex<T>&);
    template<class T> constexpr complex<T> atan(const complex<T>&);
    template<class T> constexpr complex<T> acosh(const complex<T>&);
    template<class T> constexpr complex<T> asinh(const complex<T>&);
    template<class T> constexpr complex<T> atanh(const complex<T>&);
    template<class T> constexpr complex<T> cos (const complex<T>&);
    template<class T> constexpr complex<T> cosh (const complex<T>&);
    template<class T> constexpr complex<T> exp (const complex<T>&);
    template<class T> constexpr complex<T> log (const complex<T>&);
    template<class T> constexpr complex<T> log10(const complex<T>&);
    template<class T> constexpr complex<T> pow (const complex<T>&, const T&);
    template<class T> constexpr complex<T> pow (const complex<T>&, const complex<T>&);
    template<class T> constexpr complex<T> pow (const T&, const complex<T>&);


```cpp
template<class T> constexpr complex<T> sin (const complex<T>&);
template<class T> constexpr complex<T> sinh (const complex<T>&);
template<class T> constexpr complex<T> sqrt (const complex<T>&);
template<class T> constexpr complex<T> tan (const complex<T>&);
template<class T> constexpr complex<T> tanh (const complex<T>&);

// 28.4.9, tuple interface
template<class T> struct tuple_size;
template<size_t I, class T> struct tuple_element;
template<class T> struct tuple_size<complex<T>>;
template<size_t I, class T> struct tuple_element<I, complex<T>>;

template<size_t I, class T>
constexpr T& get(complex<T>&) noexcept;
template<size_t I, class T>
constexpr T&& get(complex<T>&&) noexcept;
template<size_t I, class T>
constexpr const T& get(const complex<T>&) noexcept;
template<size_t I, class T>
constexpr const T&& get(const complex<T>&&) noexcept;

// 28.4.11, complex literals
inline namespace literals {
    inline namespace complex_literals {
        constexpr complex<long double> operator"il(long double);
        constexpr complex<long double> operator"il(unsigned long long);
        constexpr complex<double> operator"if(long double);
        constexpr complex<double> operator"if(unsigned long long);
    }
}
```

### 28.4.3 Class template complex

```cpp
namespace std {
    template<class T> class complex {
    public:
        using value_type = T;

        constexpr complex(const T& re = T(), const T& im = T());
        constexpr complex(const complex&) = default;
        template<class X> constexpr explicit(see below) complex(const complex<X>&);

        constexpr T real() const;
        constexpr void real(T);
        constexpr T imag() const;
        constexpr void imag(T);

        constexpr complex& operator= (const T&);
        constexpr complex& operator+=(const T&);
        constexpr complex& operator-=(const T&);
        constexpr complex& operator*=(const T&);
        constexpr complex& operator/=(const T&);
        template<class X> constexpr complex& operator= (const complex<X>&);
        template<class X> constexpr complex& operator+=(const complex<X>&);
        template<class X> constexpr complex& operator-=(const complex<X>&);
        template<class X> constexpr complex& operator*=(const complex<X>&);
        template<class X> constexpr complex& operator/=(const complex<X>&);
    };
}
```
The class `complex` describes an object that can store the Cartesian components, `real()` and `imag()`, of a complex number.

### 28.4.4 Member functions

```cpp
class complex
{
public:
    constexpr complex(const T& re = T(), const T& im = T());
    Postconditions: real() == re && imag() == im is true.

template<class X> constexpr explicit(see below) complex(const complex<X>& other);

    Effects: Initializes the real part with `other.real()` and the imaginary part with `other.imag()`.

    Remarks: The expression inside `explicit` evaluates to `false` if and only if the floating-point conversion rank of `T` is greater than or equal to the floating-point conversion rank of `X`.

    constexpr T real() const;
    Returns: The value of the real component.

    constexpr void real(T val);
    Effects: Assigns `val` to the real component.

    constexpr T imag() const;
    Returns: The value of the imaginary component.

    constexpr void imag(T val);
    Effects: Assigns `val` to the imaginary component.

private:
}

```
Returns: *this.

template<class X> constexpr complex& operator*=(const complex<X>& rhs);
Effects: Multiplies the complex value rhs by the complex value *this and stores the product in *this.
Returns: *this.

template<class X> constexpr complex& operator/=(const complex<X>& rhs);
Effects: Divides the complex value rhs into the complex value *this and stores the quotient in *this.
Returns: *this.

28.4.6 Non-member operations
[complex.ops]

template<class T> constexpr complex<T> operator+(const complex<T>& lhs);
Returns: complex<T>(lhs).

template<class T> constexpr complex<T> operator+(const complex<T>& lhs, const complex<T>& rhs);

template<class T> constexpr complex<T> operator+(const complex<T>& lhs, const T& rhs);

template<class T> constexpr complex<T> operator+(const T& lhs, const complex<T>& rhs);
Returns: complex<T>(lhs) += rhs.

template<class T> constexpr complex<T> operator-(const complex<T>& lhs, const complex<T>& rhs);

template<class T> constexpr complex<T> operator-(const complex<T>& lhs, const T& rhs);

template<class T> constexpr complex<T> operator-(const T& lhs, const complex<T>& rhs);
Returns: complex<T>(lhs) -= rhs.

template<class T> constexpr complex<T> operator/(const complex<T>& lhs, const complex<T>& rhs);

template<class T> constexpr complex<T> operator/(const complex<T>& lhs, const T& rhs);

template<class T> constexpr complex<T> operator/(const T& lhs, const complex<T>& rhs);
Returns: complex<T>(lhs) /= rhs.

template<class T> constexpr bool operator==(const complex<T>& lhs, const complex<T>& rhs);

template<class T> constexpr bool operator==(const complex<T>& lhs, const T& rhs);
Returns: lhs.real() == rhs.real() && lhs.imag() == rhs.imag().
Remarks: The imaginary part is assumed to be T(), or 0.0, for the T arguments.

template<class T, class charT, class traits>
basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& is, complex<T>& x);
Preconditions: The input values are convertible to T.
Effects: Extracts a complex number x of the form: u, (u), or (u,v), where u is the real part and v is the imaginary part (31.7.5.3).
If bad input is encountered, calls is.setstate(ios_base::failbit) (which may throw ios_base::failure (31.5.4.4)).
Returns: is.
Remarks: This extraction is performed as a series of simpler extractions. Therefore, the skipping of whitespace is specified to be the same for each of the simpler extractions.

template<class T, class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& o, const complex<T>& x);
Effects: Inserts the complex number x onto the stream o as if it were implemented as follows:
basic_ostringstream<charT, traits> s;
s.flags(o.flags());
s.imbue(o.getloc());
s.precision(o.precision());
s << '(' << x.real() << ',' << x.imag() << ')';
return o << s.str();

[Note 1: In a locale in which comma is used as a decimal point character, the use of comma as a field separator can be ambiguous. Inserting showpoint into the output stream forces all outputs to show an explicit decimal point character; as a result, all inserted sequences of complex numbers can be extracted unambiguously. — end note]

28.4.7 Value operations

template<class T> constexpr T real(const complex<T>& x);
Returns: x.real().

template<class T> constexpr T imag(const complex<T>& x);
Returns: x.imag().

template<class T> constexpr T abs(const complex<T>& x);
Returns: The magnitude of x.

template<class T> constexpr T arg(const complex<T>& x);
Returns: The phase angle of x, or atan2(imag(x), real(x)).

template<class T> constexpr T norm(const complex<T>& x);
Returns: The squared magnitude of x.

template<class T> constexpr complex<T> conj(const complex<T>& x);
Returns: The complex conjugate of x.

template<class T> constexpr complex<T> proj(const complex<T>& x);
Returns: The projection of x onto the Riemann sphere.
Remarks: Behaves the same as the C function cproj. See also: ISO/IEC 9899:2018, 7.3.9.5

template<class T> constexpr complex<T> polar(const T& rho, const T& theta = T());
Preconditions: rho is non-negative and non-NaN. theta is finite.
Returns: The complex value corresponding to a complex number whose magnitude is rho and whose phase angle is theta.

28.4.8 Transcendentals

template<class T> constexpr complex<T> acos(const complex<T>& x);
Returns: The complex arc cosine of x.
Remarks: Behaves the same as the C function cacosh. See also: ISO/IEC 9899:2018, 7.3.5.1

template<class T> constexpr complex<T> asin(const complex<T>& x);
Returns: The complex arc sine of x.
Remarks: Behaves the same as the C function casin. See also: ISO/IEC 9899:2018, 7.3.5.2

template<class T> constexpr complex<T> atan(const complex<T>& x);
Returns: The complex arc tangent of x.
Remarks: Behaves the same as the C function catan. See also: ISO/IEC 9899:2018, 7.3.5.3

template<class T> constexpr complex<T> acosh(const complex<T>& x);
Returns: The complex arc hyperbolic cosine of x.
Remarks: Behaves the same as the C function cacosh. See also: ISO/IEC 9899:2018, 7.3.6.1
template<class T> constexpr complex<T> asinh(const complex<T>& x);
   
   Returns: The complex arc hyperbolic sine of \( x \).
   
   Remarks: Behaves the same as the C function \texttt{casinh}. See \texttt{ISO/IEC 9899:2018}, 7.3.6.2

template<class T> constexpr complex<T> atanh(const complex<T>& x);
   
   Returns: The complex arc hyperbolic tangent of \( x \).
   
   Remarks: Behaves the same as the C function \texttt{catanh}. See \texttt{ISO/IEC 9899:2018}, 7.3.6.3

template<class T> constexpr complex<T> cos(const complex<T>& x);
   
   Returns: The complex cosine of \( x \).

template<class T> constexpr complex<T> cosh(const complex<T>& x);
   
   Returns: The complex hyperbolic cosine of \( x \).

template<class T> constexpr complex<T> exp(const complex<T>& x);
   
   Returns: The complex base-\( e \) exponential of \( x \).

template<class T> constexpr complex<T> log(const complex<T>& x);
   
   Returns: The complex natural (base-\( e \)) logarithm of \( x \). For all \( x \), \( \text{imag}(\text{log}(x)) \) lies in the interval \([-\pi, \pi] \).
   
   [Note 1: The semantics of this function are intended to be the same in C++ as they are for \texttt{clog} in C. —end note]
   
   Remarks: The branch cuts are along the negative real axis.

template<class T> constexpr complex<T> log10(const complex<T>& x);
   
   Returns: The complex common (base-10) logarithm of \( x \), defined as \( \text{log}(x) / \text{log}(10) \).
   
   Remarks: The branch cuts are along the negative real axis.

template<class T> constexpr complex<T> pow(const complex<T>& x, const complex<T>& y);
template<class T> constexpr complex<T> pow(const complex<T>& x, const T& y);
template<class T> constexpr complex<T> pow(const T& x, const complex<T>& y);
   
   Returns: The complex power of base \( x \) raised to the \( y \)th power, defined as \( \exp(y \ast \text{log}(x)) \). The value returned for \( \text{pow}(0, 0) \) is implementation-defined.
   
   Remarks: The branch cuts are along the negative real axis.

template<class T> constexpr complex<T> sin(const complex<T>& x);
   
   Returns: The complex sine of \( x \).

template<class T> constexpr complex<T> sinh(const complex<T>& x);
   
   Returns: The complex hyperbolic sine of \( x \).

template<class T> constexpr complex<T> sqrt(const complex<T>& x);
   
   Returns: The complex square root of \( x \), in the range of the right half-plane.
   
   [Note 2: The semantics of this function are intended to be the same in C++ as they are for \texttt{csqrt} in C. —end note]
   
   Remarks: The branch cuts are along the negative real axis.

template<class T> constexpr complex<T> tan(const complex<T>& x);
   
   Returns: The complex tangent of \( x \).

template<class T> constexpr complex<T> tanh(const complex<T>& x);
   
   Returns: The complex hyperbolic tangent of \( x \).

28.4.9 Tuple interface

template<class T>
struct tuple_size<complex<T>> : integral_constant<size_t, 2> {};
template<
    size_t I,
    class T>
struct tuple_element<I, complex<T>> {
    using type = T;
};

Mandates: \( I < 2 \) is true.

```
28.4.10 Additional overloads

The following function templates have additional constexpr overloads:

arg norm
conj proj
imag real

Mandates: \( I < 2 \) is true.

Returns: A reference to the real part of \( z \) if \( I == 0 \) is true, otherwise a reference to the imaginary part of \( z \).
```

```28.4.11 Suffixes for complex number literals

This subclause describes literal suffixes for constructing complex number literals. The suffixes \( i \), \( il \), and \( if \) create complex numbers of the types \( \text{complex<double>} \), \( \text{complex<long double>} \), and \( \text{complex<float>} \) respectively, with their imaginary part denoted by the given literal number and the real part being zero.

constexpr complex<long double> operator""il(long double d);
constexpr complex<long double> operator""il(unsigned long long d);

Returns: \( \text{complex<long double>} \{0.0L, \text{static_cast<long double>(d)}\} \).

```

```
28.5 Random number generation

28.5.1 General

Subclause 28.5 defines a facility for generating (pseudo-)random numbers.

In addition to a few utilities, four categories of entities are described: uniform random bit generators, random number engines, random number engine adaptors, and random number distributions. These categorizations are applicable to types that meet the corresponding requirements, to objects instantiated from such types, and to templates producing such types when instantiated.
```
[Note 1: These entities are specified in such a way as to permit the binding of any uniform random bit generator
object \( e \) as the argument to any random number distribution object \( d \), thus producing a zero-argument function object
such as given by \( \text{bind}(d,e) \). — end note]

Each of the entities specified in 28.5 has an associated arithmetic type (6.8.2) identified as result_type. With \( T \) as the result_type thus associated with such an entity, that entity is characterized:

\[(3.1)\] as boolean or equivalently as boolean-valued, if \( T \) is bool;
\[(3.2)\] otherwise as integral or equivalently as integer-valued, if numeric_limits<\( T \>::\text{is_integer} \) is true;
\[(3.3)\] otherwise as floating-point or equivalently as real-valued.

If integer-valued, an entity may optionally be further characterized as signed or unsigned, according to numeric_limits<\( T \>::\text{is_signed} \).

Unless otherwise specified, all descriptions of calculations in 28.5 use mathematical real numbers.

Throughout 28.5, the operators bitand, bitor, and xor denote the respective conventional bitwise operations. Further:

\[(5.1)\] the operator rshift denotes a bitwise right shift with zero-valued bits appearing in the high bits of the result, and
\[(5.2)\] the operator lshift\(_w\) denotes a bitwise left shift with zero-valued bits appearing in the low bits of the result, and whose result is always taken modulo \( 2^w \).

### 28.5.2 Header <random> synopsis

```cpp
#include <initializer_list> // see 17.10.2

namespace std {
    // 28.5.3.3, uniform random bit generator requirements
template<class G>
    concept uniform_random_bit_generator = see below;

    // 28.5.4.2, class template linear_congruential_engine
template<class UIntType, UIntType a, UIntType c, UIntType m>
    class linear_congruential_engine;

    // 28.5.4.3, class template mersenne_twister_engine
template<class UIntType, size_t w, size_t n, size_t m, size_t r,
             UIntType a, size_t u, UIntType d, size_t s,
             UIntType b, size_t t,
            (UIntType c, size_t l, UIntType f>
    class mersenne_twister_engine;

    // 28.5.4.4, class template subtract_with_carry_engine
template<class UIntType, size_t w, size_t s, size_t r>
    class subtract_with_carry_engine;

    // 28.5.5.2, class template discard_block_engine
template<class Engine, size_t p, size_t r>
    class discard_block_engine;

    // 28.5.5.3, class template independent_bits_engine
    template<class Engine, size_t w, class UIntType>
    class independent_bits_engine;

    // 28.5.5.4, class template shuffle_order_engine
    template<class Engine, size_t k>
    class shuffle_order_engine;

    // 28.5.6, engines and engine adaptors with predefined parameters
    using minstd_rand0 = see below;
    using minstd_rand = see below;
    using mt19937 = see below;
    using mt19937_64 = see below;
    using ranlux24_base = see below;
}
```

© ISO/IEC 14841 1484
using ranlux48_base = see below;
using ranlux24 = see below;
using ranlux48 = see below;
using knuth_b = see below;

using default_random_engine = see below;

// 28.5.7, class random_device
class random_device;

// 28.5.8.1, class seed_seq
class seed_seq;

// 28.5.8.2, function template generate_canonical
template<class RealType, size_t digits, class URBG>
  RealType generate_canonical(URBG& g);

namespace ranges {
  // 27.12.2, generate_random
template<class R, class G>
  requires output_range<R, invoke_result_t<G&>> &&
    uniform_random_bit_generator<remove_cvref_t<G>>
  constexpr borrowed_iterator_t<R> generate_random(R&& r, G&& g);

  template<class G, output_iterator<invoke_result_t<G&>> O, sentinel_for<O> S>
  requires uniform_random_bit_generator<remove_cvref_t<G>>
  constexpr O generate_random(O first, S last, G&& g);

  template<class R, class G, class D>
  requires output_range<R, invoke_result_t<D&, G&>> && invocable<D&, G&> &&
    uniform_random_bit_generator<remove_cvref_t<G>>
  constexpr borrowed_iterator_t<R> generate_random(R&& r, G&& g, D&& d);

  template<class G, class D, output_iterator<invoke_result_t<D&, G&>> O, sentinel_for<O> S>
  requires invocable<D&, G&> && uniform_random_bit_generator<remove_cvref_t<G>>
  constexpr O generate_random(O first, S last, G&& g, D&& d);
}

// 28.5.9.2.1, class template uniform_int_distribution
template<class IntType = int>
  class uniform_int_distribution;

// 28.5.9.2.2, class template uniform_real_distribution
template<class RealType = double>
  class uniform_real_distribution;

// 28.5.9.3.1, class bernoulli_distribution
class bernoulli_distribution;

// 28.5.9.3.2, class template binomial_distribution
template<class IntType = int>
  class binomial_distribution;

// 28.5.9.3.3, class template geometric_distribution
template<class IntType = int>
  class geometric_distribution;

// 28.5.9.3.4, class template negative_binomial_distribution
template<class IntType = int>
  class negative_binomial_distribution;

// 28.5.9.4.1, class template poisson_distribution
template<class IntType = int>
  class poisson_distribution;
// 28.5.9.4.2, class template exponential_distribution
template<class RealType = double>
class exponential_distribution;

// 28.5.9.4.3, class template gamma_distribution
template<class RealType = double>
class gamma_distribution;

// 28.5.9.4.4, class template weibull_distribution
template<class RealType = double>
class weibull_distribution;

// 28.5.9.4.5, class template extreme_value_distribution
template<class RealType = double>
class extreme_value_distribution;

// 28.5.9.5.1, class template normal_distribution
template<class RealType = double>
class normal_distribution;

// 28.5.9.5.2, class template lognormal_distribution
template<class RealType = double>
class lognormal_distribution;

// 28.5.9.5.3, class template chi_squared_distribution
template<class RealType = double>
class chi_squared_distribution;

// 28.5.9.5.4, class template cauchy_distribution
template<class RealType = double>
class cauchy_distribution;

// 28.5.9.5.5, class template fisher_f_distribution
template<class RealType = double>
class fisher_f_distribution;

// 28.5.9.5.6, class template student_t_distribution
template<class RealType = double>
class student_t_distribution;

// 28.5.9.6.1, class template discrete_distribution
template<class IntType = int>
class discrete_distribution;

// 28.5.9.6.2, class template piecewise_constant_distribution
template<class RealType = double>
class piecewise_constant_distribution;

// 28.5.9.6.3, class template piecewise_linear_distribution
template<class RealType = double>
class piecewise_linear_distribution;

} // namespace std

28.5.3 Requirements

28.5.3.1 General requirements

1 Throughout 28.5, the effect of instantiating a template:

  (1.1) — that has a template type parameter named $S\text{seq}$ is undefined unless the corresponding template argument is cv-unqualified and meets the requirements of seed sequence (28.5.3.2).

  (1.2) — that has a template type parameter named $URBG$ is undefined unless the corresponding template argument is cv-unqualified and meets the requirements of uniform random bit generator (28.5.3.3).
that has a template type parameter named `Engine` is undefined unless the corresponding template argument is cv-unqualified and meets the requirements of random number engine (28.5.3.4).

— that has a template type parameter named `RealType` is undefined unless the corresponding template argument is cv-unqualified and is one of `float`, `double`, or `long double`.

— that has a template type parameter named `IntType` is undefined unless the corresponding template argument is cv-unqualified and is one of `short`, `int`, `long`, `long long`, `unsigned short`, `unsigned int`, `unsigned long`, or `unsigned long long`.

— that has a template type parameter named `UIntType` is undefined unless the corresponding template argument is cv-unqualified and is one of `unsigned short`, `unsigned int`, `unsigned long`, or `unsigned long long`.

Throughout 28.5, phrases of the form “x is an iterator of a specific kind” shall be interpreted as equivalent to the more formal requirement that “x is a value of a type meeting the requirements of the specified iterator type”.

Throughout 28.5, any constructor that can be called with a single argument and that meets a requirement specified in this subclause shall be declared `explicit`.

### 28.5.3.2 Seed sequence requirements

A seed sequence is an object that consumes a sequence of integer-valued data and produces a requested number of unsigned integer values \(0 \leq i < 2^{32}\), based on the consumed data.

[Note 1: Such an object provides a mechanism to avoid replication of streams of random variates. This can be useful, for example, in applications requiring large numbers of random number engines. —end note]

A class \(S\) meets the requirements of a seed sequence if the expressions shown in Table 98 are valid and have the indicated semantics, and if \(S\) also meets all other requirements of 28.5.3.2. In Table 98 and throughout this subclause:

- \(T\) is the type named by \(S\)'s associated `result_type`;
- \(q\) is a value of type \(S\) and \(r\) is a value of type \(S\) or `const S`;
- \(ib\) and \(ie\) are input iterators with an unsigned integer `value_type` of at least 32 bits;
- \(rb\) and \(re\) are mutable random access iterators with an unsigned integer `value_type` of at least 32 bits;
- \(ob\) is an output iterator; and
- \(il\) is a value of type `initializer_list<T>`.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S::result_type)</td>
<td>(T)</td>
<td>(T) is an unsigned integer type (6.8.2) of at least 32 bits.</td>
<td>compile-time</td>
</tr>
<tr>
<td>(S())</td>
<td></td>
<td>Creates a seed sequence with the same initial state as all other default-constructed seed sequences of type (S).</td>
<td>constant</td>
</tr>
<tr>
<td>(S(ib,ie))</td>
<td></td>
<td>Creates a seed sequence having internal state that depends on some or all of the bits of the supplied sequence ([ib,ie)).</td>
<td>(O(ie - ib))</td>
</tr>
<tr>
<td>(S(il))</td>
<td></td>
<td>Same as (S(il.begin()), il.end()).</td>
<td>same as (S(il.begin()), il.end())</td>
</tr>
</tbody>
</table>
Table 98 — Seed sequence requirements (continued)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>q.generate(rb,re)</td>
<td>void</td>
<td>Does nothing if rb == re. Otherwise, fills the supplied sequence ([rb, re]) with 32-bit quantities that depend on the sequence supplied to the constructor and possibly also depend on the history of (\text{generate}'s) previous invocations.</td>
<td>(\mathcal{O}(re - rb))</td>
</tr>
<tr>
<td>r.size()</td>
<td>size_t</td>
<td>The number of 32-bit units that would be copied by a call to (\text{r.param}).</td>
<td>constant</td>
</tr>
<tr>
<td>r.param(ob)</td>
<td>void</td>
<td>Copies to the given destination a sequence of 32-bit units that can be provided to the constructor of a second object of type (S), and that would reproduce in that second object a state indistinguishable from the state of the first object.</td>
<td>(\mathcal{O}(r\text{.size()})</td>
</tr>
</tbody>
</table>

28.5.3.3 Uniform random bit generator requirements

A uniform random bit generator \(g\) of type \(G\) is a function object returning unsigned integer values such that each value in the range of possible results has (ideally) equal probability of being returned.

[Note 1: The degree to which \(g\)'s results approximate the ideal is often determined statistically. — end note]

```
template<class G>
concept uniform_random_bit_generator =
invocable<G&> &\& unsigned_integral<invoke_result_t<G&>> &\& requires {
    { G::min() } -> same_as<invoke_result_t<G&>>;
    { G::max() } -> same_as<invoke_result_t<G&>>;
    requires bool_constant<(G::min() < G::max())>::value;
};
```

Let \(g\) be an object of type \(G\). \(G\) models uniform_random_bit_generator only if

1. \(G::\text{min()} \leq g()\),
2. \(g() \leq G::\text{max()}\), and
3. \(g()\) has amortized constant complexity.

A class \(G\) meets the uniform random bit generator requirements if \(G\) models uniform_random_bit_generator, \(\text{invoke_result_t}<G>\) is an unsigned integer type (6.8.2), and \(G\) provides a nested typedef-name result_type that denotes the same type as \(\text{invoke_result_t}<G>\).

28.5.3.4 Random number engine requirements

A random number engine (commonly shortened to engine) \(e\) of type \(E\) is a uniform random bit generator that additionally meets the requirements (e.g., for seeding and for input/output) specified in this subclause.

At any given time, \(e\) has a state \(e_i\) for some integer \(i \geq 0\). Upon construction, \(e\) has an initial state \(e_0\). An engine's state may be established via a constructor, a seed function, assignment, or a suitable operator\(\gg\).

E's specification shall define:

1. the size of \(E\)'s state in multiples of the size of \text{result_type}, given as an integral constant expression;
2. the \text{transition algorithm} \(TA\) by which \(e\)'s state \(e_i\) is advanced to its successor state \(e_{i+1}\); and
3. the \text{generation algorithm} \(GA\) by which an engine's state is mapped to a value of type result_type.
A class $E$ that meets the requirements of a uniform random bit generator (28.5.3.3) also meets the requirements of a random number engine if the expressions shown in Table 99 are valid and have the indicated semantics, and if $E$ also meets all other requirements of 28.5.3.4. In Table 99 and throughout this subclause:

1. $T$ is the type named by $E$'s associated `result_type`;
2. $e$ is a value of $E$, $v$ is an lvalue of $E$, $x$ and $y$ are (possibly const) values of $E$;
3. $s$ is a value of $T$;
4. $q$ is an lvalue meeting the requirements of a seed sequence (28.5.3.2);
5. $z$ is a value of type `unsigned long long`;
6. $os$ is an lvalue of the type of some class template specialization `basic_ostream<charT, traits>`; and
7. $is$ is a value of the type of some class template specialization `basic_istream<charT, traits>`;

where `charT` and `traits` are constrained according to Clause 23 and Clause 31.

Table 99 — Random number engine requirements  

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E()$</td>
<td>void</td>
<td>$e == E()$.</td>
<td>$O(\text{size of state})$</td>
</tr>
<tr>
<td>$E(x)$</td>
<td>void</td>
<td>$e == E(e_i)$.</td>
<td>$O(\text{size of state})$</td>
</tr>
<tr>
<td>$E(s)$</td>
<td>void</td>
<td>$e == E(s)$.</td>
<td>$O(\text{size of state})$</td>
</tr>
<tr>
<td>$E(q)$</td>
<td>void</td>
<td>$e == E(q)$.</td>
<td>$O(\text{size of state})$</td>
</tr>
<tr>
<td>$e().()$</td>
<td>$T$</td>
<td><code>true</code></td>
<td>n/a</td>
</tr>
<tr>
<td>$e.seed()$</td>
<td>void</td>
<td><code>false</code></td>
<td>n/a</td>
</tr>
<tr>
<td>$e.seed(s)$</td>
<td>void</td>
<td><code>false</code></td>
<td>n/a</td>
</tr>
<tr>
<td>$e.seed(q)$</td>
<td>void</td>
<td><code>false</code></td>
<td>n/a</td>
</tr>
<tr>
<td>$x == y$</td>
<td>bool</td>
<td><code>false</code></td>
<td>n/a</td>
</tr>
</tbody>
</table>

220) This constructor (as well as the subsequent corresponding `seed()` function) can be particularly useful to applications requiring a large number of independent random sequences.
221) This operation is common in user code, and can often be implemented in an engine-specific manner so as to provide significant performance improvements over an equivalent naive loop that makes $z$ consecutive calls $e()$. 

§ 28.5.3.4 ©ISO/IEC 1489
<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>os &lt;&lt; x</code></td>
<td>reference to the type of <code>os</code></td>
<td>With <code>os.fmtflags</code> set to <code>ios_base::dec</code> and the fill character set to the space character, writes to <code>os</code> the textual representation of <code>x</code>’s current state. In the output, adjacent numbers are separated by one or more space characters. <em>Postconditions:</em> The <code>os.fmtflags</code> and fill character are unchanged.</td>
<td>$O(\text{size of state})$</td>
</tr>
<tr>
<td><code>is &gt;&gt; v</code></td>
<td>reference to the type of <code>is</code></td>
<td>With <code>is.fmtflags</code> set to <code>ios_base::dec</code>, sets <code>v</code>’s state as determined by reading its textual representation from <code>is</code>. If bad input is encountered, ensures that <code>v</code>’s state is unchanged by the operation and calls <code>is.setstate(ios_base::failbit)</code> (which may throw <code>ios_base::failure</code> (31.5.4.4)). If a textual representation written via <code>os &lt;&lt; x</code> was subsequently read via <code>is &gt;&gt; v</code>, then <code>x == v</code> provided that there have been no intervening invocations of <code>x</code> or of <code>v</code>. <em>Preconditions:</em> <code>is</code> provides a textual representation that was previously written using an output stream whose imbued locale was the same as that of <code>is</code>, and whose type’s template specialization arguments <code>charT</code> and <code>traits</code> were respectively the same as those of <code>is</code>. <em>Postconditions:</em> The <code>is.fmtflags</code> are unchanged.</td>
<td>$O(\text{size of state})$</td>
</tr>
</tbody>
</table>

5. E shall meet the `Cpp17CopyConstructible` (Table 32) and `Cpp17CopyAssignable` (Table 34) requirements. These operations shall each be of complexity no worse than $O(\text{size of state})$.

### 28.5.3.5 Random number engine adaptor requirements [rand.req.adapt]

1. A random number engine adaptor (commonly shortened to adaptor) `a` of type `A` is a random number engine that takes values produced by some other random number engine, and applies an algorithm to those values in order to deliver a sequence of values with different randomness properties. An engine `b` of type `B` adapted in this way is termed a base engine in this context. The expression `a.base()` shall be valid and shall return a const reference to `a`’s base engine.

2. The requirements of a random number engine type shall be interpreted as follows with respect to a random number engine adaptor type.

   ```cpp
   A::A();
   ```

   **Effects:** The base engine is initialized as if by its default constructor.

   ```cpp
   bool operator==(const A& a1, const A& a2);
   ```

   **Returns:** `true` if `a1`’s base engine is equal to `a2`’s base engine. Otherwise returns `false`. 

§ 28.5.3.5 ©ISO/IEC 1490
A::A(result_type s);

Effects: The base engine is initialized with s.

template<class Sseq> A::A(Sseq& q);

Effects: The base engine is initialized with q.

void seed();

Effects: With b as the base engine, invokes b.seed().

void seed(result_type s);

Effects: With b as the base engine, invokes b.seed(s).

template<class Sseq> void seed(Sseq& q);

Effects: With b as the base engine, invokes b.seed(q).

A shall also meet the following additional requirements:

(10.1) — The complexity of each function shall not exceed the complexity of the corresponding function applied to the base engine.
(10.2) — The state of A shall include the state of its base engine. The size of A’s state shall be no less than the size of the base engine.
(10.3) — Copying A’s state (e.g., during copy construction or copy assignment) shall include copying the state of the base engine of A.
(10.4) — The textual representation of A shall include the textual representation of its base engine.

28.5.3.6 Random number distribution requirements [rand.req.dist]

A random number distribution (commonly shortened to distribution) d of type D is a function object returning values that are distributed according to an associated mathematical probability density function p(z) or according to an associated discrete probability function P(z). A distribution’s specification identifies its associated probability function p(z) or P(z).

An associated probability function is typically expressed using certain externally-supplied quantities known as the parameters of the distribution. Such distribution parameters are identified in this context by writing, for example, p(z | a, b) or P(z | a, b), to name specific parameters, or by writing, for example, p(z | {p}) or P(z | {p}), to denote a distribution’s parameters p taken as a whole.

A class D meets the requirements of a random number distribution if the expressions shown in Table 100 are valid and have the indicated semantics, and if D and its associated types also meet all other requirements of 28.5.3.6. In Table 100 and throughout this subclause,

(3.1) — T is the type named by D’s associated result_type;
(3.2) — P is the type named by D’s associated param_type;
(3.3) — d is a value of D, and x and y are (possibly const) values of D;
(3.4) — glb and lub are values of T respectively corresponding to the greatest lower bound and the least upper bound on the values potentially returned by d’s operator(), as determined by the current values of d’s parameters;
(3.5) — p is a (possibly const) value of P;
(3.6) — g, g1, and g2 are lvalues of a type meeting the requirements of a uniform random bit generator (28.5.3.3);
(3.7) — os is an lvalue of the type of some class template specialization basic_ostream<charT, traits>; and
(3.8) — is is an lvalue of the type of some class template specialization basic_istream<charT, traits>;

where charT and traits are constrained according to Clause 23 and Clause 31.

<p>| Table 100 — Random number distribution requirements [tab:rand.req.dist] |
|------------------|--------|-----------------|------------------|
| Expression       | Return type | Pre/post-condition                | Complexity       |
| D::result_type   | T       | T is an arithmetic type (6.8.2), compile-time |
| D::param_type    | P       | compile-time                      |</p>
<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>D()</td>
<td></td>
<td>Creates a distribution whose behavior is indistinguishable from that of any other newly default-constructed distribution of type D.</td>
<td>constant</td>
</tr>
<tr>
<td>D(p)</td>
<td></td>
<td>Creates a distribution whose behavior is indistinguishable from that of a distribution newly constructed directly from the values used to construct p.</td>
<td>same as p’s construction</td>
</tr>
<tr>
<td>d.reset()</td>
<td>void</td>
<td>Subsequent uses of d do not depend on values produced by any engine prior to invoking reset.</td>
<td>constant</td>
</tr>
<tr>
<td>x.param()</td>
<td>P</td>
<td>Returns a value p such that D(p).param() == p.</td>
<td>no worse than the complexity of D(p)</td>
</tr>
<tr>
<td>d.param(p)</td>
<td>void</td>
<td>Postconditions: d.param() == p.</td>
<td>no worse than the complexity of D(p)</td>
</tr>
<tr>
<td>d(g)</td>
<td>T</td>
<td>With p = d.param(), the sequence of numbers returned by successive invocations with the same object g is randomly distributed according to the associated p(z</td>
<td>{p}) or P(z_i</td>
</tr>
<tr>
<td>d(g,p)</td>
<td>T</td>
<td>The sequence of numbers returned by successive invocations with the same objects g and p is randomly distributed according to the associated p(z</td>
<td>{p}) or P(z_i</td>
</tr>
<tr>
<td>x.min()</td>
<td>T</td>
<td>Returns glb.</td>
<td>constant</td>
</tr>
<tr>
<td>x.max()</td>
<td>T</td>
<td>Returns lub.</td>
<td>constant</td>
</tr>
<tr>
<td>x == y</td>
<td>bool</td>
<td>This operator is an equivalence relation. Returns true if x.param() == y.param() and S_1 = S_2, where S_1 and S_2 are the infinite sequences of values that would be generated, respectively, by repeated future calls to x(g1) and y(g2) whenever g_1 == g_2. Otherwise returns false.</td>
<td>constant</td>
</tr>
<tr>
<td>x != y</td>
<td>bool</td>
<td>!(x == y).</td>
<td>same as x == y.</td>
</tr>
<tr>
<td>os &lt;&lt; x</td>
<td>reference to the type of os</td>
<td>Writes to os a textual representation for the parameters and the additional internal data of x. Postconditions: The os. fmtflags and fill character are unchanged.</td>
<td>same as x == y.</td>
</tr>
<tr>
<td>Expression</td>
<td>Return type</td>
<td>Pre/post-condition</td>
<td>Complexity</td>
</tr>
<tr>
<td>------------</td>
<td>---------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>is &gt;&gt; d</td>
<td>reference to the type of is</td>
<td>Restores from is the parameters and additional internal data of the lvalue d. If bad input is encountered, ensures that d is unchanged by the operation and calls is.setstate(ios_base::failbit) (which may throw ios_base::failure (31.5.4.4)).</td>
<td></td>
</tr>
</tbody>
</table>

**Preconditions:**
is provides a textual representation that was previously written using an os whose imbued locale and whose type’s template specialization arguments charT and traits were the same as those of is.

**Postconditions:** The is.fmtflags are unchanged.

---

4 D shall meet the Cpp17CopyConstructible (Table 32) and Cpp17CopyAssignable (Table 34) requirements.

5 The sequence of numbers produced by repeated invocations of d(g) shall be independent of any invocation of os << d or of any const member function of D between any of the invocations of d(g).

6 If a textual representation is written using os << x and that representation is restored into the same or a different object y of the same type using is >> y, repeated invocations of y(g) shall produce the same sequence of numbers as would repeated invocations of x(g).

7 It is unspecified whether D::param_type is declared as a (nested) class or via a typedef. In 28.5, declarations of D::param_type are in the form of typedefs for convenience of exposition only.

8 P shall meet the Cpp17CopyConstructible (Table 32), Cpp17CopyAssignable (Table 34), and Cpp17Equality-Comparable (Table 28) requirements.

9 For each of the constructors of D taking arguments corresponding to parameters of the distribution, P shall have a corresponding constructor subject to the same requirements and taking arguments identical in number, type, and default values. Moreover, for each of the member functions of D that return values corresponding to parameters of the distribution, P shall have a corresponding member function with the identical name, type, and semantics.

10 P shall have a declaration of the form

```
using distribution_type = D;
```

---

### 28.5.4 Random number engine class templates

#### [rand.eng]

#### 28.5.4.1 General

[rand.eng.general]

1 Each type instantiated from a class template specified in 28.5.4 meets the requirements of a random number engine (28.5.3.4) type.

2 Except where specified otherwise, the complexity of each function specified in 28.5.4 is constant.

3 Except where specified otherwise, no function described in 28.5.4 throws an exception.

4 Every function described in 28.5.4 that has a function parameter q of type Sseq& for a template type parameter named Sseq that is different from type seed_seq throws what and when the invocation of q.generate throws.

5 Descriptions are provided in 28.5.4 only for engine operations that are not described in 28.5.3.4 or for operations where there is additional semantic information. In particular, declarations for copy constructors, for copy assignment operators, for streaming operators, and for equality and inequality operators are not shown in the synopses.
Each template specified in 28.5.4 requires one or more relationships, involving the value(s) of its non-type template parameter(s), to hold. A program instantiating any of these templates is ill-formed if any such required relationship fails to hold.

For every random number engine and for every random number engine adaptor X defined in 28.5.4 and in 28.5.5:

(7.1) — if the constructor

```
template<class Sseq> explicit X(Sseq& q);
```

is called with a type Sseq that does not qualify as a seed sequence, then this constructor shall not participate in overload resolution;

(7.2) — if the member function

```
template<class Sseq> void seed(Sseq& q);
```

is called with a type Sseq that does not qualify as a seed sequence, then this function shall not participate in overload resolution.

The extent to which an implementation determines that a type cannot be a seed sequence is unspecified, except that as a minimum a type shall not qualify as a seed sequence if it is implicitly convertible to X::result_type.

### 28.5.4.2 Class template linear_congruential_engine

A linear_congruential_engine random number engine produces unsigned integer random numbers. The state \( x_i \) of a linear_congruential_engine object \( x \) is of size 1 and consists of a single integer. The transition algorithm is a modular linear function of the form \( T_A(x_i) = (a \cdot x_i + c) \mod m \); the generation algorithm is \( G_A(x_i) = x_i + 1 \).

```cpp
namespace std {
    template<class UIntType, UIntType a, UIntType c, UIntType m>
    class linear_congruential_engine {
        public:
            // types
            using result_type = UIntType;
            // engine characteristics
            static constexpr result_type multiplier = a;
            static constexpr result_type increment = c;
            static constexpr result_type modulus = m;
            static constexpr result_type min() { return c == 0u ? 1u : 0u; }
            static constexpr result_type max() { return m - 1u; }
            static constexpr result_type default_seed = 1u;
            // constructors and seeding functions
            linear_congruential_engine() : linear_congruential_engine(default_seed) {};
            explicit linear_congruential_engine(result_type s);
            template<class Sseq> explicit linear_congruential_engine(Sseq& q);
            void seed(result_type s = default_seed);
            template<class Sseq> void seed(Sseq& q);
            // equality operators
            friend bool operator==(const linear_congruential_engine& x, const linear_congruential_engine& y);
            // generating functions
            result_type operator()();
            void discard(unsigned long long z);
            // inserters and extractors
            template<class charT, class traits>
            friend basic_ostream<charT, traits>& operator<< (basic_ostream<charT, traits>& os, const linear_congruential_engine& x);
            template<class charT, class traits>
            friend basic_istream<charT, traits>& operator>> (basic_istream<charT, traits>& is, linear_congruential_engine& x);
    }
}
```
Let (3.4)\]

With (2.1)\]

Concatenate the upper $w - r$ bits of $X_{i-n}$ with the lower $r$ bits of $X_{i+1-n}$ to obtain an unsigned integer value $Y$.

With $\alpha = a \cdot (Y \text{ bitand } 1)$, set $X_i$ to $X_{i+m-n} \text{ xor } (Y \text{ rshift } 1) \text{ xor } \alpha$.

The sequence $X$ is initialized with the help of an initialization multiplier $f$.

The generation algorithm determines the unsigned integer values $z_1, z_2, z_3, z_4$ as follows, then delivers $z_4$ as its result:

- Let $z_1 = X_i \text{ xor } ((X_i \text{ rshift } w) \text{ bitand } d)$.
- Let $z_2 = z_1 \text{ xor } ((z_1 \text{ lshift } w) \text{ bitand } b)$.
- Let $z_3 = z_2 \text{ xor } ((z_2 \text{ lshift } w) \text{ bitand } c)$.
- Let $z_4 = z_3 \text{ xor } (z_3 \text{ rshift } \ell)$.

namespace std {
    template<class UIntType, size_t w, size_t n, size_t m, size_t r, 
             UIntType a, size_t u, UIntType d, size_t s, 
             UIntType b, size_t t, 
             UIntType c, size_t l, UIntType f>
    class mersenne_twister_engine {
        public:
            // types
            using result_type = UIntType;

            // engine characteristics
            static constexpr size_t word_size = w;
            static constexpr size_t state_size = m;
            static constexpr size_t shift_size = s;
            static constexpr size_t mask_bits = r;

Note 1: $m$ need not be representable as a value of type result_type. — end note

If the template parameter $m$ is not 0, the following relations shall hold: $a < m$ and $c < m$.

The textual representation consists of the value of $x_i$.

Explicit linear_congruential_engine

Effects: If $c \text{ mod } m$ is 0 and $s \text{ mod } m$ is 0, sets the engine’s state to 1, otherwise sets the engine’s state to $s \text{ mod } m$.

template<class Sseq> explicit linear_congruential_engine(Sseq& q);

Effects: With $k = \left\lceil \frac{\log_2 m}{32} \right\rceil$ and $a$ an array (or equivalent) of length $k + 3$, invokes $q.\text{generate}(a + 0, a + k + 3)$ and then computes $S = \left( \sum_{j=0}^{k-1} a_j \cdot 2^{32j} \right) \text{ mod } m$. If $c \text{ mod } m$ is 0 and $S$ is 0, sets the engine’s state to 1, else sets the engine’s state to $S$.

28.5.4.3 Class template mersenne_twister_engine

A mersenne_twister_engine random number engine produces unsigned integer random numbers in the closed interval $[0, 2^w - 1]$. The state $x_i$ of a mersenne_twister_engine object $x$ is of size $n$ and consists of a sequence $X$ of $n$ values of the type delivered by $x$; all subscripts applied to $X$ are to be taken modulo $n$.

The transition algorithm employs a twisted generalized feedback shift register defined by shift values $n$ and $m$, a twist value $r$, and a conditional xor-mask $a$. To improve the uniformity of the result, the bits of the raw shift register are additionally tempered (i.e., scrambled) according to a bit-scrambling matrix defined by values $u$, $d$, $s$, $b$, $t$, $c$, and $\ell$.

The state transition is performed as follows:

- Concatenate the upper $w - r$ bits of $X_{i-n}$ with the lower $r$ bits of $X_{i+1-n}$ to obtain an unsigned integer value $Y$.
- With $\alpha = a \cdot (Y \text{ bitand } 1)$, set $X_i$ to $X_{i+m-n} \text{ xor } (Y \text{ rshift } 1) \text{ xor } \alpha$.

The sequence $X$ is initialized with the help of an initialization multiplier $f$.

The generation algorithm determines the unsigned integer values $z_1, z_2, z_3, z_4$ as follows, then delivers $z_4$ as its result:

- Let $z_1 = X_i \text{ xor } ((X_i \text{ rshift } w) \text{ bitand } d)$.
- Let $z_2 = z_1 \text{ xor } ((z_1 \text{ lshift } w) \text{ bitand } b)$.
- Let $z_3 = z_2 \text{ xor } ((z_2 \text{ lshift } w) \text{ bitand } c)$.
- Let $z_4 = z_3 \text{ xor } (z_3 \text{ rshift } \ell)$.

222) The name of this engine refers, in part, to a property of its period: For properly-selected values of the parameters, the period is closely related to a large Mersenne prime number.
static constexpr UIntType xor_mask = a;
static constexpr size_t tempering_u = u;
static constexpr UIntType tempering_d = d;
static constexpr size_t tempering_s = s;
static constexpr UIntType tempering_b = b;
static constexpr size_t tempering_t = t;
static constexpr size_t tempering_l = l;
static constexpr UIntType initialization_multiplier = f;
static constexpr result_type min() { return 0; }
static constexpr result_type max() { return 2u - 1u; }
static constexpr result_type default_seed = 5489u;

// constructors and seeding functions
mersenne_twister_engine() : mersenne_twister_engine(default_seed) {}
explicit mersenne_twister_engine(result_type value);
template<class Sseq> explicit mersenne_twister_engine(Sseq& q);
void seed(result_type value = default_seed);
template<class Sseq> void seed(Sseq& q);

// equality operators
friend bool operator==(const mersenne_twister_engine& x, const mersenne_twister_engine& y);

// generating functions
result_type operator()();
void discard(unsigned long long z);

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const mersenne_twister_engine& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, mersenne_twister_engine& x);

4 The following relations shall hold: 0 < m, m <= n, 2u < w, u <= w, s <= w, t <= w, l <= w, w <=
numeric_limits<UIntType>::digits, a <= (1u<<w) - 1u, b <= (1u<<w) - 1u, c <= (1u<<w) - 1u, d <= (1u<<w) - 1u, and f <= (1u<<w) - 1u.

5 The textual representation of \( x_i \) consists of the values of \( X_{i-n}, \ldots, X_{i-1} \), in that order.

explicit mersenne_twister_engine(result_type value);

6 Effects: Sets \( X_{-n} \) to value mod \( 2^w \). Then, iteratively for \( i = 1 - n, \ldots, -1 \), sets \( X_i \) to
\[ [f \cdot (X_{i-1} \text{xor} (X_{i-1} \text{shift} (w - 2))) + (i \mod n)] \mod 2^w .\]

7 Complexity: \( O(n) \).

template<class Sseq> explicit mersenne_twister_engine(Sseq& q);

8 Effects: With \( k = \lceil w/32 \rfloor \) and \( a \) an array (or equivalent) of length \( n \cdot k \), invokes \( q \text{.generate}(a + 0, \ a + n \cdot k) \) and then, iteratively for \( i = -n, \ldots, -1 \), sets \( X_i \) to
\( \left( \sum_{j=0}^{k-1} a_{k(i+n)+j} \cdot 2^{32j} \right) \mod 2^w \). Finally, if the most significant \( w - r \) bits of \( X_{-n} \) are zero, and if each of the other resulting \( X_i \) is 0, changes \( X_{-n} \) to \( 2^w - 1 \).

28.5.4.4 Class template subtract_with_carry_engine

1 A subtract_with_carry_engine random number engine produces unsigned integer random numbers.

2 The state \( x_i \) of a subtract_with_carry_engine object \( x \) is of size \( O(r) \), and consists of a sequence \( X \) of \( r \) integer values \( 0 \leq X_i < m = 2^w \); all subscripts applied to \( X \) are to be taken modulo \( r \). The state \( x_i \) additionally consists of an integer \( c \) (known as the carry) whose value is either 0 or 1.

3 The state transition is performed as follows:
Let \( Y = X_{i-s} - X_{i-r} - c \).

Set \( X_i \) to \( y = Y \mod m \). Set \( c \) to 1 if \( Y < 0 \), otherwise set \( c \) to 0.

(Note 1: This algorithm corresponds to a modular linear function of the form \( TA(x_i) = (a \cdot x_i) \mod b \), where \( b \) is of the form \( m^r - m^s + 1 \) and \( a = b - (b - 1)/m \). — end note)

The generation algorithm is given by \( GA(x_i) = y \), where \( y \) is the value produced as a result of advancing the engine's state as described above.

```cpp
namespace std {
    template<class UIntType, size_t w, size_t s, size_t r>
    class subtract_with_carry_engine {
    public:
        // types
        using result_type = UIntType;

        // engine characteristics
        static constexpr size_t word_size = w;
        static constexpr size_t short_lag = s;
        static constexpr size_t long_lag = r;
        static constexpr result_type min() { return 0; }
        static constexpr result_type max() { return m - 1; }
        static constexpr uint_least32_t default_seed = 19780503u;

        // constructors and seeding functions
        subtract_with_carry_engine() : subtract_with_carry_engine(0u) {} // default
        explicit subtract_with_carry_engine(result_type value);
        template<class Sseq> explicit subtract_with_carry_engine(Sseq& q);
        void seed(result_type value = 0u);
        template<class Sseq> void seed(Sseq& q);

        // equality operators
        friend bool operator==(const subtract_with_carry_engine& x, const subtract_with_carry_engine& y);

        // generating functions
        result_type operator()();
        void discard(unsigned long long z);

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const subtract_with_carry_engine& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& is, subtract_with_carry_engine& x);
    }
}
```

The following relations shall hold: \( 0u < s \), \( s < r \), \( 0 < w \), and \( w \leq \text{numeric\_limits<UIntType>::digits} \).

The textual representation consists of the values of \( X_{i-r}, \ldots, X_{i-1} \), in that order, followed by \( c \).

```cpp
explicit subtract_with_carry_engine(result_type value);
```

Effects: Sets the values of \( X_{r}, \ldots, X_{-1} \), in that order, as specified below. If \( X_{-1} \) is then 0, sets \( c \) to 1; otherwise sets \( c \) to 0.

To set the values \( X_k \), first construct \( e \), a `linear_congruential_engine` object, as if by the following definition:

```cpp
linear_congruential_engine<
    uint_least32_t,
    40016u, 0u, 2147483563u> e(value == 0u ? default_seed : value);
```

Then, to set each \( X_k \), obtain new values \( z_0, \ldots, z_{n-1} \) from \( n = \lceil w/32 \rceil \) successive invocations of \( e \). Set \( X_k \) to \( \left( \sum_{j=0}^{n-1} z_j \cdot 2^{32j} \right) \mod m \).

Complexity: Exactly \( n \cdot r \) invocations of \( e \).
template<class Sseq> explicit subtract_with_carry_engine(Sseq& q);

Effects: With \( k = \lceil w/32 \rceil \) and an array (or equivalent) of length \( r \cdot k \), invokes \( q.generate(a + 0, a + r \cdot k) \) and then, iteratively for \( i = -r, \ldots, -1 \), sets \( X_i \) to \( (\sum_{j=0}^{k-1} a_{k(i+r)+j} \cdot 2^{32j}) \mod m \). If \( X_{-1} \) is then 0, sets \( c \) to 1; otherwise sets \( c \) to 0.

28.5.5 Random number engine adaptor class templates

28.5.5.1 General

Each type instantiated from a class template specified in 28.5.5 meets the requirements of a random number engine adaptor (28.5.3.5) type.

Except where specified otherwise, the complexity of each function specified in 28.5.5 is constant.

Except where specified otherwise, no function described in 28.5.5 throws an exception.

Every function described in 28.5.5 that has a function parameter \( q \) of type \( Sseq \) for a template type parameter named \( Sseq \) that is different from type \( seed_seq \) throws what and when the invocation of \( q.generate \) throws.

Descriptions are provided in 28.5.5 only for adaptor operations that are not described in subclause 28.5.3.5 or for operations where there is additional semantic information. In particular, declarations for copy constructors, for copy assignment operators, for streaming operators, and for equality and inequality operators are not shown in the synopses.

Each template specified in 28.5.5 requires one or more relationships, involving the value(s) of its non-type template parameter(s), to hold. A program instantiating any of these templates is ill-formed if any such required relationship fails to hold.

28.5.5.2 Class template discard_block_engine

A \( discard_block_engine \) random number engine adaptor produces random numbers selected from those produced by some base engine \( e \). The state \( x_i \) of a \( discard_block_engine \) engine adaptor object \( x \) consists of the state \( e_i \) of its base engine \( e \) and an additional integer \( n \). The size of the state is the size of \( e \)'s state plus 1.

The transition algorithm discards all but \( r > 0 \) values from each block of \( p \geq r \) values delivered by \( e \). The state transition is performed as follows: If \( n \geq r \), advance the state of \( e \) from \( e_i \) to \( e_i + p - r \) and set \( n \) to 0. In any case, then increment \( n \) and advance \( e \)'s then-current state \( e_j \) to \( e_{j+1} \).

The generation algorithm yields the value returned by the last invocation of \( e() \) while advancing \( e \)'s state as described above.

```cpp
namespace std {
  template<class Engine, size_t p, size_t r>
  class discard_block_engine {
    public:
      // types
      using result_type = typename Engine::result_type;

      // engine characteristics
      static constexpr size_t block_size = p;
      static constexpr size_t used_block = r;
      static constexpr result_type min() { return Engine::min(); } // not really static
      static constexpr result_type max() { return Engine::max(); } // not really static

      // constructors and seeding functions
      discard_block_engine();
      explicit discard_block_engine(const Engine& e);
      explicit discard_block_engine(Engine&& e);
      explicit discard_block_engine(result_type s);
      template<class Sseq> explicit discard_block_engine(Sseq& q);
      void seed();
      void seed(result_type s);
      template<class Sseq> void seed(Sseq& q);

      // equality operators
      friend bool operator==(const discard_block_engine& x, const discard_block_engine& y);
  };
}
```

§ 28.5.5.2 ©ISO/IEC 1498
// generating functions
result_type operator()();
void discard(unsigned long long z);

// property functions
const Engine& base() const noexcept { return e; }

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const discard_block_engine& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, discard_block_engine& x);

private:
Engine e; // exposition only
size_t n;  // exposition only
};

4 The following relations shall hold: 0 < r and r <= p.
5 The textual representation consists of the textual representation of e followed by the value of n.
6 In addition to its behavior pursuant to subclause 28.5.3.5, each constructor that is not a copy constructor
sets n to 0.

28.5.5.3 Class template independent_bits_engine [rand.adapt.ibits]

An independent_bits_engine random number engine adaptor combines random numbers that are produced
by some base engine e, so as to produce random numbers with a specified number of bits w. The state $x_i$ of
an independent_bits_engine engine adaptor object x consists of the state $e_i$ of its base engine e; the size
of the state is the size of e’s state.

2 The transition and generation algorithms are described in terms of the following integral constants:

\[(2.1) \quad \text{Let } R = e.\text{max()} - e.\text{min()} + 1 \text{ and } m = \lceil \log_2 R \rceil.\]
\[(2.2) \quad \text{With } n \text{ as determined below, let } w_0 = \lfloor w/n \rfloor,\ n_0 = n - w \mod n,\ y_0 = 2^{w_0} \lfloor R/2^{w_0} \rfloor,\ \text{and } y_1 = 2^{w_0+1} \lfloor R/2^{w_0+1} \rfloor.\]
\[(2.3) \quad \text{Let } n = \lceil w/m \rceil \text{ if and only if the relation } R - y_0 \leq \lfloor y_0/n \rfloor \text{ holds as a result. Otherwise let } n = 1 + \lfloor w/m \rfloor.\]

[Note 1: The relation $w = n_0w_0 + (n - n_0)(w_0 + 1)$ always holds. — end note]

3 The transition algorithm is carried out by invoking e() as often as needed to obtain $n_0$ values less than
$y_0 + e.\text{min()}$ and $n - n_0$ values less than $y_1 + e.\text{min()}$.

4 The generation algorithm uses the values produced while advancing the state as described above to yield a
quantity $S$ obtained as if by the following algorithm:

\[S = 0;\]
\[\text{for } (k = 0; \ k \neq n_0; \ k \leftarrow 1) \ { \}
\[\text{do } u = e() - e.\text{min(); while } (u \geq y_0);\]
\[S = 2^{w_0} \cdot S + u \mod 2^{w_0};\]
\}
\[\text{for } (k = n_0; \ k \neq n; \ k \leftarrow 1) \ { \}
\[\text{do } u = e() - e.\text{min(); while } (u \geq y_1);\]
\[S = 2^{w_0+1} \cdot S + u \mod 2^{w_0+1};\]
\}

namespace std {
    template<class Engine, size_t w, class UIntType>
    class independent_bits_engine {
    public:
        // types
        using result_type = UIntType;
    }
// engine characteristics
static constexpr result_type min() { return 0; }
static constexpr result_type max() { return 2^w - 1; }

// constructors and seeding functions
independent_bits_engine();
explicit independent_bits_engine(const Engine& e);
explicit independent_bits_engine(Engine&& e);
explicit independent_bits_engine(result_type s);
template<class Sseq> explicit independent_bits_engine(Sseq& q);
void seed();
void seed(result_type s);
template<class Sseq> void seed(Sseq& q);

// equality operators
friend bool operator==(const independent_bits_engine& x, const independent_bits_engine& y);

// generating functions
result_type operator()();
void discard(unsigned long long z);

// property functions
const Engine& base() const noexcept { return e; }

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const independent_bits_engine& x);

friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, independent_bits_engine& x);

private:
  Engine e; // exposition only
};

The following relations shall hold: 0 < w and w <= numeric_limits<result_type>::digits.

The textual representation consists of the textual representation of e.

28.5.5.4 Class template shuffle_order_engine

A shuffle_order_engine random number engine adaptor produces the same random numbers that are
produced by some base engine e, but delivers them in a different sequence. The state x of a shuffle_order_engine engine adaptor object x consists of the state e of its base engine e, an additional value Y of the type delivered by e, and an additional sequence V of k values also of the type delivered by e. The size of the state is the size of e’s state plus k + 1.

The transition algorithm permutes the values produced by e. The state transition is performed as follows:

1. Calculate an integer \( j = \left\lfloor \frac{k \cdot (Y - c_{\text{min}})}{c_{\text{max}} - c_{\text{min}} + 1} \right\rfloor \).
2. Set Y to V_j and then set V_j to e().

The generation algorithm yields the last value of Y produced while advancing e’s state as described above.

namespace std {
  template<class Engine, size_t k>
  class shuffle_order_engine {
  public:
    // types
    using result_type = typename Engine::result_type;
    
    // engine characteristics
    static constexpr size_t table_size = k;
    static constexpr result_type min() { return Engine::min(); }
  }
static constexpr result_type max() { return Engine::max(); }

// constructors and seeding functions
shuffle_order_engine();
explicit shuffle_order_engine(const Engine& e);
explicit shuffle_order_engine(Engine&& e);
explicit shuffle_order_engine(result_type s);
template<class Sseq> explicit shuffle_order_engine(Sseq& q);
void seed();
void seed(result_type s);
template<class Sseq> void seed(Sseq& q);

// equality operators
friend bool operator==(const shuffle_order_engine& x, const shuffle_order_engine& y);

// generating functions
result_type operator()();
void discard(unsigned long long z);

// property functions
const Engine& base() const noexcept { return e; }

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const shuffle_order_engine& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, shuffle_order_engine& x);

private:
Engine e;    // exposition only
result_type V[k];  // exposition only
result_type Y;  // exposition only
};

4 The following relation shall hold: 0 < k.
5 The textual representation consists of the textual representation of e, followed by the k values of V, followed by the value of Y.
6 In addition to its behavior pursuant to subclause 28.5.3.5, each constructor that is not a copy constructor initializes V[0],... ,V[k-1] and Y, in that order, with values returned by successive invocations of e().

28.5.6 Engines and engine adaptors with predefined parameters

using minstd_rand0 =
linear_congruential_engine<uint_fast32_t, 16'807, 0, 2'147'483'647>;

Required behavior: The 10000th consecutive invocation of a default-constructed object of type minstd_rand0 produces the value 1043618065.

using minstd_rand =
linear_congruential_engine<uint_fast32_t, 48'271, 0, 2'147'483'647>;

Required behavior: The 10000th consecutive invocation of a default-constructed object of type minstd_rand produces the value 399268537.

using mt19937 =
mersenne_twister_engine<uint_fast32_t, 32, 624, 397, 31,
0x9908'b0df, 11, 0xffffffff, 7, 0x9d2c'5680, 15, 0xefc6'0000, 18, 1'812'433'253>;

Required behavior: The 10000th consecutive invocation of a default-constructed object of type mt19937 produces the value 4123659995.
using mt19937_64 =
    mersenne_twister_engine<uint_fast64_t, 64, 312, 156, 31,
     0xb502'6f5a'a966'19e9, 29, 0x5555'5555'5555'5555, 17,
     0x71d6'7fff'eda6'0000, 37, 0xff7'eee0'0000'0000, 43,
     6'364'136'223'846'793'005>;

4

Required behavior: The 10000th consecutive invocation of a default-constructed object of type mt19937_64 produces the value 9981545732273789042.

using ranlux24_base =
    subtract_with_carry_engine<uint_fast32_t, 24, 10, 24>;

5

Required behavior: The 10000th consecutive invocation of a default-constructed object of type ranlux24_base produces the value 7937952.

using ranlux48_base =
    subtract_with_carry_engine<uint_fast64_t, 48, 5, 12>;

6

Required behavior: The 10000th consecutive invocation of a default-constructed object of type ranlux48_base produces the value 61839128582725.

using ranlux24 = discard_block_engine<ranlux24_base, 223, 23>;

7

Required behavior: The 10000th consecutive invocation of a default-constructed object of type ranlux24 produces the value 9901578.

using ranlux48 = discard_block_engine<ranlux48_base, 389, 11>;

8

Required behavior: The 10000th consecutive invocation of a default-constructed object of type ranlux48 produces the value 249142670248501.

using knuth_b = shuffle_order_engine<minstd_rand0, 256>;

9

Required behavior: The 10000th consecutive invocation of a default-constructed object of type knuth_b produces the value 1112339016.

using default_random_engine = implementation-defined;

10

Remarks: The choice of engine type named by this typedef is implementation-defined.

[Note 1: The implementation can select this type on the basis of performance, size, quality, or any combination of such factors, so as to provide at least acceptable engine behavior for relatively casual, inexpert, and/or lightweight use. Because different implementations can select different underlying engine types, code that uses this typedef need not generate identical sequences across implementations. —end note]

28.5.7 Class random_device

A random_device uniform random bit generator produces nondeterministic random numbers.

If implementation limitations prevent generating nondeterministic random numbers, the implementation may employ a random number engine.

namespace std {
  class random_device {
    public:
      // types
      using result_type = unsigned int;

      // generator characteristics
      static constexpr result_type min() { return numeric_limits<result_type>::min(); }
      static constexpr result_type max() { return numeric_limits<result_type>::max(); }

      // constructors
      random_device() : random_device(implementation-defined) {}
      explicit random_device(const string& token);

      // generating functions
      result_type operator()();

      // property functions
      double entropy() const noexcept;
  }
}

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1502
random_device(const random_device&) = delete;
void operator=(const random_device&) = delete;
};
}

explicit random_device(const string& token);

Throws: A value of an implementation-defined type derived from exception if the random_device cannot be initialized.

Remarks: The semantics of the token parameter and the token value used by the default constructor are implementation-defined.\textsuperscript{223}

double entropy() const noexcept;

Returns: If the implementation employs a random number engine, returns 0.0. Otherwise, returns an entropy estimate\textsuperscript{224} for the random numbers returned by operator(), in the range min() to log₂(max() + 1).

result_type operator()();

Returns: A nondeterministic random value, uniformly distributed between min() and max() (inclusive). It is implementation-defined how these values are generated.

Throws: A value of an implementation-defined type derived from exception if a random number cannot be obtained.

\section{Utilities} [rand.util]

\subsection{Class seed_seq} [rand.util.seedseq]

namespace std {
  class seed_seq {
    public:
      // types
      using result_type = uint_least32_t;

      // constructors
      seed_seq() noexcept;
      template<class T>
        seed_seq(initializer_list<T> il);
      template<class InputIterator>
        seed_seq(InputIterator begin, InputIterator end);

      // generating functions
      template<class RandomAccessIterator>
        void generate(RandomAccessIterator begin, RandomAccessIterator end);

      // property functions
      size_t size() const noexcept;
      template<class OutputIterator>
        void param(OutputIterator dest) const;

      // no copy functions
      seed_seq(const seed_seq&) = delete;
      void operator=(const seed_seq&) = delete;

    private:
      vector<result_type> v;  // exposition only
  };
}

\textsuperscript{223} The parameter is intended to allow an implementation to differentiate between different sources of randomness.

\textsuperscript{224} If a device has \(n\) states whose respective probabilities are \(p_0, \ldots, p_{n-1}\), the device entropy \(S\) is defined as

\[
S = -\sum_{i=0}^{n-1} p_i \cdot \log p_i.
\]
Postconditions: \( v.\text{empty()} \) is true.

Constraints: \( T \) is an integer type.

Effects: Same as `seed_seq(il.begin(), il.end())`.

Preconditions: `InputIterator` meets the `Cpp17InputIterator` requirements (25.3.5.3).

Effects: Initializes \( v \) by the following algorithm:

\[
\text{for } (\text{InputIterator } s = \text{begin}; s != \text{end}; ++s) \quad v.\text{push_back}((\ast s) \mod 2^{32});
\]

Mandates: `iterator_traits<InputIterator>::value_type` is an integer type.

Preconditions: `RandomAccessIterator` meets the `Cpp17RandomAccessIterator` requirements (25.3.5.7) and the requirements of a mutable iterator.

Effects: Does nothing if `begin == end`. Otherwise, with \( s = v.\text{size()} \) and \( n = \text{end} - \text{begin} \), fills the supplied range \([\text{begin}, \text{end})\) according to the following algorithm in which each operation is to be carried out modulo \( 2^{32} \), each indexing operator applied to \( \text{begin} \) is to be taken modulo \( n \), and \( T(x) \) is defined as \( x \xor (x \ll 27) \):

\[
\begin{align*}
(9.1) & \quad \text{— By way of initialization, set each element of the range to the value } 0x8b8b8b8b. \text{ Additionally, for use in subsequent steps, let } t = (n \geq 623) \cdot 11 : (n \geq 68) \cdot 7 : (n \geq 39) \cdot 5 : (n \geq 7) \cdot 3 : (n - 1)/2; \\
(9.2) & \quad \text{— With } m \text{ as the larger of } s + 1 \text{ and } n, \text{ transform the elements of the range: iteratively for } k = 0, \ldots, m - 1, \text{ calculate values} \\
& \quad \quad r_1 = 1664525 \cdot T(\text{begin}[k] \xor \text{begin}[k + p] \xor \text{begin}[k - 1]) \\
& \quad \quad r_2 = r_1 + \begin{cases} \\
& 0 & , k = 0 \\
& k \mod n + v[k - 1] & , 0 < k \leq s \\
& k \mod n & , s < k \\
\end{cases} \\
& \text{and, in order, increment } \text{begin}[k + p] \text{ by } r_1, \text{ increment } \text{begin}[k + q] \text{ by } r_2, \text{ and set } \text{begin}[k] \text{ to } r_2. \\
(9.3) & \quad \text{— Transform the elements of the range again, beginning where the previous step ended: iteratively for } k = m, \ldots, m + n - 1, \text{ calculate values} \\
& \quad \quad r_3 = 1566083941 \cdot T(\text{begin}[k] + \text{begin}[k + p] + \text{begin}[k - 1]) \\
& \quad \quad r_4 = r_3 - (k \mod n) \\
& \text{and, in order, update } \text{begin}[k + p] \text{ by xorring it with } r_3, \text{ update } \text{begin}[k + q] \text{ by xorring it with } r_4, \text{ and set } \text{begin}[k] \text{ to } r_4. \\
\end{align*}
\]

Throws: What and when `RandomAccessIterator` operations of `begin` and `end` throw.

Returns: The number of 32-bit units that would be returned by a call to \( \text{param}() \).

Complexity: Constant time.
template<class OutputIterator>
void param(OutputIterator dest) const;

Mandates: Values of type result_type are writable (25.3.1) to dest.

Preconditions: OutputIterator meets the Cpp17OutputIterator requirements (25.3.5.4).

Effects: Copies the sequence of prepared 32-bit units to the given destination, as if by executing the following statement:
copy(v.begin(), v.end(), dest);

Throws: What and when OutputIterator operations of dest throw.

28.5.8.2 Function template generate_canonical

```
template<class RealType, size_t digits, class URBG>
RealType generate_canonical(URBG& g);
```

Let

(1.1) \( r \) be numeric_limits<RealType>::radix,
(1.2) \( R \) be g.max() - g.min() + 1,
(1.3) \( d \) be the smaller of digits and numeric_limits<RealType>::digits,
(1.4) \( k \) be the smallest integer such that \( R^k \geq r^d \), and
(1.5) \( x \) be \( \lfloor R^k / r^d \rfloor \).

An attempt is \( k \) invocations of \( g() \) to obtain values \( g_0, \ldots, g_{k-1} \), respectively, and the calculation of a quantity \( S \) given by Formula 28.1:

\[
S = \sum_{i=0}^{k-1} (g_i - g().min()) \cdot R^i
\] (28.1)

Effects: Attempts are made until \( S < x r^d \).

[Note 1: When \( R \) is a power of \( r \), precisely one attempt is made. — end note]

Returns: \( \lfloor S/x \rfloor / r^d \).

[Note 2: The return value \( c \) satisfies \( 0 \leq c < 1 \). — end note]

Throws: What and when \( g \) throws.

Complexity: Exactly \( k \) invocations of \( g() \) per attempt.

[Note 3: If the values \( g_i \) produced by \( g \) are uniformly distributed, the instantiation’s results are distributed as uniformly as possible. Obtaining a value in this way can be a useful step in the process of transforming a value generated by a uniform random bit generator into a value that can be delivered by a random number distribution. — end note]

[Note 4: When \( R \) is a power of \( r \), an implementation can avoid using an arithmetic type that is wider than the output when computing \( S \). — end note]

28.5.9 Random number distribution class templates

28.5.9.1 General

Each type instantiated from a class template specified in 28.5.9 meets the requirements of a random number distribution (28.5.3.6) type.

Descriptions are provided in 28.5.9 only for distribution operations that are not described in 28.5.3.6 or for operations where there is additional semantic information. In particular, declarations for copy constructors, for copy assignment operators, for streaming operators, and for equality and inequality operators are not shown in the synopses.

The algorithms for producing each of the specified distributions are implementation-defined.

The value of each probability density function \( p(z) \) and of each discrete probability function \( P(z_i) \) specified in this subclause is 0 everywhere outside its stated domain.

Note 25: \( d \) is introduced to avoid any attempt to produce more bits of randomness than can be held in RealType.

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28.5.9.2 Uniform distributions

28.5.9.2.1 Class template uniform_int_distribution

A uniform_int_distribution random number distribution produces random integers \( a \leq i \leq b \), distributed according to the constant discrete probability function in Formula 28.2.

\[
P(i|a,b) = \frac{1}{b-a+1}
\]  

(28.2)

```cpp
namespace std {
    template<class IntType = int>
    class uniform_int_distribution {
    public:
        // types
        using result_type = IntType;
        using param_type = unspecified;

        // constructors and reset functions
        uniform_int_distribution() : uniform_int_distribution(0) {}
        explicit uniform_int_distribution(IntType a, IntType b = numeric_limits<IntType>::max());
        explicit uniform_int_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const uniform_int_distribution& x, const uniform_int_distribution& y);

        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);

        // property functions
        result_type a() const;
        result_type b() const;
        param_type param() const;
        void param(const param_type& parm);
        result_type min() const;
        result_type max() const;

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
        operator<<(basic_ostream<charT, traits>& os, const uniform_int_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
        operator>>(basic_istream<charT, traits>& is, uniform_int_distribution& x);
    };
}
```

1. Preconditions: \( a \leq b \).
2. Remarks: \( a \) and \( b \) correspond to the respective parameters of the distribution.
3. Returns: The value of the \( a \) parameter with which the object was constructed.
4. Returns: The value of the \( b \) parameter with which the object was constructed.
28.5.9.2.2 Class template uniform_real_distribution

A `uniform_real_distribution` random number distribution produces random numbers \( x, a \leq x < b \), distributed according to the constant probability density function in Formula 28.3.

\[
p(x | a, b) = \frac{1}{b - a}
\]

(28.3)

[Note 1: This implies that \( p(x | a, b) \) is undefined when \( a = b \). — end note]

```cpp
namespace std {
    template<class RealType = double>
    class uniform_real_distribution {
    public:
        // types
        using result_type = RealType;
        using param_type = unspecified;
        // constructors and reset functions
        uniform_real_distribution() : uniform_real_distribution(0.0) {}
        explicit uniform_real_distribution(RealType a, RealType b = 1.0);
        explicit uniform_real_distribution(const param_type& parm);
        void reset();
        // equality operators
        friend bool operator==(const uniform_real_distribution& x,
                                const uniform_real_distribution& y);
        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);
        // property functions
        result_type a() const;
        result_type b() const;
        param_type param() const;
        void param(const param_type& parm);
        result_type min() const;
        result_type max() const;
        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
            operator<<(basic_ostream<charT, traits>& os, const uniform_real_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
            operator>>(basic_istream<charT, traits>& is, uniform_real_distribution& x);
    }
}
```

2. Preconditions: \( a \leq b \) and \( b - a \leq \text{numeric_limits<RealType>::max()} \).
3. Remarks: \( a \) and \( b \) correspond to the respective parameters of the distribution.

4. `result_type a() const;` Returns: The value of the \( a \) parameter with which the object was constructed.

5. `result_type b() const;` Returns: The value of the \( b \) parameter with which the object was constructed.
28.5.9.3 Bernoulli distributions

A bernoulli_distribution random number distribution produces bool values \( b \) distributed according to the discrete probability function in Formula 28.4.

\[
P(b|p) = \begin{cases} 
p & \text{if } b = \text{true}, \text{ or} \\
1-p & \text{if } b = \text{false}.
\end{cases} \tag{28.4}
\]

```cpp
namespace std {
    class bernoulli_distribution {
        public:
            // types
            using result_type = bool;
            using param_type = unspecified;

            // constructors and reset functions
            bernoulli_distribution() : bernoulli_distribution(0.5) {}
            explicit bernoulli_distribution(double p);
            explicit bernoulli_distribution(const param_type& parm);
            void reset();

            // equality operators
            friend bool operator==(const bernoulli_distribution& x, const bernoulli_distribution& y);

            // generating functions
            template<class URBG>
            result_type operator()(URBG& g);
            template<class URBG>
            result_type operator()(URBG& g, const param_type& parm);

            // property functions
            double p() const;
            param_type param() const;
            void param(const param_type& parm);
            result_type min() const;
            result_type max() const;

            // inserters and extractors
            template<class charT, class traits>
            friend basic_ostream<charT, traits>&
            operator<<(basic_ostream<charT, traits>& os, const bernoulli_distribution& x);
            template<class charT, class traits>
            friend basic_istream<charT, traits>&
            operator>>(basic_istream<charT, traits>& is, bernoulli_distribution& x);
    };
}
```

### Preconditions
0 \leq p \leq 1.

### Remarks
\( p \) corresponds to the parameter of the distribution.

### Returns
The value of the \( p \) parameter with which the object was constructed.

28.5.9.3.2 Class template binomial_distribution

A binomial_distribution random number distribution produces integer values \( i \geq 0 \) distributed according to the discrete probability function in Formula 28.5.

\[
P(i|t,p) = \binom{t}{i} \cdot p^i \cdot (1-p)^{t-i} \tag{28.5}
\]
namespace std {
    template<class IntType = int>
    class binomial_distribution {
    public:
        // types
        using result_type = IntType;
        using param_type = unspecified;

        // constructors and reset functions
        binomial_distribution() : binomial_distribution(1) {}
        explicit binomial_distribution(IntType t, double p = 0.5);
        explicit binomial_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const binomial_distribution& x, const binomial_distribution& y);

        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);

        // property functions
        IntType t() const;
        double p() const;
        param_type param() const;
        result_type min() const;
        result_type max() const;

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
        operator<<(basic_ostream<charT, traits>& os, const binomial_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
        operator>>(basic_istream<charT, traits>& is, binomial_distribution& x);
    }
}

explicit binomial_distribution(IntType t, double p = 0.5);

Preconditions: 0 ≤ p ≤ 1 and 0 ≤ t.
Remarks: t and p correspond to the respective parameters of the distribution.

IntType t() const;
Returns: The value of the t parameter with which the object was constructed.

double p() const;
Returns: The value of the p parameter with which the object was constructed.

28.5.9.3.3 Class template geometric_distribution [rand.dist.bern.geo]
A geometric_distribution random number distribution produces integer values \( i \geq 0 \) distributed according to the discrete probability function in Formula 28.6.

\[
P(i\mid p) = p \cdot (1 - p)^i
\] (28.6)

namespace std {
    template<class IntType = int>
    class geometric_distribution {
    public:
        // types
        using result_type = IntType;
    }
using param_type = unspecified;

// constructors and reset functions
geometric_distribution() : geometric_distribution(0.5) {}
explicit geometric_distribution(double p);
explicit geometric_distribution(const param_type& parm);
void reset();

// equality operators
friend bool operator==(const geometric_distribution& x, const geometric_distribution& y);

// generating functions
template<class URBG>
result_type operator()(URBG& g);
template<class URBG>
result_type operator()(URBG& g, const param_type& parm);

// property functions
double p() const;
param_type param() const;
void param(const param_type& parm);
result_type min() const;
result_type max() const;

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const geometric_distribution& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, geometric_distribution& x);

explicit geometric_distribution(double p);

Preconditions: 0 < p < 1.
Remarks: p corresponds to the parameter of the distribution.

double p() const;

Returns: The value of the p parameter with which the object was constructed.

28.5.9.3.4 Class template negative_binomial_distribution [rand.dist.bern.negbin]
A negative_binomial_distribution random number distribution produces random integers \( i \geq 0 \) distributed according to the discrete probability function in Formula 28.7.

\[
P(i \mid k, p) = \binom{k + i - 1}{i} \cdot p^k \cdot (1 - p)^i
\]  

(28.7)

[Note 1: This implies that \( P(i \mid k, p) \) is undefined when \( p = 1 \). — end note]

namespace std {
    template<class IntType = int>
    class negative_binomial_distribution {
        public:
            // types
            using result_type = IntType;
            using param_type = unspecified;

            // constructor and reset functions
            negative_binomial_distribution() : negative_binomial_distribution(1) {}
            explicit negative_binomial_distribution(IntType k, double p = 0.5);
            explicit negative_binomial_distribution(const param_type& parm);
            void reset();
    }
}
friend bool operator==(const negative_binomial_distribution& x, const negative_binomial_distribution& y);

// generating functions
template<class URBG>
result_type operator()(URBG& g);
template<class URBG>
result_type operator()(URBG& g, const param_type& parm);

// property functions
IntType k() const;
double p() const;
param_type param() const;
void param(const param_type& parm);
result_type min() const;
result_type max() const;

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const negative_binomial_distribution& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, negative_binomial_distribution& x);

explicit negative_binomial_distribution(IntType k, double p = 0.5);

Preconditions: 0 < p ≤ 1 and 0 < k.
Remarks: k and p correspond to the respective parameters of the distribution.

IntType k() const;
Returns: The value of the k parameter with which the object was constructed.
double p() const;
Returns: The value of the p parameter with which the object was constructed.

28.5.9.4 Poisson distributions
28.5.9.4.1 Class template poisson_distribution
A poisson_distribution random number distribution produces integer values i ≥ 0 distributed according to the discrete probability function in Formula 28.8.

\[ P(i | \mu) = \frac{e^{-\mu} \mu^i}{i!} \] (28.8)

The distribution parameter \( \mu \) is also known as this distribution's mean.

namespace std {
    template<class IntType = int>
    class poisson_distribution {
        public:
            // types
            using result_type = IntType;
            using param_type = unspecified;

            // constructors and reset functions
            poisson_distribution() : poisson_distribution(1.0) {}
            explicit poisson_distribution(double mean);
            explicit poisson_distribution(const param_type& parm);
            void reset();
    }
// equality operators
friend bool operator==(const poisson_distribution& x, const poisson_distribution& y);

// generating functions
template<class URGB>
result_type operator()(URBG& g);
template<class URBG>
result_type operator()(URBG& g, const param_type& parm);

// property functions
double mean() const;
param_type param() const;
void param(const param_type& parm);
result_type min() const;
result_type max() const;

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const poisson_distribution& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, poisson_distribution& x);

explicit poisson_distribution(double mean);

Preconditions: 0 < mean.
Remarks: mean corresponds to the parameter of the distribution.
Returns: The value of the mean parameter with which the object was constructed.

28.5.9.4.2 Class template exponential_distribution [rand.dist.pois.exp]

An exponential_distribution random number distribution produces random numbers \( x > 0 \) distributed according to the probability density function in Formula 28.9.

\[
p(x \mid \lambda) = \lambda e^{-\lambda x}
\]  

(28.9)

namespace std {
    template<class RealType = double>
    class exponential_distribution {
    public:
    
        using result_type = RealType;
        using param_type = unspecified;

        // constructors and reset functions
        exponential_distribution() : exponential_distribution(1.0) {}
        explicit exponential_distribution(RealType lambda);
        explicit exponential_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const exponential_distribution& x, const exponential_distribution& y);

        // generating functions
        template<class URGB>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);
    }


// property functions
RealType lambda() const;
param_type param() const;
void param(const param_type& parm);
result_type min() const;
result_type max() const;

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const exponential_distribution& x);

explicit exponential_distribution(RealType lambda);

Preconditions: 0 < lambda.
Remarks: lambda corresponds to the parameter of the distribution.

RealType lambda() const;
Returns: The value of the lambda parameter with which the object was constructed.

§ 28.5.9.4.3 Class template gamma_distribution

A gamma_distribution random number distribution produces random numbers x > 0 distributed according to the probability density function in Formula 28.10.

\[ p(x | \alpha, \beta) = \frac{e^{-x/\beta}}{\beta^\alpha \cdot \Gamma(\alpha)} \cdot x^{\alpha-1} \]  

(28.10)
// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const gamma_distribution& x);

template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, gamma_distribution& x);

explicit gamma_distribution(RealType alpha, RealType beta = 1.0);

// Preconditions: 0 < alpha and 0 < beta.

// Remarks: alpha and beta correspond to the parameters of the distribution.

namespace std {
  template<class RealType = double>
  class weibull_distribution {
  public:
  // types
  using result_type = RealType;
  using param_type = unspecified;

  // constructor and reset functions
  weibull_distribution() : weibull_distribution(1.0) {}
  explicit weibull_distribution(RealType a, RealType b = 1.0);
  explicit weibull_distribution(const param_type& parm);
  void reset();

  // equality operators
  friend bool operator==(const weibull_distribution& x, const weibull_distribution& y);

  // generating functions
  template<class URBG>
  result_type operator()(URBG& g);
  template<class URBG>
  result_type operator()(URBG& g, const param_type& parm);

  // property functions
  RealType a() const;
  RealType b() const;
  param_type param() const;
  void param(const param_type& parm);
  result_type min() const;
  result_type max() const;

  // inserters and extractors
  template<class charT, class traits>
  friend basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const weibull_distribution& x);

  § 28.5.9.4.4 © ISO/IEC 1514
template<class charT, class traits>
friend basic_istream<charT, traits>&
    operator>>(basic_istream<charT, traits>& is, weibull_distribution& x);
}

explicit weibull_distribution(RealType a, RealType b = 1.0);

Preconditions: 0 < a and 0 < b.

Remarks: a and b correspond to the respective parameters of the distribution.

RealType a() const;

Returns: The value of the a parameter with which the object was constructed.

RealType b() const;

Returns: The value of the b parameter with which the object was constructed.

28.5.9.4.5 Class template extreme_value_distribution

An extreme_value_distribution random number distribution produces random numbers x distributed according to the probability density function in Formula 28.12.226

\[ p(x \mid a, b) = \frac{1}{b} \cdot \exp \left( \frac{a - x}{b} - \exp \left( \frac{a - x}{b} \right) \right) \]  

226) The distribution corresponding to this probability density function is also known (with a possible change of variable) as the Gumbel Type I, the log-Weibull, or the Fisher-Tippett Type I distribution.
template<
class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, extreme_value_distribution& x);
};

explicit extreme_value_distribution(RealType a, RealType b = 1.0);

Preconditions: 0 < b.

Remarks: a and b correspond to the respective parameters of the distribution.

RealType a() const;

Returns: The value of the a parameter with which the object was constructed.

RealType b() const;

Returns: The value of the b parameter with which the object was constructed.

28.5.9.5 Normal distributions [rand.dist.norm]
28.5.9.5.1 Class template normal_distribution [rand.dist.norm.normal]

A normal_distribution random number distribution produces random numbers x distributed according to the probability density function in Formula 28.13.

\[
p(x | \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} \cdot \exp \left( -\frac{(x - \mu)^2}{2\sigma^2} \right)
\]  \hspace{1cm} (28.13)

The distribution parameters \( \mu \) and \( \sigma \) are also known as this distribution’s mean and standard deviation.

namespace std {
    template<class RealType = double>
    class normal_distribution {
public:
    // types
    using result_type = RealType;
    using param_type = unspecified;

    // constructors and reset functions
    normal_distribution() : normal_distribution(0.0) {}  
    explicit normal_distribution(RealType mean, RealType stddev = 1.0);
    explicit normal_distribution(const param_type& parm);
    void reset();

    // equality operators
    friend bool operator==(const normal_distribution& x, const normal_distribution& y);

    // generating functions
    template<class URBG>
    result_type operator()(URBG& g);
    template<class URBG>
    result_type operator()(URBG& g, const param_type& parm);

    // property functions
    RealType mean() const;
    RealType stddev() const;
    param_type param() const;
    void param(const param_type& parm);
    result_type min() const;
    result_type max() const;

    // inserters and extractors
    template<class charT, class traits>
    friend basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const normal_distribution& x);

§ 28.5.9.5.1 \hspace{1cm} © ISO/IEC
1516
template<class charT, class traits>
friend basic_istream<charT, traits>&
   operator>>(basic_istream<charT, traits>& is, normal_distribution& x);
};

explicit normal_distribution(RealType mean, RealType stddev = 1.0);

Preconditions: 0 < stddev.

Remarks: mean and stddev correspond to the respective parameters of the distribution.

RealType mean() const;

Returns: The value of the mean parameter with which the object was constructed.

RealType stddev() const;

Returns: The value of the stddev parameter with which the object was constructed.

28.5.9.5.2 Class template lognormal_distribution

A lognormal_distribution random number distribution produces random numbers $x > 0$ distributed according to the probability density function in Formula 28.14.

$$p(x|m,s) = \frac{1}{sx\sqrt{2\pi}} \exp\left(-\frac{(\ln x - m)^2}{2s^2}\right)$$

namespace std {
    template<class RealType = double>
    class lognormal_distribution {
    public:
        // types
        using result_type = RealType;
        using param_type = unspecified;

        // constructor and reset functions
        lognormal_distribution() : lognormal_distribution(0.0) {};
        explicit lognormal_distribution(RealType m, RealType s = 1.0);
        explicit lognormal_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const lognormal_distribution& x, const lognormal_distribution& y);

        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);

        // property functions
        RealType m() const;
        RealType s() const;
        param_type param() const;
        void param(const param_type& parm);
        result_type min() const;
        result_type max() const;

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
           operator<<(basic_ostream<charT, traits>& os, const lognormal_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
           operator>>(basic_istream<charT, traits>& is, lognormal_distribution& x);
    };
explicit lognormal_distribution(RealType m, RealType s = 1.0);

Preconditions: $0 < s$.

Remarks: $m$ and $s$ correspond to the respective parameters of the distribution.

RealType m() const;

Returns: The value of the $m$ parameter with which the object was constructed.

RealType s() const;

Returns: The value of the $s$ parameter with which the object was constructed.

28.5.9.5.3 Class template chi_squared_distribution

A chi_squared_distribution random number distribution produces random numbers $x > 0$ distributed according to the probability density function in Formula 28.15.

$$p(x | n) = x^{(n/2)-1} e^{-x/2} \frac{1}{\Gamma(n/2)} \cdot 2^{n/2}$$ (28.15)

namespace std {
    template<class RealType = double>
    class chi_squared_distribution {
        public:
            // types
            using result_type = RealType;
            using param_type = unspecified;

            // constructor and reset functions
            chi_squared_distribution() : chi_squared_distribution(1.0) {}
            explicit chi_squared_distribution(RealType n);
            explicit chi_squared_distribution(const param_type& parm);
            void reset();

            // equality operators
            friend bool operator==(const chi_squared_distribution& x, const chi_squared_distribution& y);

            // generating functions
            template<class URBG>
            result_type operator()(URBG& g);
            template<class URBG>
            result_type operator()(URBG& g, const param_type& parm);

            // property functions
            RealType n() const;
            param_type param() const;
            void param(const param_type& parm);
            result_type min() const;
            result_type max() const;

            // inserters and extractors
            template<class charT, class traits>
            friend basic_ostream<charT, traits>&
            operator<<(basic_ostream<charT, traits>& os, const chi_squared_distribution& x);
            template<class charT, class traits>
            friend basic_istream<charT, traits>&
            operator>>(basic_istream<charT, traits>& is, chi_squared_distribution& x);
    }
}

explicit chi_squared_distribution(RealType n);

Preconditions: $0 < n$. 

§ 28.5.9.5.3 © ISO/IEC 1518
Remarks: \( n \) corresponds to the parameter of the distribution.

\[
\text{RealType } n() \text{ const;}
\]

Returns: The value of the \( n \) parameter with which the object was constructed.

28.5.9.5.4 Class template cauchy_distribution

A \texttt{cauchy_distribution} random number distribution produces random numbers \( x \) distributed according to the probability density function in Formula 28.16.

\[
p(x \mid a, b) = \left( \frac{\pi b}{1 + \left( \frac{x - a}{b} \right)^2} \right)^{-1}
\]  

(28.16)

namespace std {
  template<class RealType = double>
  class cauchy_distribution {
    public:
      // types
      using result_type = RealType;
      using param_type = unspecified;
      // constructor and reset functions
      cauchy_distribution() : cauchy_distribution(0.0) {}
      explicit cauchy_distribution(RealType a, RealType b = 1.0);
      explicit cauchy_distribution(const param_type& parm);
      void reset();
      // equality operators
      friend bool operator==(const cauchy_distribution& x, const cauchy_distribution& y);
      // generating functions
      template<class URBG>
      result_type operator()(URBG& g);
      template<class URBG>
      result_type operator()(URBG& g, const param_type& parm);
      // property functions
      RealType a() const;
      RealType b() const;
      param_type param() const;
      void param(const param_type& parm);
      result_type min() const;
      result_type max() const;
      // inserters and extractors
      template<class charT, class traits>
      friend basic_ostream<charT, traits>&
      operator<<(basic_ostream<charT, traits>& os, const cauchy_distribution& x);
      template<class charT, class traits>
      friend basic_istream<charT, traits>&
      operator>>(basic_istream<charT, traits>& is, cauchy_distribution& x);
  }
}

explicit cauchy_distribution(RealType a, RealType b = 1.0);

Preconditions: \( 0 < b \).

Remarks: \( a \) and \( b \) correspond to the respective parameters of the distribution.

RealType a() const;

Returns: The value of the \( a \) parameter with which the object was constructed.

RealType b() const;

Returns: The value of the \( b \) parameter with which the object was constructed.
A fisher_f_distribution random number distribution produces random numbers $x \geq 0$ distributed according to the probability density function in Formula 28.17.

\[ p(x \mid m, n) = \frac{\Gamma((m + n)/2)}{\Gamma(m/2) \Gamma(n/2)} \cdot \left(\frac{m}{n}\right)^{m/2} \cdot x^{(m/2)-1} \cdot \left(1 + \frac{mx}{n}\right)^{-(m+n)/2} \]  

(28.17)

```cpp
def fisher_f_distribution(RealType m, RealType n = 1.0):
    # Preconditions:
    # 0 < m and 0 < n.

    # Remarks: m and n correspond to the respective parameters of the distribution.

    RealType m() const;

    # Returns: The value of the m parameter with which the object was constructed.

    RealType n() const;

    # Returns: The value of the n parameter with which the object was constructed.
```
28.5.9.5.6  Class template student_t_distribution

A student_t_distribution random number distribution produces random numbers \( x \) distributed according to the probability density function in Formula 28.18.

\[
p(x \mid n) = \frac{1}{\sqrt{n\pi}} \frac{\Gamma((n+1)/2)}{\Gamma(n/2)} \left( 1 + \frac{x^2}{n} \right)^{-(n+1)/2}
\]  

(28.18)

namespace std {
    template<class RealType = double>
    class student_t_distribution {
    public:
        // types
        using result_type = RealType;
        using param_type = unspecified;

        // constructor and reset functions
        student_t_distribution() : student_t_distribution(1.0) {}
        explicit student_t_distribution(RealType n);
        explicit student_t_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const student_t_distribution& x, const student_t_distribution& y);

        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);

        // property functions
        RealType n() const;
        param_type param() const;
        void param(const param_type& parm);
        result_type min() const;
        result_type max() const;

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
        operator<<(basic_ostream<charT, traits>& os, const student_t_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
        operator>>(basic_istream<charT, traits>& is, student_t_distribution& x);
    };
}

explicit student_t_distribution(RealType n);

Preconditions: 0 < n.

Remarks: \( n \) corresponds to the parameter of the distribution.

RealType n() const;

Returns: The value of the \( n \) parameter with which the object was constructed.

28.5.9.6  Sampling distributions

28.5.9.6.1  Class template discrete_distribution

A discrete_distribution random number distribution produces random integers \( i, 0 \leq i < n \), distributed according to the discrete probability function in Formula 28.19.

\[
P(i \mid p_0, \ldots, p_{n-1}) = p_i
\]  

(28.19)
Unless specified otherwise, the distribution parameters are calculated as: \( p_k = w_k / S \) for \( k = 0, \ldots, n - 1 \), in which the values \( w_k \), commonly known as the \textit{weights}, shall be non-negative, non-NaN, and non-infinity. Moreover, the following relation shall hold: \( 0 < S = w_0 + \cdots + w_{n-1} \).

```cpp
namespace std {
    template<class IntType = int>
    class discrete_distribution {
    public:
        // types
        using result_type = IntType;
        using param_type = unspecified;

        // constructor and reset functions
        discrete_distribution();
        template<class InputIterator>
        discrete_distribution(InputIterator firstW, InputIterator lastW);
        discrete_distribution(initializer_list<double> w1);
        template<class UnaryOperation>
        discrete_distribution(size_t nw, double xmin, double xmax, UnaryOperation fw);
        explicit discrete_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const discrete_distribution& x, const discrete_distribution& y);

        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);

        // property functions
        vector<double> probabilities() const;
        param_type param() const;
        void param(const param_type& parm);
        result_type min() const;
        result_type max() const;

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
        operator<<(basic_ostream<charT, traits>& os, const discrete_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
        operator>>(basic_istream<charT, traits>& is, discrete_distribution& x);
    }
}
```

\[ \text{Effects: Constructs a } \texttt{discrete\_distribution} \text{ object with } n = 1 \text{ and } p_0 = 1. \]

\[ \text{Note 1: Such an object will always deliver the value 0. — end note} \]

```cpp
template<class InputIterator>
 discrete_distribution(InputIterator firstW, InputIterator lastW);
```

\[ \text{Mandates: } \texttt{is\_convertible\_v<iterator\_traits<InputIterator>::value\_type, double>} \text{ is true.} \]

\[ \text{Preconditions: } \texttt{InputIterator} \text{ meets the } \texttt{Cpp17InputIterator} \text{ requirements (25.3.5.3). If } \texttt{firstW} = \texttt{lastW}, \text{ let } n = 1 \text{ and } w_0 = 1. \text{ Otherwise, } \texttt{[firstW, lastW]} \text{ forms a sequence } w \text{ of length } n > 0. \]

\[ \text{Effects: Constructs a } \texttt{discrete\_distribution} \text{ object with probabilities given by the Formula 28.19.} \]

```cpp
discrete_distribution(initializer_list<double> w1);
```

\[ \text{Effects: Same as } \texttt{discrete\_distribution(w1.begin(), w1.end())}. \]
template<class UnaryOperation>
  discrete_distribution(size_t nw, double xmin, double xmax, UnaryOperation fw);

Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.

Preconditions: If nw = 0, let n = 1, otherwise let n = nw. The relation 0 < δ = (xmax − xmin)/n holds.

Effects: Constructs a discrete_distribution object with probabilities given by the formula above, using the following values: If nw = 0, let w₀ = 1. Otherwise, let wk = fw(xmin + k · δ + δ/2) for k = 0, ..., n − 1.

Complexity: The number of invocations of fw does not exceed n.

vector<double> probabilities() const;

Returns: A vector<double> whose size member returns n and whose operator[] member returns pk when invoked with argument k for k = 0, ..., n − 1.

28.5.9.6.2 Class template piecewise_constant_distribution [rand.dist.samp.pconst]

A piecewise_constant_distribution random number distribution produces random numbers x, b₀ ≤ x < bₙ, uniformly distributed over each subinterval [bᵢ, bᵢ₊₁) according to the probability density function in Formula 28.20.

\[ p(x|b₀, ..., bₙ, ρ₀, ..., ρₙ−₁) = ρᵢ, \text{ for } bᵢ ≤ x < bᵢ₊₁. \] (28.20)

The n + 1 distribution parameters bᵢ, also known as this distribution’s interval boundaries, shall satisfy the relation bᵢ < bᵢ₊₁ for i = 0, ..., n − 1. Unless specified otherwise, the remaining n distribution parameters are calculated as:

\[ ρₖ = \frac{wₖ}{S - (bₙ - b₀)} \text{ for } k = 0, ..., n - 1, \]

in which the values wₖ, commonly known as the weights, shall be non-negative, non-NaN, and non-infinity. Moreover, the following relation shall hold: 0 < S = w₀ + ⋯ + wₙ₋₁.
// property functions
vector<result_type> intervals() const;
vector<result_type> densities() const;
param_type param() const;
void param(const param_type& parm);
result_type min() const;
result_type max() const;

// inserters and extractors
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const piecewise_constant_distribution& x);
template<class charT, class traits>
friend basic_istream<charT, traits>&
operator>>(basic_istream<charT, traits>& is, piecewise_constant_distribution& x);

piecewise_constant_distribution();

3 Effects: Constructs a piecewise_constant_distribution object with \( n = 1, \rho_0 = 1, b_0 = 0, \) and \( b_1 = 1. \)

template<class InputIteratorB, class InputIteratorW>
piecewise_constant_distribution(InputIteratorB firstB, InputIteratorB lastB,
    InputIteratorW firstW);

4 Mandates: Both of

\[
(4.1) \quad \text{is_convertible_v<iterator_traits<InputIteratorB>::value_type, double>}
\]

\[
(4.2) \quad \text{is_convertible_v<iterator_traits<InputIteratorW>::value_type, double>}
\]

are true.

5 Preconditions: InputIteratorB and InputIteratorW each meet the Cpp17InputIterator requirements (25.3.5.3). If firstB == lastB or ++firstB == lastB, let \( n = 1, w_0 = 1, b_0 = 0, \) and \( b_1 = 1. \) Otherwise, \([\text{firstB},\text{lastB}]\) forms a sequence \( b \) of length \( n + 1 \), the length of the sequence \( w \) starting from firstW is at least \( n \), and any \( w_k \) for \( k \geq n \) are ignored by the distribution.

6 Effects: Constructs a piecewise_constant_distribution object with parameters as specified above.

template<class UnaryOperation>
piecewise_constant_distribution(initializer_list<RealType> bl, UnaryOperation fw);

7 Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.

8 Effects: Constructs a piecewise_constant_distribution object with parameters taken or calculated from the following values: If bl.size() < 2, let \( n = 1, w_0 = 1, b_0 = 0, \) and \( b_1 = 1. \) Otherwise, let \([\text{bl.begin()},\text{bl.end()}]\) form a sequence \( b_0,\ldots,b_n, \) and let \( w_k = \text{fw}((b_{k+1}+b_k)/2) \) for \( k = 0,\ldots,n-1. \)

9 Complexity: The number of invocations of \( \text{fw} \) does not exceed \( n. \)

template<class UnaryOperation>
piecewise_constant_distribution(size_t nw, RealType xmin, RealType xmax, UnaryOperation fw);

10 Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.

11 Preconditions: If nw = 0, let \( n = 1, \) otherwise let \( n = \text{nw}. \) The relation \( 0 < \delta = (\text{xmax} - \text{xmin})/n \) holds.

12 Effects: Constructs a piecewise_constant_distribution object with parameters taken or calculated from the following values: Let \( b_k = \text{xmin} + k \cdot \delta \) for \( k = 0,\ldots,n, \) and \( w_k = \text{fw}(b_k+\delta/2) \) for \( k = 0,\ldots,n-1. \)

13 Complexity: The number of invocations of \( \text{fw} \) does not exceed \( n. \)

vector<result_type> intervals() const;

14 Returns: A vector<result_type> whose size member returns \( n + 1 \) and whose operator[] member returns \( b_k \) when invoked with argument \( k \) for \( k = 0,\ldots,n. \)
vector<result_type> densities() const;

Returns: A vector<result_type> whose size member returns \( n \) and whose operator[] member returns \( \rho_k \) when invoked with argument \( k \) for \( k = 0, \ldots, n-1 \).

28.5.9.6.3 Class template piecewise_linear_distribution

A piecewise_linear_distribution random number distribution produces random numbers \( x \), \( b_0 \leq x < b_n \), distributed over each subinterval \([b_i, b_{i+1})\) according to the probability density function in Formula 28.21.

\[
p(x \mid b_0, \ldots, b_n, \rho_0, \ldots, \rho_n) = \rho_i \cdot \frac{b_{i+1} - x}{b_{i+1} - b_i} + \rho_{i+1} \cdot \frac{x - b_i}{b_{i+1} - b_i}, \quad \text{for } b_i \leq x < b_{i+1}.
\] (28.21)

The \( n+1 \) distribution parameters \( b_i \), also known as this distribution’s interval boundaries, shall satisfy the relation \( b_i < b_{i+1} \) for \( i = 0, \ldots, n-1 \). Unless specified otherwise, the remaining \( n+1 \) distribution parameters are calculated as \( \rho_k = w_k/S \) for \( k = 0, \ldots, n \), in which the values \( w_k \), commonly known as the weights at boundaries, shall be non-negative, non-NaN, and non-infinity. Moreover, the following relation shall hold:

\[
0 < S = \frac{1}{2} \cdot \sum_{k=0}^{n-1} (w_k + w_{k+1}) \cdot (b_{k+1} - b_k).
\]

namespace std {

    template<class RealType = double>
    class piecewise_linear_distribution {
    public:
        // types
        using result_type = RealType;
        using param_type = unspecified;

        // constructor and reset functions
        piecewise_linear_distribution();
        template<class InputIteratorB, class InputIteratorW>
        piecewise_linear_distribution(InputIteratorB firstB, InputIteratorB lastB,
                                      InputIteratorW firstW);
        template<class UnaryOperation>
        piecewise_linear_distribution(initializer_list<RealType> bl, UnaryOperation fw);
        template<class UnaryOperation>
        piecewise_linear_distribution(size_t nw, RealType xmin, RealType xmax, UnaryOperation fw);
        explicit piecewise_linear_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const piecewise_linear_distribution& x,
                               const piecewise_linear_distribution& y);

        // generating functions
        template<class URBG>
        result_type operator()(URBG& g);
        template<class URBG>
        result_type operator()(URBG& g, const param_type& parm);

        // property functions
        vector<result_type> intervals() const;
        vector<result_type> densities() const;
        param_type param() const;
        void param(const param_type& parm);
        result_type min() const;
        result_type max() const;

        // inserters and extractors
        template<class charT, class traits>
        friend basic_ostream<charT, traits>&
        operator<<<basic_ostream<charT, traits>& os, const piecewise_linear_distribution& x);
    } // class

§ 28.5.9.6.3 © ISO/IEC 1525
template<class charT, class traits>
friend basic_istream<charT, traits>&
    operator>>(basic_istream<charT, traits>& is, piecewise_linear_distribution& x);
};

piecewise_linear_distribution();

Effects: Constructs a piecewise_linear_distribution object with \( n = 1, \rho_0 = \rho_1 = 1, b_0 = 0, \) and \( b_1 = 1. \)

template<class InputIteratorB, class InputIteratorW>
piecewise_linear_distribution(InputIteratorB firstB, InputIteratorB lastB,
                        InputIteratorW firstW);

Mandates: Both of
\begin{align*}
1 & \text{is_convertible_v<iterator_traits<InputIteratorB>::value_type, double>} \\
2 & \text{is_convertible_v<iterator_traits<InputIteratorW>::value_type, double}}
\end{align*}

Preconditions: InputIteratorB and InputIteratorW each meet the Cpp17InputIterator requirements (25.3.5.3). If \( \text{firstB} == \text{lastB} \) or \( ++\text{firstB} == \text{lastB} \), let \( n = 1, \rho_0 = \rho_1 = 1, b_0 = 0, \) and \( b_1 = 1. \) Otherwise, \( [\text{firstB}, \text{lastB}) \) forms a sequence \( b \) of length \( n + 1 \), the length of the sequence \( w \) starting from \( \text{firstW} \) is at least \( n + 1 \), and any \( w_k \) for \( k \geq n + 1 \) are ignored by the distribution.

Effects: Constructs a piecewise_linear_distribution object with parameters as specified above.

template<class UnaryOperation>
piecewise_linear_distribution(initializer_list<RealType> bl, UnaryOperation fw);

Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.

Effects: Constructs a piecewise_linear_distribution object with parameters taken or calculated from the following values: If \( \text{bl.size()} < 2 \), let \( n = 1, \rho_0 = \rho_1 = 1, b_0 = 0, \) and \( b_1 = 1. \) Otherwise, let \( [\text{bl.begin()}, \text{bl.end()}) \) form a sequence \( b_0, \ldots, b_n \), and let \( w_k = \text{fw}(b_k) \) for \( k = 0, \ldots, n. \)

Complexity: The number of invocations of \( \text{fw} \) does not exceed \( n + 1 \).

template<class UnaryOperation>
piecewise_linear_distribution(size_t nw, RealType xmin, RealType xmax, UnaryOperation fw);

Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.

Preconditions: If \( \text{nw} = 0 \), let \( n = 1, \) otherwise let \( n = \text{nw} \). The relation \( 0 < \delta = (\text{xmax} - \text{xmin})/n \) holds.

Effects: Constructs a piecewise_linear_distribution object with parameters taken or calculated from the following values: Let \( b_k = \text{xmin} + k \cdot \delta \) for \( k = 0, \ldots, n \), and \( w_k = \text{fw}(b_k) \) for \( k = 0, \ldots, n. \)

Complexity: The number of invocations of \( \text{fw} \) does not exceed \( n + 1 \).

vector<result_type> intervals() const;

Returns: A vector<result_type> whose size member returns \( n + 1 \) and whose operator[] member returns \( b_k \) when invoked with argument \( k \) for \( k = 0, \ldots, n. \)

vector<result_type> densities() const;

Returns: A vector<result_type> whose size member returns \( n \) and whose operator[] member returns \( \rho_k \) when invoked with argument \( k \) for \( k = 0, \ldots, n. \)

28.5.10 Low-quality random number generation [c.math.rand]

[Note 1: The header <cstdlib> (17.2.2) declares the functions described in this subclause. — end note]

int rand();
void srand(unsigned int seed);

Effects: The rand and srand functions have the semantics specified in the C standard library.

Remarks: The implementation may specify that particular library functions may call rand. It is implementation-defined whether the rand function may introduce data races (16.4.6.10).
[Note 2: The other random number generation facilities in this document (28.5) are often preferable to rand, because rand’s underlying algorithm is unspecified. Use of rand therefore continues to be non-portable, with unpredictable and oft-questionable quality and performance. — end note]

SEE ALSO: ISO/IEC 9899:2018, 7.22.2

28.6 Numeric arrays

28.6.1 Header <valarray> synopsis

```
#include <initializer_list>  // see 17.10.2

namespace std {
    template<class T> class valarray;  // An array of type T
    class slice;  // a BLAS-like slice out of an array
    template<class T> class slice_array;
    class gslice;  // a generalised slice out of an array
    template<class T> class gslice_array;
    template<class T> class mask_array;  // a masked array
    template<class T> class indirect_array;  // an indirected array

    template<class T> void swap(valarray<T>&, valarray<T>&) noexcept;

    template<class T> valarray<T> operator* (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator* (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator* (const typename valarray<T>::value_type&, const valarray<T>&);

    template<class T> valarray<T> operator/ (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator/ (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator/ (const typename valarray<T>::value_type&, const valarray<T>&);

    template<class T> valarray<T> operator% (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator% (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator% (const typename valarray<T>::value_type&, const valarray<T>&);

    template<class T> valarray<T> operator+ (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator+ (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator+ (const typename valarray<T>::value_type&, const valarray<T>&);

    template<class T> valarray<T> operator- (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator- (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator- (const typename valarray<T>::value_type&, const valarray<T>&);

    template<class T> valarray<T> operator^ (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator^ (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator^ (const typename valarray<T>::value_type&, const valarray<T>&);

    template<class T> valarray<T> operator& (const valarray<T>&, const valarray<T>&);
    template<class T> valarray<T> operator& (const valarray<T>&, const typename valarray<T>::value_type&);
    template<class T> valarray<T> operator& (const typename valarray<T>::value_type&, const valarray<T>&);
}
```
template<class T> valarray<T> operator| (const valarray<T>&, const valarray<T>&);
template<class T> valarray<T> operator| (const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<T> operator| (const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<T> operator<<(const valarray<T>&, const valarray<T>&);
template<class T> valarray<T> operator<<(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<T> operator<<(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<T> operator>>(const valarray<T>&, const valarray<T>&);
template<class T> valarray<T> operator>>(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<T> operator>>(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator&&(const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator&&(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator&&(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator||(const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator||(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator||(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator==(const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator==(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator==(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator!=(const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator!=(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator!=(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator< (const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator< (const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator< (const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator> (const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator> (const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator> (const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator<=(const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator<=(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator<=(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<bool> operator>=(const valarray<T>&, const valarray<T>&);
template<class T> valarray<bool> operator>=(const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<bool> operator>=(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<T> abs (const valarray<T>&);
template<class T> valarray<T> acos (const valarray<T>&);
The header `<valarray>` defines five class templates (`valarray`, `slice_array`, `gslice_array`, `mask_array`, and `indirect_array`), two classes (`slice` and `gslice`), and a series of related function templates for representing and manipulating arrays of values.

Any function returning a `valarray<T>` is permitted to return an object of another type, provided all the `const` member functions of `valarray<T>` are also applicable to this type. This return type shall not add more than two levels of template nesting over the most deeply nested argument type.\(^{227}\)

Implementations introducing such replacement types shall provide additional functions and operators as follows:

1. For every function taking a `const valarray<T>&` other than `begin` and `end` (28.6.10), identical functions taking the replacement types shall be added;
2. For every function taking two `const valarray<T>&` arguments, identical functions taking every combination of `const valarray<T>&` and replacement types shall be added.

In particular, an implementation shall allow a `valarray<T>` to be constructed from such replacement types and shall allow assignments and compound assignments of such types to `valarray<T>`, `slice_array<T>`, `gslice_array<T>`, `mask_array<T>` and `indirect_array<T>` objects.

These library functions are permitted to throw a `bad_alloc` (17.6.4.1) exception if there are not sufficient resources available to carry out the operation. Note that the exception is not mandated.

### 28.6.2 Class template `valarray` [template.valarray]

#### 28.6.2.1 Overview [template.valarray.overview]

```cpp
namespace std {
    template<class T> class valarray {
        public:
            using value_type = T;

    }  
```

\(^{227}\) Annex B recommends a minimum number of recursively nested template instantiations. This requirement thus indirectly suggests a minimum allowable complexity for valarray expressions.
// 28.6.2.2, construct/destroy
valarray();
explicit valarray(size_t);
valarray(const T&, size_t);
valarray(const T*, size_t);
valarray(const valarray&);
valarray(valarray&&) noexcept;
valarray(const slice_array<T>&);
valarray(const gslice_array<T>&);
valarray(const mask_array<T>&);
valarray(const indirect_array<T>&);
valarray(initializer_list<T>);
~valarray();

// 28.6.2.3, assignment
valarray& operator=(const valarray&);
valarray& operator=(valarray&&) noexcept;
valarray& operator=(initializer_list<T>);
valarray& operator=(const T&);
valarray& operator=(const slice_array<T>&);
valarray& operator=(const gslice_array<T>&);
valarray& operator=(const mask_array<T>&);
valarray& operator=(const indirect_array<T>&);

// 28.6.2.4, element access
const T& operator[](size_t) const;
T& operator[](size_t);

// 28.6.2.5, subset operations
valarray operator[](slice) const;
slice_array<T> operator[](slice);
valarray operator[](const gslice&) const;
gslice_array<T> operator[](const gslice&);
valarray operator[](const valarray<bool>&) const;
mask_array<T> operator[](const valarray<bool>&);
valarray operator[](const valarray<size_t>&) const;
indirect_array<T> operator[](const valarray<size_t>&);

// 28.6.2.6, unary operators
valarray operator+() const;
valarray operator-() const;
valarray operator~() const;
valarray<bool> operator!() const;

// 28.6.2.7, compound assignment
valarray& operator*=(const T&);
valarray& operator/=(const T&);
valarray& operator%=(const T&);
valarray& operator+= (const T&);
valarray& operator-= (const T&);
valarray& operator^=(const T&);
valarray& operator&= (const T&);
valarray& operator|= (const T&);
valarray& operator<<=(const T&);
valarray& operator>>=(const T&);
valarray& operator*=(const valarray&);
valarray& operator/=(const valarray&);
valarray& operator%=(const valarray&);
valarray& operator+=(const valarray&);
valarray& operator-=(const valarray&);
valarray& operator^=(const valarray&);
valarray& operator&=(const valarray&);
The class template `valarray<T>` is a one-dimensional smart array, with elements numbered sequentially from zero. It is a representation of the mathematical concept of an ordered set of values. For convenience, an object of type `valarray<T>` is referred to as an “array” throughout the remainder of 28.6. The illusion of higher dimensionality may be produced by the familiar idiom of computed indices, together with the powerful subsetting capabilities provided by the generalized subscript operators.\(^{228}\)

### 28.6.2.2 Constructors

#### `valarray()`

**Effects:** Constructs a `valarray` that has zero length.\(^{229}\)

#### `explicit valarray(size_t n)`

**Effects:** Constructs a `valarray` that has length `n`. Each element of the array is value-initialized (9.4).

#### `valarray(const T& v, size_t n)`

**Effects:** Constructs a `valarray` that has length `n`. Each element of the array is initialized with `v`.

#### `valarray(const T* p, size_t n)`

**Preconditions:** \([p, p + n)\) is a valid range.

**Effects:** Constructs a `valarray` that has length `n`. The values of the elements of the array are initialized with the first `n` values pointed to by the first argument.\(^{230}\)

#### `valarray(const valarray& v)`

**Effects:** Constructs a `valarray` that has the same length as `v`. The elements are initialized with the values of the corresponding elements of `v`.\(^{231}\)

#### `valarray(valarray&& v) noexcept`

**Effects:** Constructs a `valarray` that has the same length as `v`. The elements are initialized with the values of the corresponding elements of `v`.

**Complexity:** Constant.

---

\(^{228}\) The intent is to specify an array template that has the minimum functionality necessary to address aliasing ambiguities and the proliferation of temporary objects. Thus, the `valarray` template is neither a matrix class nor a field class. However, it is a very useful building block for designing such classes.

\(^{229}\) This default constructor is essential, since arrays of `valarray` can be useful. After initialization, the length of an empty array can be increased with the `resize` member function.

\(^{230}\) This constructor is the preferred method for converting a C array to a `valarray` object.

\(^{231}\) This copy constructor creates a distinct array rather than an alias. Implementations in which arrays share storage are permitted, but they would need to implement a copy-on-reference mechanism to ensure that arrays are conceptually distinct.
valarray(initializer_list<T> il);

Effects: Equivalent to valarray(il.begin(), il.size()).

valarray(const slice_array<T>&);
valarray(const gslice_array<T>&);
valarray(const mask_array<T>&);
valarray(const indirect_array<T>&);

These conversion constructors convert one of the four reference templates to a valarray.

=valarray();

Effects: The destructor is applied to every element of *this; an implementation may return all allocated memory.

28.6.2.3 Assignment

valarray& operator=(const valarray& v);

Effects: Each element of the *this array is assigned the value of the corresponding element of v. If the length of v is not equal to the length of *this, resizes *this to make the two arrays the same length, as if by calling resize(v.size()), before performing the assignment.

Postconditions: size() == v.size().

Returns: *this.

valarray& operator=(valarray&& v) noexcept;

Effects: *this obtains the value of v. The value of v after the assignment is not specified.

Returns: *this.

Complexity: Linear.

valarray& operator=(initializer_list<T> il);

Effects: Equivalent to: return *this = valarray(il);

valarray& operator=(const T& v);

Effects: Assigns v to each element of *this.

Returns: *this.

Preconditions: The length of the array to which the argument refers equals size(). The value of an element in the left-hand side of a valarray assignment operator does not depend on the value of another element in that left-hand side.

These operators allow the results of a generalized subscripting operation to be assigned directly to a valarray.

28.6.2.4 Element access

const T& operator[](size_t n) const;
T& operator[](size_t n);

Preconditions: n < size() is true.

Returns: A reference to the corresponding element of the array.

[Note 1: The expression (a[i] = q, a[i]) == q evaluates to true for any non-constant valarray<T> a, any T q, and for any size_t i such that the value of i is less than the length of a. — end note]

Remarks: The expression addressof(a[i+j]) == addressof(a[i]) + j evaluates to true for all size_t i and size_t j such that i+j < a.size().

The expression addressof(a[i]) != addressof(b[j]) evaluates to true for any two arrays a and b and for any size_t i and size_t j such that i < a.size() and j < b.size().
[Note 2: This property indicates an absence of aliasing and can be used to advantage by optimizing compilers. Compilers can take advantage of inlining, constant propagation, loop fusion, tracking of pointers obtained from operator new, and other techniques to generate efficient valarrays. — end note]

The reference returned by the subscript operator for an array shall be valid until the member function resize(size_t, T) (28.6.2.8) is called for that array or until the lifetime of that array ends, whichever happens first.

28.6.2.5 Subset operations [valarray.sub]

1 The member operator[] is overloaded to provide several ways to select sequences of elements from among those controlled by *this. Each of these operations returns a subset of the array. The const-qualified versions return this subset as a new valarray object. The non-const versions return a class template object which has reference semantics to the original array, working in conjunction with various overloads of operator= and other assigning operators to allow selective replacement (slicing) of the controlled sequence. In each case the selected element(s) shall exist.

valarray operator[](slice slicearr) const;

2 Returns: A valarray containing those elements of the controlled sequence designated by slicearr.

[Example 1:
  const valarray<char> v0("abcdefghijklmnop", 16);
  // v0[slice(2, 5, 3)] returns valarray<char>("cfilo", 5)
  — end example]

slice_array<T> operator[](slice slicearr);

3 Returns: An object that holds references to elements of the controlled sequence selected by slicearr.

[Example 2:
  valarray<char> v0("abcdefghijklmnop", 16);
  valarray<char> v1("ABCDE", 5);
  v0[slice(2, 5, 3)] = v1;
  // v0 == valarray<char>("abAdeBghCjkDmnEp", 16);
  — end example]

valarray operator[](const gslice& gslicearr) const;

4 Returns: A valarray containing those elements of the controlled sequence designated by gslicearr.

[Example 3:
  const valarray<char> v0("abcdefghijklmnop", 16);
  const size_t lv[] = { 2, 3 };
  const size_t dv[] = { 7, 2 };
  const valarray<size_t> len(lv, 2), str(dv, 2);
  // v0[gslice(3, len, str)] returns valarray<char>("dfhkmno", 6)
  — end example]

gslice_array<T> operator[](const gslice& gslicearr);

5 Returns: An object that holds references to elements of the controlled sequence selected by gslicearr.

[Example 4:
  valarray<char> v0("abcdefghijklmnop", 16);
  valarray<char> v1("ABCDEF", 6);
  const size_t lv[] = { 2, 3 };
  const size_t dv[] = { 7, 2 };
  const valarray<size_t> len(lv, 2), str(dv, 2);
  v0[gslice(3, len, str)] = v1;
  // v0 == valarray<char>("abcAeBgCijDlEnFp", 16)
  — end example]

valarray operator[](const valarray<bool>& boolarr) const;

6 Returns: A valarray containing those elements of the controlled sequence designated by boolarr.

§ 28.6.2.5
[Example 5:
    const valarray<char>& v0("abcdefghijklmnopqrstuvwxyz", 16);
    const bool vb[] = { false, false, true, true, false, true }; // v0[valarray<bool>(vb, 6)] returns
    // valarray<char>("cdf", 3)
    — end example]

    mask_array<T>()(const valarray<bool>& boolarr);

    Returns: An object that holds references to elements of the controlled sequence selected by boolarr.

    [Example 6:
    valarray<char>& v0("abcdefghijklmnopqrstuvwxyz", 16);
    valarray<char>& v1("ABC", 3);
    const bool vb[] = { false, false, true, true, false, true }; // v0 = valarray<char>("abABeCghijklmnop", 16)
    — end example]

    valarray operator[](const valarray<size_t>& indarr) const;

    Returns: A valarray containing those elements of the controlled sequence designated by indarr.

    [Example 7:
    const valarray<char>& v0("abcdefghijklmnopqrstuvwxyz", 16);
    const size_t vi[] = { 7, 5, 2, 3, 8 }; // v0[valarray<size_t>(vi, 5)] returns
    // valarray<char>("hfcdi", 5)
    — end example]

    indirect_array<T>()(const valarray<size_t>& indarr);

    Returns: An object that holds references to elements of the controlled sequence selected by indarr.

    [Example 8:
    valarray<char>& v0("abcdefghijklmnopqrstuvwxyz", 16);
    valarray<char>& v1("ABCDE", 5);
    const size_t vi[] = { 7, 5, 2, 3, 8 }; // v0 = valarray<char>("abCDeBgAEjklmnop", 16)
    — end example]

28.6.2.6 Unary operators

valarray operator+() const;
valarray operator-() const;
valarray operator~() const;
valarray<bool> operator!() const;

Mandates: The indicated operator can be applied to operands of type T and returns a value of type T (bool for operator!) or which may be unambiguously implicitly converted to type T (bool for operator!).

Returns: A valarray whose length is size(). Each element of the returned array is initialized with the result of applying the indicated operator to the corresponding element of the array.

28.6.2.7 Compound assignment

valarray& operator== (const valarray& v);
valarray& operator/= (const valarray& v);
valarray& operator%= (const valarray& v);
valarray& operator+= (const valarray& v);
valarray& operator-= (const valarray& v);
valarray& operator^= (const valarray& v);
valarray& operator&= (const valarray& v);
valarray& operator|= (const valarray& v);
valarray& operator! (const valarray& v);
valarray& operator<<=(const valarray& v);
valarray& operator>>=(const valarray& v);

Mandates: The indicated operator can be applied to two operands of type T.

Preconditions: size() == v.size() is true.
The value of an element in the left-hand side of a valarray compound assignment operator does not
depend on the value of another element in that left hand side.

Effects: Each of these operators performs the indicated operation on each of the elements of *this and
the corresponding element of v.

Returns: *this.
Remarks: The appearance of an array on the left-hand side of a compound assignment does not
invalidate references or pointers.

valarray& operator*= (const T& v);
valarray& operator/= (const T& v);
valarray& operator%= (const T& v);
valarray& operator+= (const T& v);
valarray& operator-= (const T& v);
valarray& operator^= (const T& v);
valarray& operator&= (const T& v);
valarray& operator|= (const T& v);
valarray& operator<<=(const T& v);
valarray& operator>>=(const T& v);

Mandates: The indicated operator can be applied to two operands of type T.

Effects: Each of these operators applies the indicated operation to each element of *this and v.

Returns: *this
Remarks: The appearance of an array on the left-hand side of a compound assignment does not
 invalidate references or pointers to the elements of the array.

28.6.2.8 Member functions

void swap(valarray& v) noexcept;

Effects: *this obtains the value of v. v obtains the value of *this.

Complexity: Constant.

size_t size() const;

Returns: The number of elements in the array.

Complexity: Constant time.

T sum() const;

Mandates: operator+= can be applied to operands of type T.

Preconditions: size() > 0 is true.

Returns: The sum of all the elements of the array. If the array has length 1, returns the value of
element 0. Otherwise, the returned value is calculated by applying operator+= to a copy of an element
of the array and all other elements of the array in an unspecified order.

T min() const;

Preconditions: size() > 0 is true.

Returns: The minimum value contained in *this. For an array of length 1, the value of element 0 is
returned. For all other array lengths, the determination is made using operator<.

T max() const;

Preconditions: size() > 0 is true.

Returns: The maximum value contained in *this. For an array of length 1, the value of element 0 is
returned. For all other array lengths, the determination is made using operator<.
valarray shift(int n) const;

Returns: A valarray of length size(), each of whose elements I is (*this)[I + n] if I + n is non-negative and less than size(), otherwise T().

[Note 1: If element zero is taken as the leftmost element, a positive value of n shifts the elements left n places, with zero fill. — end note]

[Example 1: If the argument has the value −2, the first two elements of the result will be value-initialized (9.4); the third element of the result will be assigned the value of the first element of *this; etc. — end example]

valarray cshift(int n) const;

Returns: A valarray of length size() that is a circular shift of *this. If element zero is taken as the leftmost element, a non-negative value of n shifts the elements circularly left n places and a negative value of n shifts the elements circularly right −n places.

valarray apply(T func(T)) const;
valarray apply(T func(const T&)) const;

Returns: A valarray whose length is size(). Each element of the returned array is assigned the value returned by applying the argument function to the corresponding element of *this.

void resize(size_t sz, T c = T());

Effects: Changes the length of the *this array to sz and then assigns to each element the value of the second argument. Resizing invalidates all pointers and references to elements in the array.

28.6.3 valarray non-member operations [valarray.nonmembers]

28.6.3.1 Binary operators [valarray.binary]

template<class T> valarray<T> operator* (const valarray<T>&, const typename valarray<T>::value_type&);

Mandates: The indicated operator can be applied to operands of type T and returns a value of type T or which can be unambiguously implicitly converted to T.

Preconditions: The argument arrays have the same length.

Returns: A valarray whose length is equal to the lengths of the argument arrays. Each element of the returned array is initialized with the result of applying the indicated operator to the corresponding elements of the argument arrays.

template<class T> valarray<T> operator* (const valarray<T>&, const valarray<T>&);
template<class T> valarray<T> operator/ (const valarray<T>&, const typename valarray<T>::value_type&);
template<class T> valarray<T> operator/ (const typename valarray<T>::value_type&, const valarray<T>&);

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template<class T> valarray<T> operator- (const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<T> operator^ (const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<T> operator^ (const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<T> operator& (const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<T> operator& (const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<T> operator| (const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<T> operator| (const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<T> operator<<(const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<T> operator<<(const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<T> operator>>(const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<T> operator>>(const typename valarray<T>::value_type&,
const valarray<T>&);

Mandates: The indicated operator can be applied to operands of type T and returns a value of type T
or which can be unambiguously implicitly converted to T.

Returns: A valarray whose length is equal to the length of the array argument. Each element of the
returned array is initialized with the result of applying the indicated operator to the corresponding
element of the array argument and the non-array argument.

28.6.3.2 Logical operators

template<class T> valarray<bool> operator==(const valarray<T>&, const valarray<T>&);

template<class T> valarray<bool> operator!=(const valarray<T>&, const valarray<T>&);

template<class T> valarray<bool> operator< (const valarray<T>&, const valarray<T>&);

template<class T> valarray<bool> operator> (const valarray<T>&, const valarray<T>&);

template<class T> valarray<bool> operator<=(const valarray<T>&, const valarray<T>&);

template<class T> valarray<bool> operator>=(const valarray<T>&, const valarray<T>&);

Mandates: The indicated operator can be applied to operands of type T and returns a value of type bool
or which can be unambiguously implicitly converted to bool.

Preconditions: The two array arguments have the same length.

Returns: A valarray<bool> whose length is equal to the length of the array arguments. Each element
of the returned array is initialized with the result of applying the indicated operator to the corresponding
elements of the argument arrays.

template<class T> valarray<bool> operator==(const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<bool> operator==(const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<bool> operator!=(const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<bool> operator!=(const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<bool> operator< (const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<bool> operator< (const typename valarray<T>::value_type&,
const valarray<T>&);

template<class T> valarray<bool> operator> (const valarray<T>&,
const typename valarray<T>::value_type&);

template<class T> valarray<bool> operator> (const typename valarray<T>::value_type&,
const valarray<T>&);

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1537
template<class T> valarray<bool> operator<=(const valarray<T>&, const typename valarray<T>::value_type&);

template<class T> valarray<bool> operator<=(const typename valarray<T>::value_type&, const valarray<T>&);

Mandates: The indicated operator can be applied to operands of type T and returns a value of type bool or which can be unambiguously implicitly converted to bool.

Returns: A valarray<bool> whose length is equal to the length of the array argument. Each element of the returned array is initialized with the result of applying the indicated operator to the corresponding element of the array and the non-array argument.

28.6.3.3 Transcendentals

Mandates: A unique function with the indicated name can be applied (unqualified) to an operand of type T. This function returns a value of type T or which can be unambiguously implicitly converted to type T.

28.6.4 Specialized algorithms

Effects: Equivalent to x.swap(y).

28.6.4 Class slice

28.6.4.1 Overview

namespace std {
    class slice {
        public:
            slice();
            slice(size_t, size_t, size_t);
            slice(const slice&);
    }
The slice class represents a BLAS-like slice from an array. Such a slice is specified by a starting index, a length, and a stride.\footnote{BLAS stands for Basic Linear Algebra Subprograms. C++ programs can instantiate this class. See, for example, Dongarra, Du Croz, Duff, and Hammerling: A set of Level 3 Basic Linear Algebra Subprograms; Technical Report MCS-P1-0888, Argonne National Laboratory (USA), Mathematics and Computer Science Division, August, 1988.}

### Constructors

```cpp
slice();
slice(size_t start, size_t length, size_t stride);
```

The default constructor is equivalent to `slice(0, 0, 0)`. A default constructor is provided only to permit the declaration of arrays of slices. The constructor with arguments for a slice takes a start, length, and stride parameter.

#### Example 1:

`slice(3, 8, 2)` constructs a slice which selects elements 3, 5, 7, ... , 17 from an array.

### Access functions

```cpp
size_t start() const;
size_t size() const;
size_t stride() const;
```

*Returns:* The start, length, or stride specified by a `slice` object.

*Complexity:* Constant time.

### Operators

```cpp
friend bool operator==(const slice& x, const slice& y);
```

*Effects:* Equivalent to:

```cpp
return x.start() == y.start() && x.size() == y.size() && x.stride() == y.stride();
```

### Class template slice_array

#### Overview

```cpp
namespace std {

template<class T> class slice_array {
public:
    using value_type = T;
    void operator= (const valarray<T>&) const;
    void operator*= (const valarray<T>&) const;
    void operator/= (const valarray<T>&) const;
    void operator%= (const valarray<T>&) const;
    void operator+= (const valarray<T>&) const;
    void operator-= (const valarray<T>&) const;
    void operator^= (const valarray<T>&) const;
    void operator&= (const valarray<T>&) const;
    void operator|= (const valarray<T>&) const;
    void operator<<=(const valarray<T>&) const;
    void operator>>=(const valarray<T>&) const;

    slice_array(const slice_array&);
    ~slice_array();
    const slice_array& operator=(const slice_array&);
    void operator=(const T&);

    slice_array(const slice_array&);
    ~slice_array();
    const slice_array& operator=(const slice_array&);
    void operator=(const T&);

    slice_array(const slice_array&);
    ~slice_array();
    const slice_array& operator=(const slice_array&);
    void operator=(const T&);

};
```
slice_array() = delete;       // as implied by declaring copy constructor above
};

This template is a helper template used by the slice subscript operator

slice_array<T> valarray<T>::operator[] (slice);

It has reference semantics to a subset of an array specified by a slice object.

[Example 1: The expression a[slice(1, 5, 3)] = b; has the effect of assigning the elements of b to a slice of the elements in a. For the slice shown, the elements selected from a are 1, 4, . . . , 13. — end example]

28.6.5.2 Assignment

void operator=(const valarray<T>&) const;
const slice_array& operator=(const slice_array&) const;

1 These assignment operators have reference semantics, assigning the values of the argument array elements to selected elements of the valarray<T> object to which the slice_array object refers.

28.6.5.3 Compound assignment

void operator*= (const valarray<T>&) const;
void operator/= (const valarray<T>&) const;
void operator%= (const valarray<T>&) const;
void operator-= (const valarray<T>&) const;
void operator&= (const valarray<T>&) const;
void operator|= (const valarray<T>&) const;
void operator^= (const valarray<T>&) const;
void operator<<=(const valarray<T>&) const;
void operator>>=(const valarray<T>&) const;

1 These compound assignments have reference semantics, applying the indicated operation to the elements of the argument array and selected elements of the valarray<T> object to which the slice_array object refers.

28.6.5.4 Fill function

void operator=(const T&) const;

1 This function has reference semantics, assigning the value of its argument to the elements of the valarray<T> object to which the slice_array object refers.

28.6.6 The gslice class

28.6.6.1 Overview

namespace std {


class gslice {

public:


gslice();
gslice(size_t s, const valarray<size_t>& l, const valarray<size_t>& d);

size_t start() const;
valarray<size_t> size() const;
valarray<size_t> stride() const;

};

} 

1 This class represents a generalized slice out of an array. A gslice is defined by a starting offset (s), a set of lengths (l_j), and a set of strides (d_j). The number of lengths shall equal the number of strides.

2 A gslice represents a mapping from a set of indices (i_j), equal in number to the number of strides, to a single index k. It is useful for building multidimensional array classes using the valarray template, which is one-dimensional. The set of one-dimensional index values specified by a gslice are

\[ k = s + \sum_{j} i_j d_j \]

where the multidimensional indices i_j range in value from 0 to l_{ij} – 1.

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Example 1: The gslice specification

\[
\begin{align*}
\text{start} & = 3 \\
\text{length} & = \{2, 4, 3\} \\
\text{stride} & = \{19, 4, 1\}
\end{align*}
\]

yields the sequence of one-dimensional indices

\[
k = 3 + (0, 1) \times 19 + (0, 1, 2, 3) \times 4 + (0, 1, 2) \times 1
\]

which are ordered as shown in the following table:

\[
(i_0, i_1, i_2, k) =
\begin{align*}
(0, 0, 0, 3), \\
(0, 0, 1, 4), \\
(0, 0, 2, 5), \\
(0, 1, 0, 7), \\
(0, 1, 1, 8), \\
(0, 1, 2, 9), \\
(0, 2, 0, 11), \\
(0, 2, 1, 12), \\
(0, 2, 2, 13), \\
(0, 3, 0, 15), \\
(0, 3, 1, 16), \\
(0, 3, 2, 17), \\
(1, 0, 0, 22), \\
(1, 0, 1, 23), \\
\ldots \\
(1, 3, 2, 36)
\end{align*}
\]

That is, the highest-ordered index turns fastest. — end example]

It is possible to have degenerate generalized slices in which an address is repeated.

Example 2: If the stride parameters in the previous example are changed to \{1, 1, 1\}, the first few elements of the resulting sequence of indices will be

\[
(0, 0, 0, 3), \\
(0, 0, 1, 4), \\
(0, 0, 2, 5), \\
(0, 1, 0, 4), \\
(0, 1, 1, 5), \\
(0, 1, 2, 6), \\
\ldots
\]

— end example]

If a degenerate slice is used as the argument to the non-const version of \texttt{operator[]} (\texttt{const gslice&}), the behavior is undefined.

28.6.6.2 Constructors

\texttt{gslice();}
\texttt{gslice(size_t start, const valarray<size_t>& lengths,}
\texttt{ const valarray<size_t>& strides);}

The default constructor is equivalent to \texttt{gslice(0, valarray<size_t>(), valarray<size_t>())}. The constructor with arguments builds a \texttt{gslice} based on a specification of start, lengths, and strides, as explained in the previous subclause.

28.6.6.3 Access functions

\texttt{size_t start() const;}
\texttt{valarray<size_t> size() const;}
\texttt{valarray<size_t> stride() const;}

1 Returns: The representation of the start, lengths, or strides specified for the \texttt{gslice}.

2 Complexity: \texttt{start()} is constant time. \texttt{size()} and \texttt{stride()} are linear in the number of strides.
28.6.7 Class template gslice_array

28.6.7.1 Overview

namespace std {
    template<class T> class gslice_array {
    public:
        using value_type = T;

        void operator= (const valarray<T>&) const;
        void operator*= (const valarray<T>&) const;
        void operator/= (const valarray<T>&) const;
        void operator%= (const valarray<T>&) const;
        void operator+= (const valarray<T>&) const;
        void operator-= (const valarray<T>&) const;
        void operator^= (const valarray<T>&) const;
        void operator&= (const valarray<T>&) const;
        void operator|= (const valarray<T>&) const;
        void operator<<=(const valarray<T>&) const;
        void operator>>=(const valarray<T>&) const;
        gslice_array(const gslice_array&);
        ~gslice_array();
        const gslice_array& operator=(const gslice_array&) const;
        void operator=(const T&) const;
        gslice_array() = delete;    // as implied by declaring copy constructor above
    };
}

1 This template is a helper template used by the gslice subscript operator

```
gslice_array<T> valarray<T>::operator[](const gslice&);
```

2 It has reference semantics to a subset of an array specified by a gslice object. Thus, the expression

```
a[gslice(1, length, stride)] = b
```

has the effect of assigning the elements of b to a generalized slice of the elements in a.

28.6.7.2 Assignment

```
void operator= (const valarray<T>&) const;
const gslice_array& operator=(const gslice_array&) const;
```

1 These assignment operators have reference semantics, assigning the values of the argument array elements to selected elements of the valarray<T> object to which the gslice_array refers.

28.6.7.3 Compound assignment

```
void operator*= (const valarray<T>&) const;
void operator/= (const valarray<T>&) const;
void operator%= (const valarray<T>&) const;
void operator+= (const valarray<T>&) const;
void operator-= (const valarray<T>&) const;
void operator^= (const valarray<T>&) const;
void operator&= (const valarray<T>&) const;
void operator|= (const valarray<T>&) const;
void operator<<=(const valarray<T>&) const;
void operator>>=(const valarray<T>&) const;
```

1 These compound assignments have reference semantics, applying the indicated operation to the elements of the argument array and selected elements of the valarray<T> object to which the gslice_array refers.

28.6.7.4 Fill function

```
void operator=(const T&) const;
```

1 This function has reference semantics, assigning the value of its argument to the elements of the valarray<T> object to which the gslice_array object refers.
28.6.8 Class template mask_array

28.6.8.1 Overview

```cpp
namespace std {
    template<class T> class mask_array {
    public:
        using value_type = T;
        void operator= (const valarray<T>&) const;
        void operator*= (const valarray<T>&) const;
        void operator/= (const valarray<T>&) const;
        void operator%= (const valarray<T>&) const;
        void operator+= (const valarray<T>&) const;
        void operator-= (const valarray<T>&) const;
        void operator^= (const valarray<T>&) const;
        void operator&= (const valarray<T>&) const;
        void operator|= (const valarray<T>&) const;
        void operator<<=(const valarray<T>&) const;
        void operator>>=(const valarray<T>&) const;
        mask_array(const mask_array&);
        ~mask_array();
        const mask_array& operator=(const mask_array&) const;
        void operator=(const T&) const;
    };
}
```

This template is a helper template used by the mask subscript operator:
```
mask_array<T> valarray<T>::operator[](const valarray<bool>&);
```

It has reference semantics to a subset of an array specified by a boolean mask. Thus, the expression `a[mask] = b;` has the effect of assigning the elements of `b` to the masked elements in `a` (those for which the corresponding element in `mask` is `true`).

28.6.8.2 Assignment

```cpp
void operator=(const valarray<T>&) const;
const mask_array& operator=(const mask_array&) const;
```

These assignment operators have reference semantics, assigning the values of the argument array elements to selected elements of the `valarray<T>` object to which the `mask_array` object refers.

28.6.8.3 Compound assignment

```cpp
void operator== (const valarray<T>&) const;
void operator/= (const valarray<T>&) const;
void operator%= (const valarray<T>&) const;
void operator+= (const valarray<T>&) const;
void operator-= (const valarray<T>&) const;
void operator^= (const valarray<T>&) const;
void operator&= (const valarray<T>&) const;
void operator|= (const valarray<T>&) const;
void operator<<=(const valarray<T>&) const;
void operator>>=(const valarray<T>&) const;
```

These compound assignments have reference semantics, applying the indicated operation to the elements of the argument array and selected elements of the `valarray<T>` object to which the `mask_array` object refers.

28.6.8.4 Fill function

```cpp
void operator=(const T&) const;
```

This function has reference semantics, assigning the value of its argument to the elements of the `valarray<T>` object to which the `mask_array` object refers.

---

1 This template is a helper template used by the mask subscript operator:

2 It has reference semantics to a subset of an array specified by a boolean mask. Thus, the expression `a[mask] = b;` has the effect of assigning the elements of `b` to the masked elements in `a` (those for which the corresponding element in `mask` is `true`).
28.6.9 Class template indirect_array

28.6.9.1 Overview

namespace std {
    template<class T> class indirect_array {
        public:
            using value_type = T;

            void operator= (const valarray<T>&) const;
            void operator*= (const valarray<T>&) const;
            void operator/= (const valarray<T>&) const;
            void operator%= (const valarray<T>&) const;
            void operator+= (const valarray<T>&) const;
            void operator-= (const valarray<T>&) const;
            void operator^= (const valarray<T>&) const;
            void operator&= (const valarray<T>&) const;
            void operator|= (const valarray<T>&) const;
            void operator<<=(const valarray<T>&) const;
            void operator>>=(const valarray<T>&) const;

            indirect_array(const indirect_array&);
            ~indirect_array();
            const indirect_array& operator=(const indirect_array&) const;
            void operator=(const T&) const;
            indirect_array() = delete; // as implied by declaring copy constructor above
    };
}

1 This template is a helper template used by the indirect subscript operator
    indirect_array<T> valarray<T>::operator[] (const valarray<size_t>&);
2 It has reference semantics to a subset of an array specified by an indirect_array. Thus, the expression
    a[indirect] = b; has the effect of assigning the elements of b to the elements in a whose indices appear in
    indirect.

28.6.9.2 Assignment

    void operator= (const valarray<T>&) const;
    const indirect_array& operator=(const indirect_array&) const;

1 These assignment operators have reference semantics, assigning the values of the argument array
    elements to selected elements of the valarray<T> object to which it refers.
2 If the indirect_array specifies an element in the valarray<T> object to which it refers more than
    once, the behavior is undefined.

3 [Example 1:
    int addr[] = {2, 3, 1, 4, 4};
    valarray<size_t> indirect(addr, 5);
    valarray<double> a(0., 10), b(1., 5);
    a[indirect] = b;
    results in undefined behavior since element 4 is specified twice in the indirection. — end example]

28.6.9.3 Compound assignment

    void operator== (const valarray<T>&) const;
    void operator/= (const valarray<T>&) const;
    void operator%= (const valarray<T>&) const;
    void operator+= (const valarray<T>&) const;
    void operator-= (const valarray<T>&) const;
    void operator^= (const valarray<T>&) const;
    void operator&= (const valarray<T>&) const;
    void operator|= (const valarray<T>&) const;
    void operator<== (const valarray<T>&) const;
    void operator>>= (const valarray<T>&) const;

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void operator>>(const valarray<T>&) const;

These compound assignments have reference semantics, applying the indicated operation to the elements of the argument array and selected elements of the valarray<T> object to which the indirect_array object refers.

If the indirect_array specifies an element in the valarray<T> object to which it refers more than once, the behavior is undefined.

28.6.9.4 Fill function

void operator=(const T&) const;

This function has reference semantics, assigning the value of its argument to the elements of the valarray<T> object to which the indirect_array object refers.

28.6.10 valarray range access

In the begin and end function templates that follow, unspecified1 is a type that meets the requirements of a mutable Cpp17RandomAccessIterator (25.3.5.7) and models contiguous_iterator (25.3.4.14), whose value_type is the template parameter T and whose reference type is T&. unspecified2 is a type that meets the requirements of a constant Cpp17RandomAccessIterator and models contiguous_iterator, whose value_type is the template parameter T and whose reference type is const T&.

The iterators returned by begin and end for an array are guaranteed to be valid until the member function resize(size_t, T) (28.6.2.8) is called for that array or until the lifetime of that array ends, whichever happens first.

template<class T> unspecified1 begin(valarray<T>& v);
template<class T> unspecified2 begin(const valarray<T>& v);

Returns: An iterator referencing the first value in the array.

template<class T> unspecified1 end(valarray<T>& v);
template<class T> unspecified2 end(const valarray<T>& v);

Returns: An iterator referencing one past the last value in the array.

28.7 Mathematical functions for floating-point types

28.7.1 Header <cmath> synopsis

namespace std {
  using float_t = see below;
  using double_t = see below;
}

#define HUGE_VAL see below
#define HUGE_VALF see below
#define HUGE_VALL see below
#define INFINITY see below
#define NAN see below
#define FP_INFINITE see below
#define FP_NAN see below
#define FP_NORMAL see below
#define FP_SUBNORMAL see below
#define FP_ZERO see below
#define FP_FAST_FMA see below
#define FP_FAST_FMAF see below
#define FP_FAST_FMAL see below
#define FP_ILOG0 see below
#define FP_ILOGBNAN see below
#define MATH_ERRNO see below
#define MATH_ERREXCEPT see below
#define math_errhandling see below
#define math_errhandler see below
namespace std {
    constexpr floating-point-type acos(floating-point-type x);
    constexpr float acosf(float x);
    constexpr long double acosl(long double x);

    constexpr floating-point-type asin(floating-point-type x);
    constexpr float asinf(float x);
    constexpr long double asinl(long double x);

    constexpr floating-point-type atan(floating-point-type x);
    constexpr float atanf(float x);
    constexpr long double atanl(long double x);

    constexpr floating-point-type atan2(floating-point-type y, floating-point-type x);
    constexpr float atan2f(float y, float x);
    constexpr long double atan2l(long double y, long double x);

    constexpr floating-point-type cos(floating-point-type x);
    constexpr float cosf(float x);
    constexpr long double cosl(long double x);

    constexpr floating-point-type sin(floating-point-type x);
    constexpr float sinf(float x);
    constexpr long double sinl(long double x);

    constexpr floating-point-type tan(floating-point-type x);
    constexpr float tanf(float x);
    constexpr long double tanl(long double x);

    constexpr floating-point-type acosh(floating-point-type x);
    constexpr float acoshf(float x);
    constexpr long double acoshl(long double x);

    constexpr floating-point-type asinh(floating-point-type x);
    constexpr float asinhf(float x);
    constexpr long double asinhl(long double x);

    constexpr floating-point-type atanh(floating-point-type x);
    constexpr float atanhf(float x);
    constexpr long double atanhl(long double x);

    constexpr floating-point-type cosh(floating-point-type x);
    constexpr float coshf(float x);
    constexpr long double coshl(long double x);

    constexpr floating-point-type sinh(floating-point-type x);
    constexpr float sinhf(float x);
    constexpr long double sinhl(long double x);

    constexpr floating-point-type tanh(floating-point-type x);
    constexpr float tanhf(float x);
    constexpr long double tanhl(long double x);

    constexpr floating-point-type exp(floating-point-type x);
    constexpr float expf(float x);
    constexpr long double expl(long double x);

    constexpr floating-point-type exp2(floating-point-type x);
    constexpr float exp2f(float x);
    constexpr long double exp2l(long double x);

    constexpr floating-point-type expm1(floating-point-type x);
    constexpr float expm1f(float x);
    constexpr long double expm1l(long double x);
}
constexpr floating-point-type frexp(floating-point-type value, int* exp);
constexpr float frexpf(float value, int* exp);
constexpr long double frexpl(long double value, int* exp);

constexpr int ilogb(floating-point-type x);
constexpr int ilogbf(float x);
constexpr int ilogbl(long double x);

constexpr floating-point-type ldexp(floating-point-type x, int exp);
constexpr float ldexpf(float x, int exp);
constexpr long double ldexpl(long double x, int exp);

constexpr floating-point-type log(floating-point-type x);
constexpr float logf(float x);
constexpr long double logl(long double x);

constexpr floating-point-type log10(floating-point-type x);
constexpr float log10f(float x);
constexpr long double log10l(long double x);

constexpr floating-point-type log2(floating-point-type x);
constexpr float log2f(float x);
constexpr long double log2l(long double x);

constexpr floating-point-type logb(floating-point-type x);
constexpr float logbf(float x);
constexpr long double logbl(long double x);

constexpr floating-point-type modf(floating-point-type value, floating-point-type* iptr);
constexpr float modff(float value, float* iptr);
constexpr long double modfl(long double value, long double* iptr);

constexpr floating-point-type scalbn(floating-point-type x, int n);
constexpr float scalbnf(float x, int n);
constexpr long double scalbnl(long double x, int n);

constexpr floating-point-type scalbln(floating-point-type x, long int n);
constexpr float scalblnf(float x, long int n);
constexpr long double scalblnl(long double x, long int n);

constexpr floating-point-type cbrt(floating-point-type x);
constexpr float cbrtf(float x);
constexpr long double cbrtl(long double x);

// 28.7.2, absolute values
constexpr int abs(int j); // freestanding
constexpr long int abs(long int j); // freestanding
constexpr long long int abs(long long int j); // freestanding
constexpr floating-point-type fabs(floating-point-type x); // freestanding-deleted
constexpr float fabsf(float x);
constexpr long double fabsl(long double x);

constexpr floating-point-type hypot(floating-point-type x, floating-point-type y);
constexpr float hypotf(float x, float y);
constexpr long double hypotl(long double x, long double y);
// 28.7.3, three-dimensional hypotenuse
constexpr floating-point-type hypot(floating-point-type x, floating-point-type y, floating-point-type z);

constexpr floating-point-type pow(floating-point-type x, floating-point-type y);
constexpr long double powl(long double x, long double y);

constexpr floating-point-type sqrt(floating-point-type x);
constexpr float sqrtf(float x);
constexpr long double sqrtl(long double x);

constexpr floating-point-type erf(floating-point-type x);
constexpr float erff(float x);
constexpr long double erfl(long double x);

constexpr floating-point-type erfc(floating-point-type x);
constexpr float erfcf(float x);
constexpr long double erfcl(long double x);

constexpr floating-point-type lgamma(floating-point-type x);
constexpr float lgammaf(float x);
constexpr long double lgammal(long double x);

constexpr floating-point-type tgamma(floating-point-type x);
constexpr float tgammaf(float x);
constexpr long double tgammal(long double x);

constexpr floating-point-type ceil(floating-point-type x);
constexpr float ceilf(float x);
constexpr long double ceill(long double x);

floating-point-type nearbyint(floating-point-type x);
float nearbyintf(float x);
long double nearbyintl(long double x);

floating-point-type rint(floating-point-type x);
float rintf(float x);
long double rintl(long double x);

long int lrint(floating-point-type x);
long int lrintf(float x);
long int lrintl(long double x);

long long int llrint(floating-point-type x);
long long int llrintf(float x);
long long int llrintl(long double x);

constexpr floating-point-type round(floating-point-type x);
constexpr float roundf(float x);
constexpr long double roundl(long double x);

constexpr long int lround(floating-point-type x);
constexpr long int lroundf(float x);
constexpr long int lroundl(long double x);

constexpr long long int llround(floating-point-type x);
constexpr long long int llroundf(float x);
constexpr long long int llroundl(long double x);
constexpr floating-point-type trunc(floating-point-type x);
constexpr float truncf(float x);
constexpr long double truncl(long double x);

constexpr floating-point-type fmod(floating-point-type x, floating-point-type y);
constexpr float fmodf(float x, float y);
constexpr long double fmodl(long double x, long double y);

constexpr floating-point-type remainder(floating-point-type x, floating-point-type y);
constexpr float remainderef(float x, float y);
constexpr long double remainderrl(long double x, long double y);

constexpr floating-point-type remquo(floating-point-type x, floating-point-type y, int* quo);
constexpr float remquof(float x, float y, int* quo);
constexpr long double remquol(long double x, long double y, int* quo);

constexpr floating-point-type copysign(floating-point-type x, floating-point-type y);
constexpr float copysignf(float x, float y);
constexpr long double copysignl(long double x, long double y);

double nan(const char* tagp);
float nanf(const char* tagp);
long double nanl(const char* tagp);

constexpr floating-point-type nextafter(floating-point-type x, floating-point-type y);
constexpr float nextafterf(float x, float y);
constexpr long double nextafterl(long double x, long double y);

constexpr floating-point-type nexttoward(floating-point-type x, long double y);
constexpr float nexttowardf(float x, long double y);
constexpr long double nexttowardl(long double x, long double y);

constexpr floating-point-type fdim(floating-point-type x, floating-point-type y);
constexpr float fdimf(float x, float y);
constexpr long double fdiml(long double x, long double y);

constexpr floating-point-type fmax(floating-point-type x, floating-point-type y);
constexpr float fmaxf(float x, float y);
constexpr long double fmaxl(long double x, long double y);

constexpr floating-point-type fmin(floating-point-type x, floating-point-type y);
constexpr float fminf(float x, float y);
constexpr long double fminl(long double x, long double y);

constexpr floating-point-type fma(floating-point-type x, floating-point-type y, floating-point-type z);
constexpr float fmaf(float x, float y, float z);
constexpr long double fmal(long double x, long double y, long double z);

// 28.7.4, linear interpolation
constexpr floating-point-type lerp(floating-point-type a, floating-point-type b, floating-point-type t) noexcept;

// 28.7.5, classification / comparison functions
constexpr int fpclassify(floating-point-type x);
constexpr bool infinite(floating-point-type x);
constexpr bool isinf(floating-point-type x);
constexpr bool isnan(floating-point-type x);
constexpr bool isnormal(floating-point-type x);
constexpr bool signbit(floating-point-type x);
constexpr bool isgreater(floating-point-type x, floating-point-type y);
constexpr bool isgreaterequal(floating-point-type x, floating-point-type y);
constexpr bool isless(floating-point-type x, floating-point-type y);
constexpr bool islessequal(floating-point-type x, floating-point-type y);
constexpr bool islessgreater(floating-point-type x, floating-point-type y);
constexpr bool isunordered(floating-point-type x, floating-point-type y);

// 28.7.6, mathematical special functions

// 28.7.6.2, associated Laguerre polynomials
floating-point-type assoc_laguerre(unsigned n, unsigned m, floating-point-type x);
float assoc_laguerref(unsigned n, unsigned m, float x);
long double assoc_laguerrel(unsigned n, unsigned m, long double x);

// 28.7.6.3, associated Legendre functions
floating-point-type assoc_legendre(unsigned l, unsigned m, floating-point-type x);
float assoc_legendref(unsigned l, unsigned m, float x);
long double assoc_legendrel(unsigned l, unsigned m, long double x);

// 28.7.6.4, beta function
floating-point-type beta(floating-point-type x, floating-point-type y);
float betaf(float x, float y);
long double betal(long double x, long double y);

// 28.7.6.5, complete elliptic integral of the first kind
floating-point-type comp_ellint_1(floating-point-type k);
float comp_ellint_1f(float k);
long double comp_ellint_1l(long double k);

// 28.7.6.6, complete elliptic integral of the second kind
floating-point-type comp_ellint_2(floating-point-type k);
float comp_ellint_2f(float k);
long double comp_ellint_2l(long double k);

// 28.7.6.7, complete elliptic integral of the third kind
floating-point-type comp_ellint_3(floating-point-type k, floating-point-type nu);
float comp_ellint_3f(float k, float nu);
long double comp_ellint_3l(long double k, long double nu);

// 28.7.6.8, regular modified cylindrical Bessel functions
floating-point-type cyl_bessel_i(floating-point-type nu, floating-point-type x);
float cyl_bessel_if(float nu, float x);
long double cyl_bessel_il(long double nu, long double x);

// 28.7.6.9, cylindrical Bessel functions of the first kind
floating-point-type cyl_bessel_j(floating-point-type nu, floating-point-type x);
float cyl_bessel_jf(float nu, float x);
long double cyl_bessel jl(long double nu, long double x);

// 28.7.6.10, irregular modified cylindrical Bessel functions
floating-point-type cyl_bessel_k(floating-point-type nu, floating-point-type x);
float cyl_bessel_kf(float nu, float x);
long double cyl_bessel_kl(long double nu, long double x);

// 28.7.6.11, cylindrical Neumann functions
// cylindrical Bessel functions of the second kind
floating-point-type cyl_neumann(floating-point-type nu, floating-point-type x);
float cyl_neumannf(float nu, float x);
long double cyl_neumannl(long double nu, long double x);

// 28.7.6.12, incomplete elliptic integral of the first kind
floating-point-type ellint_1(floating-point-type k, floating-point-type phi);
float ellint_1f(float k, float phi);
long double ellint_1l(long double k, long double phi);

// 28.7.6.13, incomplete elliptic integral of the second kind
floating-point-type ellint_2(floating-point-type k, floating-point-type phi);
float ellint_2f(float k, float phi);
long double ellint_2l(long double k, long double phi);

// 28.7.6.14, incomplete elliptic integral of the third kind
floating-point-type ellint_3(floating-point-type k, floating-point-type nu, floating-point-type phi);
float ellint_3f(float k, float nu, float phi);
long double ellint_3l(long double k, long double nu, long double phi);

// 28.7.6.15, exponential integral
floating-point-type expint(floating-point-type x);
float expintf(float x);
long double expintl(long double x);

// 28.7.6.16, Hermite polynomials
floating-point-type hermite(unsigned n, floating-point-type x);
float hermitef(unsigned n, float x);
long double hermitel(unsigned n, long double x);

// 28.7.6.17, Laguerre polynomials
floating-point-type laguerre(unsigned n, floating-point-type x);
float laguerref(unsigned n, float x);
long double laguerrel(unsigned n, long double x);

// 28.7.6.18, Legendre polynomials
floating-point-type legendre(unsigned l, floating-point-type x);
float legendref(unsigned l, float x);
long double legendrel(unsigned l, long double x);

// 28.7.6.19, Riemann zeta function
floating-point-type riemann_zeta(floating-point-type x);
float riemann_zetaf(float x);
long double riemann_zetal(long double x);

// 28.7.6.20, spherical Bessel functions of the first kind
floating-point-type sph_bessel(unsigned n, floating-point-type x);
float sph_besself(unsigned n, float x);
long double sph_bessell(unsigned n, long double x);

// 28.7.6.21, spherical associated Legendre functions
floating-point-type sph_legendre(unsigned l, unsigned m, floating-point-type theta);
float sph_legendref(unsigned l, unsigned m, float theta);
long double sph_legendrel(unsigned l, unsigned m, long double theta);

§ 28.7.6.22, spherical Neumann functions;
// spherical Bessel functions of the second kind
floating-point-type sph_neumann(unsigned n, floating-point-type x);
float sph_neumannf(unsigned n, float x);
long double sph_neumannl(unsigned n, long double x);
}

1 The contents and meaning of the header `<cmath>` are the same as the C standard library header `<math.h>`, with the addition of a three-dimensional hypotenuse function (28.7.3), a linear interpolation function (28.7.4), and the mathematical special functions described in 28.7.6.

[Note 1: Several functions have additional overloads in this document, but they have the same behavior as in the C standard library (16.2). — end note]

2 For each function with at least one parameter of type `floating-point-type`, the implementation provides an overload for each cv-unqualified floating-point type (6.8.2) where all uses of `floating-point-type` in the function signature are replaced with that floating-point type.

3 For each function with at least one parameter of type `floating-point-type` other than `abs`, the implementation also provides additional overloads sufficient to ensure that, if every argument corresponding to a `floating-point-type` parameter has arithmetic type, then every such argument is effectively cast to the floating-point type with the greatest floating-point conversion rank and greatest floating-point conversion subrank among the types of
all such arguments, where arguments of integer type are considered to have the same floating-point conversion rank as double. If no such floating-point type with the greatest rank and subrank exists, then overload resolution does not result in a usable candidate (12.2.1) from the overloads provided by the implementation.

4 An invocation of nexttoward is ill-formed if the argument corresponding to the floating-point-type parameter has extended floating-point type.


28.7.2 Absolute values [c.math.abs]

1 [Note 1: The headers <cstdlib> (17.2.2) and <cmath> (28.7.1) declare the functions described in this subclause. —end note]

castexpr int abs(int j);
castexpr long int abs(long int j);
castexpr long long int abs(long long int j);

2 Effects: These functions have the semantics specified in the C standard library for the functions abs, labs, and llabs, respectively.

3 Remarks: If abs is called with an argument of type X for which is_unsigned_v<X> is true and if X cannot be converted to int by integral promotion (7.3.7), the program is ill-formed.

[Note 2: Allowing arguments that can be promoted to int provides compatibility with C. —end note]

castexpr floating-point-type abs(floating-point-type x);

4 Returns: The absolute value of x.


28.7.3 Three-dimensional hypotenuse [c.math.hypot3]

1 Returns: $\sqrt{x^2 + y^2 + z^2}$.

28.7.4 Linear interpolation [c.math.lerp]

1 Returns: $a + t(b - a)$.

2 Remarks: Let r be the value returned. If isfinite(a) && isfinite(b), then:

(2.1) — If $t == 0$, then $r == a$.

(2.2) — If $t == 1$, then $r == b$.

(2.3) — If $t >= 0$ && $t <= 1$, then isfinite(r).

(2.4) — If isfinite(t) && a == b, then $r == a$.

(2.5) — If isfinite(t) || !isnan(t) && b-a != 0, then !isnan(r).

Let CMP(x,y) be 1 if $x > y$, -1 if $x < y$, and 0 otherwise. For any $t_1$ and $t_2$, the product of CMP(x,y) be 1 if $x > y$, -1 if $x < y$, and 0 otherwise. For any $t_1$ and $t_2$, the product of CMP(lerp(a,b,t2),lerp(a,b,t1)), CMP(t2,t1), and CMP(b,a) is non-negative.

28.7.5 Classification / comparison functions [c.math.fpclass]

1 The classification / comparison functions behave the same as the C macros with the corresponding names defined in the C standard library.


28.7.6 Mathematical special functions [sf.cmath]

28.7.6.1 General [sf.cmath.general]

1 If any argument value to any of the functions specified in 28.7.6 is a NaN (Not a Number), the function shall return a NaN but it shall not report a domain error. Otherwise, the function shall report a domain error for just those argument values for which:
— the function description’s Returns: element explicitly specifies a domain and those argument values fall outside the specified domain, or
— the corresponding mathematical function value has a nonzero imaginary component, or
— the corresponding mathematical function is not mathematically defined.

Unless otherwise specified, each function is defined for all finite values, for negative infinity, and for positive infinity.

### 28.7.6.2 Associated Laguerre polynomials

```c
floating-point-type assoc_laguerre(unsigned n, unsigned m, floating-point-type x);
float assoc_laguerref(unsigned n, unsigned m, float x);
long double assoc_laguerrel(unsigned n, unsigned m, long double x);
```

1. **Effects:** These functions compute the associated Laguerre polynomials of their respective arguments `n`, `m`, and `x`.
2. **Returns:** \( L_n^m(x) \), where \( L_n^m \) is given by Formula 28.22, \( n \) is \( n \), \( m \) is \( m \), and \( x \) is \( x \).

\[
L_n^m(x) = (-1)^m \frac{d^m}{dx^m} L_{n+m}(x), \text{ for } x \geq 0
\]  

(28.22)

3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( n \geq 128 \) or if \( m \geq 128 \).

### 28.7.6.3 Associated Legendre functions

```c
floating-point-type assoc_legendre(unsigned l, unsigned m, floating-point-type x);
float assoc_legendref(unsigned l, unsigned m, float x);
long double assoc_legendrel(unsigned l, unsigned m, long double x);
```

1. **Effects:** These functions compute the associated Legendre functions of their respective arguments `l`, `m`, and `x`.
2. **Returns:** \( P_l^m(x) \), where \( P_l^m \) is given by Formula 28.23, \( l \) is \( l \), \( m \) is \( m \), and \( x \) is \( x \).

\[
P_l^m(x) = (1-x^2)^{m/2} \frac{d^m}{dx^m} P_l(x), \text{ for } |x| \leq 1
\]  

(28.23)

3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( l \geq 128 \).

### 28.7.6.4 Beta function

```c
floating-point-type beta(floating-point-type x, floating-point-type y);
float betaf(float x, float y);
long double betal(long double x, long double y);
```

1. **Effects:** These functions compute the beta function of their respective arguments `x` and `y`.
2. **Returns:** \( B(x,y) \), where \( B \) is given by Formula 28.24, \( x \) is \( x \) and \( y \) is \( y \).

\[
B(x,y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}, \text{ for } x > 0, y > 0
\]  

(28.24)

### 28.7.6.5 Complete elliptic integral of the first kind

```c
floating-point-type comp_ellint_1(floating-point-type k);
float comp_ellint_1f(float k);
long double comp_ellint_1l(long double k);
```

1. **Effects:** These functions compute the complete elliptic integral of the first kind of their respective arguments `k`.
2. **Returns:** \( K(k) \), where \( K \) is given by Formula 28.25 and \( k \) is \( k \).

\[
K(k) = F(k, \pi/2), \text{ for } |k| \leq 1
\]  

(28.25)

3. **See also** 28.7.6.12.

---

(233) A mathematical function is mathematically defined for a given set of argument values (a) if it is explicitly defined for that set of argument values, or (b) if its limiting value exists and does not depend on the direction of approach.
28.7.6.6 Complete elliptic integral of the second kind

\[ \text{comp\_ellint\_2}(k) \]

1. **Effects:** These functions compute the complete elliptic integral of the second kind of their respective arguments \( k \).
2. **Returns:** \( E(k) \), where \( E \) is given by Formula 28.26 and \( k \) is \( k \).
   \[ E(k) = E(k, \pi/2), \quad \text{for } |k| \leq 1 \]  
   (28.26)
3. See also 28.7.6.13.

28.7.6.7 Complete elliptic integral of the third kind

\[ \text{comp\_ellint\_3}(k, \nu) \]

1. **Effects:** These functions compute the complete elliptic integral of the third kind of their respective arguments \( k \) and \( \nu \).
2. **Returns:** \( \Pi(\nu, k) \), where \( \Pi \) is given by Formula 28.27, \( k \) is \( k \), and \( \nu \) is \( nu \).
   \[ \Pi(\nu, k) = \Pi(\nu, k, \pi/2), \quad \text{for } |k| \leq 1 \]  
   (28.27)
3. See also 28.7.6.14.

28.7.6.8 Regular modified cylindrical Bessel functions

\[ \text{cyl\_bessel\_i}(\nu, x) \]

1. **Effects:** These functions compute the regular modified cylindrical Bessel functions of their respective arguments \( \nu \) and \( x \).
2. **Returns:** \( I_{\nu}(x) \), where \( I_{\nu} \) is given by Formula 28.28, \( \nu \) is \( nu \), and \( x \) is \( x \).
   \[ I_{\nu}(x) = i^{-\nu}J_{\nu}(ix) = \sum_{k=0}^{\infty} \frac{(x/2)^{\nu+2k}}{k! \Gamma(\nu+k+1)} , \quad \text{for } x \geq 0 \]  
   (28.28)
3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( \nu \geq 128 \).
4. See also 28.7.6.9.

28.7.6.9 Cylindrical Bessel functions of the first kind

\[ \text{cyl\_bessel\_j}(\nu, x) \]

1. **Effects:** These functions compute the cylindrical Bessel functions of the first kind of their respective arguments \( \nu \) and \( x \).
2. **Returns:** \( J_{\nu}(x) \), where \( J_{\nu} \) is given by Formula 28.29, \( \nu \) is \( nu \), and \( x \) is \( x \).
   \[ J_{\nu}(x) = \sum_{k=0}^{\infty} \frac{(-1)^k(x/2)^{\nu+2k}}{k! \Gamma(\nu+k+1)} , \quad \text{for } x \geq 0 \]  
   (28.29)
3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( \nu \geq 128 \).
28.7.6.10 Irregular modified cylindrical Bessel functions

```
#include <cmath>

double cyl_bessel_k(double nu, double x);
long double cyl_bessel_kl(long double nu, long double x);
```

**Effects:** These functions compute the irregular modified cylindrical Bessel functions of their respective arguments \( \nu \) and \( x \).

**Returns:** \( K_\nu(x) \), where \( K_\nu \) is given by Formula 28.30, \( \nu \) is \( \nu \), and \( x \) is \( x \).

\[
K_\nu(x) = \frac{\pi}{2} i^{\nu+1} \left( J_\nu(ix) + i N_\nu(ix) \right) =
\begin{cases}
\frac{\pi}{2} \frac{I_{\nu-\mu}(x) - I_{\nu}(x)}{\sin \mu \pi}, & \text{for } x \geq 0 \text{ and non-integral } \nu \\
\lim_{\mu \to \nu} \frac{I_{\mu}(x) - I_{\mu-\nu}(x)}{\sin \mu \pi}, & \text{for } x \geq 0 \text{ and integral } \nu
\end{cases}
\] (28.30)

**Remarks:** The effect of calling each of these functions is implementation-defined if \( \nu \geq 128 \).

See also 28.7.6.8, 28.7.6.9, 28.7.6.11.

28.7.6.11 Cylindrical Neumann functions

```
#include <cmath>

double cyl_neumann(double nu, double x);
long double cyl_neumannl(long double nu, long double x);
```

**Effects:** These functions compute the cylindrical Neumann functions, also known as the cylindrical Bessel functions of the second kind, of their respective arguments \( \nu \) and \( x \).

**Returns:** \( N_\nu(x) \), where \( N_\nu \) is given by Formula 28.31, \( \nu \) is \( \nu \), and \( x \) is \( x \).

\[
N_\nu(x) =
\begin{cases}
\frac{J_\nu(x) \cos \nu \pi - J_{\nu-\nu}(x)}{\sin \nu \pi}, & \text{for } x \geq 0 \text{ and non-integral } \nu \\
\lim_{\nu \to \nu} \frac{J_{\nu}(x) \cos \nu \pi - J_{\nu-\nu}(x)}{\sin \nu \pi}, & \text{for } x \geq 0 \text{ and integral } \nu
\end{cases}
\] (28.31)

**Remarks:** The effect of calling each of these functions is implementation-defined if \( \nu \geq 128 \).

See also 28.7.6.9.

28.7.6.12 Incomplete elliptic integral of the first kind

```
#include <cmath>

double ellint_1(double k, double phi);
long double ellint_1l(long double k, long double phi);
```

**Effects:** These functions compute the incomplete elliptic integral of the first kind of their respective arguments \( k \) and \( \phi \) (\( \phi \) measured in radians).

**Returns:** \( F(k, \phi) \), where \( F \) is given by Formula 28.32, \( k \) is \( k \), and \( \phi \) is \( \phi \).

\[
F(k, \phi) = \int_0^\phi \frac{d\theta}{\sqrt{1 - k^2 \sin^2 \theta}}, \quad \text{for } |k| \leq 1
\] (28.32)

28.7.6.13 Incomplete elliptic integral of the second kind

```
#include <cmath>

double ellint_2(double k, double phi);
long double ellint_2l(long double k, long double phi);
```

**Effects:** These functions compute the incomplete elliptic integral of the second kind of their respective arguments \( k \) and \( \phi \) (\( \phi \) measured in radians).

**Returns:** \( E(k, \phi) \), where \( E \) is given by Formula 28.33, \( k \) is \( k \), and \( \phi \) is \( \phi \).

\[
E(k, \phi) = \int_0^\phi \sqrt{1 - k^2 \sin^2 \theta} d\theta, \quad \text{for } |k| \leq 1
\] (28.33)
28.7.6.14 Incomplete elliptic integral of the third kind

```c
floating-point-type ellint_3(floating-point-type k, floating-point-type nu, floating-point-type phi);
float ellint_3f(float k, float nu, float phi);
long double ellint_3l(long double k, long double nu, long double phi);
```

1. **Effects:** These functions compute the incomplete elliptic integral of the third kind of their respective arguments \( k, \nu, \) and \( \phi \) (\( \phi \) measured in radians).

2. **Returns:** \( \Pi(\nu, k, \phi) \), where \( \Pi \) is given by Formula 28.34, \( \nu \) is \( \nu \), \( k \) is \( k \), and \( \phi \) is \( \phi \).

\[
\Pi(\nu, k, \phi) = \int_{\phi}^{0} \frac{d\theta}{(1 - \nu \sin^2 \theta)\sqrt{1 - k^2 \sin^2 \theta}}, \quad \text{for } |k| \leq 1 \tag{28.34}
\]

28.7.6.15 Exponential integral

```c
floating-point-type expint(floating-point-type x);
float expintf(float x);
long double expintl(long double x);
```

1. **Effects:** These functions compute the exponential integral of their respective arguments \( x \).

2. **Returns:** \( \text{Ei}(x) \), where \( \text{Ei} \) is given by Formula 28.35 and \( x \) is \( x \).

\[
\text{Ei}(x) = -\int_{-\infty}^{x} \frac{e^{-t}}{t} \, dt \tag{28.35}
\]

28.7.6.16 Hermite polynomials

```c
floating-point-type hermite(unsigned n, floating-point-type x);
float hermitef(unsigned n, float x);
long double hermitel(unsigned n, long double x);
```

1. **Effects:** These functions compute the Hermite polynomials of their respective arguments \( n \) and \( x \).

2. **Returns:** \( H_n(x) \), where \( H_n \) is given by Formula 28.36, \( n \) is \( n \), and \( x \) is \( x \).

\[
H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2} \tag{28.36}
\]

3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( n \geq 128 \).

28.7.6.17 Laguerre polynomials

```c
floating-point-type laguerre(unsigned n, floating-point-type x);
float laguerref(unsigned n, float x);
long double laguerrel(unsigned n, long double x);
```

1. **Effects:** These functions compute the Laguerre polynomials of their respective arguments \( n \) and \( x \).

2. **Returns:** \( L_n(x) \), where \( L_n \) is given by Formula 28.37, \( n \) is \( n \), and \( x \) is \( x \).

\[
L_n(x) = \frac{e^x}{n!} \frac{d^n}{dx^n} (x^n e^{-x}) \tag{28.37}
\]

3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( n \geq 128 \).

28.7.6.18 Legendre polynomials

```c
floating-point-type legendre(unsigned l, floating-point-type x);
float legendref(unsigned l, float x);
long double legendrel(unsigned l, long double x);
```

1. **Effects:** These functions compute the Legendre polynomials of their respective arguments \( l \) and \( x \).

2. **Returns:** \( P_l(x) \), where \( P_l \) is given by Formula 28.38, \( l \) is \( l \), and \( x \) is \( x \).

\[
P_l(x) = \frac{1}{2^l l!} \frac{d^l}{dx^l} (x^2 - 1)^l, \quad \text{for } |x| \leq 1 \tag{28.38}
\]

3. **Remarks:** The effect of calling each of these functions is implementation-defined if \( l \geq 128 \).
28.7.6.19 Riemann zeta function

\[ \text{riemann\_zeta}(\text{floating-point-type } x); \]
\[ \text{float } \text{riemann\_zeta}(\text{float } x); \]
\[ \text{long double } \text{riemann\_zeta}(\text{long double } x); \]

1 Effects: These functions compute the Riemann zeta function of their respective arguments \( x \).

2 Returns: \( \zeta(x) \), where \( \zeta \) is given by Formula 28.39 and \( x \) is \( x \).

\[ \zeta(x) = \begin{cases} \sum_{k=1}^{\infty} k^{-x}, & \text{for } x > 1 \\ \frac{1}{1-2^{1-x}} \sum_{k=1}^{\infty} (-1)^{k-1} k^{-x}, & \text{for } 0 \leq x \leq 1 \\ 2^{x-1} \sin\left(\frac{\pi x}{2}\right) \Gamma(1-x) \zeta(1-x), & \text{for } x < 0 \end{cases} \quad (28.39) \]

28.7.6.20 Spherical Bessel functions of the first kind

\[ \text{sph\_bessel}(\text{unsigned } n, \text{floating-point-type } x); \]
\[ \text{float } \text{sph\_besself}(\text{unsigned } n, \text{float } x); \]
\[ \text{long double } \text{sph\_bessell}(\text{unsigned } n, \text{long double } x); \]

1 Effects: These functions compute the spherical Bessel functions of the first kind of their respective arguments \( n \) and \( x \).

2 Returns: \( j_n(x) \), where \( j_n \) is given by Formula 28.40, \( n \) is \( n \), and \( x \) is \( x \).

\[ j_n(x) = \left(\frac{\pi}{2x}\right)^{1/2} J_{n+1/2}(x), \quad \text{for } x \geq 0 \quad (28.40) \]

3 Remarks: The effect of calling each of these functions is implementation-defined if \( n \geq 128 \).

See also 28.7.6.9.

28.7.6.21 Spherical associated Legendre functions

\[ \text{sph\_legendre}(\text{unsigned } l, \text{unsigned } m, \text{floating-point-type } \theta); \]
\[ \text{float } \text{sph\_legendref}(\text{unsigned } l, \text{unsigned } m, \text{float } \theta); \]
\[ \text{long double } \text{sph\_legendrel}(\text{unsigned } l, \text{unsigned } m, \text{long double } \theta); \]

1 Effects: These functions compute the spherical associated Legendre functions of their respective arguments \( l \), \( m \), and \( \theta \) (\( \theta \) measured in radians).

2 Returns: \( Y_m^l(\theta, 0) \), where \( Y_m^l \) is given by Formula 28.41, \( l \) is \( l \), \( m \) is \( m \), and \( \theta \) is \( \theta \).

\[ Y_m^l(\theta, \phi) = (-1)^m \left[ \frac{(2l+1)}{4\pi} \frac{(l-m)!}{(l+m)!} \right]^{1/2} P_m^l(\cos \theta) e^{im\phi}, \quad \text{for } |m| \leq l \quad (28.41) \]

3 Remarks: The effect of calling each of these functions is implementation-defined if \( l \geq 128 \).

See also 28.7.6.3.

28.7.6.22 Spherical Neumann functions

\[ \text{sph\_neumann}(\text{unsigned } n, \text{floating-point-type } x); \]
\[ \text{float } \text{sph\_neumannf}(\text{unsigned } n, \text{float } x); \]
\[ \text{long double } \text{sph\_neunnal}(\text{unsigned } n, \text{long double } x); \]

1 Effects: These functions compute the spherical Neumann functions, also known as the spherical Bessel functions of the second kind, of their respective arguments \( n \) and \( x \).

2 Returns: \( n_n(x) \), where \( n_n \) is given by Formula 28.42, \( n \) is \( n \), and \( x \) is \( x \).

\[ n_n(x) = \left(\frac{\pi}{2x}\right)^{1/2} N_{n+1/2}(x), \quad \text{for } x \geq 0 \quad (28.42) \]

3 Remarks: The effect of calling each of these functions is implementation-defined if \( n \geq 128 \).

See also 28.7.6.11.
28.8 Numbers

28.8.1 Header <numbers> synopsis

namespace std::numbers {
  template<class T> constexpr T e_v = unspecified;
  template<class T> constexpr T log2e_v = unspecified;
  template<class T> constexpr T log10e_v = unspecified;
  template<class T> constexpr T pi_v = unspecified;
  template<class T> constexpr T inv_pi_v = unspecified;
  template<class T> constexpr T inv_sqrtpi_v = unspecified;
  template<class T> constexpr T ln2_v = unspecified;
  template<class T> constexpr T ln10_v = unspecified;
  template<class T> constexpr T sqrt2_v = unspecified;
  template<class T> constexpr T sqrt3_v = unspecified;
  template<class T> constexpr T inv_sqrt3_v = unspecified;
  template<class T> constexpr T egamma_v = unspecified;
  template<class T> constexpr T phi_v = unspecified;

template<floating_point T> constexpr T e_v<T> = see below;
  template<floating_point T> constexpr T log2e_v<T> = see below;
  template<floating_point T> constexpr T log10e_v<T> = see below;
  template<floating_point T> constexpr T pi_v<T> = see below;
  template<floating_point T> constexpr T inv_pi_v<T> = see below;
  template<floating_point T> constexpr T inv_sqrtpi_v<T> = see below;
  template<floating_point T> constexpr T ln2_v<T> = see below;
  template<floating_point T> constexpr T ln10_v<T> = see below;
  template<floating_point T> constexpr T sqrt2_v<T> = see below;
  template<floating_point T> constexpr T sqrt3_v<T> = see below;
  template<floating_point T> constexpr T inv_sqrt3_v<T> = see below;
  template<floating_point T> constexpr T egamma_v<T> = see below;
  template<floating_point T> constexpr T phi_v<T> = see below;

inline constexpr double e = e_v<double>;
inline constexpr double log2e = log2e_v<double>;
inline constexpr double log10e = log10e_v<double>;
inline constexpr double pi = pi_v<double>;
inline constexpr double inv_pi = inv_pi_v<double>;
inline constexpr double inv_sqrtpi = inv_sqrtpi_v<double>;
inline constexpr double ln2 = ln2_v<double>;
inline constexpr double ln10 = ln10_v<double>;
inline constexpr double sqrt2 = sqrt2_v<double>;
inline constexpr double sqrt3 = sqrt3_v<double>;
inline constexpr double inv_sqrt3 = inv_sqrt3_v<double>;
inline constexpr double egamma = egamma_v<double>;
inline constexpr double phi = phi_v<double>;
}

28.8.2 Mathematical constants

1 The library-defined partial specializations of mathematical constant variable templates are initialized with the nearest representable values of $e$, $\log_2 e$, $\log_{10} e$, $\pi$, $\frac{1}{\pi}$, $\frac{1}{\sqrt{\pi}}$, $\ln 2$, $\ln 10$, $\sqrt{2}$, $\sqrt{3}$, $\frac{1}{\sqrt{3}}$, the Euler-Mascheroni $\gamma$ constant, and the golden ratio $\phi$ constant $\frac{1+\sqrt{5}}{2}$, respectively.

2 Pursuant to 16.4.5.2.1, a program may partially or explicitly specialize a mathematical constant variable template provided that the specialization depends on a program-defined type.

3 A program that instantiates a primary template of a mathematical constant variable template is ill-formed.

28.9 Basic linear algebra algorithms

28.9.1 Overview

1 Subclause 28.9 defines basic linear algebra algorithms. The algorithms that access the elements of arrays view those elements through `mdspan` (24.7.3).
namespace std::linalg {
    // 28.9.5.1, storage order tags
    struct column_major_t;  
    inline constexpr column_major_t column_major;
    struct row_major_t;    
    inline constexpr row_major_t row_major;

    // 28.9.5.2, triangle tags
    struct upper_triangle_t;    
    inline constexpr upper_triangle_t upper_triangle;
    struct lower_triangle_t;    
    inline constexpr lower_triangle_t lower_triangle;

    // 28.9.5.3, diagonal tags
    struct implicit_unit_diagonal_t;  
    inline constexpr implicit_unit_diagonal_t implicit_unit_diagonal;
    struct explicit_diagonal_t;       
    inline constexpr explicit_diagonal_t explicit_diagonal;

    // 28.9.6, class template layout_blas_packed
    template<class Triangle, class StorageOrder>  
    class layout_blas_packed;

    // 28.9.7, exposition-only helpers

    // 28.9.7.5, linear algebra argument concepts
    template<class T>
        constexpr bool is-mdspan = see below;  // exposition only

    template<class T>  
        concept in-vector = see below;   // exposition only

    template<class T>  
        concept out-vector = see below;  // exposition only

    template<class T>  
        concept inout-vector = see below; // exposition only

    template<class T>  
        concept in-matrix = see below;    // exposition only

    template<class T>  
        concept out-matrix = see below;   // exposition only

    template<class T>  
        concept inout-matrix = see below; // exposition only

    template<class T>  
        concept possibly-packed-inout-matrix = see below; // exposition only

    template<class T>  
        concept in-object = see below;     // exposition only

    template<class T>  
        concept out-object = see below;    // exposition only

    template<class T>  
        concept inout-object = see below;  // exposition only

    // 28.9.8, scaled in-place transformation
// 28.9.2, class template scaled_accessor
template<class ScalingFactor, class NestedAccessor>
class scaled_accessor;

// 28.9.3, function template scaled
template<class ScalingFactor,
     class ElementType, class Extents, class Layout, class Accessor>
constexpr auto scaled(ScalingFactor alpha, mdspan<ElementType, Extents, Layout, Accessor> x);

// 28.9.9, conjugated in-place transformation
// 28.9.9.2, class template conjugated_accessor
template<class NestedAccessor>
class conjugated_accessor;

// 28.9.9.3, function template conjugated
template<class ElementType, class Extents, class Layout, class Accessor>
constexpr auto conjugated(mdspan<ElementType, Extents, Layout, Accessor> a);

// 28.9.10, transpose in-place transformation
// 28.9.10.3, class template layout_transpose
template<class Layout>
class layout_transpose;

// 28.9.13, BLAS 1 algorithms
// 28.9.13.2, Givens rotations
// 28.9.13.2.1, compute Givens rotation
template<class Real>
struct setup_givens_rotation_result {
    Real c;
    Real s;
    Real r;
};
template<class Real>
struct setup_givens_rotation_result<complex<Real>> {
    Real c;
    complex<Real> s;
    complex<Real> r;
};
template<class Real>
setup_givens_rotation_result<Real> setup_givens_rotation(Real a, Real b) noexcept;
template<class Real>
setup_givens_rotation_result<complex<Real>>
setup_givens_rotation(complex<Real> a, complex<Real> b) noexcept;

// 28.9.13.2.2, apply computed Givens rotation
template<InOut-vector InOutVec1, InOut-vector InOutVec2, class Real>
void apply_givens_rotation(InOutVec1 x, InOutVec2 y, Real c, Real s);
template<class ExecutionPolicy, inout-vector InOutVec1, inout-vector InOutVec2, class Real>
void apply_givens_rotation(ExecutionPolicy&& exec,
InOutVec1 x, InOutVec2 y, Real c, Real s);

template<inout-vector InOutVec1, inout-vector InOutVec2, class Real>
void apply_givens_rotation(InOutVec1 x, InOutVec2 y, Real c, complex<Real> s);

template<class ExecutionPolicy, inout-vector InOutVec1, inout-vector InOutVec2, class Real>
void apply_givens_rotation(ExecutionPolicy&& exec,
InOutVec1 x, InOutVec2 y, Real c, complex<Real> s);

// 28.9.13.3, swap elements
template<inout-object InOutObj1, inout-object InOutObj2>
void swap_elements(InOutObj1 x, InOutObj2 y);

template<class ExecutionPolicy, inout-object InOutObj1, inout-object InOutObj2>
void swap_elements(ExecutionPolicy&& exec,
InOutObj1 x, InOutObj2 y);

// 28.9.13.4, multiply elements by scalar
template<class Scalar, inout-object InOutObj>
void scale(Scalar alpha, InOutObj x);

template<class ExecutionPolicy, class Scalar, inout-object InOutObj>
void scale(ExecutionPolicy&& exec,
Scalar alpha, InOutObj x);

// 28.9.13.5, copy elements
template<in-object InObj, out-object OutObj>
void copy(InObj x, OutObj y);

template<class ExecutionPolicy, in-object InObj, out-object OutObj>
void copy(ExecutionPolicy&& exec,
InObj x, OutObj y);

// 28.9.13.6, add elementwise
template<in-object InObj1, in-object InObj2, out-object OutObj>
void add(InObj1 x, InObj2 y, OutObj z);

template<class ExecutionPolicy, in-object InObj1, in-object InObj2, out-object OutObj>
void add(ExecutionPolicy&& exec,
InObj1 x, InObj2 y, OutObj z);

// 28.9.13.7, dot product of two vectors
template<in-vector InVec1, in-vector InVec2, class Scalar>
Scalar dot(InVec1 v1, InVec2 v2, Scalar init);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, class Scalar>
Scalar dot(ExecutionPolicy&& exec,
InVec1 v1, InVec2 v2, Scalar init);

template<in-vector InVec1, in-vector InVec2>
auto dot(InVec1 v1, InVec2 v2);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2>
auto dot(ExecutionPolicy&& exec,
InVec1 v1, InVec2 v2);

// 28.9.13.8, scaled sum of squares of a vector’s elements
template<class Scalar>
struct sum_of_squares_result {
  Scalar scaling_factor;
};
N4986

Scalar scaled_sum_of_squares;
};
template<in-vector InVec, class Scalar>
sum_of_squares_result<Scalar>
vector_sum_of_squares(InVec v, sum_of_squares_result<Scalar> init);
template<class ExecutionPolicy, in-vector InVec, class Scalar>
sum_of_squares_result<Scalar>
vector_sum_of_squares(ExecutionPolicy& exec, InVec v, sum_of_squares_result<Scalar> init);

// 28.9.13.9, Euclidean norm of a vector
template<in-vector InVec, class Scalar>
Scalar vector_two_norm(InVec v, Scalar init);
template<class ExecutionPolicy, in-vector InVec, class Scalar>
Scalar vector_two_norm(ExecutionPolicy& exec, InVec v, Scalar init);
template<in-vector InVec>
auto vector_two_norm(InVec v);
template<class ExecutionPolicy, in-vector InVec>
auto vector_two_norm(ExecutionPolicy& exec, InVec v);

// 28.9.13.10, sum of absolute values of vector elements
template<in-vector InVec, class Scalar>
Scalar vector_abs_sum(InVec v, Scalar init);
template<class ExecutionPolicy, in-vector InVec, class Scalar>
Scalar vector_abs_sum(ExecutionPolicy& exec, InVec v, Scalar init);
template<in-vector InVec>
auto vector_abs_sum(InVec v);
template<class ExecutionPolicy, in-vector InVec>
auto vector_abs_sum(ExecutionPolicy& exec, InVec v);

// 28.9.13.11, index of maximum absolute value of vector elements
template<in-vector InVec>
typename InVec::extents_type vector_idx_abs_max(InVec v);
template<class ExecutionPolicy, in-vector InVec>
typename InVec::extents_type vector_idx_abs_max(ExecutionPolicy& exec, InVec v);

// 28.9.13.12, Frobenius norm of a matrix
template<in-matrix InMat, class Scalar>
Scalar matrix_frob_norm(InMat A, Scalar init);
template<class ExecutionPolicy, in-matrix InMat, class Scalar>
Scalar matrix_frob_norm(ExecutionPolicy& exec, InMat A, Scalar init);
template<in-matrix InMat>
auto matrix_frob_norm(InMat A);
template<class ExecutionPolicy, in-matrix InMat>
auto matrix_frob_norm(ExecutionPolicy& exec, InMat A);

// 28.9.13.13, one norm of a matrix
template<in-matrix InMat, class Scalar>
Scalar matrix_one_norm(InMat A, Scalar init);
template<class ExecutionPolicy, in-matrix InMat, class Scalar>
Scalar matrix_one_norm(ExecutionPolicy& exec, InMat A, Scalar init);
template<in-matrix InMat>
auto matrix_one_norm(InMat A);
template<class ExecutionPolicy, in-matrix InMat>
auto matrix_one_norm(ExecutionPolicy& exec, InMat A);

// 28.9.13.14, infinity norm of a matrix
template<in-matrix InMat, class Scalar>
Scalar matrix_inf_norm(InMat A, Scalar init);
template<class ExecutionPolicy, in-matrix InMat, class Scalar>
Scalar matrix_inf_norm(ExecutionPolicy& exec, InMat A, Scalar init);
template<in-matrix InMat>
auto matrix_inf_norm(InMat A);
template<class ExecutionPolicy, in-matrix InMat>
auto matrix_inf_norm(ExecutionPolicy&& exec, InMat A);

// 28.9.14, BLAS 2 algorithms

// 28.9.14.1, general matrix-vector product
template<in-matrix InMat, in-vector InVec, out-vector OutVec>
void matrix_vector_product(InMat A, InVec x, OutVec y);
template<class ExecutionPolicy, in-matrix InMat, in-vector InVec, out-vector OutVec>
void matrix_vector_product(ExecutionPolicy&& exec,
InMat A, InVec x, OutVec y);
template<in-matrix InMat, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void matrix_vector_product(InMat A, InVec1 x, InVec2 y, OutVec z);
template<class ExecutionPolicy,
in-matrix InMat, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void matrix_vector_product(ExecutionPolicy&& exec,
InMat A, InVec1 x, InVec2 y, OutVec z);

template<in-matrix InMat, class Triangle, in-vector InVec, out-vector OutVec>
void symmetric_matrix_vector_product(InMat A, Triangle t, InVec x, OutVec y);
template<class ExecutionPolicy,
in-matrix InMat, class Triangle, in-vector InVec, out-vector OutVec>
void symmetric_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, InVec x, OutVec y);
template<in-matrix InMat, class Triangle, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void symmetric_matrix_vector_product(InMat A, Triangle t, InVec1 x, InVec2 y, OutVec z);
template<class ExecutionPolicy,
in-matrix InMat, class Triangle, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void symmetric_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, InVec1 x, InVec2 y, OutVec z);

template<in-matrix InMat, class Triangle, in-vector InVec, out-vector OutVec>
void hermitian_matrix_vector_product(InMat A, Triangle t, InVec x, OutVec y);
template<class ExecutionPolicy,
in-matrix InMat, class Triangle, in-vector InVec, out-vector OutVec>
void hermitian_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, InVec x, OutVec y);
template<in-matrix InMat, class Triangle, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void hermitian_matrix_vector_product(InMat A, Triangle t, InVec1 x, InVec2 y, OutVec z);
template<class ExecutionPolicy,
in-matrix InMat, class Triangle, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void hermitian_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, InVec1 x, InVec2 y, OutVec z);

// 28.9.14.4, triangular matrix-vector product

// Overwriting triangular matrix-vector product
template<in-matrix InMat, class Triangle, class DiagonalStorage, in-vector InVec, out-vector OutVec>
void triangular_matrix_vector_product(InMat A, Triangle t, DiagonalStorage d, InVec x, OutVec y);
template<class ExecutionPolicy,
in-matrix InMat, class Triangle, class DiagonalStorage, in-vector InVec, out-vector OutVec>
void triangular_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, DiagonalStorage d, InVec x, OutVec y);
// In-place triangular matrix-vector product
void triangular_matrix_vector_product(InMat A, Triangle t, DiagonalStorage d, InOutVec y);

// Updating triangular matrix-vector product
void triangular_matrix_vector_product(InMat A, Triangle t, DiagonalStorage d, InOutVec y);

// Solve a triangular linear system
void triangular_matrix_vector_solve(InMat A, Triangle t, DiagonalStorage d, InOutVec b, BinaryDivideOp divide);

// Solve a triangular linear system, in place
void triangular_matrix_vector_solve(InMat A, Triangle t, DiagonalStorage d, InOutVec b);

// 28.9.14.6, nonsymmetric rank-1 matrix update
void matrix_rank_1_update(InVec1 x, InVec2 y, InOutMat A);

§ 28.9.2
template<in-vector InVec1, in-vector InVec2, inout-matrix InOutMat>
void matrix_rank_1_update_c(InVec1 x, InVec2 y, InOutMat A);

// 28.9.14.7, symmetric or Hermitian rank-1 matrix update

template<class Scalar, in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(Scalar alpha, InVec x, InOutMat A, Triangle t);

template<class ExecutionPolicy,
in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(ExecutionPolicy&& exec,
Scalar alpha, InVec x, InOutMat A, Triangle t);

template<in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(InVec x, InOutMat A, Triangle t);

// 28.9.14.8, symmetric and Hermitian rank-2 matrix updates

// symmetric rank-2 matrix update

template<in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2_update(InVec1 x, InVec2 y, InOutMat A, Triangle t);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2_update(ExecutionPolicy&& exec,
InVec1 x, InVec2 y, InOutMat A, Triangle t);

// Hermitian rank-2 matrix update

template<in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2_update(InVec1 x, InVec2 y, InOutMat A, Triangle t);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2_update(ExecutionPolicy&& exec,
InVec1 x, InVec2 y, InOutMat A, Triangle t);

// 28.9.15, BLAS 3 algorithms

// 28.9.15.1, general matrix-matrix product

template<in-matrix InMat1, in-matrix InMat2, out-matrix OutMat>
void matrix_product(InMat1 A, InMat2 B, OutMat C);

template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, out-matrix OutMat>
void matrix_product(ExecutionPolicy&& exec,
InMat1 A, InMat2 B, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void matrix_product(InMat1 A, InMat2 B, InMat3 E, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void matrix_product(ExecutionPolicy&& exec,
InMat1 A, InMat2 B, InMat3 E, OutMat C);

// 28.9.15.2, symmetric, Hermitian, and triangular matrix-matrix product

template<in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, Triangle t, InMat2 B, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy&& exec,
InMat1 A, Triangle t, InMat2 B, OutMat C);

template<in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, Triangle t, InMat2 B, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy&& exec,
InMat1 A, Triangle t, InMat2 B, OutMat C);

template<in-matrix InMat1, class Triangle, class DiagonalStorage, in-matrix InMat2, out-matrix OutMat>
void triangular_matrix_product(InMat1 A, Triangle t, DiagonalStorage d, InMat2 B, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, class Triangle, class DiagonalStorage, in-matrix InMat2, out-matrix OutMat>
void triangular_matrix_product(ExecutionPolicy&& exec,
InMat1 A, Triangle t, DiagonalStorage d, InMat2 B, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, InMat2 B, Triangle t, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy&& exec,
InMat1 A, InMat2 B, Triangle t, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, InMat2 B, Triangle t, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy&& exec,
InMat1 A, InMat2 B, Triangle t, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, class Triangle, class DiagonalStorage, out-matrix OutMat>
void triangular_matrix_product(InMat1 A, InMat2 B, Triangle t, DiagonalStorage d, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, class Triangle, class DiagonalStorage, out-matrix OutMat>
void triangular_matrix_product(ExecutionPolicy&& exec,
InMat1 A, InMat2 B, Triangle t, DiagonalStorage d, OutMat C);

template<in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<class ExecutionPolicy, in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy&& exec,
InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, 
        out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<class ExecutionPolicy, 
in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, 
        out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy&& exec, 
InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);

template<in-matrix InMat1, class Triangle, class DiagonalStorage, 
in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(InMat1 A, Triangle t, DiagonalStorage d, InMat2 B, InMat3 E, 
OutMat C);
template<class ExecutionPolicy, 
in-matrix InMat1, class Triangle, class DiagonalStorage, 
in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(ExecutionPolicy&& exec, 
InMat1 A, Triangle t, DiagonalStorage d, InMat2 B, InMat3 E, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, class Triangle, in-matrix InMat3, 
        out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, InMat2 B, Triangle t, InMat3 E, OutMat C);
template<class ExecutionPolicy, 
in-matrix InMat1, in-matrix InMat2, class Triangle, in-matrix InMat3, 
        out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy&& exec, 
InMat1 A, InMat2 B, Triangle t, InMat3 E, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, class Triangle, in-matrix InMat3, 
        out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, InMat2 B, Triangle t, InMat3 E, OutMat C);
template<class ExecutionPolicy, 
in-matrix InMat1, in-matrix InMat2, class Triangle, in-matrix InMat3, 
        out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy&& exec, 
InMat1 A, InMat2 B, Triangle t, InMat3 E, OutMat C);

template<in-matrix InMat1, in-matrix InMat2, class Triangle, class DiagonalStorage, 
in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(InMat1 A, InMat2 B, Triangle t, DiagonalStorage d, InMat3 E, 
OutMat C);
template<class ExecutionPolicy, 
in-matrix InMat1, in-matrix InMat2, class Triangle, class DiagonalStorage, 
in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(ExecutionPolicy&& exec, 
InMat1 A, InMat2 B, Triangle t, DiagonalStorage d, InMat3 E, OutMat C);

// 28.9.15.3, in-place triangular matrix-matrix product

template<in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_left_product(InMat A, Triangle t, DiagonalStorage d, InOutMat C);
template<class ExecutionPolicy, 
in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_left_product(ExecutionPolicy&& exec, 
InMat A, Triangle t, DiagonalStorage d, InOutMat C);

template<in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_right_product(InMat A, Triangle t, DiagonalStorage d, InOutMat C);
template<class ExecutionPolicy, 
in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_right_product(ExecutionPolicy&& exec, 
InMat A, Triangle t, DiagonalStorage d, InOutMat C);
// 28.9.15.4, rank-k update of a symmetric or Hermitian matrix

// rank-k symmetric matrix update
template<class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_k_update(Scalar alpha, InMat A, InOutMat C, Triangle t);

// rank-k symmetric matrix update
template<class ExecutionPolicy, class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_k_update(ExecutionPolicy& exec, Scalar alpha, InMat A, InOutMat C, Triangle t);

// rank-k Hermitian matrix update
template<class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_k_update(Scalar alpha, InMat A, InOutMat C, Triangle t);

// rank-k Hermitian matrix update
template<class ExecutionPolicy, class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_k_update(ExecutionPolicy& exec, InMat A, InOutMat C, Triangle t);

// 28.9.15.5, rank-2k update of a symmetric or Hermitian matrix

// rank-2k symmetric matrix update
template<in-matrix InMat1, in-matrix InMat2, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2k_update(InMat1 A, InMat2 B, InOutMat C, Triangle t);

// rank-2k symmetric matrix update
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2k_update(ExecutionPolicy& exec, InMat1 A, InMat2 B, InOutMat C, Triangle t);

// rank-2k Hermitian matrix update
template<in-matrix InMat1, in-matrix InMat2, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2k_update(InMat1 A, InMat2 B, InOutMat C, Triangle t);

// rank-2k Hermitian matrix update
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2k_update(ExecutionPolicy& exec, InMat1 A, InMat2 B, InOutMat C, Triangle t);

// 28.9.15.6, solve multiple triangular linear systems

// solve multiple triangular systems on the left, not-in-place
template<in-matrix InMat1, class Triangle, class DiagonalStorage, out-matrix OutMat, class BinaryDivideOp>
void triangular_matrix_matrix_left_solve(InMat1 A, Triangle t, DiagonalStorage d, OutMat X, BinaryDivideOp divide);

// solve multiple triangular systems on the left, not-in-place
template<class ExecutionPolicy, in-matrix InMat1, class Triangle, class DiagonalStorage, out-matrix OutMat, class BinaryDivideOp>
void triangular_matrix_matrix_left_solve(ExecutionPolicy& exec, InMat1 A, Triangle t, DiagonalStorage d, OutMat X, BinaryDivideOp divide);
void triangular_matrix_matrix_left_solve(ExecutionPolicy&& exec,
    InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X, BinaryDivideOp divide);

void triangular_matrix_matrix_left_solve(InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X);

void triangular_matrix_matrix_left_solve(InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X);

// solve multiple triangular systems on the right, not-in-place
void triangular_matrix_matrix_right_solve(InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X, BinaryDivideOp divide);

void triangular_matrix_matrix_right_solve(InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X, BinaryDivideOp divide);

void triangular_matrix_matrix_right_solve(InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X);

void triangular_matrix_matrix_right_solve(ExecutionPolicy&& exec,
    InMat1 A, Triangle t, DiagonalStorage d,
    InMat2 B, OutMat X);

// solve multiple triangular systems on the left, in-place
void triangular_matrix_matrix_left_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B, BinaryDivideOp divide);

void triangular_matrix_matrix_left_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B, BinaryDivideOp divide);

void triangular_matrix_matrix_left_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B);

void triangular_matrix_matrix_left_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B);

// solve multiple triangular systems on the right, in-place
void triangular_matrix_matrix_right_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B, BinaryDivideOp divide);

void triangular_matrix_matrix_right_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B, BinaryDivideOp divide);

void triangular_matrix_matrix_right_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B);

void triangular_matrix_matrix_right_solve(InMat A, Triangle t, DiagonalStorage d,
    InOutMat B);
void triangular_matrix_matrix_right_solve(ExecutionPolicy&& exec,
InMat A, Triangle t, DiagonalStorage d,
InOutMat B, BinaryDivideOp divide);

template<in-matrix InMat, class Triangle, class DiagonalStorage,
inout-matrix InOutMat>
void triangular_matrix_matrix_right_solve(InMat A, Triangle t, DiagonalStorage d,
InOutMat B);

template<class ExecutionPolicy,
in-matrix InMat, class Triangle, class DiagonalStorage,
inout-matrix InOutMat>
void triangular_matrix_matrix_right_solve(ExecutionPolicy&& exec,
InMat A, Triangle t, DiagonalStorage d,
InOutMat B);

28.9.3 General

For the effects of all functions in 28.9, when the effects are described as “computes \( R = E \)” or “compute \( R = E \)” (for some \( R \)) and mathematical expression \( E \)), the following apply:

1. \( E \) has the conventional mathematical meaning as written.
2. The pattern \( x^T \) should be read as “the transpose of \( x \).”
3. The pattern \( x^H \) should be read as “the conjugate transpose of \( x \).”
4. When \( R \) is the same name as a function parameter whose type is a template parameter with \( \text{Out} \) in its name, the intent is that the result of the computation is written to the elements of the function parameter \( R \).

Some of the functions and types in 28.9 distinguish between the “rows” and the “columns” of a matrix. For a matrix \( A \) and a multidimensional index \( i, j \) in \( A.\text{extents()} \),

1. \( \text{row} \) \( i \) of \( A \) is the set of elements \( A[i, k1] \) for all \( k1 \) such that \( i, k1 \) in \( A.\text{extents()} \); and
2. \( \text{column} \) \( j \) of \( A \) is the set of elements \( A[k0, j] \) for all \( k0 \) such that \( k0, j \) is in \( A.\text{extents()} \).

Some of the functions in 28.9 distinguish between the “upper triangle,” “lower triangle,” and “diagonal” of a matrix.

1. The \( \text{diagonal} \) is the set of all elements of \( A \) accessed by \( A[i, i] \) for \( 0 \leq i < \min(A.\text{extent}(0), A.\text{extent}(1)) \).
2. The \( \text{upper triangle} \) of a matrix \( A \) is the set of all elements of \( A \) accessed by \( A[i, j] \) with \( i \leq j \). It includes the diagonal.
3. The \( \text{lower triangle} \) of \( A \) is the set of all elements of \( A \) accessed by \( A[i, j] \) with \( i \geq j \). It includes the diagonal.

For any function \( F \) that takes a parameter named \( t \), \( t \) applies to accesses done through the parameter preceding \( t \) in the parameter list of \( F \). Let \( m \) be such an access-modified function parameter. \( F \) will only access the triangle of \( m \) specified by \( t \). For accesses \( m[i, j] \) outside the triangle specified by \( t \), \( F \) will use the value

1. \( \text{conj-if-needed}(m[j, i]) \) if the name of \( F \) starts with \( \text{hermitian} \),
2. \( m[j, i] \) if the name of \( F \) starts with \( \text{symmetric} \), or
3. the additive identity if the name of \( F \) starts with \( \text{triangular} \).

[Example 1]: Small vector product accessing only specified triangle. It would not be a precondition violation for the non-accessed matrix element to be non-zero.

```cpp
template<class Triangle>
void triangular_matrix_vector_2x2_product(
    mdspan<const float, extents<int, 2, 2>> m,
    Triangle t,
    mdspan<const float, extents<int, 2, 2>> x,
    mdspan<float, extents<int, 2, 2>> y) {
    static_assert(is_same_v<Triangle, lower_triangle_t> ||
        is_same_v<Triangle, upper_triangle_t>);

    if constexpr (is_same_v<Triangle, lower_triangle_t>) {
        y[0] = m[0,0] * x[0];  // + 0 * x[1]
    }
```
For any function $F$ that takes a parameter named $d$, $d$ applies to accesses done through the previous-of-the-previous parameter of $d$ in the parameter list of $F$. Let $m$ be such an access-modified function parameter. If $d$ specifies that an implicit unit diagonal is to be assumed, then

- $F$ will not access the diagonal of $m$; and
- the algorithm will interpret $m$ as if it has a unit diagonal, that is, a diagonal each of whose elements behaves as a two-sided multiplicative identity (even if $m$’s value type does not have a two-sided multiplicative identity).

Otherwise, if $d$ specifies that an explicit diagonal is to be assumed, then $F$ will access the diagonal of $m$.

Two `mdspan` objects $x$ and $y$ alias each other, if they have the same extents $e$, and for every pack of integers $i$ which is a multidimensional index in $e$, $x[i...]$ and $y[i...]$ refer to the same element.

"Note 1: This means that $x$ and $y$ view the same elements in the same order. —end note"

Two `mdspan` objects $x$ and $y$ overlap each other, if for some pack of integers $i$ that is a multidimensional index in $x$.extents(), there exists a pack of integers $j$ that is a multidimensional index in $y$.extents(), such that $x[i...]$ and $y[j...]$ refer to the same element.

"Note 2: Aliasing is a special case of overlapping. If $x$ and $y$ do not overlap, then they also do not alias each other. —end note"

### 28.9.4 Requirements

#### 28.9.4.1 Linear algebra value types

Throughout 28.9, the following types are *linear algebra value type*:

- the `value_type` type alias of any input or output `mdspan` parameter(s) of any function in 28.9; and
- the `Scalar` template parameter (if any) of any function or class in 28.9.

Linear algebra value types shall model *semiregular*.

A value-initialized object of linear algebra value type shall act as the additive identity.

#### 28.9.4.2 Algorithm and class requirements

1. All of the following statements presume that the algorithm’s asymptotic complexity requirements, if any, are satisfied.

- The function may make arbitrarily many objects of any linear algebra value type, value-initializing or direct-initializing them with any existing object of that type.

- The `triangular solve algorithms` in 28.9.14.5, 28.9.15.3, 28.9.15.6, and 28.9.15.7 either have a `BinaryDivideOp` template parameter (see 28.9.12) and a binary function object parameter `divide` of that type, or they have effects equivalent to invoking such an algorithm. Triangular solve algorithms interpret `divide(a, b)` as $a$ times the multiplicative inverse of $b$. Each triangular solve algorithm uses a sequence of evaluations of $\star$, $\star=$, `divide`, unary $\star$, binary $\star$, $\star=$, unary $\star=$, binary $\star=$, $\star=$, and $\star=$ operators that would produce the result specified by the algorithm’s *Effects* and *Remarks* when operating on elements of a field with noncommutative multiplication. It is a precondition of the algorithm that any addend, any subtrahend, any partial sum of addends in any order (treating any difference as a sum with the second term negated), any factor, any partial product of factors respecting their order, any numerator (first argument of `divide`), any denominator (second argument of `divide`), and any assignment is a well-formed expression.

- Each function in 28.9.13, 28.9.14, and 28.9.15 that is not a triangular solve algorithm will use a sequence of evaluations of $\star$, $\star=$, $\star+$, $\star=$, and $\star$ operators that would produce the result specified by the algorithm’s
Effects and Remarks when operating on elements of a semiring with noncommutative multiplication. It is a precondition of the algorithm that any addend, any partial sum of addends in any order, any factor, any partial product of factors respecting their order, and any assignment is a well-formed expression.

(2.4) If the function has an output `mdspan`, then all addends, subtrahends (for the triangular solve algorithms), or results of the `divide` parameter on intermediate terms (if the function takes a `divide` parameter) are assignable and convertible to the output `mdspan`'s `value_type`.

(2.5) The function may reorder addends and partial sums arbitrarily.

[Note 1: Factors in each product are not reordered; multiplication is not necessarily commutative. — end note]

[Note 2: The above requirements do not prohibit implementation approaches and optimization techniques which are not user-observable. In particular, if for all input and output arguments the `value_type` is a floating-point type, implementers are free to leverage approximations, use arithmetic operations not explicitly listed above, and compute floating point sums in any way that improves their accuracy. — end note]

3 [Note 3: For all functions in 28.9, suppose that all input and output `mdspan` have as `value_type` a floating-point type, and any `Scalar` template argument has a floating-point type. Then, functions can do all of the following:

(3.1) compute floating-point sums in any way that improves their accuracy for arbitrary input;

(3.2) perform additional arithmetic operations (other than those specified by the function’s wording and 28.9.4.2) in order to improve performance or accuracy; and

(3.3) use approximations (that might not be exact even if computing with real numbers), instead of computations that would be exact if it were possible to compute without rounding error; as long as

(3.4) the function satisfies the complexity requirements; and

(3.5) the function is logarithmically stable, as defined in Demmel 2007[16]. Strassen’s algorithm for matrix-matrix multiply is an example of a logarithmically stable algorithm.

— end note]

28.9.5 Tag classes [linalg.tags]

28.9.5.1 Storage order tags [linalg.tags.order]

1 The storage order tags describe the order of elements in an `mdspan` with `layout_blas_packed` (28.9.6) layout.

```cpp
struct column_major_t {
    explicit column_major_t() = default;
};
inline constexpr column_major_t column_major{};

struct row_major_t {
    explicit row_major_t() = default;
};
inline constexpr row_major_t row_major{};
```

2 `column_major_t` indicates a column-major order, and `row_major_t` indicates a row-major order.

28.9.5.2 Triangle tags [linalg.tags.triangle]

```cpp
struct upper_triangle_t {
    explicit upper_triangle_t() = default;
};
inline constexpr upper_triangle_t upper_triangle{};

struct lower_triangle_t {
    explicit lower_triangle_t() = default;
};
inline constexpr lower_triangle_t lower_triangle{};
```

1 These tag classes specify whether algorithms and other users of a matrix (represented as an `mdspan`) access the upper triangle (`upper_triangle_t`) or lower triangle (`lower_triangle_t`) of the matrix (see also 28.9.3). This is also subject to the restrictions of `implicit_unit_diagonal_t` if that tag is also used as a function argument; see below.
28.9.5.3 Diagonal tags

```cpp
struct implicit_unit_diagonal_t {
    explicit implicit_unit_diagonal_t() = default;
};
inline constexpr implicit_unit_diagonal_t implicit_unit_diagonal{};

struct explicit_diagonal_t {
    explicit explicit_diagonal_t() = default;
};
inline constexpr explicit_diagonal_t explicit_diagonal{};
```

1 These tag classes specify whether algorithms access the matrix’s diagonal entries, and if not, then how
   algorithms interpret the matrix’s implicitly represented diagonal values.

2 The `implicit_unit_diagonal_t` tag indicates that an implicit unit diagonal is to be assumed (28.9.3).

3 The `explicit_diagonal_t` tag indicates that an explicit diagonal is used (28.9.3).

28.9.6 Layouts for packed matrix types

28.9.6.1 Overview

```cpp
layout_blas_packed is an mdspan layout mapping policy that represents a square matrix that stores only
   the entries in one triangle, in a packed contiguous format. Its `Triangle` template parameter determines
   whether an mdspan with this layout stores the upper or lower triangle of the matrix. Its `StorageOrder`
   template parameter determines whether the layout packs the matrix’s elements in column-major or row-major
   order.
```

1 A `StorageOrder` of `column_major_t` indicates column-major ordering. This packs matrix elements starting
   with the leftmost (least column index) column, and proceeding column by column, from the top entry (least
   row index).

3 A `StorageOrder` of `row_major_t` indicates row-major ordering. This packs matrix elements starting with
   the topmost (least row index) row, and proceeding row by row, from the leftmost (least column index) entry.

4 [Note 1: `layout_blas_packed` describes the data layout used by the BLAS’ Symmetric Packed (SP), Hermitian
    Packed (HP), and Triangular Packed (TP) matrix types. — end note]

```cpp
namespace std::linalg {
    template<class Triangle, class StorageOrder>
    class layout_blas_packed {
public:
        using triangle_type = Triangle;
        using storage_order_type = StorageOrder;

        template<class Extents>
        struct mapping {
            using extents_type = Extents;
            using index_type = typename extents_type::index_type;
            using size_type = typename extents_type::size_type;
            using rank_type =typename extents_type::rank_type;
            using layout_type = layout_blas_packed;

            // 28.9.6.2, constructors
            constexpr mapping() noexcept = default;
            constexpr mapping(const mapping&) noexcept = default;
            constexpr mapping(const extents_type&) noexcept;
            template<class OtherExtents>
            constexpr explicit(!is_convertible_v<OtherExtents, extents_type>)
                mapping(const mapping<OtherExtents>& other) noexcept;
            constexpr mapping& operator=(const mapping&) noexcept = default;

            // 28.9.6.3, observers
            constexpr const extents_type& extents() const noexcept { return extents_; }
        }
    }
}
```
constexpr index_type required_span_size() const noexcept;

template<class Index0, class Index1>
constexpr index_type operator() (Index0 ind0, Index1 ind1) const noexcept;

static constexpr bool is_always_unique() noexcept {
    return (extents_type::static_extent(0) != dynamic_extent &&
            extents_type::static_extent(0) < 2) ||
            (extents_type::static_extent(1) != dynamic_extent &&
            extents_type::static_extent(1) < 2);
}

static constexpr bool is_always_exhaustive() noexcept { return true; }
static constexpr bool is_always_strided() noexcept {
    return is_always_unique();
}

constexpr bool is_unique() const noexcept {
    return extents_.extent(0) < 2;
}

constexpr bool is_exhaustive() const noexcept { return true; }
constexpr bool is_strided() const noexcept {
    return extents_.extent(0) < 2;
}

constexpr index_type stride(rank_type) const noexcept;

template<class OtherExtents>
friend constexpr bool operator==(const mapping&, const mapping<OtherExtents>&) noexcept;

private:
    extents_type extents_;  // exposition only
};

5

Mandates:

(5.1) Triangle is either upper_triangle_t or lower_triangle_t,
(5.2) StorageOrder is either column_major_t or row_major_t,
(5.3) Extents is a specialization of std::extents,
(5.4) Extents::rank() equals 2,
(5.5) one of
    extents_type::static_extent(0) == dynamic_extent,
    extents_type::static_extent(1) == dynamic_extent, or
    extents_type::static_extent(0) == extents_type::static_extent(1)
    is true, and
(5.6) if Extents::rank_dynamic() == 0 is true, let Ns be equal to Extents::static_extent(0);
    then, Ns × (Ns + 1) is representable as a value of type index_type.

6

layout_blas_packed<T, SO>::mapping<E> is a trivially copyable type that models regular for each
T, SO, and E.

28.9.6.2 Constructors

constexpr mapping(const extents_type& e) noexcept;

Preconditions:

(1.1) Let N be equal to e.extent(0). Then, N × (N + 1) is representable as a value of type index_type
(6.8.2).
(1.2) e.extent(0) equals e.extent(1).

Effects: Direct-non-list-initializes extents_ with e.
template<class OtherExtents>
  explicit(!is_convertible_v<OtherExtents, extents_type>)
  constexpr mapping(const mapping<OtherExtents>& other) noexcept;

  Constraints: is_constructible_v<extents_type, OtherExtents> is true.
  Preconditions: Let \( N \) be other.extents().extent(0). Then, \( N \times (N + 1) \) is representable as a value of type index_type (6.8.2).
  Effects: Direct-non-list-initializes extents_ with other.extents().

28.9.6.3 Observers

constexpr index_type required_span_size() const noexcept;

  Returns: extents_.extent(0) * (extents_.extent(0) + 1)/2.
  Note: For example, a 5 x 5 packed matrix only stores 15 matrix elements. — end note

template<class Index0, class Index1>
constexpr index_type operator() (Index0 ind0, Index1 ind1) const noexcept;

  Constraints:
  (2.1) is_convertible_v<Index0, index_type> is true,
  (2.2) is_convertible_v<Index1, index_type> is true,
  (2.3) is_nothrow_constructible_v<index_type, Index0> is true, and
  (2.4) is_nothrow_constructible_v<index_type, Index1> is true.
  Preconditions: i, j is a multidimensional index in extents_ (24.7.3.1).
  Returns: Let \( N \) be extents_.extent(0). Then
  (5.1) (*this)(j, i) if \( i > j \) is true; otherwise
  (5.2) i + j * (j + 1)/2 if
  is_same_v<StorageOrder, column_major_t> && is_same_v<Triangle, upper_triangle_t>
  is true or
  is_same_v<StorageOrder, row_major_t> && is_same_v<Triangle, lower_triangle_t>
  is true; otherwise
  (5.3) j + N * i - i * (i + 1)/2.

constexpr index_type stride(rank_type r) const noexcept;

  Preconditions:
  (6.1) is_strided() is true, and
  (6.2) r < extents_type::rank() is true.
  Returns: 1.

template<class OtherExtents>
friend constexpr bool operator==(const mapping& x, const mapping<OtherExtents>& y) noexcept;

  Effects: Equivalent to: return x.extents() == y.extents();

28.9.7 Exposition-only helpers

28.9.7.1 abs-if-needed

The name abs-if-needed denotes an exposition-only function object. The expression abs-if-needed(E) for a subexpression E whose type is T is expression-equivalent to:

- E if T is an unsigned integer;
- otherwise, std::abs(E) if T is an arithmetic type,
- otherwise, abs(E), if that expression is valid, with overload resolution performed in a context that includes the declaration


```cpp
template<class T> T abs(T) = delete;
```

If the function selected by overload resolution does not return the absolute value of its input, the program is ill-formed, no diagnostic required.

### 28.9.7.2 `conj-if-needed`  

The name `conj-if-needed` denotes an exposition-only function object. The expression `conj-if-needed(E)` for a subexpression `E` whose type is `T` is expression-equivalent to:

1. `conj(E)`, if `T` is not an arithmetic type and the expression `conj(E)` is valid, with overload resolution performed in a context that includes the declaration

   ```cpp
   template<class T> T conj(const T&) = delete;
   ```

   If the function selected by overload resolution does not return the complex conjugate of its input, the program is ill-formed, no diagnostic required;

2. otherwise, `E`.

### 28.9.7.3 `real-if-needed`  

The name `real-if-needed` denotes an exposition-only function object. The expression `real-if-needed(E)` for a subexpression `E` whose type is `T` is expression-equivalent to:

1. `real(E)`, if `T` is not an arithmetic type and the expression `real(E)` is valid, with overload resolution performed in a context that includes the declaration

   ```cpp
   template<class T> T real(const T&) = delete;
   ```

   If the function selected by overload resolution does not return the real part of its input, the program is ill-formed, no diagnostic required;

2. otherwise, `E`.

### 28.9.7.4 `imag-if-needed`  

The name `imag-if-needed` denotes an exposition-only function object. The expression `imag-if-needed(E)` for a subexpression `E` whose type is `T` is expression-equivalent to:

1. `imag(E)`, if `T` is not an arithmetic type and the expression `imag(E)` is valid, with overload resolution performed in a context that includes the declaration

   ```cpp
   template<class T> T imag(const T&) = delete;
   ```

   If the function selected by overload resolution does not return the imaginary part of its input, the program is ill-formed, no diagnostic required;

2. otherwise, `((void)E, T{})`.

### 28.9.7.5 Argument concepts  

The exposition-only concepts defined in this section constrain the algorithms in 28.9.

```cpp
template<class T>
constexpr bool is-mdspan = false;
```

```cpp
template<class ElementType, class Extents, class Layout, class Accessor>
constexpr bool is-mdspan<mdspan<ElementType, Extents, Layout, Accessor>> = true;
```

```cpp
template<class T>
concept in-vector =
    is-mdspan<T> && T::rank() == 1;
```

```cpp
template<class T>
concept out-vector =
    is-mdspan<T> && T::rank() == 1 &&
    is_assignable_v<typename T::reference, typename T::element_type> && T::is_always_unique();
```

```cpp
template<class T>
concept inout-vector =
    is-mdspan<T> && T::rank() == 1 &&
    is_assignable_v<typename T::reference, typename T::element_type> && T::is_always_unique();
```
template<class T>
concept in-matrix =
    is-mdspan<T> && T::rank() == 2;

template<class T>
concept out-matrix =
    is-mdspan<T> && T::rank() == 2 &&
    is_assignable_v<tyepname T::reference, typename T::element_type> && T::is_always_unique();

template<class T>
concept inout-matrix =
    is-mdspan<T> && T::rank() == 2 &&
    is_assignable_v<tyepname T::reference, typename T::element_type> && T::is_always_unique();

template<class T>
constexpr bool is-layout-blas-packed = false;  // exposition only

template<class Triangle, class StorageOrder>
constexpr bool is-layout-blas-packed<layout_blas_packed<Triangle, StorageOrder>> = true;

template<class T>
concept possibly-packed-inout-matrix =
    is-mdspan<T> && T::rank() == 2 &&
    is_assignable_v<tyepname T::reference, typename T::element_type> &&
    (T::is_always_unique() || is-layout-blas-packed<typename T::layout_type>);

2 If a function in 28.9 accesses the elements of a parameter constrained by in-vector, in-matrix, or
   in-object, those accesses will not modify the elements.

3 Unless explicitly permitted, any inout-vector, inout-matrix, inout-object, out-vector, out-matrix,
   out-object, or possibly-packed-inout-matrix parameter of a function in 28.9 shall not overlap any
   other mdspan parameter of the function.

28.9.7.6 Mandates [linalg.helpers.mandates]

1 [Note 1: These exposition-only helper functions use the less constraining input concepts even for the output arguments,
    because the additional constraint for assignability of elements is not necessary, and they are sometimes used in a
    context where the third argument is an input type too. — end note]
template<in-matrix In1, in-matrix In2, in-matrix Out>
constexpr bool possibly-addable() { // exposition only
    return compatible-static-extents<Out, In1>(0, 0) &&
           compatible-static-extents<Out, In1>(1, 1) &&
           compatible-static-extents<Out, In2>(0, 0) &&
           compatible-static-extents<Out, In2>(1, 1) &&
           compatible-static-extents<In1, In2>(0, 0) &&
           compatible-static-extents<In1, In2>(1, 1);
}

template<in-matrix InMat, in-vector InVec, in-vector OutVec>
constexpr bool possibly-multipliable() { // exposition only
    return compatible-static-extents<OutVec, InMat>(0, 0) &&
           compatible-static-extents<InMat, InVec>(1, 0);
}

28.9.7.7 Preconditions [linalg.helpers.precond]

Note 1: These exposition-only helper functions use the less constraining input concepts even for the output arguments, because the additional constraint for assignability of elements is not necessary, and they are sometimes used in a context where the third argument is an input type too. — end note

constexpr bool addable(const in-vector auto& in1, const in-vector auto& in2, const in-vector auto& out) {
    return out.extent(0) == in1.extent(0) && out.extent(0) == in2.extent(0);
}

constexpr bool addable(const in-matrix auto& in1, const in-matrix auto& in2, const in-matrix auto& out) {
    return out.extent(0) == in1.extent(0) && out.extent(1) == in1.extent(1) &&
           out.extent(0) == in2.extent(0) && out.extent(1) == in2.extent(1);
}

constexpr bool multipliable(const in-matrix auto& in_mat, const in-vector auto& in_vec, const in-vector auto& out_vec) {
    return out_vec.extent(0) == in_mat.extent(0) && in_mat.extent(1) == in_vec.extent(0);
}

constexpr bool multipliable(const in-vector auto& in_vec, const in-matrix auto& in_mat, const in-vector auto& out_vec) {
    return out_vec.extent(0) == in_mat.extent(1) && in_mat.extent(0) == in_vec.extent(0);
}

constexpr bool multipliable(const in-matrix auto& in_mat1, const in-matrix auto& in_mat2, const in-matrix auto& out_mat) {
    return out_mat.extent(0) == in_mat1.extent(0) && out_mat.extent(1) == in_mat2.extent(1) &&
           in1_mat.extent(1) == in_mat2.extent(0);
28.9.8 Scaled in-place transformation

28.9.8.1 Introduction

The `scaled` function takes a value `alpha` and an `mdspan x`, and returns a new read-only `mdspan` that represents the elementwise product of `alpha` with each element of `x`.

[Example 1:

```cpp
using Vec = mdspan<double, dextents<size_t, 1>>;

// z = alpha * x + y
void z_equals_alpha_times_x_plus_y(double alpha, Vec x, Vec y, Vec z) {
    add(scaled(alpha, x), y, z);
}

// z = alpha * x + beta * y
void z_equals_alpha_times_x_plus_beta_times_y(double alpha, Vec x, double beta, Vec y, Vec z) {
    add(scaled(alpha, x), scaled(beta, y), z);
}
```
—end example]

28.9.8.2 Class template scaled_accessor

The class template `scaled_accessor` is an `mdspan` accessor policy which upon access produces scaled elements. It is part of the implementation of `scaled` (28.9.8.3).

```cpp
namespace std::linalg {
    template<class ScalingFactor, class NestedAccessor>
    class scaled_accessor {
        public:
            using element_type = add_const_t<decltype(declval<ScalingFactor>() * declval<NestedAccessor::element_type>())>;
            using reference = remove_const_t<element_type>;
            using data_handle_type = NestedAccessor::data_handle_type;
            using offset_policy = scaled_accessor<ScalingFactor, NestedAccessor::offset_policy>;

            constexpr scaled_accessor() = default;
            template<class OtherNestedAccessor>
                explicit(!is_convertible_v<OtherNestedAccessor, NestedAccessor>)
                    constexpr scaled_accessor(const scaled_accessor<ScalingFactor, OtherNestedAccessor>& other);
            constexpr scaled_accessor(const ScalingFactor& s, const NestedAccessor& a);

            constexpr reference access(data_handle_type p, size_t i) const;
            constexpr offset_policy::data_handle_type offset(data_handle_type p, size_t i) const;

            constexpr const ScalingFactor& scaling_factor() const noexcept { return scaling_factor; }
            constexpr const NestedAccessor& nested_accessor() const noexcept { return nested_accessor; }

        private:
            ScalingFactor scaling_factor{};
            NestedAccessor nested_accessor{};  // exposition only
        }
    };
}
```

Mandates:

(2.1) — `element_type` is valid and denotes a type,
(2.2) — `is_copy_constructible_v<reference>` is true,
(2.3) — `is_reference_v<element_type>` is false,
(2.4) — `ScalingFactor` models semiregular, and
(2.5) — `NestedAccessor` meets the accessor policy requirements (24.7.3.5.2).
template<class OtherNestedAccessor>
explicit(!is_convertible_v<OtherNestedAccessor, NestedAccessor>)
constexpr scaled_accessor(const scaled_accessor<ScalingFactor, OtherNestedAccessor>& other);

Constraints: is_constructible_v<NestedAccessor, const OtherNestedAccessor&> is true.

Effects:
(4.1) — Direct-non-list-initializes scaling-factor with other.scaling_factor(), and
(4.2) — direct-non-list-initializes nested-accessor with other.nested_accessor().

constexpr scaled_accessor(const ScalingFactor&, const NestedAccessor&);

Effects:
(5.1) — Direct-non-list-initializes scaling-factor with s, and
(5.2) — direct-non-list-initializes nested-accessor with a.

constexpr reference access(data_handle_type p, size_t i) const;

Returns:
scaling_factor() * NestedAccessor::element_type(nested-accessor.access(p, i))

constexpr offset_policy::data_handle_type offset(data_handle_type p, size_t i) const;

Returns: nested-accessor.offset(p, i)

28.9.8.3 Function template scaled [linalg.scaled.scaled]
The scaled function template takes a scaling factor alpha and an mdspan x, and returns a new read-only mdspan with the same domain as x, that represents the elementwise product of alpha with each element of x.

template<class ScalingFactor, class ElementType, class Extents, class Layout, class Accessor>
constexpr auto scaled(ScalingFactor alpha, mdspan<ElementType, Extents, Layout, Accessor> x);

Let SA be scaled_accessor<ScalingFactor, Accessor>.

Returns:
mdspan<typename SA::element_type, Extents, Layout, SA>(x.data_handle(), x.mapping(),
SA(alpha, x.accessor()));

[Example 1: void test_scaled(mdspan<double, extents<int, 10>> x)
{ auto x_scaled = scaled(5.0, x); for (int i = 0; i < x.extent(0); ++i) { assert(x_scaled[i] == 5.0 * x[i]); }
} — end example]

28.9.9 Conjugated in-place transformation [linalg.conj]

28.9.9.1 Introduction [linalg.conj.intro]
The conjugated function takes an mdspan x, and returns a new read-only mdspan y with the same domain as x, whose elements are the complex conjugates of the corresponding elements of x.

28.9.9.2 Class template conjugated_accessor [linalg.conj.conjugatedaccessor]
The class template conjugated_accessor is an mdspan accessor policy which upon access produces conjugate elements. It is part of the implementation of conjugated (28.9.9.3).

namespace std::linalg {
    template<class NestedAccessor>
    class conjugated_accessor {
        public:
            using element_type =
                add_const_t<decltype(conj-if-needed(declval<NestedAccessor::element_type>()))>>;

§ 28.9.9.2 © ISO/IEC 1580
using reference = remove_const_t<element_type>;
using data_handle_type = typename NestedAccessor::data_handle_type;
using offset_policy = conjugated_accessor<NestedAccessor::offset_policy>;

constexpr conjugated_accessor() = default;
template<class OtherNestedAccessor>
  explicit(!is_convertible_v<OtherNestedAccessor, NestedAccessor>)
    constexpr conjugated_accessor(const conjugated_accessor<OtherNestedAccessor>& other);

constexpr reference access(data_handle_type p, size_t i) const;
constexpr typename offset_policy::data_handle_type
  offset(data_handle_type p, size_t i) const;

private:
  NestedAccessor nested_accessor_{};

  // exposition only
};

2

Mandates:
(2.1) — element_type is valid and denotes a type,
(2.2) — is_copy_constructible_v<reference> is true,
(2.3) — is_reference_v<element_type> is false, and
(2.4) — NestedAccessor meets the accessor policy requirements (24.7.3.5.2).

constexpr conjugated_accessor(const NestedAccessor& acc);

3

Effects: Direct-non-list-initializes nested-accessor_ with acc.

template<class OtherNestedAccessor>
  explicit(!is_convertible_v<OtherNestedAccessor, NestedAccessor>)
    constexpr conjugated_accessor(const conjugated_accessor<OtherNestedAccessor>& other);

Constraints: is_constructible_v<NestedAccessor, const OtherNestedAccessor&> is true.

5

Effects: Direct-non-list-initializes nested-accessor_ with other.nested_accessor().

constexpr reference access(data_handle_type p, size_t i) const;

6

Returns: conj-if-needed(NestedAccessor::element_type(nested-accessor_.access(p, i)))

constexpr typename offset_policy::data_handle_type offset(data_handle_type p, size_t i) const;

7

Returns: nested-accessor_.offset(p, i)

28.9.9.3 Function template conjugated

[finalg.conj.conjugated]

template<class ElementType, class Extents, class Layout, class Accessor>
  constexpr auto conjugated(mdspan<ElementType, Extents, Layout, Accessor> a);

1

Let A be remove_cvref_t<decltype(a.accessor().nested_accessor())> if Accessor is a specialization of conjugated_accessor, and otherwise conjugated_accessor<Accessor>.

2

Returns:
(2.1) — If Accessor is a specialization of conjugated_accessor,

  mdspan<typeName A::element_type, Extents, Layout, A>(a.data_handle(), a.mapping(),
          a.accessor().nested_accessor())

(2.2) — otherwise,

  mdspan<typeName A::element_type, Extents, Layout, A>(a.data_handle(), a.mapping(),
          conjugated_accessor(a.accessor()))

3

Example 1:
void test_conjugated_complex(mdspan<complex<double>, extents<int, 10>> a) {
  auto a_conj = conjugated(a);
for (int i = 0; i < a.extent(0); ++i) {
    assert(a_conj[i] == conj(a[i]));
}
auto a_conj_conj = conjugated(a_conj);
for (int i = 0; i < a.extent(0); ++i) {
    assert(a_conj_conj[i] == a[i]);
}
}

void test_conjugated_real(mdspan<double, extents<int, 10>> a) {
    auto a_conj = conjugated(a);
    for (int i = 0; i < a.extent(0); ++i) {
        assert(a_conj[i] == a[i]);
    }
    auto a_conj_conj = conjugated(a_conj);
    for (int i = 0; i < a.extent(0); ++i) {
        assert(a_conj_conj[i] == a[i]);
    }
}

—with example—

28.9.10 Transpose in-place transformation

28.9.10.1 Introduction

1 layout_transpose is an mdspan layout mapping policy that swaps the two indices, extents, and strides of any unique mdspan layout mapping policy.

2 The transposed function takes an mdspan representing a matrix, and returns a new mdspan representing the transpose of the input matrix.

28.9.10.2 Exposition-only helpers for layout_transpose and transposed

1 The exposition-only transpose-extents function takes an extents object representing the extents of a matrix, and returns a new extents object representing the extents of the transpose of the matrix.

2 The exposition-only alias template transpose-extents-t<InputExtents> gives the type of transpose-extents(e) for a given extents object e of type InputExtents.

template<class IndexType, size_t InputExtent0, size_t InputExtent1>
constexpr extents<IndexType, InputExtent1, InputExtent0>
transpose-extents(const extents<IndexType, InputExtent0, InputExtent1>& in); // exposition only

Returns: extents<IndexType, InputExtent1, InputExtent0>(in.extent(1), in.extent(0))

3 template<class InputExtents>
    using transpose-extents-t = decltype(transpose-extents(declval<InputExtents>())); // exposition only

28.9.10.3 Class template layout_transpose

1 layout_transpose is an mdspan layout mapping policy that swaps the two indices, extents, and strides of any mdspan layout mapping policy.

namespace std::linalg {
    template<class Layout>
    class layout_transpose {
        using nested_layout_type = Layout;

        template<class Extents>
        struct mapping {
            private:
                using nested-mapping-type =
                    typename Layout::template mapping<
                        transpose-extents-t<Extents>>; // exposition only
public:
using extents_type = Extents;
using index_type = typename extents_type::index_type;
using size_type = typename extents_type::size_type;
using rank_type = typename extents_type::rank_type;
using layout_type = layout_transpose;

constexpr explicit mapping(const nested-mapping-type &);

constexpr const extents_type & extents() const noexcept { return extents_; }

constexpr index_type required_span_size() const
{ return nested-mapping_.required_span_size(); }

template<class Index0, class Index1>
constexpr index_type operator()(Index0 ind0, Index1 ind1) const
{ return nested-mapping_(ind1, ind0); }

constexpr const nested-mapping-type & nested_mapping() const noexcept
{ return nested-mapping_; }

static constexpr bool is_always_unique() noexcept
{ return nested-mapping-type::is_always_unique(); }

static constexpr bool is_always_exhaustive() noexcept
{ return nested-mapping-type::is_always_exhaustive(); }

static constexpr bool is_always_strided() noexcept
{ return nested-mapping-type::is_always_strided(); }

constexpr bool is_unique() const { return nested-mapping_.is_unique(); }

constexpr bool is_exhaustive() const { return nested-mapping_.is_exhaustive(); }

constexpr bool is_strided() const { return nested-mapping_.is_strided(); }

constexpr index_type stride(size_t r) const;

template<class OtherExtents>
friend constexpr bool operator==(const mapping & x, const mapping<OtherExtents>& y);

private:

nested-mapping-type nested_mapping_; // exposition only

extents_type extents_; // exposition only

};

Layout shall meet the layout mapping policy requirements (24.7.3.4.3).

Mandates:

(3.1) — Extents is a specialization of std::extents, and

(3.2) — Extents::rank() equals 2.

constexpr explicit mapping(const nested-mapping-type & map);

Effects:

(4.1) — Initializes nested-mapping_ with map, and

(4.2) — initializes extents_ with transpose-extents(map.extents()).

constexpr index_type stride(size_t r) const;

Preconditions:

(5.1) — is_strided() is true, and

(5.2) — r < 2 is true.

Returns: nested-mapping_.stride(r == 0 ? 1 : 0)
template<class OtherExtents>
friend constexpr bool operator==(const mapping& x, const mapping<OtherExtents>& y);

Constraints: The expression \(x.nested\text{-}mapping_ == y.nested\text{-}mapping_\) is well-formed and its result is convertible to bool.

Returns: \(x.nested\text{-}mapping_ == y.nested\text{-}mapping_\).

### 28.9.10.4 Function template transposed

The \texttt{transposed} function takes a rank-2 \texttt{mdspan} representing a matrix, and returns a new \texttt{mdspan} representing the input matrix's transpose. The input matrix's data are not modified, and the returned \texttt{mdspan} accesses the input matrix's data in place.

```
template<class ElementType, class Extents, class Layout, class Accessor>
constexpr auto transposed(mdspan<ElementType, Extents, Layout, Accessor> a);
```

Mandates: \texttt{Extents}::\texttt{rank()} == 2 is true.

Let \texttt{ReturnExtents} be \texttt{transpose\text{-}extents\text{-}t<Extents>}. Let \(R\) be \texttt{mdspan<ElementType, ReturnExtents, ReturnLayout, Accessor>}, where \texttt{ReturnLayout} is:

\begin{enumerate}
\item layout\texttt{right} if \texttt{Layout} is layout\texttt{left};
\item otherwise, layout\texttt{left} if \texttt{Layout} is layout\texttt{right};
\item otherwise, layout\texttt{stride} if \texttt{Layout} is layout\texttt{stride};
\item otherwise, layout\texttt{blas\_packed}\texttt{<OppositeTriangle, OppositeStorageOrder>}, if \texttt{Layout} is layout\texttt{blas\_packed}\texttt{<Triangle, StorageOrder>} for some \texttt{Triangle} and \texttt{StorageOrder}, where
\begin{enumerate}
\item \texttt{OppositeTriangle} is \texttt{conditional\texttt{t}<is\texttt{same\_v<Triangle, upper\texttt{triangle\_t}, lower\texttt{triangle\_t, upper\texttt{triangle\_t}>}}}
\item \texttt{OppositeStorageOrder} is \texttt{conditional\texttt{t}<is\texttt{same\_v<StorageOrder, column\_major\_t>, row\_major\_t, column\_major\_t>}}
\item otherwise, \texttt{NestedLayout} if \texttt{Layout} is layout\texttt{transpose}\texttt{<NestedLayout>} for some \texttt{NestedLayout};
\item otherwise, layout\texttt{transpose}\texttt{<Layout>}.
\end{enumerate}
\end{enumerate}

Returns: With \texttt{ReturnMapping} being the type \texttt{typename ReturnLayout::\texttt{template mapping<ReturnExtents>}}:

\begin{enumerate}
\item if \texttt{Layout} is layout\texttt{left}, layout\texttt{right}, or a specialization of layout\texttt{blas\_packed},
\[R(a.data\_handle(), ReturnMapping(transpose\texttt{-}extents(a.mapping().extents())), a.accessor())\]
\item otherwise, if \texttt{Layout} is layout\texttt{stride},
\[R(a.data\_handle(), ReturnMapping(transpose\texttt{-}extents(a.mapping().extents())),
Array(a.mapping().stride(1), a.mapping().stride(0)), a.accessor())\]
\item otherwise, if \texttt{Layout} is a specialization of layout\texttt{transpose},
\[R(a.data\_handle(), a.mapping().nested\_mapping(), a.accessor())\]
\item otherwise,
\[R(a.data\_handle(), ReturnMapping(a.mapping()), a.accessor())\]
\end{enumerate}

[Example 1]:
```
void test_transposed(mdspan<double, extents<size_t, 3, 4>> a) {
    const auto num_rows = a.extent(0);
    const auto num_cols = a.extent(1);

    auto a_t = transposed(a);
    assert(num_rows == a_t.extent(1));
    assert(num_rows == a_t.extent(0));
```
assert(a.stride(0) == a_t.stride(1));
assert(a.stride(1) == a_t.stride(0));

for (size_t row = 0; row < num_rows; ++row) {
    for (size_t col = 0; col < num_rows; ++col) {
        assert(a[row, col] == a_t[col, row]);
    }
}

auto a_t_t = transposed(a_t);
assert(num_rows == a_t_t.extent(0));
assert(num_cols == a_t_t.extent(1));
assert(a.stride(0) == a_t_t.stride(0));
assert(a.stride(1) == a_t_t.stride(1));

for (size_t row = 0; row < num_rows; ++row) {
    for (size_t col = 0; col < num_rows; ++col) {
        assert(a[row, col] == a_t_t[row, col]);
    }
}

—end example—

28.9.11 Conjugate transpose in-place transform

The conjugate_transposed function returns a conjugate transpose view of an object. This combines the effects of transposed and conjugated.

1 The conjugate_transposed function returns a conjugate transpose view of an object. This combines the effects of transposed and conjugated.

2 template<class ElementType, class Extents, class Layout, class Accessor>
    constexpr auto conjugate_transposed(mdspan<ElementType, Extents, Layout, Accessor> a);

3 [Example 1]:

    void test_conjugate_transposed(mdspan<complex<double>, extents<size_t, 3, 4>> a) {
        const auto num_rows = a.extent(0);
        const auto num_cols = a.extent(1);

        auto a_ct = conjugate_transposed(a);
        assert(num_rows == a_ct.extent(1));
        assert(num_cols == a_ct.extent(0));
        assert(a.stride(0) == a_ct.stride(1));
        assert(a.stride(1) == a_ct.stride(0));

        for (size_t row = 0; row < num_rows; ++row) {
            for (size_t col = 0; col < num_rows; ++col) {
                assert(a[row, col] == conj(a_ct[col, row]));
            }
        }

        auto a_ct_ct = conjugate_transposed(a_ct);
        assert(num_rows == a_ct_ct.extent(0));
        assert(num_cols == a_ct_ct.extent(1));
        assert(a.stride(0) == a_ct_ct.stride(0));
        assert(a.stride(1) == a_ct_ct.stride(1));

        for (size_t row = 0; row < num_rows; ++row) {
            for (size_t col = 0; col < num_rows; ++col) {
                assert(a[row, col] == a_ct_ct[row, col]);
                assert(conj(a_ct[col, row]) == a_ct_ct[row, col]);
            }
        }
    }

—end example—

§ 28.9.11 © ISO/IEC 1585
28.9.12 Algorithm requirements based on template parameter name

Throughout 28.9.13, 28.9.14, and 28.9.15, where the template parameters are not constrained, the names of template parameters are used to express the following constraints.

1. \( \text{is_execution_policy<ExecutionPolicy>::value} \) is true (22.12.3).
2. \( \text{Real} \) is any type such that \( \text{complex<Real>} \) is specified (28.4.1).
3. \( \text{Triangle} \) is either \( \text{upper_triangle_t} \) or \( \text{lower_triangle_t} \).
4. \( \text{DiagonalStorage} \) is either \( \text{implicit_unit_diagonal_t} \) or \( \text{explicit_diagonal_t} \).

[Note 1: Function templates that have a template parameter named \text{ExecutionPolicy} are parallel algorithms (27.3.1).
—end note]

28.9.13 BLAS 1 algorithms

28.9.13.1 Complexity

Complexity: All algorithms in 28.9.13 with \text{mdspan} parameters perform a count of \text{mdspan} array accesses and arithmetic operations that is linear in the maximum product of extents of any \text{mdspan} parameter.

28.9.13.2 Givens rotations

28.9.13.2.1 Compute Givens rotation

\begin{verbatim}
template<class Real>
setup_givens_rotation_result<Real> setup_givens_rotation(Real a, Real b) noexcept; 

template<class Real>
setup_givens_rotation_result<complex<Real>>
setup_givens_rotation(complex<Real> a, complex<Real> b) noexcept; 
\end{verbatim}

These functions compute the Givens plane rotation represented by the two values \( c \) and \( s \) such that the 2 x 2 system of equations

\begin{equation}
\begin{bmatrix}
c & s \\
-\bar{s} & c \\
\end{bmatrix}
\begin{bmatrix}
a \\
b \\
\end{bmatrix}
= 
\begin{bmatrix}
r \\
0 \\
\end{bmatrix}
\end{equation}

holds, where \( c \) is always a real scalar, and \( c^2 + |s|^2 = 1 \). That is, \( c \) and \( s \) represent a 2 x 2 matrix, that when multiplied by the right by the input vector whose components are \( a \) and \( b \), produces a result vector whose first component \( r \) is the Euclidean norm of the input vector, and whose second component is zero.

[Note 1: These functions correspond to the LAPACK function \text{xLARTG}\[20\]. —end note]

Returns: \( c, s, r \), where \( c \) and \( s \) form the Givens plane rotation corresponding to the input \( a \) and \( b \), and \( r \) is the Euclidean norm of the two-component vector formed by \( a \) and \( b \).

28.9.13.2.2 Apply a computed Givens rotation to vectors

\begin{verbatim}
template<\text{inout-vector InOutVec1, inout-vector InOutVec2, class Real}>
void apply_givens_rotation(InOutVec1 x, InOutVec2 y, Real c, Real s); 

template<\text{ExecutionPolicy, inout-vector InOutVec1, inout-vector InOutVec2, class Real}>
void apply_givens_rotation(ExecutionPolicy&& exec,
InOutVec1 x, InOutVec2 y, Real c, Real s); 

template<\text{inout-vector InOutVec1, inout-vector InOutVec2, class Real}>
void apply_givens_rotation(InOutVec1 x, InOutVec2 y, Real c, complex<Real> s); 

template<\text{ExecutionPolicy, inout-vector InOutVec1, inout-vector InOutVec2, class Real}>
void apply_givens_rotation(ExecutionPolicy&& exec,
InOutVec1 x, InOutVec2 y, Real c, complex<Real> s); 
\end{verbatim}

[Note 1: These functions correspond to the BLAS function \text{xROT}\[17\]. —end note]

Mandates: \text{compatible-static-extents<InOutVec1, InOutVec2>(0, 0)} \) is true.

Preconditions: \( x.\text{extent}(0) \) equals \( y.\text{extent}(0) \).

Effects: Applies the plane rotation specified by \( c \) and \( s \) to the input vectors \( x \) and \( y \), as if the rotation were a 2 x 2 matrix and the input vectors were successive rows of a matrix with two rows.
28.9.13.3 Swap matrix or vector elements

template<inout-object InOutObj1, inout-object InOutObj2>
void swap_elements(InOutObj1 x, InOutObj2 y);

template<class ExecutionPolicy, inout-object InOutObj1, inout-object InOutObj2>
void swap_elements(ExecutionPolicy&& exec, InOutObj1 x, InOutObj2 y);

[Note 1: These functions correspond to the BLAS function xSWAP\textsuperscript{[17].} — end note]

Constraints: x.rank() equals y.rank().

Mandates: For all r in the range \([0, x.rank())\),
compatible-static-extents<InOutObj1, InOutObj2>(r, r)
is true.

Preconditions: x.extents() equals y.extents().

Effects: Swaps all corresponding elements of x and y.

28.9.13.4 Multiply the elements of an object in place by a scalar

template<class Scalar, inout-object InOutObj>
void scale(Scalar alpha, InOutObj x);

template<class ExecutionPolicy, class Scalar, inout-object InOutObj>
void scale(ExecutionPolicy&& exec, Scalar alpha, InOutObj x);

[Note 1: These functions correspond to the BLAS function xSCAL\textsuperscript{[17].} — end note]

Effects: Overwrites x with the result of computing the elementwise multiplication \(\alpha x\), where the scalar \(\alpha\) is alpha.

28.9.13.5 Copy elements of one matrix or vector into another

template<in-object InObj, out-object OutObj>
void copy(InObj x, OutObj y);

template<class ExecutionPolicy, in-object InObj, out-object OutObj>
void copy(ExecutionPolicy&& exec, InObj x, OutObj y);

[Note 1: These functions correspond to the BLAS function xCOPY\textsuperscript{[17].} — end note]

Constraints: x.rank() equals y.rank().

Mandates: For all r in the range \([0, x.rank())\),
compatible-static-extents<InObj, OutObj>(r, r)
is true.

Preconditions: x.extents() equals y.extents().

Effects: Assigns each element of x to the corresponding element of y.

28.9.13.6 Add vectors or matrices elementwise

template<in-object InObj1, in-object InObj2, out-object OutObj>
void add(InObj1 x, InObj2 y, OutObj z);

template<class ExecutionPolicy, in-object InObj1, in-object InObj2, out-object OutObj>
void add(ExecutionPolicy&& exec, InObj1 x, InObj2 y, OutObj z);

[Note 1: These functions correspond to the BLAS function xAXPY\textsuperscript{[17].} — end note]

Constraints: x.rank(), y.rank(), and z.rank() are all equal.

Mandates: possibly-addable<InObj1, InObj2, OutObj>() is true.

Preconditions: addable(x, y, z) is true.

Effects: Computes \(z = x + y\).

Remarks: z may alias x or y.

28.9.13.7 Dot product of two vectors

[Note 1: The functions in this section correspond to the BLAS functions xDOT, xDOTU, and xDOTC\textsuperscript{[17].} — end note]
The following elements apply to all functions in §28.9.13.7.

Mandates: compatible-static-extents<InVec1, InVec2>(0, 0) is true.

Preconditions: v1.extent(0) equals v2.extent(0).

template<in-vector InVec1, in-vector InVec2, class Scalar>
Scalar dot(InVec1 v1, InVec2 v2, Scalar init);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, class Scalar>
Scalar dot(ExecutionPolicy& exec,
InVec1 v1, InVec2 v2, Scalar init);

These functions compute a non-conjugated dot product with an explicitly specified result type.

Returns: Let N be v1.extent(0).

(6.1) init if N is zero;
(6.2) otherwise, GENERALIZED_SUM(plus<>(), init, v1[0]*v2[0], ..., v1[N-1]*v2[N-1]).

Remarks: If InVec1::value_type, InVec2::value_type, and Scalar are all floating-point types or specializations of complex, and if Scalar has higher precision than InVec1::value_type or InVec2::value_type, then intermediate terms in the sum use Scalar's precision or greater.

template<in-vector InVec1, in-vector InVec2>
auto dot(InVec1 v1, InVec2 v2);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2>
auto dot(ExecutionPolicy& exec,
InVec1 v1, InVec2 v2);

These functions compute a non-conjugated dot product with a default result type.

Effects: Let T be decltype(declval<typename InVec1::value_type>() * declval<typename InVec2::value_type>())(). Then,

(9.1) the two-parameter overload is equivalent to:
return dot(v1, v2, T());
and
(9.2) the three-parameter overload is equivalent to:
return dot(std::forward<ExecutionPolicy>(exec), v1, v2, T());

template<in-vector InVec1, in-vector InVec2, class Scalar>
Scalar dotc(InVec1 v1, InVec2 v2, Scalar init);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, class Scalar>
Scalar dotc(ExecutionPolicy& exec,
InVec1 v1, InVec2 v2, Scalar init);

These functions compute a conjugated dot product with an explicitly specified result type.

Effects:

(11.1) The three-parameter overload is equivalent to:
return dot(conjugated(v1), v2, init);
and
(11.2) the four-parameter overload is equivalent to:
return dot(std::forward<ExecutionPolicy>(exec), conjugated(v1), v2, init);

template<in-vector InVec1, in-vector InVec2>
auto dotc(InVec1 v1, InVec2 v2);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2>
auto dotc(ExecutionPolicy& exec,
InVec1 v1, InVec2 v2);

These functions compute a conjugated dot product with a default result type.

Effects: Let T be decltype(conj-if-needed(declval<typename InVec1::value_type>() * declval<typename InVec2::value_type>())(). Then,
(13.1) the two-parameter overload is equivalent to:
   return dotc(v1, v2, T{});
and
(13.2) the three-parameter overload is equivalent to
   return dotc(std::forward<ExecutionPolicy>(exec), v1, v2, T{});

28.9.13.8 Scaled sum of squares of a vector’s elements

template<in-vector InVec, class Scalar>
sum_of_squares_result<scalar> vector_sum_of_squares(InVec v, sum_of_squares_result<scalar> init);

Note 1: These functions correspond to the LAPACK function xLASSQ\[20\]. —end note

Mandates: decltype(abs-if-needed(declval<typename InVec::value_type>())) is convertible to Scalar.

Effects: Returns a value result such that
   — result.scaling_factor is the maximum of init.scaling_factor and abs-if-needed(x[i])
     for all i in the domain of v; and
   — let s2init be
     init.scaling_factor * init.scaling_factor * init.scaled_sum_of_squares
     then result.scaling_factor * result.scaling_factor * result.scaled_sum_of_squares
     equals the sum of s2init and the squares of abs-if-needed(x[i]) for all i in the domain of v.

Remarks: If InVec::value_type, and Scalar are all floating-point types or specializations of complex,
and if Scalar has higher precision than InVec::value_type, then intermediate terms in the sum use
Scalar's precision or greater.

28.9.13.9 Euclidean norm of a vector

template<in-vector InVec, class Scalar>
Scalar vector_two_norm(InVec v, Scalar init);

Note 1: These functions correspond to the BLAS function xNRM2\[17\]. —end note

Mandates: Let a be abs-if-needed(declval<typename InVec::value_type>')(). Then, decltype(
   init + a * a) is convertible to Scalar.

Returns: The square root of the sum of the square of init and the squares of the absolute values of
the elements of v.

Note 2: For init equal to zero, this is the Euclidean norm (also called 2-norm) of the vector v. —end note

Remarks: If InVec::value_type, and Scalar are all floating-point types or specializations of complex,
and if Scalar has higher precision than InVec::value_type, then intermediate terms in the sum use
Scalar's precision or greater.

Note 3: An implementation of this function for floating-point types T can use the scaled_sum_of_squares
result from vector_sum_of_squares(x, {.scaling_factor=1.0, .scaled_sum_of_squares=init}). —end note

template<in-vector InVec>
auto vector_two_norm(InVec v);

Note 3: An implementation of this function for floating-point types T can use the scaled_sum_of_squares
result from vector_sum_of_squares(x, {.scaling_factor=1.0, .scaled_sum_of_squares=init}). —end note

Effects: Let a be abs-if-needed(declval<typename InVec::value_type>()). Let T be decltype(a
   * a). Then,
   — the one-parameter overload is equivalent to:
     return vector_two_norm(v, T{});
and

(5.2) — the two-parameter overload is equivalent to:

return vector_two_norm(std::forward<ExecutionPolicy>(exec), v, T{});

28.9.13.10 Sum of absolute values of vector elements

template<in-vector InVec, class Scalar>
Scalar vector_abs_sum(InVec v, Scalar init);
template<class ExecutionPolicy, in-vector InVec, class Scalar>
Scalar vector_abs_sum(ExecutionPolicy& exec, InVec v, Scalar init);

[Note 1: These functions correspond to the BLAS functions SASUM, DASUM, SCASUM, and DZASUM. —end note]

Mandates:

declayte(init + abs-if-needed(real-if-needed(declval<typename InVec::value_type>(v[0]))) +
abs-if-needed(imag-if-needed(declval<typename InVec::value_type>(v[0])))

is convertible to Scalar.

Returns: Let \( N \) be \( v.\text{extent}(0) \).

— init if \( N \) is zero;
(3.1) — otherwise, if InVec::value_type is an arithmetic type,

\[
\text{GENERALIZED\_SUM}(\text{plus}(), \text{init}, \text{abs-if-needed}(v[0]), \ldots, \text{abs-if-needed}(v[N-1])
\]
(3.2) — otherwise,

\[
\text{GENERALIZED\_SUM}(\text{plus}(), \text{init},
\text{abs-if-needed}(\text{real-if-needed}(v[0])) + \text{abs-if-needed}(\text{imag-if-needed}(v[0])),
\ldots,
\text{abs-if-needed}(\text{real-if-needed}(v[N-1])) + \text{abs-if-needed}(\text{imag-if-needed}(v[N-1]))
\]

Remarks: If InVec::value_type and Scalar are all floating-point types or specializations of complex, and if Scalar has higher precision than InVec::value_type, then intermediate terms in the sum use Scalar’s precision or greater.

template<in-vector InVec>
auto vector_abs_sum(InVec v);
template<class ExecutionPolicy, in-vector InVec>
auto vector_abs_sum(ExecutionPolicy& exec, InVec v);

Effects: Let \( T \) be typename InVec::value_type. Then,

(5.1) — the one-parameter overload is equivalent to:

return vector_abs_sum(v, T{});

and

(5.2) — the two-parameter overload is equivalent to:

return vector_abs_sum(std::forward<ExecutionPolicy>(exec), v, T{});

28.9.13.11 Index of maximum absolute value of vector elements

template<in-vector InVec>
typename InVec::extents_type vector_idx_abs_max(InVec v);
template<class ExecutionPolicy, in-vector InVec>
typename InVec::extents_type vector_idx_abs_max(ExecutionPolicy& exec, InVec v);

[Note 1: These functions correspond to the BLAS function IxAMAX. —end note]

Let \( T \) be

declayte(abs-if-needed(real-if-needed(declval<typename InVec::value_type>(v[0]))) +
abs-if-needed(imag-if-needed(declval<typename InVec::value_type>(v[0])))

Mandates: declval<T>() < declval<T>() is a valid expression.

Returns:

(4.1) — numeric_limits<typename InVec::size_type>::max() if \( v \) has zero elements;
— otherwise, the index of the first element of \( v \) having largest absolute value, if \( \text{InVec}::\text{value\_type} \)

is an arithmetic type;

— otherwise, the index of the first element \( v_e \) of \( v \) for which

\[
\text{abs-if-needed}(\text{real-if-needed}(v_e)) + \text{abs-if-needed}(\text{imag-if-needed}(v_e))
\]

has the largest value.

### 28.9.13.12 Frobenius norm of a matrix

[\text{linalg.algs.blas1.matfrobnorm}]

1 [Note 1: These functions exist in the BLAS standard\(^{[21]} \) but are not part of the reference implementation. — end note]

\[
\begin{align*}
\text{template}<\text{in-matrix } \text{InMat}, \text{class Scalar}> \\
\quad & \text{Scalar matrix_frob_norm(} \text{InMat} \text{A, Scalar init);} \\
\text{template<class ExecutionPolicy, in-matrix } \text{InMat}, \text{class Scalar}> \\
\quad & \text{Scalar matrix_frob_norm(} \text{ExecutionPolicy}&& \text{exec, InMat} \text{A, Scalar init);}
\end{align*}
\]

2 **Mandates:** Let \( a \) be \( \text{abs-if-needed}(\text{declval<typename InMat::value\_type>()}) \). Then, \( \text{decltype(} \text{init + a * a}) \) is convertible to \( \text{Scalar} \).

3 **Returns:** The square root of the sum of squares of \( \text{init} \) and the absolute values of the elements of \( \text{A} \).

[Note 2: For \( \text{init} \) equal to zero, this is the Frobenius norm of the matrix \( \text{A} \). — end note]

4 **Remarks:** If \( \text{InMat::value\_type} \) and \( \text{Scalar} \) are all floating-point types or specializations of \text{complex}, and if \( \text{Scalar} \) has higher precision than \( \text{InMat::value\_type} \), then intermediate terms in the sum use \( \text{Scalar} \)'s precision or greater.

\[
\begin{align*}
\text{template}<\text{in-matrix } \text{InMat}> \\
\quad & \text{auto matrix_frob_norm(} \text{InMat} \text{A);} \\
\text{template<class ExecutionPolicy, in-matrix } \text{InMat}> \\
\quad & \text{auto matrix_frob_norm(} \text{ExecutionPolicy}&& \text{exec, InMat} \text{A);}
\end{align*}
\]

5 **Effects:** Let \( a \) be \( \text{abs-if-needed}(\text{declval<typename InMat::value\_type>()}) \). Let \( T \) be \( \text{decltype(a * a}) \). Then,

\[
\text{(5.1)} \quad \text{the one-parameter overload is equivalent to:} \\
\quad \text{return matrix_frob_norm(A, T{});}
\]

and

\[
\text{(5.2)} \quad \text{the two-parameter overload is equivalent to:} \\
\quad \text{return matrix_frob_norm(} \text{std::forward<ExecutionPolicy>(exec), A, T{});}
\]

### 28.9.13.13 One norm of a matrix

[\text{linalg.algs.blas1.matonenorm}]

1 [Note 1: These functions exist in the BLAS standard\(^{[21]} \) but are not part of the reference implementation. — end note]

\[
\begin{align*}
\text{template}<\text{in-matrix } \text{InMat}, \text{class Scalar}> \\
\quad & \text{Scalar matrix_one_norm(} \text{InMat} \text{A, Scalar init);} \\
\text{template<class ExecutionPolicy, in-matrix } \text{InMat}, \text{class Scalar}> \\
\quad & \text{Scalar matrix_one_norm(} \text{ExecutionPolicy}&& \text{exec, InMat} \text{A, Scalar init);}
\end{align*}
\]

2 **Mandates:** \( \text{decltype(} \text{abs-if-needed}(\text{declval<typename InMat::value\_type>()}) \) is convertible to \( \text{Scalar} \).

3 **Returns:**

\[
\begin{align*}
\text{(3.1)} \quad & \text{init if } \text{A.extent(1)} \text{ is zero;} \\
\text{(3.2)} \quad & \text{otherwise, the sum of } \text{init} \text{ and the one norm of the matrix } \text{A.}
\end{align*}
\]

[Note 2: The one norm of the matrix \( \text{A} \) is the maximum over all columns of \( \text{A} \), of the sum of the absolute values of the elements of the column. — end note]

4 **Remarks:** If \( \text{InMat::value\_type} \) and \( \text{Scalar} \) are all floating-point types or specializations of \text{complex}, and if \( \text{Scalar} \) has higher precision than \( \text{InMat::value\_type} \), then intermediate terms in the sum use \( \text{Scalar} \)'s precision or greater.

§ 28.9.13.13
template<in-matrix InMat>
    auto matrix_one_norm(InMat A);

template<class ExecutionPolicy, in-matrix InMat>
    auto matrix_one_norm(ExecutionPolicy&& exec, InMat A);

Effects: Let \( T \) be `decltype(abs-if-needed(declval<typename InMat::value_type>())`. Then,

\[(5.1)\]

- the one-parameter overload is equivalent to:

\[
\text{return matrix_one_norm(A, T{);}}
\]

and

\[(5.2)\]

- the two-parameter overload is equivalent to:

\[
\text{return matrix_one_norm(std::forward<ExecutionPolicy>(exec), A, T{);}}
\]

28.9.13.14 Infinity norm of a matrix [linalg.algs.blas1.matinfnorm]

1 [Note 1: These functions exist in the BLAS standard\(^{[21]}\) but are not part of the reference implementation. — end note]

template<in-matrix InMat, class Scalar>
    Scalar matrix_inf_norm(InMat A, Scalar init);

template<class ExecutionPolicy, in-matrix InMat, class Scalar>
    Scalar matrix_inf_norm(ExecutionPolicy&& exec, InMat A, Scalar init);

Mandates: `decltype(abs-if-needed(declval<typename InMat::value_type>())`) is convertible to `Scalar`.

Returns:

\[(3.1)\]

- `init` if \( A.\text{extent}(0) \) is zero;

\[(3.2)\]

- otherwise, the sum of `init` and the infinity norm of the matrix \( A \).

[Note 2: The infinity norm of the matrix \( A \) is the maximum over all rows of \( A \), of the sum of the absolute values of the elements of the row. — end note]

Remarks: If `InMat::value_type` and `Scalar` are all floating-point types or specializations of `complex`, and if `Scalar` has higher precision than `InMat::value_type`, then intermediate terms in the sum use `Scalar`’s precision or greater.

template<in-matrix InMat>
    auto matrix_inf_norm(InMat A);

template<class ExecutionPolicy, in-matrix InMat>
    auto matrix_inf_norm(ExecutionPolicy&& exec, InMat A);

Effects: Let \( T \) be `decltype(abs-if-needed(declval<typename InMat::value_type>())`) Then,

\[(5.1)\]

- the one-parameter overload is equivalent to:

\[
\text{return matrix_inf_norm(A, T{);}}
\]

and

\[(5.2)\]

- the two-parameter overload is equivalent to:

\[
\text{return matrix_inf_norm(std::forward<ExecutionPolicy>(exec), A, T{);}}
\]

28.9.14 BLAS 2 algorithms [linalg.algs.blas2]

28.9.14.1 General matrix-vector product [linalg.algs.blas2.gemv]

1 [Note 1: These functions correspond to the BLAS function \( \text{xGEMV} \). — end note]

The following elements apply to all functions in 28.9.14.1.

Mandates:

\[(3.1)\]

- `possibly-multiplicable<decltype(A), decltype(x), decltype(y)>()` is true, and

\[(3.2)\]

- `possibly-addable< decltype(x), decltype(y), decltype(z)>()` is true for those overloads that take a \( z \) parameter.

Preconditions:

\[(4.1)\]

- `multiplicable(A,x,y)` is true, and
### 28.9.14.2 Symmetric matrix-vector product

[Note 1: These functions correspond to the BLAS functions `xSYMV` and `xSPMV`\[18\]. — end note]

The following elements apply to all functions in 28.9.14.2.

#### Mandates:

1. If `InMat` has `layout_blas_packed` layout, then the layout’s `Triangle` template argument has the same type as the function’s `Triangle` template argument;
2. `compatible-static-extents<decltype(A), decltype(A)>(0, 1)` is true;
3. `possibly-multiplyable<decltype(A), decltype(x), decltype(y)>()` is true; and
4. `possibly-addable<decltype(x), decltype(y), decltype(z)>()` is true for those overloads that take a `z` parameter.

#### Preconditions:

1. `A.extent(0)` equals `A.extent(1)`;
2. `O(x.extent(0) \times A.extent(1))`. 

The following overloads take a `z` parameter.

*template<in-matrix InMat, in-vector InVec, out-vector OutVec>*

    ```cpp
    void matrix_vector_product(InMat A, InVec x, OutVec y);
    ```

    These functions perform an overwriting matrix-vector product.

    ```cpp
    Effects: Computes `y = Ax`.
    ```

    ```cpp
    [Example 1:
     constexpr size_t num_rows = 5;
     constexpr size_t num_cols = 6;
     
     // y = 3.0 * A * x
     void scaled_matvec_1(mdspan<double, extents<size_t, num_rows, num_cols>> A, mdspan<double, extents<size_t, num_rows, num_cols>> x, mdspan<double, extents<size_t, num_rows, num_cols>> y) {
       matrix_vector_product(scaled(3.0, A), x, y);
     }
    ```

    ```cpp
    // z = 7.0 times the transpose of A, times y
    void scaled_transposed_matvec(mdspan<double, extents<size_t, num_rows, num_cols>> A, mdspan<double, extents<size_t, num_rows, num_cols>> y, mdspan<double, extents<size_t, num_cols, num_rows>> z) {
       matrix_vector_product(scaled(7.0, transposed(A)), y, z);
    }
    ```

    —end example

*template<in-matrix InMat, in-vector InVec1, in-vector InVec2, out-vector OutVec>*

    ```cpp
    void matrix_vector_product(InMat A, InVec1 x, InVec2 y, OutVec z);
    ```

    These functions perform an updating matrix-vector product.

    ```cpp
    Effects: Computes `z = y + Ax`.
    ```

    ```cpp
    Remarks: z may alias y.
    ```

    ```cpp
    [Example 2:
     // y = 3.0 * A * x + 2.0 * y
     void scaled_matvec_2(mdspan<double, extents<size_t, num_rows, num_cols>> A, mdspan<double, extents<size_t, num_rows, num_cols>> x, mdspan<double, extents<size_t, num_cols, num_rows>> y) {
       matrix_vector_product(scaled(3.0, A), x, scaled(2.0, y), y);
     }
    ```

    —end example

The following overload is addable for those overloads that take a `z` parameter.

*template<in-matrix InMat, in-vector InVec, out-vector OutVec>*

    ```cpp
    void matrix_vector_product(InMat A, InVec x, OutVec y);
    ```

    ```cpp
    template<class ExecutionPolicy, in-matrix InMat, in-vector InVec, out-vector OutVec>
    void matrix_vector_product(ExecutionPolicy&& exec, InMat A, InVec x, OutVec y);
    ```

    These overloads perform an overwriting matrix-vector product.
multipliable \((A,x,y)\) is true, and

addable \((x,y,z)\) is true for those overloads that take a \(z\) parameter.

**Complexity:** \(\mathcal{O}(x\text{.extent}(0) \times A\text{.extent}(1))\).

\[
\text{template}<\text{in-matrix} \text{InMat}, \text{class Triangle}, \text{in-vector} \text{InVec}, \text{out-vector} \text{OutVec}>
\text{void symmetric_matrix_vector_product}(\text{InMat} A, \text{Triangle} t, \text{InVec} x, \text{OutVec} y);
\]

These functions perform an overwriting symmetric matrix-vector product, taking into account the \text{Triangle} parameter that applies to the symmetric matrix \(A\) (28.9.3).

**Effects:** Computes \(y = Ax\).

\[
\text{template}<\text{in-matrix} \text{InMat}, \text{class Triangle}, \text{in-vector} \text{InVec1}, \text{in-vector} \text{InVec2}, \text{out-vector} \text{OutVec}>
\text{void symmetric_matrix_vector_product}(\text{InMat} A, \text{Triangle} t, \text{InVec1} x, \text{InVec2} y, \text{OutVec} z);
\]

These functions perform an updating symmetric matrix-vector product, taking into account the \text{Triangle} parameter that applies to the symmetric matrix \(A\) (28.9.3).

**Effects:** Computes \(z = y + Ax\).

**Remarks:** \(z\) may alias \(y\).

### 28.9.14.3 Hermitian matrix-vector product

[Note 1: These functions correspond to the BLAS functions \(\text{xHEMV}\) and \(\text{xHPMV}\), end note]

The following elements apply to all functions in 28.9.14.3.

**Mandates:**

<table>
<thead>
<tr>
<th>Precondition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3.1)</td>
<td>If (\text{InMat}) has \text{layout_blas_packed} layout, then the layout’s \text{Triangle} template argument has the same type as the function’s \text{Triangle} template argument;</td>
</tr>
<tr>
<td>(3.2)</td>
<td>\text{compatible-static-extents}(&lt;\text{decltype}(A), \text{decltype}(A)&gt;(0, 1)) is true;</td>
</tr>
<tr>
<td>(3.3)</td>
<td>\text{possibly-multipliable}(&lt;\text{decltype}(A), \text{decltype}(x), \text{decltype}(y)&gt;()) is true; and</td>
</tr>
<tr>
<td>(3.4)</td>
<td>\text{possibly-addable}(&lt;\text{decltype}(x), \text{decltype}(y), \text{decltype}(z)&gt;()) is true for those overloads that take a (z) parameter.</td>
</tr>
</tbody>
</table>

**Preconditions:**

<table>
<thead>
<tr>
<th>Precondition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.1)</td>
<td>(A\text{.extent}(0)) equals (A\text{.extent}(1));</td>
</tr>
<tr>
<td>(4.2)</td>
<td>\text{multipliable}(A, x, y) is true; and</td>
</tr>
<tr>
<td>(4.3)</td>
<td>\text{addable}(x, y, z) is true for those overloads that take a (z) parameter.</td>
</tr>
</tbody>
</table>

**Complexity:** \(\mathcal{O}(x\text{.extent}(0) \times A\text{.extent}(1))\).

\[
\text{template}<\text{in-matrix} \text{InMat}, \text{class Triangle}, \text{in-vector} \text{InVec}, \text{out-vector} \text{OutVec}>
\text{void hermitian_matrix_vector_product}(\text{InMat} A, \text{Triangle} t, \text{InVec} x, \text{OutVec} y);
\]

These functions perform an overwriting Hermitian matrix-vector product, taking into account the \text{Triangle} parameter that applies to the Hermitian matrix \(A\) (28.9.3).

**Effects:** Computes \(y = Ax\).

\[
\text{template}<\text{in-matrix} \text{InMat}, \text{class Triangle}, \text{in-vector} \text{InVec1}, \text{in-vector} \text{InVec2}, \text{out-vector} \text{OutVec}>
\text{void hermitian_matrix_vector_product}(\text{InMat} A, \text{Triangle} t, \text{InVec1} x, \text{InVec2} y, \text{OutVec} z);
\]

§ 28.9.14.3 ©ISO/IEC 1594
template<class ExecutionPolicy,
in-matrix InMat, class Triangle, in-vector InVec1, in-vector InVec2, out-vector OutVec>
void hermitian_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, InVec1 x, InVec2 y, OutVec z);

These functions perform an updating Hermitian matrix-vector product, taking into account the Triangle parameter that applies to the Hermitian matrix A (28.9.3).

Effects: Computes \( z = y + Ax \).

Remarks: \( z \) may alias \( y \).

28.9.14.4 Triangular matrix-vector product

[Note 1: These functions correspond to the BLAS functions xTRMV and xTPMV\(^{[18]} \). — end note]

The following elements apply to all functions in 28.9.14.4.

Mandates:

(3.1) — If InMat has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;

(3.2) — compatible-static-extents< decltype(A), decltype(A)> (0, 1) is true;

(3.3) — compatible-static-extents< decltype(A), decltype(y)> (0, 0) is true;

(3.4) — compatible-static-extents< decltype(A), decltype(x)> (0, 0) is true for those overloads that take an \( x \) parameter; and

(3.5) — compatible-static-extents< decltype(A), decltype(z)> (0, 0) is true for those overloads that take a \( z \) parameter.

Preconditions:

(4.1) — \( A.\text{extent}(0) \) equals \( A.\text{extent}(1) \),

(4.2) — \( A.\text{extent}(0) \) equals \( y.\text{extent}(0) \),

(4.3) — \( A.\text{extent}(0) \) equals \( x.\text{extent}(0) \) for those overloads that take an \( x \) parameter, and

(4.4) — \( A.\text{extent}(0) \) equals \( z.\text{extent}(0) \) for those overloads that take a \( z \) parameter.

template<
in-matrix InMat, class Triangle, class DiagonalStorage,
in-vector InVec,
out-vector OutVec>
void triangular_matrix_vector_product(InMat A, Triangle t, DiagonalStorage d, InVec x, OutVec y);

template<class ExecutionPolicy,
in-matrix InMat, class Triangle, class DiagonalStorage,
in-vector InVec,
out-vector OutVec>
void triangular_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, DiagonalStorage d, InVec x, OutVec y);

These functions perform an overwriting triangular matrix-vector product, taking into account the Triangle and DiagonalStorage parameters that apply to the triangular matrix A (28.9.3).

Effects: Computes \( y = Ax \).

Complexity: \( \Theta(x.\text{extent}(0) \times A.\text{extent}(1)) \).

template<
in-matrix InMat, class Triangle, class DiagonalStorage,
inout-vector InOutVec>
void triangular_matrix_vector_product(InMat A, Triangle t, DiagonalStorage d, InOutVec y);

template<class ExecutionPolicy,
in-matrix InMat, class Triangle, class DiagonalStorage,
inout-vector InOutVec>
void triangular_matrix_vector_product(ExecutionPolicy&& exec,
InMat A, Triangle t, DiagonalStorage d, InOutVec y);

These functions perform an in-place triangular matrix-vector product, taking into account the Triangle and DiagonalStorage parameters that apply to the triangular matrix A (28.9.3).

[Note 2: Performing this operation in place hinders parallelization. However, other ExecutionPolicy specific optimizations, such as vectorization, are still possible. — end note]

Effects: Computes a vector \( y’ \) such that \( y’ = Ay \), and assigns each element of \( y’ \) to the corresponding element of \( y \).

Complexity: \( \Theta(y.\text{extent}(0) \times A.\text{extent}(1)) \).
```cpp
#include <linalg/algs/blas2/28.9.14.5.hpp>

These functions perform an updating triangular matrix-vector product, taking into account the `Triangle` and `DiagonalStorage` parameters that apply to the triangular matrix \( A \) (28.9.3).

**Effects:** Computes \( z = y + Ax \).

**Complexity:** \( \Theta(x.\text{extent}(0) \times A.\text{extent}(1)) \).

**Remarks:** \( z \) may alias \( y \).

### 28.9.14.5 Solve a triangular linear system

These functions perform a triangular solve, taking into account the `Triangle` and `DiagonalStorage` parameters that apply to the triangular matrix \( A \) (28.9.3).

**Effects:** Computes a vector \( x' \) such that \( b = Ax' \), and assigns each element of \( x' \) to the corresponding element of \( x \). If no such \( x' \) exists, then the elements of \( x \) are valid but unspecified.

**Complexity:** \( \Theta(A.\text{extent}(1) \times b.\text{extent}(0)) \).

**Effects:** Equivalent to:

\[
\text{triangular_matrix_vector_solve}(A, t, d, b, x, \text{divides<void>})
\]
template<in-matrix InMat, class Triangle, class DiagonalStorage, 
inout-vector InOutVec, class BinaryDivideOp>
void triangular_matrix_vector_solve(InMat A, Triangle t, DiagonalStorage d, 
InOutVec b, BinaryDivideOp divide);

template<class ExecutionPolicy, in-matrix InMat, class Triangle, 
class DiagonalStorage, inout-vector InOutVec, class BinaryDivideOp>
void triangular_matrix_vector_solve(ExecutionPolicy&& exec, 
InMat A, Triangle t, DiagonalStorage d, 
InOutVec b, BinaryDivideOp divide);

These functions perform an in-place triangular solve, taking into account the Triangle and Diagonal- 
Storage parameters that apply to the triangular matrix A (28.9.3).

[Note 2: Performing triangular solve in place hinders parallelization. However, other ExecutionPolicy specific 
optimizations, such as vectorization, are still possible. — end note]

Effects: Computes a vector $x'$ such that $b = Ax'$, and assigns each element of $x'$ to the corresponding 
element of $b$. If no such $x'$ exists, then the elements of $b$ are valid but unspecified.

Complexity: $O(A.extent(1) \times b.extent(0))$.

28.9.14.6 Rank-1 (outer product) update of a matrix [linalg.algs.blas2.rank1]

template<in-vector InVec1, in-vector InVec2, inout-matrix InOutMat>
void matrix_rank_1_update(InVec1 x, InVec2 y, InOutMat A);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, 
inout-matrix InOutMat>
void matrix_rank_1_update(ExecutionPolicy&& exec, InVec1 x, InVec2 y, InOutMat A);

These functions perform a nonsymmetric nonconjugated rank-1 update.

[Note 1: These functions correspond to the BLAS functions xGER (for real element types) and xGERU (for 
complex element types)[18]. — end note]

Mandates: possibly-multipliable<InOutMat, InVec2, InVec1>() is true.

Preconditions: multipliable(A, y, x) is true.

Effects: Computes a matrix $A'$ such that $A' = A + xy^T$, and assigns each element of $A'$ to the 
corresponding element of $A$.

Complexity: $O(x.extent(0) \times y.extent(0))$.

template<in-vector InVec1, in-vector InVec2, inout-matrix InOutMat>
void matrix_rank_1_update_c(InVec1 x, InVec2 y, InOutMat A);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, 
inout-matrix InOutMat>
void matrix_rank_1_update_c(ExecutionPolicy&& exec, InVec1 x, InVec2 y, InOutMat A);

These functions perform a nonsymmetric conjugated rank-1 update.

[Note 2: These functions correspond to the BLAS functions xGER (for real element types) and xGERC (for 
complex element types)[18]. — end note]
Effects:

(7.1) For the overloads without an `ExecutionPolicy` argument, equivalent to:

```cpp
matrix_rank_1_update(x, conjugated(y), A);
```

(7.2) otherwise, equivalent to:

```cpp
matrix_rank_1_update(std::forward<ExecutionPolicy>(exec), x, conjugated(y), A);
```

§ 28.9.14.7 Symmetric or Hermitian Rank-1 (outer product) update of a matrix

[linalg.algs.blas2.symherrank1]

1 [Note 1: These functions correspond to the BLAS functions xSYR, xSPR, xHER, and xHPR\(^{[18]}\). They have overloads taking a scaling factor \(\alpha\), because it would be impossible to express the update \(A = A - xx^T\) otherwise. — end note]

2 The following elements apply to all functions in 28.9.14.7.

Mandates:

(3.1) If `InOutMat` has `layout_blas_packed` layout, then the layout’s `Triangle` template argument has the same type as the function’s `Triangle` template argument;

(3.2) `compatible-static-extents<decltype(A), decltype(A)>(0, 1)` is true; and

(3.3) `compatible-static-extents<decltype(A), decltype(x)>(0, 0)` is true.

Preconditions:

(4.1) \(A\).extent(0) equals \(A\).extent(1), and

(4.2) \(A\).extent(0) equals \(x\).extent(0).

Complexity: \(O(x.extent(0) \times x.extent(0))\).

```cpp
template<class Scalar, in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(Scalar alpha, InVec x, InOutMat A, Triangle t);
template<class ExecutionPolicy, class Scalar, in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(ExecutionPolicy& exec, Scalar alpha, InVec x, InOutMat A, Triangle t);
```

6 These functions perform a symmetric rank-1 update of the symmetric matrix \(A\), taking into account the `Triangle` parameter that applies to \(A\) (28.9.3).

Effects: Computes a matrix \(A'\) such that \(A' = A + \alpha xx^T\), where the scalar \(\alpha\) is \(alpha\), and assigns each element of \(A'\) to the corresponding element of \(A\).

```cpp
template<in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(InVec x, InOutMat A, Triangle t);
template<class ExecutionPolicy, in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_1_update(ExecutionPolicy& exec, InVec x, InOutMat A, Triangle t);
```

8 These functions perform a symmetric rank-1 update of the symmetric matrix \(A\), taking into account the `Triangle` parameter that applies to \(A\) (28.9.3).

Effects: Computes a matrix \(A'\) such that \(A' = A + xx^T\) and assigns each element of \(A'\) to the corresponding element of \(A\).

```cpp
template<class Scalar, in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_1_update(Scalar alpha, InVec x, InOutMat A, Triangle t);
template<class ExecutionPolicy, class Scalar, in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_1_update(ExecutionPolicy& exec, Scalar alpha, InVec x, InOutMat A, Triangle t);
```

10 These functions perform a Hermitian rank-1 update of the Hermitian matrix \(A\), taking into account the `Triangle` parameter that applies to \(A\) (28.9.3).

Effects: Computes \(A'\) such that \(A' = A + \alpha xx^H\), where the scalar \(\alpha\) is \(alpha\), and assigns each element of \(A'\) to the corresponding element of \(A\).
template<in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_1_update(InVec x, InOutMat A, Triangle t);

template<class ExecutionPolicy,
in-vector InVec, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_1_update(ExecutionPolicy&& exec, InVec x, InOutMat A, Triangle t);

These functions perform a Hermitian rank-1 update of the Hermitian matrix A, taking into account the Triangle parameter that applies to A (28.9.3).

Effects: Computes a matrix $A'$ such that $A' = A + xx^H$ and assigns each element of $A'$ to the corresponding element of $A$.

28.9.14.8 Symmetric and Hermitian rank-2 matrix updates

[linalg.algs.blas2.rank2]

[Note 1: These functions correspond to the BLAS functions xSYR2, xSPR2, xHER2 and xHPR2. —end note]

The following elements apply to all functions in 28.9.14.8.

Mandates:

1. If InOutMat has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;
2. compatible-static-extents<decltype(A), decltype(A)>(0, 1) is true; and
3. possibly-multipliable<decltype(A), decltype(x), decltype(y)>() is true.

Preconditions:

1. A.extent(0) equals A.extent(1), and
2. multipliable(A, x, y) is true.

Complexity: $O(xextent(0) \times y.extent(0))$.

template<in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2_update(InVec1 x, InVec2 y, InOutMat A, Triangle t);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2_update(ExecutionPolicy&& exec, InVec1 x, InVec2 y, InOutMat A, Triangle t);

These functions perform a symmetric rank-2 update of the symmetric matrix A, taking into account the Triangle parameter that applies to A (28.9.3).

Effects: Computes $A'$ such that $A' = A + xy^T + yx^T$ and assigns each element of $A'$ to the corresponding element of $A$.

template<in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2_update(InVec1 x, InVec2 y, InOutMat A, Triangle t);

template<class ExecutionPolicy, in-vector InVec1, in-vector InVec2, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2_update(ExecutionPolicy&& exec, InVec1 x, InVec2 y, InOutMat A, Triangle t);

These functions perform a Hermitian rank-2 update of the Hermitian matrix A, taking into account the Triangle parameter that applies to A (28.9.3).

Effects: Computes $A'$ such that $A' = A + xy^H + yx^H$ and assigns each element of $A'$ to the corresponding element of $A$.

28.9.15 BLAS 3 algorithms

28.9.15.1 General matrix-matrix product

[linalg.algs.blas3]

[Note 1: These functions correspond to the BLAS function xGEMM. —end note]

The following elements apply to all functions in 28.9.15.1 in addition to function-specific elements.

Mandates: possibly-multipliable<decltype(A), decltype(B), decltype(C)>() is true.

Preconditions: multipliable(A, B, C) is true.

Complexity: $O(A.extent(0) \times A.extent(1) \times B.extent(1))$. 

§ 28.9.15.1 ©ISO/IEC 1599
template<in-matrix InMat1, in-matrix InMat2, out-matrix OutMat>
void matrix_product(InMat1 A, InMat2 B, OutMat C);

Effects: Computes \( C = AB \).

template<in-matrix InMat1, in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void matrix_product(InMat1 A, InMat2 B, InMat3 E, OutMat C);

template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, out-matrix OutMat>
void matrix_product(ExecutionPolicy&& exec, InMat1 A, InMat2 B, OutMat C);

Mandates: possibly-addable<InMat3, InMat3, OutMat>() is true.

Preconditions: addable (E, E, C) is true.

Effects: Computes \( C = E + AB \).

Remarks: C may alias E.

28.9.15.2 Symmetric, Hermitian, and triangular matrix-matrix product
[linalg.algs.blas3.xxmm]

[Note 1: These functions correspond to the BLAS functions xSYMM, xHEMM, and xTRMM\textsuperscript{[19].} — end note]

The following elements apply to all functions in 28.9.15.2 in addition to function-specific elements.

Mandates:

(3.1) — possibly-multipliable<decltype(A), decltype(B), decltype(C)>() is true, and
(3.2) — possibly-addable<decltype(E), decltype(E), decltype(C)>() is true for those overloads that take an E parameter.

Preconditions:

(4.1) — multipliable (A, B, C) is true, and
(4.2) — addable (E, E, C) is true for those overloads that take an E parameter.

Complexity: \( O(A.\text{extent}(0) \times A.\text{extent}(1) \times B.\text{extent}(1)) \).

template<in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, Triangle t, InMat2 B, OutMat C);

template<class ExecutionPolicy,
in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy&& exec, InMat1 A, Triangle t, InMat2 B, OutMat C);

template<in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, Triangle t, InMat2 B, OutMat C);

template<class ExecutionPolicy,
in-matrix InMat1, class Triangle, in-matrix InMat2, out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy&& exec, InMat1 A, Triangle t, InMat2 B, OutMat C);

These functions perform a matrix-matrix multiply, taking into account the Triangle and Diagonal-
Storage (if applicable) parameters that apply to the symmetric, Hermitian, or triangular (respectively)
matrix A (28.9.3).

Mandates:

(7.1) — If InMat1 has layout_blas_packed layout, then the layout’s Triangle template argument has
the same type as the function’s Triangle template argument; and
(7.2) — compatible-static-extents<InMat1, InMat1>(0, 1) is true.
Preconditions: $A$.extent(0) == $A$.extent(1) is true.

Effects: Computes $C = AB$.

template<in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, InMat2 B, Triangle t, OutMat C);
template<class ExecutionPolicy,
  in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy& exec,
  InMat1 A, InMat2 B, Triangle t, OutMat C);
template<in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, InMat2 B, Triangle t, OutMat C);
template<class ExecutionPolicy,
  in-matrix InMat1, in-matrix InMat2, class Triangle, out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy& exec,
  InMat1 A, InMat2 B, Triangle t, OutMat C);
template<in-matrix InMat1, in-matrix InMat2, class Triangle, class DiagonalStorage, 
  out-matrix OutMat>
void triangular_matrix_product(InMat1 A, Triangle t, DiagonalStorage d, OutMat C);
template<class ExecutionPolicy,
  in-matrix InMat1, class Triangle, in-matrix InMat2, class DiagonalStorage, 
  in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(ExecutionPolicy& exec,
  InMat1 A, Triangle t, InMat2 B, DiagonalStorage d, OutMat C);

These functions perform a matrix-matrix multiply, taking into account the Triangle and DiagonalStorage (if applicable) parameters that apply to the symmetric, Hermitian, or triangular (respectively) matrix $B$ (28.9.3).

Mandates:
(11.1) If InMat2 has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument; and
(11.2) compatible-static-extents<InMat2, InMat2>(0, 1) is true.

Preconditions: $B$.extent(0) == $B$.extent(1) is true.

Effects: Computes $C = AB$.

template<in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, 
  out-matrix OutMat>
void symmetric_matrix_product(InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<class ExecutionPolicy,
  in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, 
  out-matrix OutMat>
void symmetric_matrix_product(ExecutionPolicy& exec,
  InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, 
  out-matrix OutMat>
void hermitian_matrix_product(InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<class ExecutionPolicy,
  in-matrix InMat1, class Triangle, in-matrix InMat2, in-matrix InMat3, 
  out-matrix OutMat>
void hermitian_matrix_product(ExecutionPolicy& exec,
  InMat1 A, Triangle t, InMat2 B, InMat3 E, OutMat C);
template<in-matrix InMat1, class Triangle, class DiagonalStorage, 
  in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(InMat1 A, Triangle t, DiagonalStorage d, InMat2 B, InMat3 E, 
  OutMat C);
template<class ExecutionPolicy,
  in-matrix InMat1, class Triangle, class DiagonalStorage, 
  in-matrix InMat2, in-matrix InMat3, out-matrix OutMat>
void triangular_matrix_product(ExecutionPolicy& exec,
These functions perform a potentially overwriting matrix-matrix multiply-add, taking into account the `Triangle` and `DiagonalStorage` (if applicable) parameters that apply to the symmetric, Hermitian, or triangular (respectively) matrix `A` (28.9.3).

*Mandates:*

- If `InMat1` has `layout_blas_packed` layout, then the layout’s `Triangle` template argument has the same type as the function’s `Triangle` template argument; and
- `compatible-static-extents<InMat1, InMat1>(0, 1)` is true.

*Preconditions:*

- `A.extent(0) == A.extent(1)` is true.

*Effects:*

- Computes `C = E + AB`.

*Remarks:*

- `C` may alias `E`.

These functions perform an in-place matrix-matrix multiply, taking into account the `Triangle` and `DiagonalStorage` (if applicable) parameters that apply to the symmetric, Hermitian, or triangular (respectively) matrix `B` (28.9.3).

*Mandates:*

- If `InMat2` has `layout_blas_packed` layout, then the layout’s `Triangle` template argument has the same type as the function’s `Triangle` template argument; and
- `compatible-static-extents<InMat2, InMat2>(0, 1)` is true.

*Preconditions:*

- `B.extent(0) == B.extent(1)` is true.

*Effects:*

- Computes `C = E + AB`.

*Remarks:*

- `C` may alias `E`.

28.9.15.3 In-place triangular matrix-matrix product

These functions perform an in-place matrix-matrix multiply, taking into account the `Triangle` and `DiagonalStorage` parameters that apply to the triangular matrix `A` (28.9.3).

*Note 1:*

These functions correspond to the BLAS function `xTRMM`[19]. — end note
template<in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_left_product(InMat A, Triangle t, DiagonalStorage d, InOutMat C);

template<class ExecutionPolicy,
in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_left_product(ExecutionPolicy&& exec, InMat A, Triangle t, DiagonalStorage d, InOutMat C);

Mandates:

(2.1) If InMat has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;
(2.2) possibly-multiplicable<InMat, InOutMat, InOutMat>() is true; and
(2.3) compatible-static-extents<InMat, InMat>(0, 1) is true.

Preconditions:

(3.1) multipliable(A, C, C) is true, and
(3.2) A.extent(0) == A.extent(1) is true.

Effects: Computes a matrix C′ such that C′ = AC and assigns each element of C′ to the corresponding element of C.

Complexity: $O(A.extent(0) \times A.extent(1) \times C.extent(0))$.

template<in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_right_product(InMat A, Triangle t, DiagonalStorage d, InOutMat C);

template<class ExecutionPolicy,
in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_right_product(ExecutionPolicy&& exec, InMat A, Triangle t, DiagonalStorage d, InOutMat C);

Mandates:

(6.1) If InMat has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;
(6.2) possibly-multiplicable<InOutMat, InMat, InOutMat>() is true; and
(6.3) compatible-static-extents<InMat, InMat>(0, 1) is true.

Preconditions:

(7.1) multipliable(C, A, C) is true, and
(7.2) A.extent(0) == A.extent(1) is true.

Effects: Computes a matrix C′ such that C′ = CA and assigns each element of C′ to the corresponding element of C.

Complexity: $O(A.extent(0) \times A.extent(1) \times C.extent(0))$.

28.9.15.4 Rank-k update of a symmetric or Hermitian matrix  [linalg.algs.blas3.rankk]

[Note 1: These functions correspond to the BLAS functions xSYRK and xHERK\(^{[19]}\). — end note]

The following elements apply to all functions in 28.9.15.4.

Mandates:

(3.1) If InOutMat has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;
(3.2) compatible-static-extents<decltype(A), decltype(A)>(0, 1) is true;
(3.3) compatible-static-extents<decltype(C), decltype(C)>(0, 1) is true; and
(3.4) compatible-static-extents<decltype(A), decltype(C)>(0, 0) is true.

Preconditions:

(4.1) A.extent(0) equals A.extent(1),
(4.2) C.extent(0) equals C.extent(1), and
(4.3) A.extent(0) equals C.extent(0).
5 Complexity: $O(A.\text{extent}(0) \times A.\text{extent}(1) \times C.\text{extent}(0))$.

```
template<class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_k_update(Scalar alpha, InMat A, InOutMat C, Triangle t);
template<class ExecutionPolicy, class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_k_update(ExecutionPolicy&& exec, 
Scalar alpha, InMat A, InOutMat C, Triangle t);
```

6 Effects: Computes a matrix $C'$ such that $C' = C + \alpha AA^T$, where the scalar $\alpha$ is $\text{alpha}$, and assigns each element of $C'$ to the corresponding element of $C$.

```
template<class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_k_update(InMat A, InOutMat C, Triangle t);
template<class ExecutionPolicy, class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_k_update(ExecutionPolicy&& exec, 
InMat A, InOutMat C, Triangle t);
```

7 Effects: Computes a matrix $C'$ such that $C' = C + AA^T$, and assigns each element of $C'$ to the corresponding element of $C$.

```
template<class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_k_update(Scalar alpha, InMat A, InOutMat C, Triangle t);
template<class ExecutionPolicy, class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_k_update(ExecutionPolicy&& exec, 
Scalar alpha, InMat A, InOutMat C, Triangle t);
```

8 Effects: Computes a matrix $C'$ such that $C' = C + \alpha AA^H$, where the scalar $\alpha$ is $\text{alpha}$, and assigns each element of $C'$ to the corresponding element of $C$.

```
template<class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_k_update(InMat A, InOutMat C, Triangle t);
template<class ExecutionPolicy, class Scalar, in-matrix InMat, possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_k_update(ExecutionPolicy&& exec, 
InMat A, InOutMat C, Triangle t);
```

9 Effects: Computes a matrix $C'$ such that $C' = C + AA^H$, and assigns each element of $C'$ to the corresponding element of $C$.

28.9.15.5 Rank-2k update of a symmetric or Hermitian matrix

```
[Note 1: These functions correspond to the BLAS functions $\text{xSYR2K}$ and $\text{xHER2K}$[19]. — end note]
```

The following elements apply to all functions in 28.9.15.5.

Mandates:

3 Preconditions:

4 Complexity: $O(A.\text{extent}(0) \times A.\text{extent}(1) \times C.\text{extent}(0))$.

```
template<class Scalar, in-matrix InMat1, in-matrix InMat2, 
    possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2k_update(InMat1 A, InMat2 B, InOutMat C, Triangle t);
template<class ExecutionPolicy, in-matrix InMat1, in-matrix InMat2, 
    possibly-packed-inout-matrix InOutMat, class Triangle>
void symmetric_matrix_rank_2k_update(ExecutionPolicy&& exec, 
```
Effects: Computes a matrix \( C' \) such that \( C' = C + AB^T + BA^T \), and assigns each element of \( C' \) to the corresponding element of \( C \).

```
template<in-matrix InMat1, in-matrix InMat2, 
          possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2k_update(InMat1 A, InMat2 B, InOutMat C, Triangle t);
```

Effects: Computes a matrix \( C' \) such that \( C' = C + AB^H + BA^H \), and assigns each element of \( C' \) to the corresponding element of \( C \).

```
template<class ExecutionPolicy, 
in-matrix InMat1, in-matrix InMat2, 
possibly-packed-inout-matrix InOutMat, class Triangle>
void hermitian_matrix_rank_2k_update(ExecutionPolicy&& exec, 
InMat1 A, InMat2 B, InOutMat C, Triangle t);
```

### 28.9.15.6 Solve multiple triangular linear systems

[template class ExecutionPolicy, in-matrix InMat1, class Triangle, class DiagonalStorage, 
in-matrix InMat2, out-matrix OutMat, class BinaryDivideOp]

```
template<class ExecutionPolicy, 
in-matrix InMat1, class Triangle, class DiagonalStorage, 
in-matrix InMat2, out-matrix OutMat, class BinaryDivideOp>
void triangular_matrix_matrix_left_solve(ExecutionPolicy&& exec, 
InMat1 A, Triangle t, DiagonalStorage d, 
InMat2 B, OutMat X, BinaryDivideOp divide);
```

These functions perform multiple matrix solves, taking into account the Triangle and DiagonalStorage parameters that apply to the triangular matrix \( A \) (28.9.3).

**Mandates:**

1. If \( \text{InMat1} \) has layout\_blas\_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;
2. \( \text{possibly-multipliable<InMat1, OutMat, InMat2>()} \) is true; and
3. \( \text{compatible-static-extents<InMat1, InMat1>(0, 1)} \) is true.

**Preconditions:**

1. \( \text{multipliable(A, X, B)} \) is true, and
2. \( \text{A.extent(0) == A.extent(1)} \) is true.

**Effects:** Computes \( X' \) such that \( AX' = B \), and assigns each element of \( X' \) to the corresponding element of \( X \). If no such \( X' \) exists, then the elements of \( X \) are valid but unspecified.

**Complexity:** \( O(\text{A.extent(0)} \times \text{X.extent(1)} \times \text{X.extent(1)}) \).

**Note 2:** Since the triangular matrix is on the left, the desired divide implementation in the case of noncommutative multiplication is mathematically equivalent to \( y^{-1}x \), where \( x \) is the first argument and \( y \) is the second argument, and \( y^{-1} \) denotes the multiplicative inverse of \( y \). —end note

```
template<in-matrix InMat1, class Triangle, class DiagonalStorage, 
in-matrix InMat2, out-matrix OutMat>
void triangular_matrix_matrix_left_solve(InMat1 A, Triangle t, DiagonalStorage d, 
InMat2 B, OutMat X);
```

**Effects:** Equivalent to:

```
triangular_matrix_matrix_left_solve(A, t, d, B, X, divides<void>{});
```

```
template<class ExecutionPolicy, in-matrix InMat1, class Triangle, class DiagonalStorage, 
in-matrix InMat2, out-matrix OutMat>
void triangular_matrix_matrix_left_solve(ExecutionPolicy&& exec, 
InMat1 A, Triangle t, DiagonalStorage d, 
InMat2 B, OutMat X);
```

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1605
InMat2 B, OutMat X);

**Effects**: Equivalent to:

\[
\text{triangular\_matrix\_matrix\_left\_solve}(	ext{std::forward<}\text{ExecutionPolicy}>(\text{exec}), \\
A, t, d, B, X, \text{divides}<\text{void}>({\text{divides}}{\{}{}));
\]

template\langle\text{in-matrix } \text{InMat1}, \text{class Triangle, class DiagonalStorage,} \\
\text{in-matrix } \text{InMat2, out-matrix } \text{OutMat, class BinaryDivideOp}\rangle
void \text{triangular\_matrix\_matrix\_left\_solve} (\text{InMat1 A, Triangle t, DiagonalStorage d,} \\
\text{InMat2 B, OutMat X, BinaryDivideOp divide});

template\langle\text{class ExecutionPolicy,} \\
\text{in-matrix } \text{InMat1, class Triangle, class DiagonalStorage,} \\
\text{in-matrix } \text{InMat2, out-matrix } \text{OutMat, class BinaryDivideOp}\rangle
void \text{triangular\_matrix\_matrix\_right\_solve} (\text{ExecutionPolicy&& exec,} \\
\text{InMat1 A, Triangle t, DiagonalStorage d,} \\
\text{InMat2 B, OutMat X, BinaryDivideOp divide});

These functions perform multiple matrix solves, taking into account the Triangle and DiagonalStorage parameters that apply to the triangular matrix A (28.9.3).

**Mandates**:

1. If InMat1 has layout_blas_packed layout, then the layout’s Triangle template argument has the same type as the function’s Triangle template argument;
2. possibly-multiplyable<OutMat, InMat1, InMat2>() is true; and
3. compatible-static-extents<InMat1, InMat1>(0,1) is true.

**Preconditions**:

1. multiplicable(X, A, B) is true, and
2. A.extent(0) == A.extent(1) is true.

**Effects**: Computes \(X'\) such that \(X' A = B\), and assigns each element of \(X'\) to the corresponding element of \(X\). If no such \(X'\) exists, then the elements of \(X\) are valid but unspecified.

**Complexity**: \(O(B.\text{extent}(0) \cdot B.\text{extent}(1) \cdot A.\text{extent}(1))\)

[Note 3: Since the triangular matrix is on the right, the desired divide implementation in the case of noncommutative multiplication is mathematically equivalent to \(x y^{-1}\), where \(x\) is the first argument and \(y\) is the second argument, and \(y^{-1}\) denotes the multiplicative inverse of \(y\). —end note]

\[
\text{template\langle\text{in-matrix } \text{InMat1, class Triangle, class DiagonalStorage,} \\
\text{in-matrix } \text{InMat2, out-matrix } \text{OutMat}\rangle}
\text{void \text{triangular\_matrix\_matrix\_right\_solve} (\text{InMat1 A, Triangle t, DiagonalStorage d,} \\
\text{InMat2 B, OutMat X});}
\]

**Effects**: Equivalent to:

\[
\text{triangular\_matrix\_matrix\_right\_solve}(A, t, d, B, X, \text{divides}<\text{void}>({\text{divides}}{\{}{}));
\]

template\langle\text{class ExecutionPolicy,} \\
\text{in-matrix } \text{InMat1, class Triangle, class DiagonalStorage,} \\
\text{in-matrix } \text{InMat2, out-matrix } \text{OutMat}\rangle
void \text{triangular\_matrix\_matrix\_right\_solve} (\text{ExecutionPolicy&& exec,} \\
\text{InMat1 A, Triangle t, DiagonalStorage d,} \\
\text{InMat2 B, OutMat X});

**Effects**: Equivalent to:

\[
\text{triangular\_matrix\_matrix\_right\_solve}(	ext{std::forward<}\text{ExecutionPolicy}>(\text{exec}), \\
A, t, d, B, X, \text{divides}<\text{void}>({\text{divides}}{\{}{}));
\]

28.9.15.7 Solve multiple triangular linear systems in-place \[\text{[linalg.algs.blas3.inplacetrsm]}\]

**Note 1**: These functions correspond to the BLAS function \(\text{xTRSM}\)[19]. —end note]

\[
\text{template\langle\text{in-matrix } \text{InMat, class Triangle, class DiagonalStorage,} \\
\text{inout-matrix } \text{InOutMat, class BinaryDivideOp}\rangle}
\text{void \text{triangular\_matrix\_matrix\_left\_solve} (\text{InMat A, Triangle t, DiagonalStorage d,} \\
\text{InOutMat B, BinaryDivideOp divide});}
\]

§ 28.9.15.7 © ISO/IEC 1606
These functions perform multiple in-place matrix solves, taking into account the `Triangle` and `DiagonalStorage` parameters that apply to the triangular matrix A (28.9.3).

[Note 2: This algorithm makes it possible to compute factorizations like Cholesky and LU in place. Performing triangular solve in place hinders parallelization. However, other `ExecutionPolicy` specific optimizations, such as vectorization, are still possible. — end note]

Mandates:

(3.1) If `InMat` has `layout_blas_packed` layout, then the layout’s `Triangle` template argument has the same type as the function’s `Triangle` template argument;

(3.2) `possibly-multipliable<InMat, InOutMat, InOutMat>()` is true; and

(3.3) `compatible-static-extents<InMat, InMat>(0, 1)` is true.

Preconditions:

(4.1) `multipliable(A, B, B)` is true, and

(4.2) `A.extent(0) == A.extent(1)` is true.

Effects: Computes \(X'\) such that \(AX' = B\), and assigns each element of \(X'\) to the corresponding element of \(B\). If no such \(X'\) exists, then the elements of \(B\) are valid but unspecified.

Complexity: \(O(A.extent(0) \times A.extent(1) \times B.extent(1))\).

These functions perform multiple in-place matrix solves, taking into account the `Triangle` and `DiagonalStorage` parameters that apply to the triangular matrix A (28.9.3).

[Note 3: This algorithm makes it possible to compute factorizations like Cholesky and LU in place. Performing triangular solve in place hinders parallelization. However, other `ExecutionPolicy` specific optimizations, such as vectorization, are still possible. — end note]

Mandates:

(10.1) If `InMat` has `layout_blas_packed` layout, then the layout’s `Triangle` template argument has the same type as the function’s `Triangle` template argument;

(10.2) `possibly-multipliable<InOutMat, InMat, InOutMat>()` is true; and
Preconditions:

(11.1) $multipliable(B, A, B)$ is true, and
(11.2) $A.extent(0) == A.extent(1)$ is true.

Effects: Computes $X'$ such that $X'A = B$, and assigns each element of $X'$ to the corresponding element of $B$. If no such $X'$ exists, then the elements of $B$ are valid but unspecified.

Complexity: $O(A.extent(0) \times A.extent(1) \times B.extent(1))$.

```cpp
template<in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_matrix_right_solve(InMat A, Triangle t, DiagonalStorage d, InOutMat B);
```

Effects: Equivalent to:

```cpp
triangular_matrix_matrix_right_solve(A, t, d, B, divides<void>{});
```

```cpp
template<class ExecutionPolicy, 
in-matrix InMat, class Triangle, class DiagonalStorage, inout-matrix InOutMat>
void triangular_matrix_matrix_right_solve(ExecutionPolicy&& exec, InMat A, Triangle t, DiagonalStorage d, InOutMat B);
```

Effects: Equivalent to:

```cpp
triangular_matrix_matrix_right_solve(std::forward<ExecutionPolicy>(exec), A, t, d, B, divides<void>{});
```
29 Time library

29.1 General

This Clause describes the chrono library (29.2) and various C functions (29.15) that provide generally useful time utilities, as summarized in Table 101.

Table 101 — Time library summary

<table>
<thead>
<tr>
<th>Subclause Header</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.3 Cpp17Clock requirements</td>
<td></td>
</tr>
<tr>
<td>29.4 Time-related traits</td>
<td>&lt;chrono&gt;</td>
</tr>
<tr>
<td>29.5 Class template duration</td>
<td></td>
</tr>
<tr>
<td>29.6 Class template time_point</td>
<td></td>
</tr>
<tr>
<td>29.7 Clocks</td>
<td></td>
</tr>
<tr>
<td>29.8 Civil calendar</td>
<td></td>
</tr>
<tr>
<td>29.9 Class template hh_mm_ss</td>
<td></td>
</tr>
<tr>
<td>29.10 12/24 hour functions</td>
<td></td>
</tr>
<tr>
<td>29.11 Time zones</td>
<td></td>
</tr>
<tr>
<td>29.12 Formatting</td>
<td></td>
</tr>
<tr>
<td>29.13 Parsing</td>
<td></td>
</tr>
<tr>
<td>29.14 Hash support</td>
<td></td>
</tr>
<tr>
<td>29.15 C library time utilities</td>
<td>&lt;ctime&gt;</td>
</tr>
</tbody>
</table>

Let \texttt{STATICALLY-WIDEN} \langle \texttt{charT} \rangle ("...") be "...", if \texttt{charT} is \texttt{char} and L"...", if \texttt{charT} is \texttt{wchar_t}.

29.2 Header <chrono> synopsis

```cpp
#include <compare> // see 17.11.1

namespace std::chrono {
    // 29.5, class template duration
template<class Rep, class Period = ratio<1>> class duration;

    // 29.6, class template time_point
template<class Clock, class Duration = typename Clock::duration> class time_point;
}

namespace std {
    // 29.4.3, common_type specializations
    template<class Rep1, class Period1, class Rep2, class Period2>
        struct common_type<chrono::duration<Rep1, Period1>,
                         chrono::duration<Rep2, Period2>>;

    template<class Clock, class Duration1, class Duration2>
        struct common_type<chrono::time_point<Clock, Duration1>,
                         chrono::time_point<Clock, Duration2>>;
}

namespace std::chrono {
    // 29.4, customization traits
    template<class Rep> struct treat_as_floating_point;
    template<class Rep>
        constexpr bool treat_as_floating_point_v = treat_as_floating_point<Rep>::value;

    template<class Rep> struct duration_values;
```
template<class T> struct is_clock;
template<class T> constexpr bool is_clock_v = is_clock<T>::value;

// 29.5.6, duration arithmetic

template<class Rep1, class Period1, class Rep2, class Period2>
constexpr common_type_t<duration<Rep1, Period1>, duration<Rep2, Period2>>
operator+(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr common_type_t<duration<Rep1, Period1>, duration<Rep2, Period2>>
operator-(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr duration<common_type_t<Rep1, Rep2>, Period1>
operator*(const duration<Rep1, Period1>& d, const Rep2& s);
template<class Rep1, class Rep2, class Period1>
constexpr duration<common_type_t<Rep1, Rep2>, Period1>
operator*(const Rep1& s, const duration<Rep2, Period1>& d);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr duration<common_type_t<Rep1, Rep2>, Period2>
operator%(const duration<Rep1, Period1>& d, const Rep2& s);
template<class Rep1, class Rep2, class Period1>
constexpr duration<common_type_t<Rep1, Rep2>, Period2>
operator%(const Rep1& s, const duration<Rep2, Period1>& d);

// 29.5.7, duration comparisons

template<class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator==(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator<( const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator>( const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator<=( const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);
template<class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator>=( const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

// 29.5.8, conversions

template<class ToDuration, class Rep, class Period>
constexpr ToDuration duration_cast(const duration<Rep, Period>& d);
template<class ToDuration, class Rep, class Period>
constexpr ToDuration floor(const duration<Rep, Period>& d);
template<class ToDuration, class Rep, class Period>
constexpr ToDuration ceil(const duration<Rep, Period>& d);
template<class ToDuration, class Rep, class Period>
constexpr ToDuration round(const duration<Rep, Period>& d);

// 29.5.11, duration I/O

template<class charT, class traits, class Rep, class Period>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os,
const duration<Rep, Period>& d);

basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
duration<Rep, Period>& d,
基本_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

// convenience typedefs
using nanoseconds = duration<
signed integer type of at least 64 bits, nano>;
using microseconds = duration<
signed integer type of at least 55 bits, micro>;
using milliseconds = duration<
signed integer type of at least 45 bits, milli>;
using seconds = duration<
signed integer type of at least 29 bits, ratio< 60>>;
using hours = duration<
signed integer type of at least 23 bits, ratio<3600>>;
using days = duration<
signed integer type of at least 25 bits,
ratio_multiply<ratio<24>, hours::period>>;
using weeks = duration<
signed integer type of at least 22 bits,
ratio_multiply<ratio<7>, days::period>>;
using years = duration<
signed integer type of at least 17 bits,
ratio_multiply<ratio<146097, 400>, days::period>>;
using months = duration<
signed integer type of at least 20 bits,
ratio_divide<years::period, ratio<12>>;

// 29.6.6, time_point arithmetic
template<class Clock, class Duration1, class Rep2, class Period2>
constexpr time_point<Clock, common_type_t<Duration1, duration<Rep2, Period2>>>
operator+(const time_point<Clock, Duration1>& lhs, const duration<Rep2, Period2>& rhs);

// 29.6.7, time_point comparisons
template<class Clock, class Duration1, class Duration2>
constexpr bool operator==(const time_point<Clock, Duration1>& lhs,
const time_point<Clock, Duration2>& rhs);

// 29.6.8, conversions
template<class ToDuration, class Clock, class Duration>
constexpr time_point<Clock, ToDuration>
time_point_cast(const time_point<Clock, Duration>& t);
template<class ToDuration, class Clock, class Duration>
  constexpr time_point<Clock, ToDuration> floor(const time_point<Clock, Duration>& tp);
template<class ToDuration, class Clock, class Duration>
  constexpr time_point<Clock, ToDuration> ceil(const time_point<Clock, Duration>& tp);
template<class ToDuration, class Clock, class Duration>
  constexpr time_point<Clock, ToDuration> round(const time_point<Clock, Duration>& tp);

// 29.5.10, specialized algorithms
template<class Rep, class Period>
  constexpr duration<Rep, Period> abs(duration<Rep, Period> d);

// 29.7.2, class system_clock
class system_clock;

  using sys_time = time_point<system_clock, Duration>;
  using sys_seconds = sys_time<seconds>;
  using sys_days = sys_time<days>;

  template<class charT, class traits, class Duration>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const sys_time<Duration>& tp);

  template<class charT, class traits>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const sys_days& dp);

  template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
    basic_istream<charT, traits>& from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                                              sys_time<Duration>& tp,
                                              basic_string<charT, traits, Alloc>* abbrev = nullptr,
                                              minutes* offset = nullptr);

// 29.7.3, class utc_clock
class utc_clock;

  using utc_time = time_point<utc_clock, Duration>;
  using utc_seconds = utc_time<seconds>;

  template<class charT, class traits, class Duration>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const utc_time<Duration>& t);

  template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
    basic_istream<charT, traits>& from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                                              utc_time<Duration>& tp,
                                              basic_string<charT, traits, Alloc>* abbrev = nullptr,
                                              minutes* offset = nullptr);

  struct leap_second_info;

  template<class Duration>
    leap_second_info get_leap_second_info(const utc_time<Duration>& ut);

// 29.7.4, class tai_clock
class tai_clock;

  using tai_time = time_point<tai_clock, Duration>;
  using tai_seconds = tai_time<seconds>;
template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const tai_time<Duration>& t);

template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
tai_time<Duration>& t,
basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

// 29.7.5, class gps_clock
class gps_clock;

template<class Duration>
using gps_time = time_point<gps_clock, Duration>;
using gps_seconds = gps_time<seconds>;

template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const gps_time<Duration>& t);

template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
gps_time<Duration>& tp,
basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

// 29.7.6, type file_clock
using file_clock = see below;

template<class Duration>
using file_time = time_point<file_clock, Duration>;

template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const file_time<Duration>& t);

template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
file_time<Duration>& tp,
basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

// 29.7.7, class steady_clock

class steady_clock;

// 29.7.8, class high_resolution_clock

class high_resolution_clock;

// 29.7.9, local time

struct local_t {};

template<class Duration>
using local_time = time_point<local_t, Duration>;
using local_seconds = local_time<seconds>;
using local_days = local_time<days>;

template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const local_time<Duration>& t);

template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
local_time<Duration>& tp,
basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

// 29.7.10, time_point conversions
template<class DestClock, class SourceClock>
struct clock_time_conversion;

template<class DestClock, class SourceClock, class Duration>
auto clock_cast(const time_point<SourceClock, Duration>& t);

// 29.8.2, class last_spec
struct last_spec;

// 29.8.3, class day
class day;

constexpr bool operator==(const day& x, const day& y) noexcept;
constexpr strong_ordering operator<=>(const day& x, const day& y) noexcept;

castday operator+(const day& x, const days& y) noexcept;
castday operator+(const days& x, const day& y) noexcept;
castday operator-(const day& x, const days& y) noexcept;
castdays operator-(const day& x, const day& y) noexcept;

template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const day& d);

template<class charT, class traits, class Alloc = allocator<charT>>
    basic_istream<charT, traits>&
    from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                day& d, basic_string<charT, traits, Alloc>* abbrev = nullptr,
                minutes* offset = nullptr);

// 29.8.4, class month
class month;

constexpr bool operator==(const month& x, const month& y) noexcept;
constexpr strong_ordering operator<=>(const month& x, const month& y) noexcept;

constexpr month operator+(const month& x, const months& y) noexcept;
constexpr month operator+(const months& x, const month& y) noexcept;
constexpr month operator-(const month& x, const months& y) noexcept;
constexpr months operator-(const month& x, const month& y) noexcept;

template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const month& m);

template<class charT, class traits, class Alloc = allocator<charT>>
    basic_istream<charT, traits>&
    from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                month& m, basic_string<charT, traits, Alloc>* abbrev = nullptr,
                minutes* offset = nullptr);

// 29.8.5, class year
class year;

constexpr bool operator==(const year& x, const year& y) noexcept;
constexpr strong_ordering operator<=>(const year& x, const year& y) noexcept;

constexpr year operator+(const year& x, const years& y) noexcept;
constexpr year operator+(const years& x, const year& y) noexcept;
constexpr year operator-(const year& x, const years& y) noexcept;
constexpr years operator-(const year& x, const year& y) noexcept;
template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const year& y);

template<class charT, class traits, class Alloc = allocator<charT>>
  basic_istream<charT, traits>&
  from_stream(basic_istream<charT, traits>& is, const charT* fmt,
              year& y, basic_string<charT, traits, Alloc>* abbrev = nullptr,
              minutes* offset = nullptr);

// 29.8.6, class weekday
class weekday;

constexpr bool operator==(const weekday& x, const weekday& y) noexcept;
constexpr weekday operator+(const weekday& x, const days& y) noexcept;
constexpr weekday operator+(const days& x, const weekday& y) noexcept;
constexpr weekday operator-(const weekday& x, const days& y) noexcept;
constexpr days operator-(const weekday& x, const weekday& y) noexcept;

template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const weekday& wd);

template<class charT, class traits, class Alloc = allocator<charT>>
  basic_istream<charT, traits>&
  from_stream(basic_istream<charT, traits>& is, const charT* fmt,
              weekday& wd, basic_string<charT, traits, Alloc>* abbrev = nullptr,
              minutes* offset = nullptr);

// 29.8.7, class weekday_indexed
class weekday_indexed;

constexpr bool operator==(const weekday_indexed& x, const weekday_indexed& y) noexcept;

template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const weekday_indexed& wdi);

// 29.8.8, class weekday_last
class weekday_last;

constexpr bool operator==(const weekday_last& x, const weekday_last& y) noexcept;

template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const weekday_last& wdl);

// 29.8.9, class month_day
class month_day;

constexpr bool operator==(const month_day& x, const month_day& y) noexcept;
constexpr strong_ordering operator<=>(const month_day& x, const month_day& y) noexcept;

template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const month_day& md);

template<class charT, class traits, class Alloc = allocator<charT>>
  basic_istream<charT, traits>&
  from_stream(basic_istream<charT, traits>& is, const charT* fmt,
              month_day& md, basic_string<charT, traits, Alloc>* abbrev = nullptr,
              minutes* offset = nullptr);
class month_day_last;

constexpr bool operator==(const month_day_last& x, const month_day_last& y) noexcept;
constexpr strong_ordering operator<=>(const month_day_last& x, const month_day_last& y) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const month_day_last& mdl);

class month_weekday;

constexpr bool operator==(const month_weekday& x, const month_weekday& y) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const month_weekday& mwd);

class month_weekday_last;

constexpr bool operator==(const month_weekday_last& x, const month_weekday_last& y) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const month_weekday_last& mwdl);

class year_month;

constexpr bool operator==(const year_month& x, const year_month& y) noexcept;
constexpr strong_ordering operator<=>(const year_month& x, const year_month& y) noexcept;
constexpr year_month operator+(const year_month& ym, const months& dm) noexcept;
constexpr year_month operator+(const months& dm, const year_month& ym) noexcept;
constexpr year_month operator-(const year_month& ym, const months& dm) noexcept;
constexpr months operator-(const year_month& x, const year_month& y) noexcept;
constexpr year_month operator+(const year_month& ym, const years& dy) noexcept;
constexpr year_month operator+(const years& dy, const year_month& ym) noexcept;
constexpr year_month operator-(const year_month& ym, const years& dy) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const year_month& ym);

template<class charT, class traits, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt, year_month& ym, basic_string<charT, traits, Alloc>* abbrev = nullptr, minutes* offset = nullptr);

class year_month_day;

constexpr bool operator==(const year_month_day& x, const year_month_day& y) noexcept;
constexpr strong_ordering operator<=>(const year_month_day& x, const year_month_day& y) noexcept;

constexpr year_month_day operator+(const year_month_day& ymd, const months& dm) noexcept;
constexpr year_month_day operator+(const months& dm, const year_month_day& ymd) noexcept;
constexpr year_month_day operator-(const year_month_day& ymd, const months& dm) noexcept;
constexpr months operator-(const year_month_day& x, const year_month_day& y) noexcept;
constexpr year_month_day operator+(const year_month_day& ymd, const years& dy) noexcept;
constexpr year_month_day operator+(const years& dy, const year_month_day& ymd) noexcept;

§ 29.2
constexpr year_month_day operator-(const year_month_day& ymd, const months& dm) noexcept;
constexpr year_month_day operator-(const year_month_day& ymd, const years& dy) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>&& os, const year_month_day& ymd);

template<class charT, class traits, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>&& is, const charT* fmt,
year_month_day& ymd, basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

// 29.8.15, class year_month_day_last
class year_month_day_last;
constexpr bool operator==(const year_month_day_last& x,
const year_month_day_last& y) noexcept;
constexpr strong_ordering operator<=>(const year_month_day_last& x,
const year_month_day_last& y) noexcept;

constexpr year_month_day_last
operator+(const year_month_day_last& ymdl, const months& dm) noexcept;
constexpr year_month_day_last
operator+(const months& dm, const year_month_day_last& ymdl) noexcept;
constexpr year_month_day_last
operator+(const year_month_day_last& ymdl, const years& dy) noexcept;
constexpr year_month_day_last
operator+(const years& dy, const year_month_day_last& ymdl) noexcept;
constexpr year_month_day_last
operator-(const year_month_day_last& ymdl, const months& dm) noexcept;
constexpr year_month_day_last
operator-(const year_month_day_last& ymdl, const years& dy) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>&& os, const year_month_day_last& ymdl);

// 29.8.16, class year_month_weekday
class year_month_weekday;
constexpr bool operator==(const year_month_weekday& x,
const year_month_weekday& y) noexcept;

constexpr year_month_weekday
operator+(const year_month_weekday& ymwd, const months& dm) noexcept;
constexpr year_month_weekday
operator+(const months& dm, const year_month_weekday& ymwd) noexcept;
constexpr year_month_weekday
operator+(const year_month_weekday& ymwd, const years& dy) noexcept;
constexpr year_month_weekday
operator+(const years& dy, const year_month_weekday& ymwd) noexcept;
constexpr year_month_weekday
operator-(const year_month_weekday& ymwd, const months& dm) noexcept;
constexpr year_month_weekday
operator-(const year_month_weekday& ymwd, const years& dy) noexcept;

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>&& os, const year_month_weekday& ymwd);

// 29.8.17, class year_month_weekday_last
class year_month_weekday_last;
constexpr bool operator==(const year_month_weekday_last& x, 
    const year_month_weekday_last& y) noexcept;

constexpr year_month_weekday_last
    operator+(const year_month_weekday_last& ymwdl, const months& dm) noexcept;
constexpr year_month_weekday_last
    operator+(const months& dm, const year_month_weekday_last& ymwdl) noexcept;
constexpr year_month_weekday_last
    operator+(const year_month_weekday_last& ymwdl, const years& dy) noexcept;
constexpr year_month_weekday_last
    operator+(const years& dy, const year_month_weekday_last& ymwdl) noexcept;
constexpr year_month_weekday_last
    operator-(const year_month_weekday_last& ymwdl, const months& dm) noexcept;
constexpr year_month_weekday_last
    operator-(const year_month_weekday_last& ymwdl, const years& dy) noexcept;

template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const year_month_weekday_last& ymwdl);

// 29.8.18, civil calendar conventional syntax operators
constexpr year_month
    operator/(const year& y, const month& m) noexcept;
constexpr year_month
    operator/(const year& y, int m) noexcept;
constexpr month_day
    operator/(const month& m, const day& d) noexcept;
constexpr month_day
    operator/(const month& m, int d) noexcept;
constexpr month_day
    operator/(int m, const day& d) noexcept;
constexpr month_day
    operator/(const day& d, const month& m) noexcept;
constexpr month_day
    operator/(const day& d, int m) noexcept;
constexpr month_day_last
    operator/(const month& m, last_spec) noexcept;
constexpr month_day_last
    operator/(int m, last_spec) noexcept;
constexpr month_day_last
    operator/(last_spec, const month& m) noexcept;
constexpr month_day_last
    operator/(last_spec, int m) noexcept;
constexpr month_weekday
    operator/(const month& m, const weekday_indexed& wdi) noexcept;
constexpr month_weekday
    operator/(int m, const weekday_indexed& wdi) noexcept;
constexpr month_weekday
    operator/(const weekday_indexed& wdi, const month& m) noexcept;
constexpr month_weekday
    operator/(const weekday_indexed& wdi, int m) noexcept;
constexpr month_weekday_last
    operator/(const month& m, const weekday_last& wdl) noexcept;
constexpr month_weekday_last
    operator/(int m, const weekday_last& wdl) noexcept;
constexpr month_weekday_last
    operator/(const weekday_last& wdl, const month& m) noexcept;
constexpr month_weekday_last
    operator/(const weekday_last& wdl, int m) noexcept;
constexpr year_month_day
    operator/(const year_month& ym, const day& d) noexcept;
constexpr year_month_day
    operator/(const year_month& ym, int d) noexcept;
constexpr year_month_day
    operator/(const year& y, const month_day& md) noexcept;
constexpr year_month_day
    operator/(int y, const month_day& md) noexcept;
constexpr year_month_day
    operator/(const month_day& md, const year& y) noexcept;
constexpr year_month_day
    operator/(const month_day& md, int y) noexcept;
constexpr year_month_day_last
    operator/(const year_month& ym, last_spec) noexcept;
constexpr year_month_day_last
    operator/(const year& y, const month_day_last& mdl) noexcept;
constexpr year_month_day_last
    operator/(int y, const month_day_last& mdl) noexcept;
constexpr year_month_day_last
    operator/(const month_day_last& mdl, const year& y) noexcept;
constexpr year_month_day_last
    operator/(const month_day_last& mdl, int y) noexcept;
constexpr year_month_weekday
    operator/(const year_month& ym, const weekday_indexed& wdi) noexcept;
constexpr year_month_weekday
    operator/(const year& y, const month_weekday& mwd) noexcept;
constexpr year_month_weekday
    operator/(int y, const month_weekday& mwd) noexcept;
constexpr year_month_weekday
    operator/(const month_weekday& mwd, const year& y) noexcept;
constexpr year_month_weekday
    operator/(const month_weekday& mwd, int y) noexcept;
constexpr year_month_weekday_last
    operator/(const year_month& ym, const weekday_last& wdl) noexcept;
constexpr year_month_weekday_last
    operator/(const year& y, const month_weekday_last& mwdl) noexcept;
constexpr year_month_weekday_last
    operator/(int y, const month_weekday_last& mwdl) noexcept;
constexpr year_month_weekday_last
    operator/(const month_weekday_last& mwdl, const year& y) noexcept;
constexpr year_month_weekday_last
    operator/(const month_weekday_last& mwdl, int y) noexcept;

// 29.9. class template hh_mm_ss
template<class Duration>
    class hh_mm_ss;

    template<class charT, class traits, class Duration>
    basic_ostream<charT, traits>&
        operator<<(basic_ostream<charT, traits>& os, const hh_mm_ss<Duration>& hms);

// 29.10, 12/24 hour functions
constexpr bool is_am(const hours& h) noexcept;
constexpr bool is_pm(const hours& h) noexcept;
constexpr hours make12(const hours& h) noexcept;
constexpr hours make24(const hours& h, bool is_pm) noexcept;

// 29.11.2, time zone database
struct tzdb;
    class tzdb_list;

// 29.11.2.3, time zone database access
    const tzdb& get_tzdb();
    tzdb_list& get_tzdb_list();
    const time_zone* locate_zone(string_view tz_name);
    const time_zone* current_zone();

// 29.11.2.4, remote time zone database support
    const tzdb& reload_tzdb();
string remote_version();

// 29.11.3, exception classes
class nonexistent_local_time;
class ambiguous_local_time;

// 29.11.4, information classes
struct sys_info;
template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const sys_info& si);

struct local_info;
template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const local_info& li);

// 29.11.5, class time_zone
enum class choose {earliest, latest};
class time_zone;

  bool operator==(const time_zone& x, const time_zone& y) noexcept;
  strong_ordering operator<=>(const time_zone& x, const time_zone& y) noexcept;

// 29.11.6, class template zoned_traits
  template<class T> struct zoned_traits;

// 29.11.7, class template zoned_time
  template<class Duration, class TimeZonePtr = const time_zone*> class zoned_time;

using zoned_seconds = zoned_time<seconds>;
template<class Duration1, class Duration2, class TimeZonePtr>
  bool operator==(const zoned_time<Duration1, TimeZonePtr>& x,
                  const zoned_time<Duration2, TimeZonePtr>& y);
template<class charT, class traits, class Duration, class TimeZonePtr>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os,
             const zoned_time<Duration, TimeZonePtr>& t);

// 29.11.8, leap second support
class leap_second;

constexpr bool operator==(const leap_second& x, const leap_second& y);
constexpr strong_ordering operator<=>(const leap_second& x, const leap_second& y);

template<class Duration>
  constexpr bool operator==(const leap_second& x, const sys_time<Duration>& y);

§ 29.2
template<class Duration>
constexpr bool operator>=(const sys_time<Duration>& x, const leap_second& y);

template<class Duration>
requires three_way_comparable_with<sys_seconds, sys_time<Duration>>
constexpr auto operator<=>(const leap_second& x, const sys_time<Duration>& y);

// 29.11.9, class time_zone_link
class time_zone_link;

bool operator==(const time_zone_link& x, const time_zone_link& y);

strong_ordering operator<=>(const time_zone_link& x, const time_zone_link& y);

// 29.12, formatting

namespace std {

namespace std::chrono {

namespace std { namespace std::chrono { // 29.13, parsing

template<class charT, class Parsable>
unspecified

§ 29.2

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parse(const charT* fmt, Parsable& tp);

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp);

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const charT* fmt, Parsable& tp,
      basic_string<charT, traits, Alloc>& abbrev);

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp,
      basic_string<charT, traits, Alloc>& abbrev);

template<class charT, class Parsable>
unspecified
parse(const charT* fmt, Parsable& tp, minutes& offset);

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp,
      minutes& offset);

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const charT* fmt, Parsable& tp,
      basic_string<charT, traits, Alloc>& abbrev, minutes& offset);

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp,
      basic_string<charT, traits, Alloc>& abbrev, minutes& offset);

// calendrical constants
inline constexpr last_spec last{};

inline constexpr weekday Sunday{0};
inline constexpr weekday Monday{1};
inline constexpr weekday Tuesday{2};
inline constexpr weekday Wednesday{3};
inline constexpr weekday Thursday{4};
inline constexpr weekday Friday{5};
inline constexpr weekday Saturday{6};

inline constexpr month January{1};
inline constexpr month February{2};
inline constexpr month March{3};
inline constexpr month April{4};
inline constexpr month May{5};
inline constexpr month June{6};
inline constexpr month July{7};
inline constexpr month August{8};
inline constexpr month September{9};
inline constexpr month October{10};
inline constexpr month November{11};
inline constexpr month December{12};

} namespace std::inline literals::inline chrono_literals {

// 29.5.9 suffixes for duration literals
constexpr chrono::hours operator"h(unsigned long long);
constexpr chrono::duration<unspecified, ratio<3600, 1>> operator"h(long double);

constexpr chrono::minutes operator"min(unsigned long long);
constexpr chrono::duration<unspecified, ratio<60, 1>> operator"min(long double);
constexpr chrono::seconds operator"s(unsigned long long);
constexpr chrono::duration<unspecified> operator"s(long double);

constexpr chrono::milliseconds operator"ms(unsigned long long);
constexpr chrono::duration<unspecified, milli> operator"ms(long double);

constexpr chrono::microseconds operator"us(unsigned long long);
constexpr chrono::duration<unspecified, micro> operator"us(long double);

constexpr chrono::nanoseconds operator"ns(unsigned long long);
constexpr chrono::duration<unspecified, nano> operator"ns(long double);

// 29.8.3.3, non-member functions
constexpr chrono::day operator"d(unsigned long long d) noexcept;

// 29.8.5.3, non-member functions
constexpr chrono::year operator"y(unsigned long long y) noexcept;

namespace std::chrono {
  using namespace literals::chrono_literals;
}

namespace std {

  // 29.14, hash support
  template<class T> struct hash;
  template<class Rep, class Period> struct hash<chrono::duration<Rep, Period>>;
  template<class Clock, class Duration> struct hash<chrono::time_point<Clock, Duration>>;
  template<> struct hash<chrono::day>;
  template<> struct hash<chrono::month>;
  template<> struct hash<chrono::year>;
  template<> struct hash<chrono::weekday>;
  template<> struct hash<chrono::weekday_indexed>;
  template<> struct hash<chrono::weekday_last>;
  template<> struct hash<chrono::month_day>;
  template<> struct hash<chrono::month_day_last>;
  template<> struct hash<chrono::month_weekday>;
  template<> struct hash<chrono::month_weekday_last>;
  template<> struct hash<chrono::year_month>;
  template<> struct hash<chrono::year_month_day>;
  template<> struct hash<chrono::year_month_day_last>;
  template<> struct hash<chrono::year_month_weekday>;
  template<> struct hash<chrono::year_month_weekday_last>;
  template<class Duration, class TimeZonePtr>
  struct hash<chrono::zoned_time<Duration, TimeZonePtr>>;
  template<> struct hash<chrono::leap_second>;
}

29.3  Cpp17Clock requirements

A clock is a bundle consisting of a duration, a time_point, and a function now() to get the current time_point. The origin of the clock’s time_point is referred to as the clock’s epoch. A clock shall meet the requirements in Table 102.

In Table 102 C1 and C2 denote clock types. t1 and t2 are values returned by C1::now() where the call returning t1 happens before (6.9.2) the call returning t2 and both of these calls occur before C1::time_point::max().

[Note 1: This means C1 did not wrap around between t1 and t2. — end note]
Table 102 — Cpp17Clock requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1::rep</td>
<td>An arithmetic type or a class emulating an arithmetic type</td>
<td>The representation type of C1::duration.</td>
</tr>
<tr>
<td>C1::period</td>
<td>a specialization of ratio</td>
<td>The tick period of the clock in seconds.</td>
</tr>
<tr>
<td>C1::duration</td>
<td>chrono::duration&lt;C1::rep, C1::period&gt;</td>
<td>The duration type of the clock.</td>
</tr>
<tr>
<td>C1::time_point</td>
<td>chrono::time_point&lt;C1&gt; or chrono::time_point&lt;C2, C1::duration&gt;</td>
<td>The time_point type of the clock. C1 and C2 shall refer to the same epoch.</td>
</tr>
<tr>
<td>C1::is_steady</td>
<td>const bool</td>
<td>true if t1 &lt;= t2 is always true and the time between clock ticks is constant, otherwise false.</td>
</tr>
<tr>
<td>C1::now()</td>
<td>C1::time_point</td>
<td>Returns a time_point object representing the current point in time.</td>
</tr>
</tbody>
</table>

3 [Note 2: The relative difference in durations between those reported by a given clock and the SI definition is a measure of the quality of implementation. — end note]

4 A type TC meets the Cpp17TrivialClock requirements if

(4.1) TC meets the Cpp17Clock requirements,

(4.2) the types TC::rep, TC::duration, and TC::time_point meet the Cpp17EqualityComparable (Table 28) and Cpp17LessThanComparable (Table 29) and Cpp17Swappable (16.4.4.3) requirements and the requirements of numeric types (28.2).  

[Note 3: This means, in particular, that operations on these types will not throw exceptions. — end note]

(4.3) the function TC::now() does not throw exceptions, and

(4.4) the type TC::time_point::clock meets the Cpp17TrivialClock requirements, recursively.

29.4 Time-related traits

29.4.1 treat_as_floating_point

template<class Rep> struct treat_as_floating_point : is_floating_point<Rep> { };  

1 The duration template uses the treat_as_floating_point trait to help determine if a duration object can be converted to another duration with a different tick period. If treat_as_floating_point_v<Rep> is true, then implicit conversions are allowed among durations. Otherwise, the implicit convertibility depends on the tick periods of the durations.

[Note 1: The intention of this trait is to indicate whether a given class behaves like a floating-point type, and thus allows division of one value by another with acceptable loss of precision. If treat_as_floating_point_v<Rep> is false, Rep will be treated as if it behaved like an integral type for the purpose of these conversions. — end note]

29.4.2 duration_values  

template<class Rep>
struct duration_values {
  public:
    static constexpr Rep zero() noexcept;
    static constexpr Rep min() noexcept;
    static constexpr Rep max() noexcept;
};

1 The duration template uses the duration_values trait to construct special values of the duration’s representation (Rep). This is done because the representation can be a class type with behavior that requires some other implementation to return these special values. In that case, the author of that class type should specialize duration_values to return the indicated values.
static constexpr Rep zero() noexcept;

Returns: Rep(0).

[Note 1: Rep(0) is specified instead of Rep() because Rep() can have some other meaning, such as an uninitialized value. — end note]

Remarks: The value returned shall be the additive identity.

static constexpr Rep min() noexcept;

Returns: numeric_limits<Rep>::lowest().

Remarks: The value returned shall compare less than or equal to zero().

static constexpr Rep max() noexcept;

Returns: numeric_limits<Rep>::max().

Remarks: The value returned shall compare greater than zero().

29.4.3 Specializations of common_type

template<class Rep1, class Period1, class Rep2, class Period2>
struct common_type<chrono::duration<Rep1, Period1>, chrono::duration<Rep2, Period2>> {
  using type = chrono::duration<common_type_t<Rep1, Rep2>, see below>;
};

The period of the duration indicated by this specialization of common_type is the greatest common divisor of Period1 and Period2.

[Note 1: This can be computed by forming a ratio of the greatest common divisor of Period1::num and Period2::num and the least common multiple of Period1::den and Period2::den. — end note]

[Note 2: The typedef name type is a synonym for the duration with the largest tick period possible where both duration arguments will convert to it without requiring a division operation. The representation of this type is intended to be able to hold any value resulting from this conversion with no truncation error, although floating-point durations can have round-off errors. — end note]

template<class Clock, class Duration1, class Duration2>
struct common_type<chrono::time_point<Clock, Duration1>, chrono::time_point<Clock, Duration2>> {
  using type = chrono::time_point<Clock, common_type_t<Duration1, Duration2>>;
};

The common type of two time_point types is a time_point with the same clock as the two types and the common type of their two durations.

29.4.4 Class template is_clock

template<class T> struct is_clock;

is_clock is a Cpp17UnaryTypeTrait (21.3.2) with a base characteristic of true_type if T meets the Cpp17Clock requirements (29.3), otherwise false_type. For the purposes of the specification of this trait, the extent to which an implementation determines that a type cannot meet the Cpp17Clock requirements is unspecified, except that as a minimum a type T shall not qualify as a Cpp17Clock unless it meets all of the following conditions:

(1.1) — the qualified-ids T::rep, T::period, T::duration, and T::time_point are valid and each denotes a type (13.10.3),

(1.2) — the expression T::is_steady is well-formed when treated as an unevaluated operand (7.2.3),

(1.3) — the expression T::now() is well-formed when treated as an unevaluated operand.

The behavior of a program that adds specializations for is_clock is undefined.

29.5 Class template duration

29.5.1 General

A duration type measures time between two points in time (time_points). A duration has a representation which holds a count of ticks and a tick period. The tick period is the amount of time which occurs from one tick to the next, in units of seconds. It is expressed as a rational constant using the template ratio.
namespace std::chrono {
    template<class Rep, class Period = ratio<1>>
    class duration {
public:
    using rep = Rep;
    using period = typename Period::type;

private:
    rep rep_; // exposition only

public:
    // 29.5.2, construct/copy/destroy
    constexpr duration() = default;
    template<class Rep2>
    constexpr explicit duration(const Rep2& r);
    template<class Rep2, class Period2>
    constexpr duration(const duration<Rep2, Period2>& d);
    ~duration() = default;
    duration(const duration&) = default;
    duration& operator=(const duration&) = default;

    // 29.5.3, observer
    constexpr rep count() const;

    // 29.5.4, arithmetic
    constexpr common_type_t<duration> operator+() const;
    constexpr common_type_t<duration> operator-() const;
    constexpr duration& operator++();
    constexpr duration operator++(int);
    constexpr duration& operator--();
    constexpr duration operator--(int);
    constexpr duration& operator+=(const duration& d);
    constexpr duration& operator-=(const duration& d);
    constexpr duration& operator*=(const rep& rhs);
    constexpr duration& operator/=(const rep& rhs);
    constexpr duration& operator%=(const rep& rhs);
    constexpr duration& operator%=(const duration& rhs);

    // 29.5.5, special values
    static constexpr duration zero() noexcept;
    static constexpr duration min() noexcept;
    static constexpr duration max() noexcept;
    
};

2 Rep shall be an arithmetic type or a class emulating an arithmetic type. If duration is instantiated with a
duration type as the argument for the template parameter Rep, the program is ill-formed.

3 If Period is not a specialization of ratio, the program is ill-formed. If Period::num is not positive, the
program is ill-formed.

4 Members of duration do not throw exceptions other than those thrown by the indicated operations on their
representations.

5 The defaulted copy constructor of duration shall be a constexpr function if and only if the required
initialization of the member rep_ for copy and move, respectively, would be constexpr-suitable (9.2.6).

6 [Example 1:

duration<long, ratio<60>> d0; // holds a count of minutes using a long
duration<long long, milli> d1; // holds a count of milliseconds using a long long
duration<double, ratio<1, 30>> d2; // holds a count with a tick period of \frac{1}{30} of a second
// (30 Hz) using a double

— end example]
29.5.2 Constructors

```cpp
template<class Rep2>
constexpr explicit duration(const Rep2& r);
```

Constraints:

- `is_convertible_v<const Rep2&, rep>` is true and
  - `treat_as_floating_point_v<rep>` is true or
  - `treat_as_floating_point_v<Rep2>` is false.

Example 1:
```cpp
duration<int, milli> d(3); // OK
duration<int, milli> d2(3.5); // error
```

Effects: Initializes `rep_` with `r`.

```cpp
template<class Rep2, class Period2>
constexpr duration(const duration<Rep2, Period2>& d);
```

Constraints: No overflow is induced in the conversion and `treat_as_floating_point_v<rep>` is true or both `ratio_divide<Period2, period>::den` is 1 and `treat_as_floating_point_v<Rep2>` is false.

Note 1: This requirement prevents implicit truncation error when converting between integral-based `duration` types. Such a construction could easily lead to confusion about the value of the `duration`. —end note

Example 2:
```cpp
duration<int, milli> ms(3);
duration<int, micro> us = ms; // OK
duration<int, milli> ms2 = us; // error
```

Effects: Initializes `rep_` with `duration_cast<duration>(d).count()`.

29.5.3 Observer

```cpp
constexpr rep count() const;
```

Returns: `rep_`.

29.5.4 Arithmetic

```cpp
constexpr common_type_t<duration> operator+(const) const;
```

Returns: `common_type_t<duration>(*this)`.

```cpp
constexpr common_type_t<duration> operator-(const) const;
```

Returns: `common_type_t<duration>(-rep_)`.

```cpp
constexpr duration& operator++();
```

Effects: Equivalent to: `++rep_`

Returns: `*this`.

```cpp
constexpr duration operator++(int);
```

Effects: Equivalent to: `return duration(rep_++);`

```cpp
constexpr duration& operator--();
```

Effects: Equivalent to: `--rep_`

Returns: `*this`.

```cpp
constexpr duration operator--(int);
```

Effects: Equivalent to: `return duration(rep_--);`
constexpr duration& operator+=(const duration& d);
   \textit{Effects}: Equivalent to: \texttt{rep\_ += d.count()}.  
   \textit{Returns}: \texttt{*this}.

constexpr duration& operator-=(const duration& d);
   \textit{Effects}: Equivalent to: \texttt{rep\_ -= d.count()}.  
   \textit{Returns}: \texttt{*this}.

constexpr duration& operator*=(const rep& rhs);
   \textit{Effects}: Equivalent to: \texttt{rep\_ *= rhs}.  
   \textit{Returns}: \texttt{*this}.

constexpr duration& operator/=(const rep& rhs);
   \textit{Effects}: Equivalent to: \texttt{rep\_ /= rhs}.  
   \textit{Returns}: \texttt{*this}.

constexpr duration& operator%=(const rep& rhs);
   \textit{Effects}: Equivalent to: \texttt{rep\_ %= rhs}.  
   \textit{Returns}: \texttt{*this}.

constexpr duration& operator%=(const duration& rhs);
   \textit{Effects}: Equivalent to: \texttt{rep\_ %= rhs.count()}.  
   \textit{Returns}: \texttt{*this}.

29.5.5 Special values \[time.duration.special\]

static constexpr duration zero() noexcept;
   \textit{Returns}: \texttt{duration(duration\_values<rep>::zero())}.

static constexpr duration min() noexcept;
   \textit{Returns}: \texttt{duration(duration\_values<rep>::min())}.

static constexpr duration max() noexcept;
   \textit{Returns}: \texttt{duration(duration\_values<rep>::max())}.

29.5.6 Non-member arithmetic \[time.duration.nonmember\]

In the function descriptions that follow, unless stated otherwise, let \texttt{CD} represent the return type of the function.

\texttt{template<class Rep1, class Period1, class Rep2, class Period2>}
\texttt{constexpr common\_type\_t<duration<Rep1, Period1>, duration<Rep2, Period2>>}
\texttt{operator+(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs)};
\texttt{Returns: CD(CD(lhs).count() + CD(rhs).count())}.

\texttt{template<class Rep1, class Period1, class Rep2, class Period2>}
\texttt{constexpr common\_type\_t<duration<Rep1, Period1>, duration<Rep2, Period2>>}
\texttt{operator-(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs)};
\texttt{Returns: CD(CD(lhs).count() - CD(rhs).count())}.

\texttt{template<class Rep1, class Period, class Rep2>
\texttt{constexpr duration<common\_type\_t<Rep1, Rep2>, Period>}
\texttt{operator*(const duration<Rep1, Period>& d, const Rep2& s)};
\texttt{Constraints: is\_convertible\_v<const Rep2&, common\_type\_t<Rep1, Rep2>> is true.}
\texttt{Returns: CD(CD(d).count() * s)}.  

\S 29.5.6
template<
class Rep1, class Rep2, class Period>
constexpr duration<
common_type_t<Rep1, Rep2>, Period>
operator*(
const Rep1& s, const duration<Rep2, Period>& d);

Constraints: is_convertible_v<const Rep1&, common_type_t<Rep1, Rep2>> is true.

Returns: d * s.

template<
class Rep1, class Period, class Rep2>
constexpr duration<
common_type_t<Rep1, Rep2>, Period>
operator/(const duration<Rep1, Period>& d, const Rep2& s);

Constraints: is_convertible_v<const Rep2&, common_type_t<Rep1, Rep2>> is true and Rep2 is not a specialization of duration.

Returns: CD(CD(d).count() / s).

template<
class Rep1, class Period1, class Rep2, class Period2>
constexpr common_type_t<Rep1, Rep2>
operator%(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

Let CD be common_type_t<
duration<Rep1, Period1>, duration<Rep2, Period2>>.

Returns: CD(lhs).count() % CD(rhs).count().

29.5.7 Comparisons
In the function descriptions that follow, CT represents common_type_t<A, B>, where A and B are the types of the two arguments to the function.

template<
class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator==(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

Returns: CT(lhs).count() == CT(rhs).count().

template<
class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator<(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

Returns: CT(lhs).count() < CT(rhs).count().

template<
class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator>(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

Returns: rhs > lhs.

template<
class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator<=(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

Returns: !(rhs < lhs).

template<
class Rep1, class Period1, class Rep2, class Period2>
constexpr bool operator>=(const duration<Rep1, Period1>& lhs, const duration<Rep2, Period2>& rhs);

Returns: !(rhs > lhs).
const duration<Rep2, Period2>& rhs);

6  Returns: !(lhs < rhs).

template<class Rep1, class Period1, class Rep2, class Period2>
requires three_way_comparable<typename CT::rep>
constexpr auto operator<=>(const duration<Rep1, Period1>& lhs,
    const duration<Rep2, Period2>& rhs);

7  Returns: CT(lhs).count() <=> CT(rhs).count().

29.5.8 Conversions
[time.duration.cast]

template<class ToDuration, class Rep, class Period>
constexpr ToDuration duration_cast(const duration<Rep, Period>& d);

1  Constraints: ToDuration is a specialization of duration.

2  Returns: Let CF be ratio_divide<Period, typename ToDuration::period>, and CR be common_type<
typename ToDuration::rep, Rep, intmax_t>::type.

(2.1) — If CF::num == 1 and CF::den == 1, returns
    ToDuration(static_cast<typename ToDuration::rep>(d.count()))

(2.2) — otherwise, if CF::num != 1 and CF::den == 1, returns
    ToDuration(static_cast<typename ToDuration::rep>(
        static_cast<CR>(d.count()) * static_cast<CR>(CF::num)))

(2.3) — otherwise, if CF::num == 1 and CF::den != 1, returns
    ToDuration(static_cast<typename ToDuration::rep>(
        static_cast<CR>(d.count()) / static_cast<CR>(CF::den)))

(2.4) — otherwise, returns
    ToDuration(static_cast<typename ToDuration::rep>(
        static_cast<CR>(d.count()) * static_cast<CR>(CF::num) / static_cast<CR>(CF::den)))

3  [Note 1: This function does not use any implicit conversions; all conversions are done with static_cast.
    It avoids multiplications and divisions when it is known at compile time that one or more arguments is 1.
    Intermediate computations are carried out in the widest representation and only converted to the destination
    representation at the final step. — end note]

template<class ToDuration, class Rep, class Period>
constexpr ToDuration floor(const duration<Rep, Period>& d);

4  Constraints: ToDuration is a specialization of duration.

5  Returns: The greatest result t representable in ToDuration for which t <= d.

template<class ToDuration, class Rep, class Period>
constexpr ToDuration ceil(const duration<Rep, Period>& d);

6  Constraints: ToDuration is a specialization of duration.

7  Returns: The least result t representable in ToDuration for which t >= d.

template<class ToDuration, class Rep, class Period>
constexpr ToDuration round(const duration<Rep, Period>& d);

8  Constraints: ToDuration is a specialization of duration and treat_as_floating_point_v<
typename ToDuration::rep> is false.

9  Returns: The value of ToDuration that is closest to d. If there are two closest values, then return the
    value t for which t % 2 == 0.

29.5.9 Suffixes for duration literals
[time.duration.literal]

This subclause describes literal suffixes for constructing duration literals. The suffixes h, min, s, ms, us, ns
denote duration values of the corresponding types hours, minutes, seconds, milliseconds, microseconds, and
nanoseconds respectively if they are applied to integer-literals.

If any of these suffixes are applied to a floating-point-literal the result is a chrono::duration literal with an
unspecified floating-point representation.

§ 29.5.9
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If any of these suffixes are applied to an integer-literal and the resulting \texttt{chrono::duration} value cannot be represented in the result type because of overflow, the program is ill-formed.

\textbf{Example 1}: The following code shows some duration literals.

\begin{verbatim}
using namespace std::chrono_literals;
auto constexpr aday=24h;
auto constexpr lesson=45min;
auto constexpr halfanhour=0.5h;
\end{verbatim}

\textit{Returns}: A duration literal representing \texttt{hours} hours.

\begin{verbatim}
constexpr chrono::hours operator"h(unsigned long long hours);
constexpr chrono::duration<unspecified, ratio<3600, 1>> operator"h(long double hours);
\end{verbatim}

\textit{Returns}: A duration literal representing \texttt{minutes} minutes.

\begin{verbatim}
constexpr chrono::minutes operator"min(unsigned long long minutes);
constexpr chrono::duration<unspecified, ratio<60, 1>> operator"min(long double minutes);
\end{verbatim}

\textit{Returns}: A duration literal representing \texttt{sec} seconds.

\begin{verbatim}
constexpr chrono::seconds operator"s(unsigned long long sec);
constexpr chrono::duration<unspecified> operator"s(long double sec);
\end{verbatim}

\textit{Returns}: A duration literal representing \texttt{msec} milliseconds.

\begin{verbatim}
constexpr chrono::milliseconds operator"ms(unsigned long long msec);
constexpr chrono::duration<milli> operator"ms(long double msec);
\end{verbatim}

\textit{Returns}: A duration literal representing \texttt{usec} microseconds.

\begin{verbatim}
constexpr chrono::microseconds operator"us(unsigned long long usec);
constexpr chrono::duration<micro> operator"us(long double usec);
\end{verbatim}

\textit{Returns}: A duration literal representing \texttt{nsec} nanoseconds.

\begin{verbatim}
constexpr chrono::nanoseconds operator"ns(unsigned long long nsec);
constexpr chrono::duration<nano> operator"ns(long double nsec);
\end{verbatim}

§ 29.5.10 Algorithms

\begin{verbatim}
template<class Rep, class Period>
constexpr duration<Rep, Period> abs(duration<Rep, Period> d);
\end{verbatim}

\textit{Constraints}: \texttt{numeric_limits<Rep>::is_signed} is true.

\textit{Returns}: If \texttt{d} >= \texttt{d.zero()}, return \texttt{d}, otherwise return \texttt{-d}.

29.5.11 I/O

\begin{verbatim}
template<class charT, class traits, class Rep, class Period>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const duration<Rep, Period>& d);
\end{verbatim}

\textit{Effects}: Inserts the duration \texttt{d} onto the stream \texttt{os} as if it were implemented as follows:

\begin{verbatim}
basic_ostringstream<charT, traits> s;
s.flags(os.flags());
s.imbue(os.getloc());
s.precision(os.precision());
s << d.count() << units-suffix;
return os << s.str();
\end{verbatim}

where \texttt{units-suffix} depends on the type \texttt{Period::type} as follows:

\begin{enumerate}
\item If \texttt{Period::type} is \texttt{atto}, \texttt{units-suffix} is "as".
\item Otherwise, if \texttt{Period::type} is \texttt{femto}, \texttt{units-suffix} is "fs".
\end{enumerate}
— Otherwise, if Period::type is pico, units-suffix is "ps".
— Otherwise, if Period::type is nano, units-suffix is "ns".
— Otherwise, if Period::type is micro, it is implementation-defined whether units-suffix is "\u00b5s" ("\u00b5\u0073") or "us".
— Otherwise, if Period::type is milli, units-suffix is "ms".
— Otherwise, if Period::type is centi, units-suffix is "cs".
— Otherwise, if Period::type is deci, units-suffix is "ds".
— Otherwise, if Period::type is ratio<1>, units-suffix is "s".
— Otherwise, if Period::type is deca, units-suffix is "das".
— Otherwise, if Period::type is hecto, units-suffix is "hs".
— Otherwise, if Period::type is kilo, units-suffix is "ks".
— Otherwise, if Period::type is mega, units-suffix is "Ms".
— Otherwise, if Period::type is giga, units-suffix is "Gs".
— Otherwise, if Period::type is tera, units-suffix is "Ts".
— Otherwise, if Period::type is peta, units-suffix is "Ps".
— Otherwise, if Period::type is exa, units-suffix is "Es".
— Otherwise, if Period::type is ratio<60>, units-suffix is "min".
— Otherwise, if Period::type is ratio<3600>, units-suffix is "h".
— Otherwise, if Period::type is ratio<86400>, units-suffix is "d".
— Otherwise, if Period::type::den == 1, units-suffix is "[num]\s".
— Otherwise, units-suffix is "[num/den]\s".

In the list above, the use of num and den refers to the static data members of Period::type, which are converted to arrays of charT using a decimal conversion with no leading zeroes.

Returns: os.

template<class charT, class traits, class Rep, class Period, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
duration<Rep, Period>& d,
basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the duration d using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid duration, is.setstate(ios_base::failbit) is called and d is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null.

Returns: is.

29.6 Class template time_point

29.6.1 General

namespace std::chrono {
    template<class Clock, class Duration = typename Clock::duration>
    class time_point {
        public:
            using clock = Clock;
            using duration = Duration;
            using rep = typename duration::rep;
            using period = typename duration::period;

        private:
            duration d_; // exposition only
    }

§ 29.6.1 ©ISO/IEC 1632
public:
    // 29.6.2, construct
    constexpr time_point();          // has value epoch
    constexpr explicit time_point(const duration& d);  // same as time_point() + d
    template<class Duration2>
        constexpr time_point(const time_point<clock, Duration2>& t);

    // 29.6.3, observer
    constexpr duration time_since_epoch() const;

    // 29.6.4, arithmetic
    constexpr time_point& operator++();
    constexpr time_point operator++(int);
    constexpr time_point& operator--();
    constexpr time_point operator--(int);
    constexpr time_point& operator+=(const duration& d);
    constexpr time_point& operator-=(const duration& d);

    // 29.6.5, special values
    static constexpr time_point min() noexcept;
    static constexpr time_point max() noexcept;
};

1 If Duration is not a specialization of duration, the program is ill-formed.

29.6.2 Constructors
    constexpr time_point();
    Effects: Initializes d_ with duration::zero(). Such a time_point object represents the epoch.

    constexpr explicit time_point(const duration& d);
    Effects: Initializes d_ with d. Such a time_point object represents the epoch + d.

    template<class Duration2>
        constexpr time_point(const time_point<clock, Duration2>& t);
    Constraints: is_convertible_v<Duration2, duration> is true.

29.6.3 Observer
    constexpr duration time_since_epoch() const;
    Returns: d_.

29.6.4 Arithmetic
    constexpr time_point& operator++();
    Effects: Equivalent to: ++d_.

    constexpr time_point operator++(int);
    Effects: Equivalent to: return time_point(d_++);

    constexpr time_point& operator--();
    Effects: Equivalent to: --d_.

    constexpr time_point operator--(int);
    Effects: Equivalent to: return time_point(d__);
constexpr time_point& operator+=(const duration& d);
    // Effects: Equivalent to: d_ += d.
    // Returns: *this.

castexpr time_point& operator-=(const duration& d);
    // Effects: Equivalent to: d_ -= d.
    // Returns: *this.

29.6.5 Special values

static constexpr time_point min() noexcept;
    // Returns: time_point(duration::min()).

static constexpr time_point max() noexcept;
    // Returns: time_point(duration::max()).

29.6.6 Non-member arithmetic

template<class Clock, class Duration1, class Rep2, class Period2>
    constexpr time_point<Clock, common_type_t<Duration1, duration<Rep2, Period2>>
        operator+(const time_point<Clock, Duration1>& lhs, const duration<Rep2, Period2>& rhs);
    // Returns: CT(lhs.time_since_epoch() + rhs), where CT is the type of the return value.

template<class Rep1, class Period1, class Clock, class Duration2>
    constexpr time_point<Clock, common_type_t<duration<Rep1, Period1>, Duration2>>
        operator+(const duration<Rep1, Period1>& lhs, const time_point<Clock, Duration2>& rhs);
    // Returns: rhs + lhs.

template<class Clock, class Duration1, class Rep2, class Period2>
    constexpr time_point<Clock, common_type_t<Duration1, duration<Rep2, Period2>>
        operator-(const time_point<Clock, Duration1>& lhs, const duration<Rep2, Period2>& rhs);
    // Returns: CT(lhs.time_since_epoch() - rhs), where CT is the type of the return value.

template<class Clock, class Duration1, class Duration2>
    constexpr common_type_t<Duration1, Duration2>
        operator-(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);
    // Returns: lhs.time_since_epoch() - rhs.time_since_epoch().

29.6.7 Comparisons

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator==(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);
    // Returns: lhs.time_since_epoch() == rhs.time_since_epoch().

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator<(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);
    // Returns: lhs.time_since_epoch() < rhs.time_since_epoch().

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator>(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);
    // Returns: rhs < lhs.

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator<=(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);
    // Returns: !(rhs < lhs).
template<class Clock, class Duration1, class Duration2>
constexpr bool operator>=(const time_point<Clock, Duration1>& lhs,
const time_point<Clock, Duration2>& rhs);

Returns: !(lhs < rhs).

template<class Clock, class Duration1, 
three_way_comparable_with<Duration1> Duration2>
constexpr auto operator<=>(const time_point<Clock, Duration1>& lhs,
const time_point<Clock, Duration2>& rhs);

Returns: lhs.time_since_epoch() <=> rhs.time_since_epoch().

29.6.8 Conversions [time.point.cast]

template<class ToDuration, class Clock, class Duration>
constexpr time_point<Clock, ToDuration> time_point_cast(const time_point<Clock, Duration>& t);

Constraints: ToDuration is a specialization of duration.

Returns:
time_point<Clock, ToDuration>(duration_cast<ToDuration>(t.time_since_epoch()))

template<class ToDuration, class Clock, class Duration>
constexpr time_point<Clock, ToDuration> floor(const time_point<Clock, Duration>& tp);

Constraints: ToDuration is a specialization of duration.

Returns: time_point<Clock, ToDuration>(floor<ToDuration>(tp.time_since_epoch())).

template<class ToDuration, class Clock, class Duration>
constexpr time_point<Clock, ToDuration> ceil(const time_point<Clock, Duration>& tp);

Constraints: ToDuration is a specialization of duration.

Returns: time_point<Clock, ToDuration>(ceil<ToDuration>(tp.time_since_epoch())).

template<class ToDuration, class Clock, class Duration>
constexpr time_point<Clock, ToDuration> round(const time_point<Clock, Duration>& tp);

Constraints: ToDuration is a specialization of duration, and treat_as_floating_point_v<typename ToDuration::rep> is false.

Returns: time_point<Clock, ToDuration>(round<ToDuration>(tp.time_since_epoch())).

29.7 Clocks [time.clock]

29.7.1 General [time.clock/general]
The types defined in 29.7 meet the Cpp17TrivialClock requirements (29.3) unless otherwise specified.

29.7.2 Class system_clock [time.clock.system]

29.7.2.1 Overview [time.clock.system.overview]

namespace std::chrono {
    class system_clock {
        public:
            using rep = see below;
            using period = ratio<unspecified, unspecified>;
            using duration = chrono::duration<rep, period>;
            using time_point = chrono::time_point<system_clock>;
            static constexpr bool is_steady = unspecified;

            static time_point now() noexcept;

            // mapping to/from C type time_t
            static time_t to_time_t (const time_point& t) noexcept;
            static time_point from_time_t(time_t t) noexcept;
    };
}
Objects of type `system_clock` represent wall clock time from the system-wide realtime clock. Objects of type `sys_time<Duration>` measure time since 1970-01-01 00:00:00 UTC excluding leap seconds. This measure is commonly referred to as *Unix time*. This measure facilitates an efficient mapping between `sys_time` and calendar types (29.8).

**Example 1:**

```plaintext
sys_seconds{sys_days{1970y/January/1}}.time_since_epoch() is 0s.
sys_seconds{sys_days{2000y/January/1}}.time_since_epoch() is 946'684'800s, which is 10'957 * 86'400s.
—end example
```

### 29.7.2.2 Members

```plaintext
using system_clock::rep = unspecified;

Constraints: system_clock::duration::min() < system_clock::duration::zero() is true.  
[Note 1: This implies that rep is a signed type. — end note]
```

```plaintext
static time_t to_time_t(const time_point& t) noexcept;

Returns: A `time_t` object that represents the same point in time as `t` when both values are restricted to the coarser of the precisions of `time_t` and `time_point`. It is implementation-defined whether values are rounded or truncated to the required precision.
```

```plaintext
static time_point from_time_t(time_t t) noexcept;

Returns: A `time_point` object that represents the same point in time as `t` when both values are restricted to the coarser of the precisions of `time_t` and `time_point`. It is implementation-defined whether values are rounded or truncated to the required precision.
```

### 29.7.2.3 Non-member functions

```plaintext
template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const sys_time<Duration>& tp);

Constraints: treat_as_floating_point_v<typename Duration::rep> is false, and Duration{1} < days{1} is true.

Effects: Equivalent to:
```
```plaintext
return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%F %T}"), tp);
```

**Example 1:**

```plaintext
cout << sys_seconds{0s} << '\n'; // 1970-01-01 00:00:00

cout << sys_seconds{946'684'800s} << '\n'; // 2000-01-01 00:00:00

cout << sys_seconds{946'688'523s} << '\n'; // 2000-01-01 01:02:03
—end example
```

```plaintext
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const sys_days& dp);

Effects: os << year_month_day(dp).
```

**Returns:** os.

```plaintext
template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt, sys_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr, minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the `sys_time tp` using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid date, `is.setstate(ios_base::failbit)` is called and `tp` is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null. Additionally, the parsed offset will be subtracted from the successfully parsed timestamp prior to assigning that difference to tp.
```

**Returns:** is.
29.7.3 Class utc_clock

29.7.3.1 Overview

namespace std::chrono {
    class utc_clock {
        public:
            using rep = a signed arithmetic type;
            using period = ratio<unspecified, unspecified>;
            using duration = chrono::duration<rep, period>;
            using time_point = chrono::time_point<utc_clock>;
            static constexpr bool is_steady = unspecified;

            static time_point now();

            template<class Duration>
                static sys_time<common_type_t<Duration, seconds>>
                    to_sys(const utc_time<Duration>& t);
            template<class Duration>
                static utc_time<common_type_t<Duration, seconds>>
                    from_sys(const sys_time<Duration>& t);
    }
}

In contrast to sys_time, which does not take leap seconds into account, utc_clock and its associated time_point, utc_time, count time, including leap seconds, since 1970-01-01 00:00:00 UTC.

[Note 1: The UTC time standard began on 1972-01-01 00:00:10 TAI. To measure time since this epoch instead, one can add/subtract the constant sys_days{1972y/1/1} - sys_days{1970y/1/1} (63'072'000s) from the utc_time. — end note]

[Example 1:
    clock_cast<utc_clock>(sys_seconds{sys_days{1970y/January/1}}).time_since_epoch() is 0s.
    clock_cast<utc_clock>(sys_seconds{sys_days{2000y/January/1}}).time_since_epoch() is 946'684'822s, which is 10’957 * 86’400s + 22s.
    — end example]

utc_clock is not a Cpp17TrivialClock unless the implementation can guarantee that utc_clock::now() does not propagate an exception.

[Note 2: noexcept(from_sys(system_clock::now())) is false. — end note]

29.7.3.2 Member functions

static time_point now();

1 Returns: from_sys(system_clock::now()), or a more accurate value of utc_time.

template<class Duration>
    static sys_time<common_type_t<Duration, seconds>>
        to_sys(const utc_time<Duration>& u);

2 Returns: A sys_time t, such that from_sys(t) == u if such a mapping exists. Otherwise u represents a time_point during a positive leap second insertion, the conversion counts that leap second as not inserted, and the last representable value of sys_time prior to the insertion of the leap second is returned.

template<class Duration>
    static utc_time<common_type_t<Duration, seconds>>
        from_sys(const sys_time<Duration>& t);

3 Returns: A utc_time u, such that u.time_since_epoch() - t.time_since_epoch() is equal to the sum of leap seconds that were inserted between t and 1970-01-01. If t is exactly the date of leap second insertion, then the conversion counts that leap second as inserted.

[Example 1:
    auto t = sys_days{July/1/2015} - 2ns;
    auto u = utc_clock::from_sys(t);
    assert(u.time_since_epoch() - t.time_since_epoch() == 25s);
    t += 1ns;]
u = utc_clock::from_sys(t);
assert(u.time_since_epoch() - t.time_since_epoch() == 25s);
t += 1ns;
u = utc_clock::from_sys(t);
assert(u.time_since_epoch() - t.time_since_epoch() == 26s);
t += 1ns;
u = utc_clock::from_sys(t);
assert(u.time_since_epoch() - t.time_since_epoch() == 26s);

—end example

29.7.3.3 Non-member functions

```
template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const utc_time<Duration>& t);

Effects: Equivalent to:
return os << format(os.getloc(), "STATICALLY-WIDEN<charT>("{:L%F %T}")", t);
```

[Example 1:
auto t = sys_days{July/1/2015} - 500ms;
auto u = clock_cast<utc_clock>(t);
for (auto i = 0; i < 8; ++i, u += 250ms)
  cerr << u << " UTC\n";

Produces this output:
2015-06-30 23:59:59.500 UTC
2015-06-30 23:59:59.750 UTC
2015-06-30 23:59:60.000 UTC
2015-06-30 23:59:60.250 UTC
2015-06-30 23:59:60.500 UTC
2015-06-30 23:59:60.750 UTC
2015-07-01 00:00:00.000 UTC
2015-07-01 00:00:00.250 UTC

—end example]

```
template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
utc_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the utc_time tp using the format flags
given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid date, is.setstate(ios_base::failbit)
is called and tp is not modified. If %Z is used and successfully parsed, that value will be
assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully
parsed, that value will be assigned to *offset if offset is non-null. Additionally, the parsed offset
will be subtracted from the successfully parsed timestamp prior to assigning that difference to tp.

Returns: is.
```

```
struct leap_second_info {
  bool is_leap_second;
  seconds elapsed;
};
```

The type leap_second_info has data members and special members specified above. It has no base
classes or members other than those specified.

```
template<class Duration>
leap_second_info get_leap_second_info(const utc_time<Duration>& ut);

Returns: A leap_second_info lsi, where lsi.is_leap_second is true if ut is during a positive leap
second insertion, and otherwise false. lsi.elapsed is the sum of leap seconds between 1970-01-01
and ut. If lsi.is_leap_second is true, the leap second referred to by ut is included in the sum.
```

§ 29.7.3.3 ©ISO/IEC

1638
29.7.4 Class tai_clock

29.7.4.1 Overview

namespace std::chrono {
    class tai_clock {
        public:
            using rep = a signed arithmetic type;
            using period = ratio<unspecified, unspecified>;
            using duration = chrono::duration<rep, period>;
            using time_point = chrono::time_point<tai_clock>;
            static constexpr bool is_steady = unspecified;

            static time_point now();

            template<class Duration>
                static utc_time<common_type_t<Duration, seconds>>
                    to_utc(const tai_time<Duration>&) noexcept;
            template<class Duration>
                static tai_time<common_type_t<Duration, seconds>>
                    from_utc(const utc_time<Duration>&) noexcept;
    };
}

1 The clock tai_clock measures seconds since 1958-01-01 00:00:00 and is offset 10s ahead of UTC at this date. That is, 1958-01-01 00:00:00 TAI is equivalent to 1957-12-31 23:59:50 UTC. Leap seconds are not inserted into TAI. Therefore every time a leap second is inserted into UTC, UTC shifts another second with respect to TAI. For example by 2000-01-01 there had been 22 positive and 0 negative leap seconds inserted so 2000-01-01 00:00:00 UTC is equivalent to 2000-01-01 00:00:32 TAI (22s plus the initial 10s offset).

2 tai_clock is not a Cpp17TrivialClock unless the implementation can guarantee that tai_clock::now() does not propagate an exception.

[Note 1: noexcept(from_utc(utc_clock::now())) is false. —end note]

29.7.4.2 Member functions

static time_point now();

1 Returns: from_utc(utc_clock::now()), or a more accurate value of tai_time.

template<class Duration>
    static utc_time<common_type_t<Duration, seconds>>
        to_utc(const tai_time<Duration>& t) noexcept;

2 Returns:
    utc_time<common_type_t<Duration, seconds>>(t.time_since_epoch()) - 378691210s

    [Note 1:
        378691210s == sys_days{1970y/January/1} - sys_days{1958y/January/1} + 10s
        —end note]

template<class Duration>
    static tai_time<common_type_t<Duration, seconds>>
        from_utc(const utc_time<Duration>& t) noexcept;

3 Returns:
    tai_time<common_type_t<Duration, seconds>>(t.time_since_epoch()) + 378691210s

    [Note 2:
        378691210s == sys_days{1970y/January/1} - sys_days{1958y/January/1} + 10s
        —end note]

29.7.4.3 Non-member functions

§ 29.7.4.3
template<class charT, class traits, class Duration>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const tai_time<Duration>& t);

effects: Equivalent to:
    return os << format(os.getloc(), "STRICTLY-WIDEN<"charT">("{:L%F %T}"), t);

[example 1:
    auto st = sys_days{2000y/January/1};
    auto tt = clock_cast<tai_clock>(st);
    cout << format("{0:%F %T %Z} == {1:%F %T %Z}\n", st, tt);
    Produces this output:
    2000-01-01 00:00:00 UTC == 2000-01-01 00:00:32 TAI
    — end example]

template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
    basic_istream<charT, traits>&
    from_stream(basic_istream<charT, traits>& is, const charT* fmt,
    tai_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr,
    minutes* offset = nullptr);

effects: Attempts to parse the input stream is into the tai_time tp using the format flags given in
the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid date, is.setstate(ios_base::failbit)
is called and tp is not modified. If %Z is used and successfully parsed, that value will
be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully
parsed, that value will be assigned to *offset if offset is non-null. Additionally, the parsed offset
will be subtracted from the successfully parsed timestamp prior to assigning that difference to tp.

returns: is.

29.7.5 Class gps_clock
29.7.5.1 Overview

namespace std::chrono {
    class gps_clock {
        public:
            using rep = a signed arithmetic type;
            using period = ratio<unspecified, unspecified>;
            using duration = chrono::duration<rep, period>;
            using time_point = chrono::time_point<gps_clock>;
            static constexpr bool is_steady = unspecified;

            static time_point now();

            template<class Duration>
                static utc_time<common_type_t<Duration, seconds>>
                    to_utc(const gps_time<Duration>&) noexcept;
            template<class Duration>
                static gps_time<common_type_t<Duration, seconds>>
                    from_utc(const utc_time<Duration>&) noexcept;
    };
}

The clock gps_clock measures seconds since the first Sunday of January, 1980 00:00:00 UTC. Leap seconds
are not inserted into GPS. Therefore every time a leap second is inserted into UTC, UTC shifts another
second with respect to GPS. Aside from the offset from 1958y/January/1 to 1980y/January/Sunday[1],
GPS is behind TAI by 18s due to the 10s offset between 1958 and 1970 and the additional 9 leap seconds

gps_clock is not a Cpp17TrivialClock unless the implementation can guarantee that gps_clock::now() does not propagate an exception.

[Note 1: noexcept(from_utc(utc_clock::now())) is false. — end note]
29.7.5.2 Member functions

static time_point now();

Returns: from_utc(utc_clock::now()), or a more accurate value of gps_time.

template<class Duration>
static utc_time<common_type_t<Duration, seconds>>
to_utc(const gps_time<Duration>& t) noexcept;

Returns:
utc_time<common_type_t<Duration, seconds>>{t.time_since_epoch()} + 315964809s
[Note 1:
315964809s == sys_days{1980y/January/Sunday[1]} - sys_days{1970y/January/1} + 9s
—end note]

template<class Duration>
static gps_time<common_type_t<Duration, seconds>>
from_utc(const utc_time<Duration>& t) noexcept;

Returns:
gps_time<common_type_t<Duration, seconds>>{t.time_since_epoch()} - 315964809s
[Note 2:
315964809s == sys_days{1980y/January/Sunday[1]} - sys_days{1970y/January/1} + 9s
—end note]

29.7.5.3 Non-member functions

template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const gps_time<Duration>& t);

Effects: Equivalent to:
return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%F %T}"), t);

[Example 1:
auto st = sys_days{2000y/January/1};
auto gt = clock_cast<gps_clock>(st);
cout << format("{0:%F %T %Z} == {1:%F %T %Z}\n", st, gt);
Produces this output:
2000-01-01 00:00:00 UTC == 2000-01-01 00:00:13 GPS
—end example]

template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
gps_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the gps_time tp using the format flags given in
the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid date, is.setstate(ios_-base::failbit) is called and tp is not modified. If %Z is used and successfully parsed, that value
will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully
parsed, that value will be assigned to *offset if offset is non-null. Additionally, the parsed offset
will be subtracted from the successfully parsed timestamp prior to assigning that difference to tp.

Returns: is.

29.7.6 Type file_clock

29.7.6.1 Overview

namespace std::chrono {
  using file_clock = see below;
}
file_clock is an alias for a type meeting the Cpp17TrivialClock requirements (29.3), and using a signed arithmetic type for file_clock::rep. file_clock is used to create the time_point system used for file_time_type (31.12). Its epoch is unspecified, and noexcept(file_clock::now()) is true.

[Note 1: The type that file_clock denotes can be in a different namespace than std::chrono, such as std::filesystem. — end note]

29.7.6.2 Member functions

The type denoted by file_clock provides precisely one of the following two sets of static member functions:

```cpp
template<class Duration>
static sys_time<see below>
  to_sys(const file_time<Duration>&);

template<class Duration>
static file_time<see below>
  from_sys(const sys_time<Duration>&);
```

or:

```cpp
template<class Duration>
static utc_time<see below>
  to_utc(const file_time<Duration>&);

template<class Duration>
static file_time<see below>
  from_utc(const utc_time<Duration>&);
```

These member functions shall provide time_point conversions consistent with those specified by utc_clock, tai_clock, and gps_clock. The Duration of the resultant time_point is computed from the Duration of the input time_point.

29.7.6.3 Non-member functions

```cpp
template<class charT, class traits, class Duration>
  basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const file_time<Duration>& t);
```

Effects: Equivalent to:

```cpp
return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%F %T}"), t);
```

```cpp
template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
  basic_istream<charT, traits>&
    from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                file_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr,
                minutes* offset = nullptr);
```

Effects: Attempts to parse the input stream is into the file_time tp using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid date, is.setstate(ios_base::failbit) is called and tp is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null. Additionally, the parsed offset will be subtracted from the successfully parsed timestamp prior to assigning that difference to tp.

Returns: is.

29.7.7 Class steady_clock

```cpp
namespace std::chrono {
  class steady_clock {
    public:
      using rep = unspecified;
      using period = ratio<unspecified, unspecified>;
      using duration = chrono::duration<rep, period>;
      using time_point = chrono::time_point<unspecified, duration>;
      static constexpr bool is_steady = true;
      static time_point now() noexcept;
    }
  }
```

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Objects of class `steady_clock` represent clocks for which values of `time_point` never decrease as physical time advances and for which values of `time_point` advance at a steady rate relative to real time. That is, the clock may not be adjusted.

29.7.8 Class `high_resolution_clock` [time.clock.hires]

```cpp
namespace std::chrono {
    class high_resolution_clock {
    public:
        using rep = unspecified;
        using period = ratio<unspecified, unspecified>;
        using duration = chronon::duration<rep, period>;
        using time_point = chronon::time_point<unspecified, duration>;
        static constexpr bool is_steady = unspecified;
        static time_point now() noexcept;
    }
}
```

Objects of class `high_resolution_clock` represent clocks with the shortest tick period. `high_resolution_clock` may be a synonym for `system_clock` or `steady_clock`.

29.7.9 Local time [time.clock.local]

The family of time points denoted by `local_time<Duration>` are based on the pseudo clock `local_t`. `local_t` has no member `now()` and thus does not meet the clock requirements. Nevertheless `local_time<Duration>` serves the vital role of representing local time with respect to a not-yet-specified time zone. Aside from being able to get the current time, the complete `time_point` algebra is available for `local_time<Duration>` (just as for `sys_time<Duration>`).

```cpp
template<class charT, class traits, class Duration>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const local_time<Duration>& lt);
```

2 Effects:

```cpp
os << sys_time<Duration>{lt.time_since_epoch()};
```

3 Returns: `os`.

```cpp
template<class charT, class traits, class Duration, class Alloc = allocator<charT>>
    basic_istream<charT, traits>&
    from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                local_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr,
                minutes* offset = nullptr);
```

4 Effects: Attempts to parse the input stream `is` into the `local_time tp` using the format flags given in the NCTCTS `fmt` as specified in 29.13. If the parse fails to decode a valid date, `is.setstate(ios_base::failbit)` is called and `tp` is not modified. If `%Z` is used and successfully parsed, that value will be assigned to `*abbrev` if `abbrev` is non-null. If `%z` (or a modified variant) is used and successfully parsed, that value will be assigned to `*offset` if `offset` is non-null.

5 Returns: `is`.

29.7.10 time_point conversions [time.clock.cast]

29.7.10.1 Class template `clock_time_conversion` [time.clock.conv]

```cpp
namespace std::chrono {
    template<class DestClock, class SourceClock>
    struct clock_time_conversion {};
}
```

clock_time_conversion serves as a trait which can be used to specify how to convert a source `time_point` of type `time_point<SourceClock, Duration>` to a destination `time_point` of type `time_point<DestClock, Duration>` via a specialization: `clock_time_conversion<DestClock, SourceClock>`. A specialization of `clock_time_conversion<DestClock, SourceClock>` shall provide a const-qualified `operator()` that takes a parameter of type `time_point<SourceClock, Duration>` and returns a `time_point<DestClock, OtherDuration>` representing an equivalent point in time. OtherDuration is a `chrono::duration` whose
specialization is computed from the input Duration in a manner which can vary for each clock_time_conversion specialization. A program may specialize clock_time_conversion if at least one of the template parameters is a user-defined clock type.

Several specializations are provided by the implementation, as described in 29.7.10.2, 29.7.10.3, 29.7.10.4, and 29.7.10.5.

29.7.10.2 Identity conversions

template<class Clock>
struct clock_time_conversion<Clock, Clock> {
    template<class Duration>
    time_point<Clock, Duration>
    operator()(const time_point<Clock, Duration>& t) const;
};

template<class Duration>
    time_point<Clock, Duration>
    operator()(const time_point<Clock, Duration>& t) const;

1 Returns: t.

template<>
struct clock_time_conversion<system_clock, system_clock> {
    template<class Duration>
    sys_time<Duration>
    operator()(const sys_time<Duration>& t) const;
};

template<class Duration>
    sys_time<Duration>
    operator()(const sys_time<Duration>& t) const;

2 Returns: t.

template<>
struct clock_time_conversion<utc_clock, utc_clock> {
    template<class Duration>
    utc_time<Duration>
    operator()(const utc_time<Duration>& t) const;
};

template<class Duration>
    utc_time<Duration>
    operator()(const utc_time<Duration>& t) const;

3 Returns: t.

29.7.10.3 Conversions between system_clock and utc_clock

template<>
struct clock_time_conversion<utc_clock, system_clock> {
    template<class Duration>
    utc_time<common_type_t<Duration, seconds>>
    operator()(const sys_time<Duration>& t) const;
};

template<class Duration>
    utc_time<common_type_t<Duration, seconds>>
    operator()(const sys_time<Duration>& t) const;

1 Returns: utc_clock::from_sys(t).

template<>
struct clock_time_conversion<system_clock, utc_clock> {
    template<class Duration>
    sys_time<common_type_t<Duration, seconds>>
    operator()(const utc_time<Duration>& t) const;
};
29.7.10.4 Conversions between system_clock and other clocks

```cpp
template<class SourceClock>
struct clock_time_conversion<system_clock, SourceClock> {
    template<class Duration>
    auto operator()(const time_point<SourceClock, Duration>& t) const
        -> decltype(SourceClock::to_sys(t));
};
```

Constraints: SourceClock::to_sys(t) is well-formed.

Mandates: SourceClock::to_sys(t) returns a sys_time<Duration2> for some type Duration2 (29.6.1).

Returns: SourceClock::to_sys(t).

template<class DestClock>
struct clock_time_conversion<DestClock, system_clock> {
    template<class Duration>
    auto operator()(const sys_time<Duration>& t) const
        -> decltype(DestClock::from_sys(t));
};
```

Constraints: DestClock::from_sys(t) is well-formed.

Mandates: DestClock::from_sys(t) returns a time_point<DestClock, Duration2> for some type Duration2 (29.6.1).

Returns: DestClock::from_sys(t).

29.7.10.5 Conversions between utc_clock and other clocks

```cpp
template<class SourceClock>
struct clock_time_conversion<utc_clock, SourceClock> {
    template<class Duration>
    auto operator()(const time_point<SourceClock, Duration>& t) const
        -> decltype(SourceClock::to_utc(t));
};
```

Constraints: SourceClock::to_utc(t) is well-formed.

Mandates: SourceClock::to_utc(t) returns a utc_time<Duration2> for some type Duration2 (29.6.1).

Returns: SourceClock::to_utc(t).

template<class DestClock>
struct clock_time_conversion<DestClock, utc_clock> {
    template<class Duration>
    auto operator()(const utc_time<Duration>& t) const
        -> decltype(DestClock::from_utc(t));
};
```
template<class Duration>
auto operator()(const utc_time<Duration>& t) const
  -> decltype(DestClock::from_utc(t));

Constraints: DestClock::from_utc(t) is well-formed.

Mandates: DestClock::from_utc(t) returns a time_point<DestClock, Duration2> for some type Duration2 (29.6.1).

Returns: DestClock::from_utc(t).

29.7.10.6 Function template clock_cast

template<class DestClock, class SourceClock, class Duration>
auto clock_cast(const time_point<SourceClock, Duration>& t);

Constraints: At least one of the following clock time conversion expressions is well-formed:

(1.1) — clock_time_conversion<DestClock, SourceClock>{}(t)
(1.2) — clock_time_conversion<DestClock, system_clock>{}(clock_time_conversion<system_clock, SourceClock>{}(t))
(1.3) — clock_time_conversion<DestClock, utc_clock>{}(clock_time_conversion<utc_clock, SourceClock>{}(t))
(1.4) — clock_time_conversion<DestClock, utc_clock>{}(clock_time_conversion<utc_clock, system_clock>{}(clock_time_conversion<system_clock, SourceClock>{}(t)))
(1.5) — clock_time_conversion<DestClock, system_clock>{}(clock_time_conversion<system_clock, utc_clock>{}(clock_time_conversion<utc_clock, SourceClock>{}(t)))

A clock time conversion expression is considered better than another clock time conversion expression if it involves fewer operator() calls on clock_time_conversion specializations.

Mandates: Among the well-formed clock time conversion expressions from the above list, there is a unique best expression.

Returns: The best well-formed clock time conversion expression in the above list.

29.8 The civil calendar

29.8.1 General

The types in 29.8 describe the civil (Gregorian) calendar and its relationship to sys_days and local_days.

29.8.2 Class last_spec

namespace std::chrono {
struct last_spec {
  explicit last_spec() = default;
};
}

The type last_spec is used in conjunction with other calendar types to specify the last in a sequence. For example, depending on context, it can represent the last day of a month, or the last day of the week of a month.

29.8.3 Class day

29.8.3.1 Overview

namespace std::chrono {
class day {
  unsigned char d_;           // exposition only
public:
  day() = default;
  constexpr explicit day(unsigned d) noexcept;
};
constexpr day& operator++() noexcept;
constexpr day operator++(int) noexcept;
constexpr day& operator--() noexcept;
constexpr day operator--(int) noexcept;

constexpr day& operator+=(const days& d) noexcept;
constexpr day& operator-=(const days& d) noexcept;

constexpr explicit operator unsigned() const noexcept;
constexpr bool ok() const noexcept;
};

1 day represents a day of a month. It normally holds values in the range 1 to 31, but may hold non-negative values outside this range. It can be constructed with any unsigned value, which will be subsequently truncated to fit into day’s unspecified internal storage. day meets the Cpp17EqualityComparable (Table 28) and Cpp17LessThanComparable (Table 29) requirements, and participates in basic arithmetic with days objects, which represent a difference between two day objects.

2 day is a trivially copyable and standard-layout class type.

### 29.8.3.2 Member functions

```cpp
constexpr explicit day(unsigned d) noexcept;
```
1 Effects: Initializes d_ with d. The value held is unspecified if d is not in the range [0, 255].

```cpp
constexpr day& operator++() noexcept;
```
2 Effects: ++d_.
3 Returns: *this.

```cpp
constexpr day operator++(int) noexcept;
```
4 Effects: ++(*this).
5 Returns: A copy of *this as it existed on entry to this member function.

```cpp
constexpr day& operator--() noexcept;
```
6 Effects: Equivalent to: --d_.
7 Returns: *this.

```cpp
constexpr day operator--(int) noexcept;
```
8 Effects: ~(this).
9 Returns: A copy of *this as it existed on entry to this member function.

```cpp
constexpr day& operator+=(const days& d) noexcept;
```
10 Effects: *this = *this + d.
11 Returns: *this.

```cpp
constexpr day& operator-=(const days& d) noexcept;
```
12 Effects: *this = *this - d.
13 Returns: *this.

```cpp
constexpr explicit operator unsigned() const noexcept;
```
14 Returns: d_.

```cpp
constexpr bool ok() const noexcept;
```
15 Returns: 1 <= d_ && d_ <= 31.

### 29.8.3.3 Non-member functions
constexpr bool operator==(const day& x, const day& y) noexcept;

    Returns: unsigned{x} == unsigned{y}.

constexpr strong_ordering operator<=>(const day& x, const day& y) noexcept;

    Returns: unsigned{x} <=> unsigned{y}.

constexpr day operator+(const day& x, const days& y) noexcept;

    Returns: day(unsigned{x} + y.count()).

constexpr day operator+(const days& x, const day& y) noexcept;

    Returns: y + x.

constexpr day operator-(const day& x, const days& y) noexcept;

    Returns: x + -y.

constexpr days operator-(const day& x, const day& y) noexcept;

    Returns: days{int(unsigned{x}) - int(unsigned{y})}.

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const day& d);

    Effects: Equivalent to:
        return os << (d.ok() ?
            format(STATICALLY-WIDEN<charT>("{:%d}"), d) :
            format(STATICALLY-WIDEN<charT>("{:%d} is not a valid day"), d));

template<class charT, class traits, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
    day& d, basic_string<charT, traits, Alloc>* abbrev = nullptr,
    minutes* offset = nullptr);

    Effects: Attempts to parse the input stream is into the day d using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid day, is.setstate(ios_base::failbit) is called and d is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null.

    Returns: is.

constexpr chrono::day operator"d(unsigned long long d) noexcept;

    Returns: day{static_cast<unsigned>(d)}.

29.8.4 Class month

29.8.4.1 Overview

namespace std::chrono {
    class month {
        unsigned char m_;          // exposition only

        public:
            month() = default;
            constexpr explicit month(unsigned m) noexcept;

            constexpr month& operator++() noexcept;
            constexpr month operator++(int) noexcept;
            constexpr month& operator--() noexcept;
            constexpr month operator--(int) noexcept;

            constexpr month& operator+=(const months& m) noexcept;
            constexpr month& operator+=(const month& m) noexcept;
            constexpr month& operator-=(const months& m) noexcept;
            constexpr month& operator-=(const month& m) noexcept;

    private:
        // exposition only
    }

} // namespace std::chrono
```cpp
constexpr explicit operator unsigned() const noexcept;
constexpr bool ok() const noexcept;
}

`month` represents a month of a year. It normally holds values in the range 1 to 12, but may hold non-negative values outside this range. It can be constructed with any `unsigned` value, which will be subsequently truncated to fit into `month`'s unspecified internal storage. `month` meets the `Cpp17EqualityComparable` (Table 28) and `Cpp17LessThanComparable` (Table 29) requirements, and participates in basic arithmetic with `months` objects, which represent a difference between two `month` objects.

`month` is a trivially copyable and standard-layout class type.

### 29.8.4.2 Member functions

```cpp
constexpr explicit month(unsigned m) noexcept;
1  
Effects: Initializes `m_` with `m`. The value held is unspecified if `m` is not in the range `[0, 255]`.

constexpr month& operator++() noexcept;
2  
Effects: `*this += months(1)`.

Returns: `*this`.
```
```
```
```
```
```
```
```
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```
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```
```
```
```
```
```
```
```
where \( \text{modulo}(n, 12) \) computes the remainder of \( n \) divided by 12 using Euclidean division.

\[*Note 1:* Given a divisor of 12, Euclidean division truncates towards negative infinity and always produces a remainder in the range \([0, 11]\). Assuming no overflow in the signed summation, this operation results in a month holding a value in the range \([1, 12]\) even if \(!x.ok()\). — *end note*

\[*Example 1:* February + months\{11\} == January. — *end example*

```cpp
constexpr month operator+(const months& x, const month& y) noexcept;
```  
4

\( \text{Returns:} y + x. \)

```cpp
constexpr month operator-(const month& x, const months& y) noexcept;
```  
5

\( \text{Returns:} x - y. \)

```cpp
constexpr months operator-(const month& x, const month& y) noexcept;
```  
6

\( \text{Returns:} \) If \( x.ok() == \text{true} \) and \( y.ok() == \text{true} \), returns a value \( m \) in the range \([\text{months\{0\}}, \text{months\{11\}}]\) satisfying \( y + m == x \). Otherwise the value returned is unspecified.

\[*Example 2:* January - February == months\{11\}. — *end example*

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const month& m);
```  
7

\( \text{Effects:} \) Equivalent to:

```cpp
return os << (m.ok() ? format(os.getloc(), STATICALLY-WIDEN<br<charT>("{:L\%b}"), m) :
format(os.getloc(), STATICALLY-WIDEN<br<charT>("{} is not a valid month"),
static_cast<unsigned>(m)));
```  

```cpp
template<class charT, class traits, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>&& is, const charT* fmt, month& m, basic_string<charT, traits, Alloc>* abbrev = nullptr, minutes* offset = nullptr);
```  
8

\( \text{Effects:} \) Attempts to parse the input stream \( is \) into the \( \text{month} \) \( m \) using the format flags given in the NTCTS \( \text{fmt} \) as specified in 29.13. If the parse fails to decode a valid month, \( is.setstate(ios_base::failbit) \) is called and \( m \) is not modified. If \( %Z \) is used and successfully parsed, that value will be assigned to \(*abbrev \) if \( abbrev \) is non-null. If \( %z \) (or a modified variant) is used and successfully parsed, that value will be assigned to \(*offset \) if \( offset \) is non-null.

\( \text{Returns:} \) \( is. \)

### 29.8.5 Class year

#### 29.8.5.1 Overview

```cpp
namespace std::chrono {
class year {
    short y_;  // exposition only
public:
    year() = default;
    constexpr explicit year(int y) noexcept;
    constexpr year& operator++() noexcept;
    constexpr year operator++(int) noexcept;
    constexpr year& operator--() noexcept;
    constexpr year operator--(int) noexcept;
    constexpr year& operator+=(const years& y) noexcept;
    constexpr year operator+=(int) noexcept;
    constexpr year& operator-=(const years& y) noexcept;
    constexpr year operator-=(int) noexcept;
    constexpr year operator+() const noexcept;
    constexpr year operator-() const noexcept;
    constexpr bool is_leap() const noexcept;
};
```  

\( § \) 29.8.5.1 © ISO/IEC 1650
```cpp
constexpr explicit operator int() const noexcept;
constexpr bool ok() const noexcept;

static constexpr year min() noexcept;
static constexpr year max() noexcept;
};
```

A `year` represents a year in the civil calendar. It can represent values in the range `[min(), max()]`. It can be constructed with any `int` value, which will be subsequently truncated to fit into `year`'s unspecified internal storage. `year` meets the `Cpp17EqualityComparable` (Table 28) and `Cpp17LessThanComparable` (Table 29) requirements, and participates in basic arithmetic with `years` objects, which represent a difference between two `year` objects.

A `year` is a trivially copyable and standard-layout class type.

### 29.8.5.2 Member functions

```cpp
constexpr explicit year(int y) noexcept;
```

**Effects:** Initializes `y_` with `y`. The value held is unspecified if `y` is not in the range `[-32767, 32767]`.

```cpp
constexpr year& operator++() noexcept;
```

**Effects:** `++y_`.

**Returns:** `*this`.

```cpp
constexpr year operator++(int) noexcept;
```

**Effects:** `++(*this)`.

**Returns:** A copy of `*this` as it existed on entry to this member function.

```cpp
constexpr year& operator--() noexcept;
```

**Effects:** `--y_`.

**Returns:** `*this`.

```cpp
constexpr year operator--(int) noexcept;
```

**Effects:** `--(*this)`.

**Returns:** A copy of `*this` as it existed on entry to this member function.

```cpp
constexpr year& operator+=(const years& y) noexcept;
```

**Effects:** `*this = *this + y`.

**Returns:** `*this`.

```cpp
constexpr year& operator-=(const years& y) noexcept;
```

**Effects:** `*this = *this - y`.

**Returns:** `*this`.

```cpp
constexpr year operator+() const noexcept;
```

**Returns:** `*this`.

```cpp
constexpr year operator-() const noexcept;
```

**Returns:** `year{-y_}`.

```cpp
constexpr bool is_leap() const noexcept;
```

**Returns:** `y_ % 4 == 0 && (y_ % 100 != 0 || y_ % 400 == 0)`.

```cpp
constexpr explicit operator int() const noexcept;
```

**Returns:** `min().y_ <= y_ && y_ <= max().y_`.

§ 29.8.5.2 © ISO/IEC
29.8.5.3 Non-member functions

static constexpr year min() noexcept;
Returns: year{-32767}.

static constexpr year max() noexcept;
Returns: year{32767}.

29.8.6 Class weekday

namespace std::chrono {

class weekday {
public:
  unsigned char wd_; // exposition only

  weekday() = default;
  constexpr explicit weekday(unsigned wd) noexcept;
  constexpr weekday(const sys_days& dp) noexcept;
  constexpr weekday(const local_days& dp) noexcept;

  constexpr bool operator==(const weekday& x, const weekday& y) noexcept;
Returns: int{x} == int{y}.

  constexpr strong_ordering operator<=>(const weekday& x, const weekday& y) noexcept;
Returns: int{x} <=> int{y}.

  constexpr weekday operator+(const weekday& x, const years& y) noexcept;
Returns: year{int{x} + static_cast<int>(y.count())}.

  constexpr weekday operator+(const years& x, const weekday& y) noexcept;
Returns: y + x.

  constexpr weekday operator-(const weekday& x, const years& y) noexcept;
Returns: x + -y.

  constexpr years operator-(const weekday& x, const weekday& y) noexcept;
Returns: years{int{x} - int{y}}.

  template<class charT, class traits>
  basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const weekday& y);
Effects: Equivalent to:
  return os << (y.ok() ? format("{:%Y}", y) : format("{:%Y} is not a valid year").

  template<class charT, class traits, class Alloc = allocator<charT>>
  basic_istream<charT, traits>& from_stream(basic_istream<charT, traits>& is, const charT* fmt, weekday& y, basic_string<charT, traits, Alloc>* abbrev = nullptr, minutes* offset = nullptr);
Effects: Attempts to parse the input stream is into the weekday y using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid year, is.setstate(ios_base::failbit) is called and y is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null.

  constexpr chrono::year operator""y(unsigned long long y) noexcept;
Returns: year{static_cast<int>(y)}.

};

};


weekday represents a day of the week in the civil calendar. It normally holds values in the range 0 to 6, corresponding to Sunday through Saturday, but it may hold non-negative values outside this range. It can be constructed with any unsigned value, which will be subsequently truncated to fit into weekday’s unspecified internal storage. weekday meets the Cpp17EqualityComparable (Table 28) requirements.

[Note 1: weekday is not Cpp17LessThanComparable because there is no universal consensus on which day is the first day of the week. weekday’s arithmetic operations treat the days of the week as a circular range, with no beginning and no end. — end note]

weekday is a trivially copyable and standard-layout class type.

§ 29.8.6.2 Member functions

constexpr explicit weekday(unsigned wd) noexcept;

Effects: Initializes _wd_ with _wd_ == 7 ? 0 : _wd_. The value held is unspecified if _wd_ is not in the range [0, 255].

constexpr weekday(const sys_days& dp) noexcept;

Effects: Computes what day of the week corresponds to the sys_days _dp_, and initializes that day of the week in _wd_.

[Example 1: If _dp_ represents 1970-01-01, the constructed weekday represents Thursday by storing 4 in _wd_. — end example]

constexpr explicit weekday(const local_days& dp) noexcept;

Effects: Computes what day of the week corresponds to the local_days _dp_, and initializes that day of the week in _wd_.

Postconditions: The value is identical to that constructed from sys_days(_dp_.time_since_epoch()).

constexpr weekday& operator++() noexcept;

Effects: *this += days(1).

Returns: *this.

constexpr weekday operator++(int) noexcept;

Effects: ++(*this).

Returns: A copy of *this as it existed on entry to this member function.

constexpr weekday& operator--() noexcept;

Effects: *this -= days(1).

Returns: *this.

constexpr weekday operator--(int) noexcept;

Effects: --(*this).

Returns: A copy of *this as it existed on entry to this member function.
constexpr weekday& operator+=(const days& d) noexcept;
  *this = *this + d.

Returns: *this.

constexpr weekday& operator-=(const days& d) noexcept;
  *this = *this - d.

Returns: *this.

constexpr unsigned c_encoding() const noexcept;
  Returns: wd_.

constexpr unsigned iso_encoding() const noexcept;
  Returns: wd_ == 0u ? 7u : wd_.

constexpr bool ok() const noexcept;
  Returns: wd_ <= 6.

constexpr weekday_indexed operator[](unsigned index) const noexcept;
  Returns: {*this, index}.

constexpr weekday_last operator[](last_spec) const noexcept;
  Returns: weekday_last{*this}.

29.8.6.3 Non-member functions

constexpr bool operator==(const weekday& x, const weekday& y) noexcept;
  Returns: x.wd_ == y.wd_.

constexpr weekday operator+(const weekday& x, const days& y) noexcept;
  Returns: weekday{modulo(static_cast<long long>(x.wd_) + y.count(), 7)}
  where modulo(n, 7) computes the remainder of n divided by 7 using Euclidean division.

[Note 1: Given a divisor of 7, Euclidean division truncates towards negative infinity and always produces a remainder in the range of [0, 6]. Assuming no overflow in the signed summation, this operation results in a weekday holding a value in the range [0, 6] even if !x.ok(). —end note]
[Example 1: Monday + days{6} == Sunday. —end example]

constexpr weekday operator+(const days& x, const weekday& y) noexcept;
  Returns: y + x.

constexpr weekday operator-(const weekday& x, const days& y) noexcept;
  Returns: x + -y.

constexpr days operator-(const weekday& x, const weekday& y) noexcept;
  Returns: If x.ok() == true and y.ok() == true, returns a value d in the range [days{0}, days{6}]
  satisfying y + d == x. Otherwise the value returned is unspecified.
[Example 2: Sunday - Monday == days{6}. —end example]

template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const weekday& wd);

Effects: Equivalent to:
  return os << (wd.ok() ?
    format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%a}", wd) :
    format(os.getloc(), STATICALLY-WIDEN<charT>("{} is not a valid weekday"),
      static_cast<unsigned>(wd.wd_))));

§ 29.8.6.3 © ISO/IEC 1654
template<class charT, class traits, class Alloc = allocator<charT>>
    basic_istream<charT, traits>&
    from_stream(basic_istream<charT, traits>& is, const charT* fmt,
                weekday& wd, basic_string<charT, traits, Alloc>* abbrev = nullptr,
                minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the weekday wd using the format flags given in
the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid weekday, is.setstate(ios_base::failbit) is called and wd is not modified. If %Z is used and successfully parsed, that value will
be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully
parsed, that value will be assigned to *offset if offset is non-null.

Returns: is.

29.8.7 Class weekday_indexed

29.8.7.1 Overview

namespace std::chrono {
    class weekday_indexed {
        chrono::weekday wd_; // exposition only
        unsigned char index_; // exposition only

    public:
        weekday_indexed() = default;
        constexpr weekday_indexed(const chrono::weekday& wd, unsigned index) noexcept;
        constexpr chrono::weekday weekday() const noexcept;
        constexpr unsigned index() const noexcept;
        constexpr bool ok() const noexcept;
    };
}

weekday_indexed represents a weekday and a small index in the range 1 to 5. This class is used to represent
the first, second, third, fourth, or fifth weekday of a month.

[Note 1: A weekday_indexed object can be constructed by indexing a weekday with an unsigned. — end note]

[Example 1:
    constexpr auto wdi = Sunday[2]; // wdi is the second Sunday of an as yet unspecified month
    static_assert(wdi.weekday() == Sunday);
    static_assert(wdi.index() == 2);
    — end example]

weekday_indexed is a trivially copyable and standard-layout class type.

29.8.7.2 Member functions

constexpr weekday_indexed(const chrono::weekday& wd, unsigned index) noexcept;

Effects: Initializes wd_ with wd and index_ with index. The values held are unspecified if !wd.ok()
or index is not in the range [0,7].

Returns: wd_.

constexpr unsigned index() const noexcept;

Returns: index_.

constexpr bool ok() const noexcept;

Returns: wd_.ok() && 1 <= index_ && index_ <= 5.

29.8.7.3 Non-member functions

constexpr bool operator==(const weekday_indexed& x, const weekday_indexed& y) noexcept;

Returns: x.weekday() == y.weekday() && x.index() == y.index().
template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const weekday_indexed& wdi);

Effects: Equivalent to:
        auto i = wdi.index();
        return os << (i >= 1 && i <= 5 ?
          format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}[{}]"), wdi.weekday(), i) :
          format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}[{} is not a valid index]"),
          wdi.weekday(), i));

29.8.8 Class weekday_last
29.8.8.1 Overview
namespace std::chrono {
    class weekday_last {
        chrono::weekday wd_; // exposition only
    
    public:
        constexpr explicit weekday_last(const chrono::weekday& wd) noexcept;
        constexpr chrono::weekday weekday() const noexcept;
        constexpr bool ok() const noexcept;
    }
}

1 weekday_last represents the last weekday of a month.

2 [Note 1: A weekday_last object can be constructed by indexing a weekday with last. — end note]

[Example 1:
    constexpr auto wdl = Sunday[last];  // wdl is the last Sunday of an as yet unspecified month
    static_assert(wdl.weekday() == Sunday);
— end example]

3 weekday_last is a trivially copyable and standard-layout class type.

29.8.8.2 Member functions

constexpr explicit weekday_last(const chrono::weekday& wd) noexcept;
Effects: Initializes wd_ with wd.

constexpr chrono::weekday weekday() const noexcept;
1 Returns: wd_.

constexpr bool ok() const noexcept;
2 Returns: wd_.ok().

29.8.8.3 Non-member functions

constexpr bool operator==(const weekday_last& x, const weekday_last& y) noexcept;
1 Returns: x.weekday() == y.weekday().

template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const weekday_last& wdl);
Effects: Equivalent to:
        return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}[{}]"), wdl.weekday());

29.8.9 Class month_day
29.8.9.1 Overview
namespace std::chrono {
    class month_day {
        chrono::month m_; // exposition only
    }
}
chrono::day d_; // exposition only

public:
    month_day() = default;
    constexpr month_day(const chrono::month& m, const chrono::day& d) noexcept;
    constexpr chrono::month month() const noexcept;
    constexpr chrono::day day() const noexcept;
    constexpr bool ok() const noexcept;

};

1 month_day represents a specific day of a specific month, but with an unspecified year. month_day meets the C++17 EqualityComparable (Table 28) and C++17 LessThanComparable (Table 29) requirements.

2 month_day is a trivially copyable and standard-layout class type.

29.8.9.2 Member functions

constexpr month_day(const chrono::month& m, const chrono::day& d) noexcept;
1 Effects: Initializes m_ with m, and d_ with d.

constexpr chrono::month month() const noexcept;
2 Returns: m_.

constexpr chrono::day day() const noexcept;
3 Returns: d_.

constexpr bool ok() const noexcept;
4 Returns: true if m_.ok() is true, 1d <= d_, and d_ is less than or equal to the number of days in month m_; otherwise returns false. When m_ == February, the number of days is considered to be 29.

29.8.9.3 Non-member functions

constexpr bool operator==(const month_day& x, const month_day& y) noexcept;
1 Returns: x.month() == y.month() && x.day() == y.day().

constexpr strong_ordering operator<=>(const month_day& x, const month_day& y) noexcept;
2 Effects: Equivalent to:
    if (auto c = x.month() <=> y.month(); c != 0) return c;
    return x.day() <=> y.day();

template<class charT, class traits>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const month_day& md);
3 Effects: Equivalent to:
    return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}/{}"),
                        md.month(), md.day());

template<class charT, class traits, class Alloc = allocator<charT>>
    basic_istream<charT, traits>&
        from_stream(basic_istream<charT, traits>&& is, const charT* fmt,
                    month_day& md, basic_string<charT, traits, Alloc>* abbrev = nullptr,
                    minutes* offset = nullptr);
4 Effects: Attempts to parse the input stream is into the month_day md using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid month_day, is.setstate(ios_base::failbit) is called and md is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null.

5 Returns: is.
29.8.10 Class `month_day_last`

```cpp
namespace std::chrono {
  class month_day_last {
    chrono::month m_; // exposition only
    
    public:
    constexpr explicit month_day_last(const chrono::month& m) noexcept;
    
    constexpr chrono::month month() const noexcept;
    constexpr bool ok() const noexcept;
  };
}
```

1. `month_day_last` represents the last day of a month.
2. `[Note 1: A `month_day_last` object can be constructed using the expression `m/last` or `last/m`, where `m` is an expression of type `month`. — end note]

   ```cpp
   constexpr explicit month_day_last(const chrono::month& m) noexcept;
   
   constexpr month month() const noexcept;
   constexpr bool ok() const noexcept;
   
   template<class charT, class traits>
   basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const month_day_last& mdl);
   
   Effects: Equivalent to:
   return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}/last"), mdl.month());
   ```

29.8.11 Class `month_weekday`

29.8.11.1 Overview

```cpp
namespace std::chrono {
  class month_weekday {
    chrono::month m_; // exposition only
    chrono::weekday_indexed wdi_; // exposition only
    
    public:
    constexpr month_weekday(const chrono::month& m, const chrono::weekday_indexed& wdi) noexcept;
    
    constexpr chrono::month month() const noexcept;
    constexpr chrono::weekday_indexed weekday_indexed() const noexcept;
    constexpr bool ok() const noexcept;
  };
}
```

1. `month_weekday` represents the \(n\)th weekday of a month, of an as yet unspecified year. To do this the `month_weekday` stores a month and a `weekday_indexed`. 

   `[time.cal.mwd]`
[Example 1:

```cpp
constexpr auto mwd = February/Tuesday[3]; // mwd is the third Tuesday of February of an as yet unspecified year
static_assert(mwd.month() == February);
static_assert(mwd.weekday_indexed() == Tuesday[3]);
```
—end example]

`month_weekday` is a trivially copyable and standard-layout class type.

### 29.8.11.2 Member functions

```cpp
constexpr month_weekday(const chrono::month& m, const chrono::weekday_indexed& wdi) noexcept;
```

**Effects:** Initializes `m_` with `m`, and `wdi_` with `wdi`.

```cpp
constexpr chrono::month month() const noexcept;
```

**Returns:** `m_`.

```cpp
constexpr chrono::weekday_indexed weekday_indexed() const noexcept;
```

**Returns:** `wdi_`.

```cpp
constexpr bool ok() const noexcept;
```

**Returns:** `m_.ok() && wdi_.ok()`.

### 29.8.11.3 Non-member functions

```cpp
constexpr bool operator==(const month_weekday& x, const month_weekday& y) noexcept;
```

**Returns:** `x.month() == y.month() && x.weekday_indexed() == y.weekday_indexed()`.

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const month_weekday& mwd);
```

**Effects:** Equivalent to:

```cpp
return os << format(os.getloc(), STATICALLY_WIDEN<charT>("{:L}/{:L}"),
    mwd.month(), mwd.weekday_indexed());
```

### 29.8.12 Class month_weekday_last

#### 29.8.12.1 Overview

```cpp
namespace std::chrono {
    class month_weekday_last {
        chrono::month m_; // exposition only
        chrono::weekday_last wdl_; // exposition only
    public:
        constexpr month_weekday_last(const chrono::month& m,
        const chrono::weekday_last& wdl) noexcept;
        constexpr chrono::month month() const noexcept;
        constexpr chrono::weekday_last weekday_last() const noexcept;
        constexpr bool ok() const noexcept;
    };}
```

`month_weekday_last` represents the last weekday of a month, of an as yet unspecified year. To do this the `month_weekday_last` stores a `month` and a `weekday_last`.

[Example 1:

```cpp
constexpr auto mwd = February/Tuesday[last]; // mwd is the last Tuesday of February of an as yet unspecified year
static_assert(mwd.month() == February);
static_assert(mwd.weekday_last() == Tuesday[last]);
```
—end example]

`month_weekday_last` is a trivially copyable and standard-layout class type.
29.8.12.2 Member functions

```cpp
cconstexpr month_weekday_last(const chrono::month& m,
    const chrono::weekday_last& wdl) noexcept;
```

**Effects:** Initializes \( m \) with \( m \), and \( wdl \) with \( wdl \).

```cpp
cconstexpr chrono::month month() const noexcept;
```

**Returns:** \( m_ \).

```cpp
cconstexpr chrono::weekday_last weekday_last() const noexcept;
```

**Returns:** \( wdl_ \).

```cpp
cconstexpr bool ok() const noexcept;
```

**Returns:** \( m_ . ok() \) && \( wdl_ . ok() \).

29.8.12.3 Non-member functions

```cpp
cconstexpr bool operator==(const month_weekday_last& x, const month_weekday_last& y) noexcept;
```

**Returns:** \( x.month() == y.month() \) && \( x.weekday_last() == y.weekday_last() \).

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const month_weekday_last& mwdl);
```

**Effects:** Equivalent to:

\[
\text{return os } \ll \text{ format(os.getloc(), } \text{STATICALLY-WIDEN}<\text{charT}>("{:L}/{:L}\text{"},
    mwdl.month(), mwdl.weekday_last());}
\]

29.8.13 Class **year_month**

29.8.13.1 Overview

```cpp
namespace std::chrono {
    class year_month {
        chrono::year y_; // exposition only
        chrono::month m_; // exposition only

    public:
        year_month() = default;
        constexpr year_month(const chrono::year& y, const chrono::month& m) noexcept;
    
        constexpr chrono::year year() const noexcept;
        constexpr chrono::month month() const noexcept;

        constexpr year_month& operator+=(const months& dm) noexcept;
        constexpr year_month& operator-=(const months& dm) noexcept;
        constexpr year_month& operator+=(const years& dy) noexcept;
        constexpr year_month& operator-=(const years& dy) noexcept;

        constexpr bool ok() const noexcept;
    }
}
```

1 **year_month** represents a specific month of a specific year, but with an unspecified day. **year_month** is

a field-based time point with a resolution of **months**. **year_month** meets the **Cpp17EqualityComparable** (Table 28) and **Cpp17LessThanComparable** (Table 29) requirements.

2 **year_month** is a trivially copyable and standard-layout class type.

29.8.13.2 Member functions

```cpp
cconstexpr year_month(const chrono::year& y, const chrono::month& m) noexcept;
```

**Effects:** Initializes \( y_ \) with \( y \), and \( m_ \) with \( m \).
constexpr chrono::year year() const noexcept;
Returns: y_.

constexpr chrono::month month() const noexcept;
Returns: m_.

constexpr year_month& operator+=(const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Effects: *this = *this + dm.
Returns: *this.

castexpr year_month& operator-=(const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Effects: *this = *this - dm.
Returns: *this.

castexpr year_month& operator+=(const years& dy) noexcept;
Effects: *this = *this + dy.
Returns: *this.

castexpr year_month& operator-=(const years& dy) noexcept;
Effects: *this = *this - dy.
Returns: *this.

constexpr bool ok() const noexcept;
Returns: y_.ok() && m_.ok().

29.8.13.3 Non-member functions
constexpr bool operator==(const year_month& x, const year_month& y) noexcept;
Returns: x.year() == y.year() && x.month() == y.month().

constexpr strong_ordering operator<=>(const year_month& x, const year_month& y) noexcept;
Effects: Equivalent to:
      if (auto c = x.year() <=> y.year(); c != 0) return c;
      return x.month() <=> y.month();

constexpr year_month operator+(const year_month& ym, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: A year_month value z such that z.ok() && z - ym == dm is true.
Complexity: \( O(1) \) with respect to the value of dm.

constexpr year_month operator+(const months& dm, const year_month& ym) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ym + dm.

constexpr year_month operator-(const year_month& ym, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ym + -dm.
constexpr months operator-(const year_month& x, const year_month& y) noexcept;

Returns:
\[ x.year() - y.year() + \text{months}\left(\text{static cast<int>(unsigned{x.month()})} - \text{static cast<int>(unsigned{y.month()})}\right) \]

cconstexpr year_month operator+(const year_month& ym, const years& dy) noexcept;

Returns: \( (ym.year() + dy) / ym.month() \).

cconstexpr year_month operator+(const years& dy, const year_month& ym) noexcept;

Returns: \( ym + dy \).

cconstexpr year_month operator-(const year_month& ym, const years& dy) noexcept;

Returns: \( ym + -dy \).

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const year_month& ym);

Effects: Equivalent to:
\[ \text{return os} \ll \text{format(os.getloc(), \text{STATICALLY-WIDEN}\langle\text{charT}\rangle(\"{}/\{\L\}\"), ym.year(), ym.month());} \]

template<class charT, class traits, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt, year_month& ym, basic_string<charT, traits, Alloc>* abbrev = nullptr, minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the year_month ym using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid year_month, is.setstate(ios_base::failbit) is called and ym is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null.

Returns: is.

29.8.14 Class year_month_day

29.8.14.1 Overview

namespace std::chrono {
class year_month_day {
    chrono::year y_; // exposition only
    chrono::month m_; // exposition only
    chrono::day d_; // exposition only

public:
    year_month_day() = default;
    constexpr year_month_day(const chrono::year& y, const chrono::month& m, const chrono::day& d) noexcept;
    constexpr year_month_day(const year_month_day_last& ymdl) noexcept;
    constexpr year_month_day(const sys_days& dp) noexcept;
    constexpr explicit year_month_day(const local_days& dp) noexcept;

    constexpr year_month_day& operator+=(const months& m) noexcept;
    constexpr year_month_day& operator-=(const months& m) noexcept;
    constexpr year_month_day& operator+=(const years& y) noexcept;
    constexpr year_month_day& operator-=(const years& y) noexcept;

    constexpr chrono::year year() const noexcept;
    constexpr chrono::month month() const noexcept;
    constexpr chrono::day day() const noexcept;

    constexpr operator sys_days() const noexcept;
    constexpr operator local_days() const noexcept;

};
constexpr bool ok() const noexcept;
};

year_month_day represents a specific year, month, and day. year_month_day is a field-based time point with a resolution of days.

[Note 1: year_month_day supports years- and months-oriented arithmetic, but not days-oriented arithmetic. For the latter, there is a conversion to sys_days, which efficiently supports days-oriented arithmetic. — end note]

year_month_day meets the Cpp17EqualityComparable (Table 28) and Cpp17LessThanComparable (Table 29) requirements.

year_month_day is a trivially copyable and standard-layout class type.

29.8.14.2 Member functions

```cpp
constexpr year_month_day(const chrono::year& y, const chrono::month& m, const chrono::day& d) noexcept;
```

Effects: Initializes y_ with y, m_ with m, and d_ with d.

```cpp
constexpr year_month_day(const year_month_day_last& ymdl) noexcept;
```

Effects: Initializes y_ with ymdl.year(), m_ with ymdl.month(), and d_ with ymdl.day().

[Note 1: This conversion from year_month_day_last to year_month_day can be more efficient than converting a year_month_day_last to a sys_days, and then converting that sys_days to a year_month_day. — end note]

```cpp
constexpr year_month_day(const sys_days& dp) noexcept;
```

Effects: Constructs an object of type year_month_day that corresponds to the date represented by dp.

Remarks: For any value ymd of type year_month_day for which ymd.ok() is true, ymd == year_month_day(sys_days{ymd}) is true.

```cpp
constexpr explicit year_month_day(const local_days& dp) noexcept;
```

Effects: Equivalent to constructing with sys_days{dp.time_since_epoch()}.

```cpp
constexpr year_month_day& operator+=(const months& m) noexcept;
```

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Effects: *this = *this + m.

Returns: *this.

```cpp
constexpr year_month_day& operator-=(const months& m) noexcept;
```

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Effects: *this = *this - m.

Returns: *this.

```cpp
constexpr year_month_day& year_month_day::operator+=(const years& y) noexcept;
```

Effects: *this = *this + y.

Returns: *this.

```cpp
constexpr year_month_day& year_month_day::operator-=(const years& y) noexcept;
```

Effects: *this = *this - y.

Returns: *this.

```cpp
constexpr chrono::year year() const noexcept;
```

Returns: y_.

```cpp
constexpr chrono::month month() const noexcept;
```

Returns: m_.

§ 29.8.14.2 © ISO/IEC 1663
constexpr chrono::day day() const noexcept;
Returns: d_.

constexpr operator sys_days() const noexcept;
Returns: If ok() returns a sys_days holding a count of days from the sys_days epoch to *this
(a negative value if *this represents a date prior to the sys_days epoch). Otherwise, if y_.ok()
& m_.ok() is true, returns sys_days(y_ / m_ / 1d) + (d_ - 1d). Otherwise the value returned is
unspecified.
Remarks: A sys_days in the range [days{-12687428}, days{11248737}] which is converted to a
year_month_day has the same value when converted back to a sys_days.

[Example 1:]
static_assert(year_month_day{sys_days{2017y/January/0}} == 2016y/December/31);
static_assert(year_month_day{sys_days{2017y/January/31}} == 2017y/January/31);
static_assert(year_month_day{sys_days{2017y/January/32}} == 2017y/February/1);
—end example]

constexpr explicit operator local_days() const noexcept;
Returns: local_days{sys_days{*this}.time_since_epoch()}.

constexpr bool ok() const noexcept;
Returns: If y_.ok() is true, and m_.ok() is true, and d_ is in the range [1d, (y_ / m_ / last).day()]
then returns true; otherwise returns false.

29.8.14.3 Non-member functions [time.cal.ymd.nonmembers]

constexpr bool operator==(const year_month_day& x, const year_month_day& y) noexcept;
Returns: x.year() == y.year() && x.month() == y.month() && x.day() == y.day().

constexpr strong_ordering operator<=>(const year_month_day& x, const year_month_day& y) noexcept;
Effects: Equivalent to:
if (auto c = x.year() <=> y.year(); c != 0) return c;
if (auto c = x.month() <=> y.month(); c != 0) return c;
return x.day() <=> y.day();

constexpr year_month_day operator+(const year_month_day& ymd, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its
implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: (ymd.year() / ymd.month() + dm) / ymd.day().
[Note 1: If ymd.day() is in the range [1d, 28d], ok() will return true for the resultant year_month_day. —end
note]

constexpr year_month_day operator+(const months& dm, const year_month_day& ymd) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its
implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ymd + dm.

constexpr year_month_day operator-(const year_month_day& ymd, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its
implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ymd + (-dm).

constexpr year_month_day operator+(const year_month_day& ymd, const years& dy) noexcept;
Returns: (ymd.year() + dy) / ymd.month() / ymd.day().
[Note 2: If ymd.month() is February and ymd.day() is not in the range [1d, 28d], ok() can return false for
the resultant year_month_day. —end note]
constexpr year_month_day operator+(const years& dy, const year_month_day& ymd) noexcept;

Returns: ymd + dy.

constexpr year_month_day operator-(const year_month_day& ymd, const years& dy) noexcept;

Returns: ymd + (-dy).

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const year_month_day& ymd);

Effects: Equivalent to:
return os << (ymd.ok() ?
    format(STATICALLY-WIDEN<charT>("{:%F}"), ymd):
    format(STATICALLY-WIDEN<charT>("{:%F} is not a valid date"), ymd));

template<class charT, class traits, class Alloc = allocator<charT>>
basic_istream<charT, traits>&
from_stream(basic_istream<charT, traits>& is, const charT* fmt,
year_month_day& ymd, basic_string<charT, traits, Alloc>* abbrev = nullptr,
minutes* offset = nullptr);

Effects: Attempts to parse the input stream is into the year_month_day ymd using the format flags given in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid year_month_day, is.setstate(ios_base::failbit) is called and ymd is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null.

Returns: is.

29.8.15 Class year_month_day_last

29.8.15.1 Overview

namespace std::chrono {
    class year_month_day_last {
    chronos::year y_; // exposition only
    chronos::month_day_last mdl_; // exposition only

    public:
    constexpr year_month_day_last(const chronos::year& y,
        const chronos::month_day_last& mdl) noexcept;
    constexpr year_month_day_last& operator+=(const months& m) noexcept;
    constexpr year_month_day_last& operator-=(const months& m) noexcept;
    constexpr year_month_day_last& operator+=(const years& y) noexcept;
    constexpr year_month_day_last& operator-=(const years& y) noexcept;
    constexpr chronos::year year() const noexcept;
    constexpr chronos::month month() const noexcept;
    constexpr chronos::month_day_last month_day_last() const noexcept;
    constexpr chronos::day day() const noexcept;

    constexpr operator sys_days() const noexcept;
    constexpr explicit operator local_days() const noexcept;
    constexpr bool ok() const noexcept;
    }
}

year_month_day_last represents the last day of a specific year and month. year_month_day_last is a field-based time point with a resolution of days, except that it is restricted to pointing to the last day of a year and month.

[Note 1: year_month_day_last supports years- and months-oriented arithmetic, but not days-oriented arithmetic. For the latter, there is a conversion to sys_days, which efficiently supports days-oriented arithmetic. — end note]

year_month_day_last meets the Cpp17EqualityComparable (Table 28) and Cpp17LessThanComparable (Table 29) requirements.
N4986

2 year_month_day_last is a trivially copyable and standard-layout class type.

29.8.15.2 Member functions [time.cal.ymdlast.members]

constexpr year_month_day_last(const chrono::year& y,
                           const chrono::month_day_last& mdl) noexcept;

Effects: Initializes y_ with y and mdl_ with mdl.

constexpr year_month_day_last& operator+=(const months& m) noexcept;

Effects: *this = *this + m.

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Returns: *this.

constexpr year_month_day_last& operator-=(const months& m) noexcept;

Effects: *this = *this - m.

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Returns: *this.

constexpr year_month_day_last& operator+=(const years& y) noexcept;

Effects: *this = *this + y.

Returns: *this.

constexpr year_month_day_last& operator-=(const years& y) noexcept;

Effects: *this = *this - y.

Returns: *this.

constexpr chrono::year year() const noexcept;

Returns: y_.

constexpr chrono::month month() const noexcept;

Returns: mdl_.month().

constexpr chrono::month_day_last month_day_last() const noexcept;

Returns: mdl_.

constexpr chrono::day day() const noexcept;

Returns: If ok() is true, returns a day representing the last day of the (year, month) pair represented by *this. Otherwise, the returned value is unspecified. 

[Note 1: This value might be computed on demand. —end note]

constexpr operator sys_days() const noexcept;

Returns: sys_days{year()/month()/day()}. 

constexpr explicit operator local_days() const noexcept;

Returns: local_days{sys_days{*this}.time_since_epoch()}. 

constexpr bool ok() const noexcept;

Returns: y_.ok() && mdl_.ok().

29.8.15.3 Non-member functions [time.cal.ymdlast.nonmembers]

constexpr bool operator==(const year_month_day_last& x, const year_month_day_last& y) noexcept;

Returns: x.year() == y.year() && x.month_day_last() == y.month_day_last().
constexpr strong_ordering operator<=(const year_month_day_last& x,
const year_month_day_last& y) noexcept;

Effects: Equivalent to:

if (auto c = x.year() <= y.year(); c != 0) return c;
return x.month_day_last() <= y.month_day_last();

constexpr year_month_day_last
operator+(const year_month_day_last& ymdl, const months& dm) noexcept;

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Returns: (ymdl.year() / ymdl.month() + dm) / last.

constexpr year_month_day_last
operator+(const months& dm, const year_month_day_last& ymdl) noexcept;

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Returns: ymdl + dm.

constexpr year_month_day_last
operator-(const year_month_day_last& ymdl, const months& dm) noexcept;

Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

Returns: ymdl + (-dm).

constexpr year_month_day_last
operator+(const year_month_day_last& ymdl, const years& dy) noexcept;

Returns: {ymdl.year()+dy, ymdl.month_day_last()}. 

constexpr year_month_day_last
operator+(const years& dy, const year_month_day_last& ymdl) noexcept;

Returns: ymdl + dy.

constexpr year_month_day_last
operator-(const year_month_day_last& ymdl, const years& dy) noexcept;

Returns: ymdl + (-dy).

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const year_month_day_last& ymdl);

Effects: Equivalent to:

return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{}/:L"),
ymdl.year(), ymdl.month_day_last());

29.8.16 Class year_month_weekday

namespace std::chrono {

class year_month_weekday {
    // exposition only
    year y_; 
    month m_; 
    weekday_indexed wdi_; 

    public:
    year_month_weekday() = default;
    constexpr year_month_weekday(const year& y, const month& m, 
const weekday_indexed& wdi) noexcept;
    constexpr explicit year_month_weekday(const sys_days& dp) noexcept;
    constexpr explicit year_month_weekday(const local_days& dp) noexcept;

    template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const year_month_weekday& y);
N4986

constexpr year_month_weekday& operator+=(const months& m) noexcept;
constexpr year_month_weekday& operator-=(const months& m) noexcept;
constexpr year_month_weekday& operator+=(const years& y) noexcept;
constexpr year_month_weekday& operator-=(const years& y) noexcept;
constexpr chrono::year year() const noexcept;
constexpr chrono::month month() const noexcept;
constexpr chrono::weekday weekday() const noexcept;
constexpr unsigned index() const noexcept;
constexpr chrono::weekday_indexed weekday_indexed() const noexcept;
constexpr operator sys_days() const noexcept;
constexpr explicit operator local_days() const noexcept;
constexpr bool ok() const noexcept;
};

1 year_month_weekday represents a specific year, month, and \( n \)th weekday of the month. year_month_weekday is a field-based time point with a resolution of days.

[Note 1: year_month_weekday supports years- and months-oriented arithmetic, but not days-oriented arithmetic. For the latter, there is a conversion to sys_days, which efficiently supports days-oriented arithmetic. — end note]

year_month_weekday meets the Cpp17EqualityComparable (Table 28) requirements.

2 year_month_weekday is a trivially copyable and standard-layout class type.

29.8.16.2 Member functions

constexpr year_month_weekday(const chrono::year& y, const chrono::month& m,
const chrono::weekday_indexed& wdi) noexcept;

1 Effects: Initializes \( y \)_ with \( y \), \( m \)_ with \( m \), and \( wdi \)_ with \( wdi \).

constexpr year_month_weekday(const sys_days& dp) noexcept;

2 Effects: Constructs an object of type year_month_weekday which corresponds to the date represented by \( dp \).

3 Remarks: For any value ymwd of type year_month_weekday for which ymwd.ok() is true, ymwd == year_month_weekday{sys_days{ymwd}} is true.

constexpr explicit year_month_weekday(const local_days& dp) noexcept;

4 Effects: Equivalent to constructing with sys_days(dp.time_since_epoch()).

constexpr year_month_weekday& operator+=(const months& m) noexcept;
5 Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
6 Effects: \*this = \*this + m.
7 Returns: \*this.

constexpr year_month_weekday& operator-=(const months& m) noexcept;
8 Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
9 Effects: \*this = \*this - m.
10 Returns: \*this.

constexpr year_month_weekday& operator+=(const years& y) noexcept;
11 Effects: \*this = \*this + y.
12 Returns: \*this.

constexpr year_month_weekday& operator-=(const years& y) noexcept;
13 Effects: \*this = \*this - y.
14 Returns: \*this.
constexpr chrono::year year() const noexcept;
Returns: y_.
constexpr chrono::month month() const noexcept;
Returns: m_.
constexpr chrono::weekday weekday() const noexcept;
Returns: wdi_.weekday().
constexpr unsigned index() const noexcept;
Returns: wdi_.index().
constexpr chrono::weekday_indexed weekday_indexed() const noexcept;
constexpr operator sys_days() const noexcept;
Returns: If y_.ok() && m_.ok() && wdi_.weekday().ok(), returns a sys_days that represents the date (index() - 1) * 7 days after the first weekday() of year()/month(). If index() is 0 the returned sys_days represents the date 7 days prior to the first weekday() of year()/month(). Otherwise the returned value is unspecified.
constexpr explicit operator local_days() const noexcept;
Returns: local_days{sys_days{*this}.time_since_epoch()}. constexpr bool ok() const noexcept;
Returns: If any of y_.ok(), m_.ok(), or wdi_.ok() is false, returns false. Otherwise, if *this represents a valid date, returns true. Otherwise, returns false.

29.8.16.3 Non-member functions

constexpr bool operator==(const year_month_weekday& x, const year_month_weekday& y) noexcept;
Returns: x.year() == y.year() && x.month() == y.month() && x.weekday_indexed() == y.weekday_indexed()
constexpr year_month_weekday operator+(const year_month_weekday& ymwd, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: (ymwd.year() / ymwd.month() + dm) / ymwd.weekday_indexed().
constexpr year_month_weekday operator+(const months& dm, const year_month_weekday& ymwd) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ymwd + dm.
constexpr year_month_weekday operator-(const year_month_weekday& ymwd, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ymwd + (-dm).
constexpr year_month_weekday operator+(const year_month_weekday& ymwd, const years& dy) noexcept;
Returns: {ymwd.year() + dy, ymwd.month(), ymwd.weekday_indexed()}. constexpr year_month_weekday operator+(const years& dy, const year_month_weekday& ymwd) noexcept;
Returns: ymwd + dy.
constexpr year_month_weekday operator-(const year_month_weekday& ymwd, const years& dy) noexcept;
Returns: ymwd + (-dy).
template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const year_month_weekday& ymwd);

Effects: Equivalent to:

    return os << format(os.getloc(), STATICALLY-WIDEN<charT>("/{:L}/-{:L}"),
                       ymwd.year(), ymwd.month(), ymwd.weekday_indexed());

29.8.17 Class year_month_weekday_last

29.8.17.1 Overview

namespace std::chrono {

    class year_month_weekday_last {
        chrono::year y_;  // exposition only
        chrono::month m_;  // exposition only
        chrono::weekday_last wdl_;  // exposition only

    public:
        constexpr year_month_weekday_last(const chrono::year& y, const chrono::month& m,
                                            const chrono::weekday_last& wdl) noexcept;
        constexpr year_month_weekday_last& operator+=(const months& m) noexcept;
        constexpr year_month_weekday_last& operator-=(const months& m) noexcept;
        constexpr year_month_weekday_last& operator+=(const years& y) noexcept;
        constexpr year_month_weekday_last& operator-=(const years& y) noexcept;
        constexpr chrono::year year() const noexcept;
        constexpr chrono::month month() const noexcept;
        constexpr chrono::weekday weekday() const noexcept;
        constexpr chrono::weekday_last weekday_last() const noexcept;
        constexpr operator sys_days() const noexcept;
        constexpr explicit operator local_days() const noexcept;
        constexpr bool ok() const noexcept;
    };

1 year_month_weekday_last represents a specific year, month, and last weekday of the month. year_month_weekday_last is a field-based time point with a resolution of days, except that it is restricted to pointing to the last weekday of a year and month.

[Note 1: year_month_weekday_last supports years- and months-oriented arithmetic, but not days-oriented arithmetic. For the latter, there is a conversion to sys_days, which efficiently supports days-oriented arithmetic. — end note]

year_month_weekday_last meets the Cpp17EqualityComparable (Table 28) requirements.

2 year_month_weekday_last is a trivially copyable and standard-layout class type.

29.8.17.2 Member functions

constexpr year_month_weekday_last(const chrono::year& y, const chrono::month& m,
                                    const chrono::weekday_last& wdl) noexcept;

1 Effects: Initializes y_ with y, m_ with m, and wdl_ with wdl.

constexpr year_month_weekday_last& operator+=(const months& m) noexcept;

2 Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

3 Effects: *this = *this + m.

4 Returns: *this.

constexpr year_month_weekday_last& operator-=(const months& m) noexcept;

5 Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).

6 Effects: *this = *this - m.
Returns: *this.
constexpr year_month_weekday_last& operator+=(const years& y) noexcept;
Effects: *this = *this + y.
Returns: *this.
constexpr year_month_weekday_last& operator-=(const years& y) noexcept;
Effects: *this = *this - y.
Returns: *this.
constexpr chrono::year year() const noexcept;
Returns: y_.
constexpr chrono::month month() const noexcept;
Returns: m_.
constexpr chrono::weekday weekday() const noexcept;
Returns: wdl_.weekday().
constexpr chrono::weekday_last weekday_last() const noexcept;
Returns: wdl_.
constexpr operator sys_days() const noexcept;
Returns: If ok() == true, returns a sys_days that represents the last weekday() of year()/month(). Otherwise the returned value is unspecified.
constexpr explicit operator local_days() const noexcept;
Returns: local_days{sys_days{*this}.time_since_epoch()}.
constexpr bool ok() const noexcept;
Returns: y_.ok() && m_.ok() && wdl_.ok().

29.8.17.3 Non-member functions [time.cal.ymwdlast.nonmembers]
constexpr bool operator==(const year_month_weekday_last& x,
    const year_month_weekday_last& y) noexcept;
Returns:
x.year() == y.year() && x.month() == y.month() && x.weekday_last() == y.weekday_last()
operator+=(const year_month_weekday_last& ymwdl, const months& dm) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: (ymwdl.year() / ymwdl.month() + dm) / ymwdl.weekday_last().
operator=(const months& dm, const year_month_weekday_last& ymwdl) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ymwdl + dm.
operator-=(const months& dm, const year_month_weekday_last& ymwdl) noexcept;
Constraints: If the argument supplied by the caller for the months parameter is convertible to years, its implicit conversion sequence to years is worse than its implicit conversion sequence to months (12.2.4.3).
Returns: ymwdl + (-dm).
constexpr year_month_weekday_last
operator+(const year_month_weekday_last& ymwdl, const years& dy) noexcept;

Returns: \{ymwdl.year()+dy, ymwdl.month(), ymwdl.weekday_last()\}.

constexpr year_month_weekday_last
operator+(const years& dy, const year_month_weekday_last& ymwdl) noexcept;

Returns: ymwdl + dy.

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const year_month_weekday_last& ymwdl);

Effects: Equivalent to:
return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{}/{:L}/{:L}"),
ymwdl.year(), ymwdl.month(), ymwdl.weekday_last());

29.8.18 Conventional syntax operators [time.cal_operators]
A set of overloaded operator/ functions provides a conventional syntax for the creation of civil calendar
dates.

[Note 1: The year, month, and day are accepted in any of the following 3 orders:
year/month/day
month/day/year
day/month/year

Anywhere a day is needed, any of the following can also be specified:
last
weekday[i]
weekday[last]
— end note]

[Note 2: Partial-date types such as year_month and month_day can be created by not applying the second division
operator for any of the three orders. For example:
year_month ym = 2015y/April;
month_day md1 = April/4;
month_day md2 = 4d/April;
— end note]

[Example 1:
auto a = 2015/4/4; // a == int(125)
auto b = 2015y/4/4; // b == year_month_day{year(2015), month(4), day(4)}
auto c = 2015y/4d/April; // error: no viable operator/ for first /
auto d = 2015/April/4; // error: no viable operator/ for first /
— end example]

castexpr year_month
operator/(const year& y, const month& m) noexcept;

Returns: \{y, m\}.

castexpr year_month
operator/(const year& y, int m) noexcept;

Returns: \(y \div \text{month}(m)\).

castexpr month_day
operator/(const month& m, const day& d) noexcept;

Returns: \{m, d\}.
constexpr month_day
operator/(const month& m, int d) noexcept;

Returns: m / day(d).

constexpr month_day
operator/(int m, const day& d) noexcept;

Returns: month(m) / d.

constexpr month_day
operator/(const day& d, const month& m) noexcept;

Returns: m / d.

constexpr month_day
operator/(const day& d, int m) noexcept;

Returns: month(m) / d.

constexpr month_day_last
operator/(const month& m, last_spec) noexcept;

Returns: month_day_last(m).

constexpr month_day_last
operator/(int m, last_spec) noexcept;

Returns: month(m) / last.

constexpr month_day_last
operator/(last_spec, const month& m) noexcept;

Returns: m / last.

constexpr month_day_last
operator/(last_spec, int m) noexcept;

Returns: month(m) / last.

constexpr month_weekday
operator/(const month& m, const weekday_indexed& wdi) noexcept;

Returns: {m, wdi}.

constexpr month_weekday
operator/(int m, const weekday_indexed& wdi) noexcept;

Returns: month(m) / wdi.

constexpr month_weekday
operator/(const weekday_indexed& wdi, const month& m) noexcept;

Returns: m / wdi.

constexpr month_weekday
operator/(const weekday_indexed& wdi, int m) noexcept;

Returns: month(m) / wdi.

constexpr month_weekday_last
operator/(const month& m, const weekday_last& wdl) noexcept;

Returns: {m, wdl}.

constexpr month_weekday_last
operator/(int m, const weekday_last& wdl) noexcept;

Returns: month(m) / wdl.

constexpr month_weekday_last
operator/(const weekday_last& wdl, const month& m) noexcept;

Returns: m / wdl.
constexpr month_weekday_last
operator/(const weekday_last& wdl, int m) noexcept;

    Returns: month(m) / wdl.

constexpr year_month_day
operator/(const year_month& ym, const day& d) noexcept;

    Returns: {ym.year(), ym.month(), d}.

constexpr year_month_day
operator/(const year_month& ym, int d) noexcept;

    Returns: ym / day(d).

constexpr year_month_day
operator/(const year_month& ym, const month_day& md) noexcept;

    Returns: y / md.month() / md.day().

constexpr year_month_day
operator/(int y, const month_day& md) noexcept;

    Returns: year(y) / md.

constexpr year_month_day
operator/(const month_day& md, const year& y) noexcept;

    Returns: md / y.

constexpr year_month_day
operator/(const month_day& md, int y) noexcept;

    Returns: year(y) / md.

constexpr year_month_day_last
operator/(const year_month& ym, last_spec) noexcept;

    Returns: {ym.year(), month_day_last{ym.month()}}.

constexpr year_month_day_last
operator/(const year& y, const month_day_last& mdl) noexcept;

    Returns: {y, mdl}.

constexpr year_month_day_last
operator/(int y, const month_day_last& mdl) noexcept;

    Returns: year(y) / mdl.

constexpr year_month_day_last
operator/(const month_day_last& mdl, const year& y) noexcept;

    Returns: y / mdl.

constexpr year_month_day_last
operator/(const month_day_last& mdl, int y) noexcept;

    Returns: year(y) / mdl.

constexpr year_month_weekday
operator/(const year_month& ym, const weekday_indexed& wdi) noexcept;

    Returns: {ym.year(), ym.month(), wdi}.

constexpr year_month_weekday
operator/(const year& y, const month_weekday& mwd) noexcept;

    Returns: {y, mwd.month(), mwd.weekday_indexed()}.

constexpr year_month_weekday
operator/(int y, const month_weekday& mwd) noexcept;

    Returns: year(y) / mwd.

§ 29.8.18 © ISO/IEC 1674
constexpr year_month_weekday
    operator/(const month_weekday& mwd, const year& y) noexcept;

Returns: y / mwd.

constexpr year_month_weekday
    operator/(const month_weekday& mwd, int y) noexcept;

Returns: year(y) / mwd.

constexpr year_month_weekday_last
    operator/(const year_month& ym, const weekday_last& wdl) noexcept;

Returns: {ym.year(), ym.month(), wdl}.

constexpr year_month_weekday_last
    operator/(const year& y, const month_weekday_last& mwdl) noexcept;

Returns: {y, mwdl.month(), mwdl.weekday_last()}.  

constexpr year_month_weekday_last
    operator/(int y, const month_weekday_last& mwdl) noexcept;

Returns: year(y) / mwdl.

constexpr year_month_weekday_last
    operator/(const month_weekday_last& mwdl, const year& y) noexcept;

Returns: y / mwdl.

constexpr year_month_weekday_last
    operator/(const month_weekday_last& mwdl, int y) noexcept;

Returns: year(y) / mwdl.

29.9 Class template hh_mm_ss
[time.hms]

29.9.1 Overview [time.hms.overview]

namespace std::chrono {
    template<class Duration> class hh_mm_ss {
    public:
        static constexpr unsigned fractional_width = see below;
        using precision = see below;

        constexpr hh_mm_ss() noexcept : hh_mm_ss(Duration::zero()) {}
        constexpr explicit hh_mm_ss(Duration d);

        constexpr bool is_negative() const noexcept;
        constexpr chrono::hours hours() const noexcept;
        constexpr chrono::minutes minutes() const noexcept;
        constexpr chrono::seconds seconds() const noexcept;
        constexpr precision subseconds() const noexcept;
        constexpr explicit operator precision() const noexcept;
        constexpr precision to_duration() const noexcept;

    private:
        bool is_neg; // exposition only
        chrono::hours h; // exposition only
        chrono::minutes m; // exposition only
        chrono::seconds s; // exposition only
        precision ss; // exposition only
    };
}

1 The hh_mm_ss class template splits a duration into a multi-field time structure hours:minutes:seconds and possibly subseconds, where subseconds will be a duration unit based on a non-positive power of 10. The Duration template parameter dictates the precision to which the time is split. A hh_mm_ss models negative durations with a distinct is_negative getter that returns true when the input duration is negative. The
individual duration fields always return non-negative durations even when \texttt{is\_negative()} indicates the structure is representing a negative duration.

2 If \texttt{Duration} is not a specialization of \texttt{duration}, the program is ill-formed.

### 29.9.2 Members

```cpp
static constexpr unsigned fractional_width = see below;
```

1 \texttt{fractional\_width} is the number of fractional decimal digits represented by \texttt{precision}. \texttt{fractional\_width} has the value of the smallest possible integer in the range \([0, 18]\) such that \texttt{precision} will exactly represent all values of \texttt{Duration}. If no such value of \texttt{fractional\_width} exists, then \texttt{fractional\_width} is 6.

[Example 1: See Table 103 for some durations, the resulting \texttt{fractional\_width}, and the formatted fractional second output of \texttt{Duration(1)}.

#### Table 103 — Examples for \texttt{fractional\_width}

<table>
<thead>
<tr>
<th>Duration</th>
<th>\texttt{fractional_width}</th>
<th>Formatted fractional second output</th>
</tr>
</thead>
<tbody>
<tr>
<td>hours, minutes, and seconds</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>milliseconds</td>
<td>3</td>
<td>0.001</td>
</tr>
<tr>
<td>microseconds</td>
<td>6</td>
<td>0.000001</td>
</tr>
<tr>
<td>nanoseconds</td>
<td>9</td>
<td>0.000000001</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 2&gt;&gt;</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 3&gt;&gt;</td>
<td>6</td>
<td>0.333333</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 4&gt;&gt;</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 5&gt;&gt;</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 6&gt;&gt;</td>
<td>6</td>
<td>0.166666</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 7&gt;&gt;</td>
<td>6</td>
<td>0.142857</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 8&gt;&gt;</td>
<td>3</td>
<td>0.125</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 9&gt;&gt;</td>
<td>6</td>
<td>0.111111</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;1, 10&gt;&gt;</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>duration&lt;int, ratio&lt;766, 625&gt;&gt;</td>
<td>4</td>
<td>0.2096</td>
</tr>
</tbody>
</table>

--- end example]

using precision = see below;

2 \texttt{precision} is

```cpp
constexpr explicit hh_mm_ss(Duration d);
```

3 \texttt{Effects}: Constructs an object of type \texttt{hh\_mm\_ss} which represents the \texttt{Duration d} with precision \texttt{precision}.

(3.1) — Initializes \texttt{is\_neg} with \texttt{d < Duration::zero()}.  
(3.2) — Initializes \texttt{h} with \texttt{duration\_cast<chrono::hours>(abs(d))}.  
(3.3) — Initializes \texttt{m} with \texttt{duration\_cast<chrono::minutes>(abs(d) - hours())}.  
(3.4) — Initializes \texttt{s} with \texttt{duration\_cast<chrono::seconds>(abs(d) - hours() - minutes())}.  
(3.5) — If \texttt{treat\_as\_floating\_point\_v<precision::rep> is true, initializes \texttt{ss} with \texttt{abs(d) - hours()} - \texttt{minutes()} - \texttt{seconds()}. Otherwise, initializes \texttt{ss} with \texttt{duration\_cast<precision>(abs(d) - hours() - minutes() - seconds())}.  

[Note 1: When \texttt{precision::rep} is integral and \texttt{precision::period} is \texttt{ratio<1>}, \texttt{subseconds()} always returns a value equal to 0s. — end note]

4 \texttt{Postconditions}: If \texttt{treat\_as\_floating\_point\_v<precision::rep> is true, \texttt{to\_duration()} returns \texttt{d}, otherwise \texttt{to\_duration()} returns \texttt{duration\_cast<precision>(d)}.

```cpp
constexpr bool is\_negative() const noexcept;
```

5 \texttt{Returns}: \texttt{is\_neg}.
constexpr chrono::hours hours() const noexcept;
Returns: h.

constexpr chrono::minutes minutes() const noexcept;
Returns: m.

constexpr chrono::seconds seconds() const noexcept;
Returns: s.

constexpr precision subseconds() const noexcept;
Returns: ss.

constexpr precision to_duration() const noexcept;
Returns: If is_neg, returns -(h + m + s + ss), otherwise returns h + m + s + ss.

constexpr explicit operator precision() const noexcept;
Returns: to_duration().

29.9.3 Non-members [time.hms.nonmembers]

template<class charT, class traits, class Duration>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const hh_mm_ss<Duration>& hms);
Effects: Equivalent to:
return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%T}"), hms);

[Example 1:
  for (auto ms : {-4083007ms, 4083007ms, 65745123ms}) {
    hh_mm_ss hms(ms);
    cout << hms << 'n';
  }
  cout << hh_mm_ss{65745s} << 'n';

Produces the output (assuming the 'C' locale):
-01:08:03.007
01:08:03.007
18:15:45.123
18:15:45
—end example]

29.10 12/24 hours functions [time.12]

These functions aid in translating between a 12h format time of day and a 24h format time of day.

constexpr bool is_am(const hours& h) noexcept;
Returns: 0h <= h && h <= 11h.

constexpr bool is_pm(const hours& h) noexcept;
Returns: 12h <= h && h <= 23h.

constexpr hours make12(const hours& h) noexcept;
Returns: The 12-hour equivalent of h in the range [1h, 12h]. If h is not in the range [0h, 23h], the value returned is unspecified.

constexpr hours make24(const hours& h, bool is_pm) noexcept;
Returns: If is_pm is false, returns the 24-hour equivalent of h in the range [0h, 11h], assuming h represents an ante meridiem hour. Otherwise, returns the 24-hour equivalent of h in the range [12h, 23h], assuming h represents a post meridiem hour. If h is not in the range [1h, 23h], the value returned is unspecified.
29.11 Time zones

29.11.1 General

29.11 describes an interface for accessing the IANA Time Zone Database that interoperates with sys_time and local_time. This interface provides time zone support to both the civil calendar types (29.8) and to user-defined calendars.

29.11.2 Time zone database

29.11.2.1 Class tzdb

namespace std::chrono {
    struct tzdb {
        string version;
        vector<time_zone> zones;
        vector<time_zone_link> links;
        vector<leap_second> leap_seconds;

        const time_zone* locate_zone(string_view tz_name) const;
        const time_zone* current_zone() const;
    }
}

1 Each vector in a tzdb object is sorted to enable fast lookup.

const time_zone* locate_zone(string_view tz_name) const;

2 Returns:

(2.1) — If zones contains an element tz for which tz.name() == tz_name, a pointer to tz;

(2.2) — otherwise, if links contains an element tz_l for which tz_l.name() == tz_name, then a pointer to the element tz of zones for which tz.name() == tz_l.target().

[Note 1: A time_zone_link specifies an alternative name for a time_zone. — end note]

3 Throws: If a const time_zone* cannot be found as described in the Returns: element, throws a runtime_error.

[Note 2: On non-exceptional return, the return value is always a pointer to a valid time_zone. — end note]

const time_zone* current_zone() const;

4 Returns: A pointer to the time zone which the computer has set as its local time zone.

29.11.2.2 Class tzdb_list

namespace std::chrono {
    class tzdb_list {
        tzdb_list(const tzdb_list&) = delete;
        tzdb_list& operator=(const tzdb_list&) = delete;

        // unspecified additional constructors

        class const_iterator;

        const tzdb& front() const noexcept;
        const_iterator erase_after(const_iterator p);
        const_iterator begin() const noexcept;
        const_iterator end() const noexcept;

        const_iterator cbegin() const noexcept;
        const_iterator cend() const noexcept;
    };
}

1 The tzdb_list database is a singleton; the unique object of type tzdb_list can be accessed via the get_tzdb_list() function.
The `tzdb_list` object contains a list of `tzdb` objects. `tzdb_list::const_iterator` is a constant iterator which meets the `Cpp17ForwardIterator` requirements and has a value type of `tzdb`.

```
const tzdb& front() const noexcept;
    Synchronization: This operation is thread-safe with respect to `reload_tzdb()`.
    [Note 2: `reload_tzdb()` pushes a new `tzdb` onto the front of this container. — end note]
    Returns: A reference to the first `tzdb` in the container.

const_iterator erase_after(const_iterator p);
    Preconditions: The iterator following `p` is dereferenceable.
    Effects: Erases the `tzdb` referred to by the iterator following `p`.
    Postconditions: No pointers, references, or iterators are invalidated except those referring to the erased `tzdb`.
    [Note 3: It is not possible to erase the `tzdb` referred to by `begin()`. — end note]
    Returns: An iterator pointing to the element following the one that was erased, or `end()` if no such element exists.
    Throws: Nothing.

const_iterator begin() const noexcept;
    Returns: An iterator referring to the first `tzdb` in the container.

const_iterator end() const noexcept;
    Returns: An iterator referring to the position one past the last `tzdb` in the container.

const_iterator cbegin() const noexcept;
    Returns: `begin()`.

const_iterator cend() const noexcept;
    Returns: `end()`.
```

### 29.11.2.3 Time zone database access

```
tzdb_list& get_tzdb_list();
    Effects: If this is the first access to the time zone database, initializes the database. If this call initializes the database, the resulting database will be a `tzdb_list` holding a single initialized `tzdb`.
    Synchronization: It is safe to call this function from multiple threads at one time.
    Returns: A reference to the database.
    Throws: `runtime_error` if for any reason a reference cannot be returned to a valid `tzdb_list` containing one or more valid `tzdb`s.

const tzdb& get_tzdb();
    Returns: `get_tzdb_list().front()`.

const time_zone* locate_zone(string_view tz_name);
    Returns: `get_tzdb().locate_zone(tz_name)`.
    [Note 1: The time zone database will be initialized if this is the first reference to the database. — end note]

const time_zone* current_zone();
    Returns: `get_tzdb().current_zone()`.
```
29.11.2.4 Remote time zone database support

The local time zone database is that supplied by the implementation when the program first accesses the database, for example via `current_zone()`. While the program is running, the implementation may choose to update the time zone database. This update shall not impact the program in any way unless the program calls the functions in this subclause. This potentially updated time zone database is referred to as the remote time zone database.

```cpp
const tzdb& reload_tzdb();
```

**Effects**: This function first checks the version of the remote time zone database. If the versions of the local and remote databases are the same, there are no effects. Otherwise the remote database is pushed to the front of the `tzdb_list` accessed by `get_tzdb_list()`.

**Synchronization**: This function is thread-safe with respect to `get_tzdb_list().front()` and `get_tzdb_list().erase_after()`.

**Postconditions**: No pointers, references, or iterators are invalidated.

**Returns**: `get_tzdb_list().front()`.

**Thros**: `runtime_error` if for any reason a reference cannot be returned to a valid `tzdb`.

```cpp
string remote_version();
```

**Returns**: The latest remote database version.

**[Note 1]**: This can be compared with `get_tzdb().version` to discover if the local and remote databases are equivalent. — end note

29.11.3 Exception classes

29.11.3.1 Class `nonexistent_local_time`

```cpp
namespace std::chrono {
    class nonexistent_local_time : public runtime_error {
        public:
            template<class Duration>
                nonexistent_local_time(const local_time<Duration>& tp, const local_info& i);
    }
}
```

**nonexistent_local_time** is thrown when an attempt is made to convert a non-existent `local_time` to a `sys_time` without specifying `choose::earliest` or `choose::latest`.

```cpp
template<class Duration>
    nonexistent_local_time(const local_time<Duration>& tp, const local_info& i);
```

**Preconditions**: `i.result == local_info::nonexistent` is true.

**Effects**: Initializes the base class with a sequence of `char` equivalent to that produced by `os.str()` initialized as shown below:

```cpp
    os << tp << " is in a gap between\n" << local_seconds{i.first.end.time_since_epoch()} + i.first.offset << " \
    << i.first.abbrev " and\n" << local_seconds{i.second.begin.time_since_epoch()} + i.second.offset << " \\
    << i.second.abbrev " which are both equivalent to\n" << i.first.end << " UTC";
```

**Example 1**:

```cpp
#include <chrono>
#include <iostream>

int main() {
    using namespace std::chrono;
    try {
        auto zt = zoned_time("America/New_York",
            local_days{Sunday[2]/March/2016} + 2h + 30min);
```
catch (const nonexistent_local_time& e) {
    std::cout << e.what() << '
';
}

Produces the output:

2016-03-13 02:30:00 is in a gap between
2016-03-13 02:00:00 EST and
2016-03-13 03:00:00 EDT which are both equivalent to
2016-03-13 07:00:00 UTC

— end example —

29.11.3.2 Class ambiguous_local_time [time.zone.exception.ambig]

namespace std::chrono {
    class ambiguous_local_time : public runtime_error {
public:
    template<class Duration>
    ambiguous_local_time(const local_time<Duration>& tp, const local_info& i);
    };
}  // namespace std::chrono

ambiguous_local_time is thrown when an attempt is made to convert an ambiguous local_time to a
sys_time without specifying choose::earliest or choose::latest.

template<class Duration>
ambiguous_local_time(const local_time<Duration>& tp, const local_info& i);

Preconditions: i.result == local_info::ambiguous is true.

Effects: Initializes the base class with a sequence of char equivalent to that produced by os.str()
initialized as shown below:

    ostringstream os;
    os << tp << " is ambiguous. It could be\n" << tp << ' ' << i.first.abbrev << " == "
    << tp - i.first.offset << " UTC or\n" << tp << ' ' << i.second.abbrev << " == "
    << tp - i.second.offset << " UTC";

[Example 1:]
#include <chrono>
#include <iostream>

int main() {
    using namespace std::chrono;
    try {
        auto zt = zoned_time("America/New_York",
            local_days{Sunday[1]/November/2016} + 1h + 30min);
    } catch (const ambiguous_local_time& e) {
        std::cout << e.what() << '
';
    }
}

Produces the output:

2016-11-06 01:30:00 is ambiguous. It could be
2016-11-06 01:30:00 EDT == 2016-11-06 05:30:00 UTC or
2016-11-06 01:30:00 EST == 2016-11-06 06:30:00 UTC

— end example —

29.11.4 Information classes [time.zone.info]

29.11.4.1 Class sys_info [time.zone.info.sys]

namespace std::chrono {
    struct sys_info {
        sys_seconds begin;
    };

§ 29.11.4.1 ©ISO/IEC 1681
A `sys_info` object can be obtained from the combination of a `time_zone` and either a `sys_time` or `local_time`. It can also be obtained from a `zoned_time`, which is effectively a pair of a `time_zone` and `sys_time`.

The `begin` and `end` data members indicate that, for the associated `time_zone` and `time_point`, the `offset` and `abbrev` are in effect in the range `[begin:end)`. This information can be used to efficiently iterate the transitions of a `time_zone`.

The `offset` data member indicates the UTC offset in effect for the associated `time_zone` and `time_point`. The relationship between `local_time` and `sys_time` is:

\[ \text{offset} = \text{local_time} - \text{sys_time} \]

The `save` data member is extra information not normally needed for conversion between `local_time` and `sys_time`. If `save \neq 0\text{min}`, this `sys_info` is said to be on “daylight saving” time, and `offset - save` suggests what offset this `time_zone` might use if it were off daylight saving time. However, this information should not be taken as authoritative. The only sure way to get such information is to query the `time_zone` with a `time_point` that returns a `sys_info` where `save == 0\text{min}`. There is no guarantee what `time_point` might return such a `sys_info` except that it is guaranteed not to be in the range `[begin,end)` (if `save \neq 0\text{min}` for this `sys_info`).

The `abbrev` data member indicates the current abbreviation used for the associated `time_zone` and `time_point`. Abbreviations are not unique among the `time_zones`, and so one cannot reliably map abbreviations back to a `time_zone` and UTC offset.

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const sys_info& r);
```

Effects: Streams out the `sys_info` object `r` in an unspecified format.

Returns: `os`.

29.11.4.2 Class local_info

Describes the result of converting a `local_time` to a `sys_time` as follows:

1. **(2.1)** When a `local_time` to `sys_time` conversion is unique, `result == unique`, `first` will be filled out with the correct `sys_info`, and `second` will be zero-initialized.

2. **(2.2)** If the conversion stems from a nonexistent `local_time` then `result == nonexistent`, `first` will be filled out with the `sys_info` that ends just prior to the `local_time`, and `second` will be filled out with the `sys_info` that begins just after the `local_time`.

3. **(2.3)** If the conversion stems from an ambiguous `local_time`, then `result == ambiguous`, `first` will be filled out with the `sys_info` that ends just after the `local_time`, and `second` will be filled out with the `sys_info` that starts just before the `local_time`.

§ 29.11.4.2 © ISO/IEC 1682
template<class charT, class traits>
  basic_ostream<charT, traits>&
  operator<<(basic_ostream<charT, traits>& os, const local_info& r);  

  Effects: Streams out the local_info object r in an unspecified format.
  Returns: os.

29.11.5 Class time_zone

29.11.5.1 Overview

namespace std::chrono {
  class time_zone {
    public:
      time_zone(time_zone&&) = default;
      time_zone& operator=(time_zone&&) = default;

      // unspecified additional constructors
      string_view name() const noexcept;

      template<class Duration>
      sys_info get_info(const sys_time<Duration>& st) const;
      template<class Duration>
      local_info get_info(const local_time<Duration>& tp) const;

      template<class Duration>
      sys_time<common_type_t<Duration, seconds>>
      to_sys(const local_time<Duration>& tp) const;

      template<class Duration>
      sys_time<common_type_t<Duration, seconds>>
      to_sys(const local_time<Duration>& tp, choose z) const;

      template<class Duration>
      local_time<common_type_t<Duration, seconds>>
      to_local(const sys_time<Duration>& tp) const;
  };
}

A time_zone represents all time zone transitions for a specific geographic area. time_zone construction is unspecified, and performed as part of database initialization.

[Note 1: const time_zone objects can be accessed via functions such as locate_zone. — end note]

29.11.5.2 Member functions

  string_view name() const noexcept;
  Returns: The name of the time_zone.

  [Example 1: "America/New_York". — end example]

  template<class Duration>
  sys_info get_info(const sys_time<Duration>& st) const;
  Returns: A sys_info i for which st is in the range [i.begin, i.end).

  template<class Duration>
  local_info get_info(const local_time<Duration>& tp) const;
  Returns: A local_info for tp.

  template<class Duration>
  sys_time<common_type_t<Duration, seconds>>
  to_sys(const local_time<Duration>& tp) const;
  Returns: A sys_time that is at least as fine as seconds, and will be finer if the argument tp has finer precision. This sys_time is the UTC equivalent of tp according to the rules of this time_zone.

  Throws: If the conversion from tp to a sys_time is ambiguous, throws ambiguous_local_time. If the tp represents a non-existent time between two UTC time_points, throws nonexistent_local_time.
template<class Duration>
  sys_time<common_type_t<Duration, seconds>>
  to_sys(const local_time<Duration>& tp, choose z) const;

Returns: A sys_time that is at least as fine as seconds, and will be finer if the argument tp has
finer precision. This sys_time is the UTC equivalent of tp according to the rules of this time-
zone. If the conversion from tp to a sys_time is ambiguous, returns the earlier sys_time if z ==
choose::earliest, and returns the later sys_time if z == choose::latest. If the tp represents a
non-existent time between two UTC time_points, then the two UTC time_points will be the same,
and that UTC time_point will be returned.

template<class Duration>
  local_time<common_type_t<Duration, seconds>>
  to_local(const sys_time<Duration>& tp) const;

Returns: The local_time associated with tp and this time_zone.

29.11.5.3 Non-member functions

bool operator==(const time_zone& x, const time_zone& y) noexcept;
  Returns: x.name() == y.name().

strong_ordering operator<=>(const time_zone& x, const time_zone& y) noexcept;
  Returns: x.name() <=> y.name().

29.11.6 Class template zoned_traits

namespace std::chrono {
  template<class T> struct zoned_traits {};
}

zoned_traits provides a means for customizing the behavior of zoned_time<Duration, TimeZonePtr>
for the zoned_time default constructor, and constructors taking string_view. A specialization for const
time_zone* is provided by the implementation:

namespace std::chrono {
  template<> struct zoned_traits<const time_zone*> {
    static const time_zone* default_zone();
    static const time_zone* locate_zone(string_view name);
  };
}

static const time_zone* default_zone();
  Returns: std::chrono::locate_zone("UTC").

static const time_zone* locate_zone(string_view name);
  Returns: std::chrono::locate_zone(name).

29.11.7 Class template zoned_time

29.11.7.1 Overview

namespace std::chrono {
  template<class Duration, class TimeZonePtr = const time_zone*> class zoned_time {
    public:
      using duration = common_type_t<Duration, seconds>;

    private:
      TimeZonePtr zone_;  // exposition only
      sys_time<duration> tp_;  // exposition only

      using traits = zoned_traits<TimeZonePtr>;  // exposition only

    public:
      zoned_time();
      zoned_time(const zoned_time&) = default;
zoned_time& operator=(const zoned_time&) = default;

zoned_time(const sys_time<Duration>& st);
explicit zoned_time(TimeZonePtr z);
explicit zoned_time(string_view name);

template<class Duration2>
 zoned_time(const zoned_time<Duration2, TimeZonePtr>& y);

zoned_time(TimeZonePtr z, const sys_time<Duration>& st);
zoned_time(string_view name, const sys_time<Duration>& st);

zoned_time(TimeZonePtr z, const local_time<Duration>& tp);
zoned_time(string_view name, const local_time<Duration>& tp);
zoned_time(TimeZonePtr z, const local_time<Duration>& tp, choose c);
zoned_time(string_view name, const local_time<Duration>& tp, choose c);

template<class Duration2, class TimeZonePtr2>
 zoned_time(TimeZonePtr z, const zoned_time<Duration2, TimeZonePtr2>& y);

template<class Duration2, class TimeZonePtr2>
 zoned_time(TimeZonePtr z, const zoned_time<Duration2, TimeZonePtr2>& y, choose);

template<class Duration2, class TimeZonePtr2>
 zoned_time(string_view name, const zoned_time<Duration2, TimeZonePtr2>& y);

template<class Duration2, class TimeZonePtr2>
 zoned_time(string_view name, const zoned_time<Duration2, TimeZonePtr2>& y, choose c);

zoned_time& operator=(const sys_time<Duration>& st);

zoned_time& operator=(const local_time<Duration>& lt);

operator sys_time<duration>() const;
explicit operator local_time<duration>() const;

TimeZonePtr get_time_zone() const;
local_time<duration> get_local_time() const;
sys_time<duration> get_sys_time() const;
sys_info get_info() const;

zoned_time() -> zoned_time<seconds>;

template<class Duration>
 zoned_time(sys_time<Duration>)
 -> zoned_time<common_type_t<Duration, seconds>>;

template<class TimeZonePtrOrName>
 using time-zone-representation = conditional_t<
   is_convertible_v<TimeZonePtrOrName, string_view>,
   const time_zone*,
   remove_cvref_t<TimeZonePtrOrName>>;

template<class TimeZonePtrOrName>
 zoned_time(TimeZonePtrOrName&&)
 -> zoned_time<seconds, time-zone-representation<TimeZonePtrOrName>>;

template<class TimeZonePtrOrName, class Duration>
 zoned_time(TimeZonePtrOrName&&, sys_time<Duration>)
 -> zoned_time<common_type_t<Duration, seconds>,
    time-zone-representation<TimeZonePtrOrName>>;

template<class TimeZonePtrOrName, class Duration>
 zoned_time(TimeZonePtrOrName&&, local_time<Duration>,
            choose = choose::earliest)
 -> zoned_time<common_type_t<Duration, seconds>,
    time-zone-representation<TimeZonePtrOrName>>;

§ 29.11.7.1 © ISO/IEC 1685
zoned_time<TimeZonePtrOrName>>;

template<class Duration, class TimeZonePtrOrName, class TimeZonePtr2>
zoned_time(TimeZonePtrOrName&&, zoned_time<Duration, TimeZonePtr2>,
    choose = choose::earliest)
-> zoned_time<common_type_t<Duration, seconds>,
    time-zone-representation<TimeZonePtrOrName>>;

1 zoned_time represents a logical pairing of a time_zone and a time_point with precision Duration. zoned_time<Duration> maintains the invariant that it always refers to a valid time zone and represents a point in time that exists and is not ambiguous in that time zone.

2 If Duration is not a specialization of chrono::duration, the program is ill-formed.

3 Every constructor of zoned_time that accepts a string_view as its first parameter does not participate in class template argument deduction (12.2.2.9).

29.11.7.2 Constructors

zoned_time();
  Constraints: traits::default_zone() is a well-formed expression.
  Effects: Initializes zone_ with traits::default_zone() and default constructs tp_.

zoned_time(const sys_time<Duration>& st);
  Constraints: traits::default_zone() is a well-formed expression.
  Effects: Initializes zone_ with traits::default_zone() and tp_ with st.

explicit zoned_time(TimeZonePtr z);
  Preconditions: z refers to a time zone.
  Effects: Initializes zone_ with std::move(z) and default constructs tp_.

explicit zoned_time(string_view name);
  Constraints: traits::locate_zone(string_view{}) is a well-formed expression and zoned_time is constructible from the return type of traits::locate_zone(string_view{}).
  Effects: Initializes zone_ with traits::default_zone() and tp_ with st.

template<class Duration2>
zoned_time(const zoned_time<Duration2, TimeZonePtr>& y);
  Constraints: is_convertible_v<sys_time<Duration2>, sys_time<Duration>> is true.
  Effects: Initializes zone_ with y.zone_ and tp_ with y.tp_.

zoned_time(TimeZonePtr z, const sys_time<Duration>& st);
  Preconditions: z refers to a time zone.
  Effects: Initializes zone_ with std::move(z) and tp_ with st.

zoned_time(string_view name, const sys_time<Duration>& st);
  Constraints: zoned_time is constructible from the return type of traits::locate_zone(name) and st.
  Effects: Equivalent to construction with {traits::locate_zone(name), st}.

zoned_time(TimeZonePtr z, const local_time<Duration>& tp);
  Constraints:
    is_convertible_v<
      decltype(declval<TimeZonePtr&>()->to_sys(local_time<Duration>{})),
      sys_time<duration>>
    is true.
  Preconditions: z refers to a time zone.
Effects: Initializes zone_ with std::move(z) and tp_ with zone_->to_sys(tp).

zoned_time(string_view name, const local_time<Duration>& tp);

Constraints: zoned_time is constructible from the return type of traits::locate_zone(name) and tp.

Effects: Equivalent to construction with {traits::locate_zone(name), tp}.

zoned_time(TimeZonePtr z, const local_time<Duration>& tp, choose c);

Constraints:

is_convertible_v<
  decltype(declval<TimeZonePtr&>()->to_sys(local_time<Duration>{}, choose::earliest)),
  sys_time<duration>>

is true.

Preconditions: z refers to a time zone.

Effects: Initializes zone_ with std::move(z) and tp_ with zone_->to_sys(tp, c).

zoned_time(string_view name, const local_time<Duration>& tp, choose c);

Constraints: zoned_time is constructible from the return type of traits::locate_zone(name), local_time<Duration>, and choose.

Effects: Equivalent to construction with {traits::locate_zone(name), tp, c}.

template<class Duration2, class TimeZonePtr2>
zoned_time(TimeZonePtr z, const zoned_time<Duration2, TimeZonePtr2>& y);

Constraints: is_convertible_v<sys_time<Duration2>, sys_time<Duration>> is true.

Preconditions: z refers to a valid time zone.

Effects: Initializes zone_ with std::move(z) and tp_ with y.tp_.

template<class Duration2, class TimeZonePtr2>
zoned_time(TimeZonePtr z, const zoned_time<Duration2, TimeZonePtr2>& y, choose);

Constraints: is_convertible_v<sys_time<Duration2>, sys_time<Duration>> is true.

Preconditions: z refers to a valid time zone.

Effects: Equivalent to construction with {z, y}.

[Note 1: The choose parameter has no effect. — end note]

template<class Duration2, class TimeZonePtr2>
zoned_time(string_view name, const zoned_time<Duration2, TimeZonePtr2>& y);

Constraints: zoned_time is constructible from the return type of traits::locate_zone(name) and the type zoned_time<Duration2, TimeZonePtr2>.

Effects: Equivalent to construction with {traits::locate_zone(name), y}.

template<class Duration2, class TimeZonePtr2>
zoned_time(string_view name, const zoned_time<Duration2, TimeZonePtr2>& y, choose c);

Constraints: zoned_time is constructible from the return type of traits::locate_zone(name), the type zoned_time<Duration2, TimeZonePtr2>, and the type choose.

Effects: Equivalent to construction with {traits::locate_zone(name), y, c}.

[Note 2: The choose parameter has no effect. — end note]

29.11.7.3 Member functions

zoned_time& operator=(const sys_time<Duration>& st);

Effects: After assignment, get_sys_time() == st. This assignment has no effect on the return value of get_time_zone().

Returns: *this.
N4986

zoned_time& operator=(const local_time<Duration>& lt);

Effects: After assignment, get_local_time() == lt. This assignment has no effect on the return value of get_time_zone().

Returns: *this.

operator sys_time<duration>() const;

Returns: get_sys_time().

explicit operator local_time<duration>() const;

Returns: get_local_time().

TimeZonePtr get_time_zone() const;

Returns: zone_.

local_time<duration> get_local_time() const;

Returns: zone_->to_local(tp_).

sys_time<duration> get_sys_time() const;

Returns: tp_.

sys_info get_info() const;

Returns: zone_->get_info(tp_).

29.11.7.4 Non-member functions

template<class Duration1, class Duration2, class TimeZonePtr>
bool operator==(const zoned_time<Duration1, TimeZonePtr>& x,
const zoned_time<Duration2, TimeZonePtr>& y);

Returns: x.zone_ == y.zone_ && x.tp_ == y.tp_.

template<class charT, class traits, class Duration, class TimeZonePtr>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os,
const zoned_time<Duration, TimeZonePtr>& t);

Effects: Equivalent to:
return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%F %T %Z}"), t);

29.11.8 Class leap_second

29.11.8.1 Overview

namespace std::chrono {
class leap_second {
public:
leap_second(const leap_second&) = default;
leap_second& operator=(const leap_second&) = default;

// unspecified additional constructors

constexpr sys_seconds date() const noexcept;
constexpr seconds value() const noexcept;
};
}

Objects of type leap_second representing the date and value of the leap second insertions are constructed and stored in the time zone database when initialized.

[Example 1:
for (auto& l : get_tzdb().leap_seconds)
if (l <= sys_days{2018y/March/17d})
cout << l.date() << ": " << l.value() << \n";
Produces the output:

```
1972-07-01 00:00:00: 1s
1973-01-01 00:00:00: 1s
1974-01-01 00:00:00: 1s
1975-01-01 00:00:00: 1s
1976-01-01 00:00:00: 1s
1977-01-01 00:00:00: 1s
1978-01-01 00:00:00: 1s
1979-01-01 00:00:00: 1s
1980-01-01 00:00:00: 1s
1981-07-01 00:00:00: 1s
1982-07-01 00:00:00: 1s
1983-07-01 00:00:00: 1s
1985-07-01 00:00:00: 1s
1988-01-01 00:00:00: 1s
1990-01-01 00:00:00: 1s
1991-01-01 00:00:00: 1s
1992-07-01 00:00:00: 1s
1993-07-01 00:00:00: 1s
1994-07-01 00:00:00: 1s
1996-01-01 00:00:00: 1s
1997-07-01 00:00:00: 1s
1999-01-01 00:00:00: 1s
2006-01-01 00:00:00: 1s
2009-01-01 00:00:00: 1s
2012-07-01 00:00:00: 1s
2015-07-01 00:00:00: 1s
2017-01-01 00:00:00: 1s
```

--- end example

### 29.11.8.2 Member functions

```cpp
constexpr sys_seconds date() const noexcept;
```

**Returns:** The date and time at which the leap second was inserted.

```cpp
constexpr seconds value() const noexcept;
```

**Returns:**`+1s` to indicate a positive leap second or`-1s` to indicate a negative leap second.

[Note 1: All leap seconds inserted up through 2022 were positive leap seconds. — end note]

### 29.11.8.3 Non-member functions

```cpp
constexpr bool operator==(const leap_second& x, const leap_second& y) noexcept;
```

**Returns:**`x.date() == y.date()`.

```cpp
constexpr strong_ordering operator<=>(const leap_second& x, const leap_second& y) noexcept;
```

**Returns:**`x.date() <=> y.date()`.

```cpp
template<class Duration>
constexpr bool operator==(const leap_second& x, const sys_time<Duration>& y) noexcept;
```

**Returns:**`x.date() == y`.

```cpp
template<class Duration>
constexpr bool operator<(const leap_second& x, const sys_time<Duration>& y) noexcept;
```

**Returns:**`x.date() < y`.

```cpp
template<class Duration>
constexpr bool operator<(const sys_time<Duration>& x, const leap_second& y) noexcept;
```

**Returns:**`x < y.date()`.
template<class Duration>
  constexpr bool operator>(const leap_second& x, const sys_time<Duration>& y) noexcept;
Returns: y < x.

template<class Duration>
  constexpr bool operator>(const sys_time<Duration>& x, const leap_second& y) noexcept;
Returns: y < x.

template<class Duration>
  constexpr bool operator<=(const leap_second& x, const sys_time<Duration>& y) noexcept;
Returns: !(y < x).

template<class Duration>
  constexpr bool operator<=(const sys_time<Duration>& x, const leap_second& y) noexcept;
Returns: !(x < y).

template<class Duration>
  constexpr bool operator>=(const leap_second& x, const sys_time<Duration>& y) noexcept;
Returns: !(x < y).

template<class Duration>
  constexpr bool operator>=(const sys_time<Duration>& x, const leap_second& y) noexcept;
Returns: !(x < y).

template<class Duration>
requires three_way_comparable_with<sys_seconds, sys_time<Duration>>
  constexpr auto operator<=>(const leap_second& x, const sys_time<Duration>& y) noexcept;
Returns: x.date() <=> y.

29.11.9 Class time_zone_link
29.11.9.1 Overview
namespace std::chrono {
  class time_zone_link {
  public:
    time_zone_link(time_zone_link&&) = default;
    time_zone_link& operator=(time_zone_link&&) = default;
    // unspecified additional constructors
    string_view name() const noexcept;
    string_view target() const noexcept;
  };
}
A time_zone_link specifies an alternative name for a time_zone. time_zone_links are constructed when
the time zone database is initialized.

29.11.9.2 Member functions
string_view name() const noexcept;
Returns: The alternative name for the time zone.

string_view target() const noexcept;
Returns: The name of the time_zone for which this time_zone_link provides an alternative name.

29.11.9.3 Non-member functions
bool operator==(const time_zone_link& x, const time_zone_link& y) noexcept;
Returns: x.name() == y.name().
strong_ordering operator<=>(const time_zone_link& x, const time_zone_link& y) noexcept;

Returns: x.name() <=> y.name().

29.12 Formatting

Each formatter (22.14.6) specialization in the chrono library (29.2) meets the Formatter requirements (22.14.6.1). The parse member functions of these formatters interpret the format specification as a chrono-format-spec according to the following syntax:

chrono-format-spec:
  fill-and-align_opt width_opt precision_opt L_opt chrono-specs_opt
chrono-specs:
  conversion-spec
  chrono-specs conversion-spec
  chrono-specs literal-char

literal-char:
  any character other than {, }, or %

conversion-spec:
  % modifier_opt type

modifier: one of
  E O

type: one of
  a A b B c C d D e E f F g G h H i I j j m m n
  p q q r R S s T t U u V v W w x X y y z Z %

The productions fill-and-align, width, and precision are described in 22.14.2. Giving a precision specification in the chrono-format-spec is valid only for types that are specializations of std::chrono::duration for which the nested typedef-name rep denotes a floating-point type. For all other types, an exception of type format_error is thrown if the chrono-format-spec contains a precision specification. All ordinary multibyte characters represented by literal-char are copied unchanged to the output.

A formatting locale is an instance of locale used by a formatting function, defined as:

1. (2.1) — the "C" locale if the L option is not present in chrono-format-spec, otherwise
2. (2.2) — the locale passed to the formatting function if any, otherwise
3. (2.3) — the global locale.

Each conversion specifier conversion-spec is replaced by appropriate characters as described in Table 104; the formats specified in ISO 8601-1:2019 shall be used where so described. Some of the conversion specifiers depend on the formatting locale. If the string literal encoding is a Unicode encoding form and the locale is among an implementation-defined set of locales, each replacement that depends on the locale is performed as if the replacement character sequence is converted to the string literal encoding. If the formatted object does not contain the information the conversion specifier refers to, an exception of type format_error is thrown.

The result of formatting a std::chrono::duration instance holding a negative value, or an hh_mm_ss object h for which h.is_negative() is true, is equivalent to the output of the corresponding positive value, with a STATICALLY-WIDEN<charT>("-") character sequence placed before the replacement of the initial conversion specifier.

[Example 1:]

```
cout << format("{:%T}", -10'000s);     // prints: -02:46:40
cout << format("{:%H:%M:%S}", -10'000s);  // prints: -02:46:40
```

```
cout << format("minutes {:%M, hours %H, seconds %S}", -10'000s);  
  // prints: minutes -46, hours 02, seconds 40
```

— end example]

5 Unless explicitly requested, the result of formatting a chrono type does not contain time zone abbreviation and time zone offset information. If the information is available, the conversion specifiers %Z and %z will format this information (respectively).

[Note 1: If the information is not available and a %Z or %z conversion specifier appears in the chrono-format-spec, an exception of type format_error is thrown, as described above. — end note]
If the type being formatted does not contain the information that the format flag needs, an exception of type `format_error` is thrown.

*Example 2*: A `duration` does not contain enough information to format as a `weekday`. — *end example*

However, if a flag refers to a “time of day” (e.g., `%H`, `%I`, `%p`, etc.), then a specialization of `duration` is interpreted as the time of day elapsed since midnight.

### Table 104 — Meaning of conversion specifiers

<table>
<thead>
<tr>
<th>Specifier</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>%a</code></td>
<td>The locale’s abbreviated weekday name. If the value does not contain a valid weekday, an exception of type <code>format_error</code> is thrown.</td>
</tr>
<tr>
<td><code>%A</code></td>
<td>The locale’s full weekday name. If the value does not contain a valid weekday, an exception of type <code>format_error</code> is thrown.</td>
</tr>
<tr>
<td><code>%b</code></td>
<td>The locale’s abbreviated month name. If the value does not contain a valid month, an exception of type <code>format_error</code> is thrown.</td>
</tr>
<tr>
<td><code>%B</code></td>
<td>The locale’s full month name. If the value does not contain a valid month, an exception of type <code>format_error</code> is thrown.</td>
</tr>
<tr>
<td><code>%c</code></td>
<td>The locale’s date and time representation. The modified command <code>%Ec</code> produces the locale’s alternate date and time representation.</td>
</tr>
<tr>
<td><code>%C</code></td>
<td>The year divided by 100 using floored division. If the result is a single decimal digit, it is prefixed with 0. The modified command <code>%EC</code> produces the locale’s alternative representation of the century.</td>
</tr>
<tr>
<td><code>%d</code></td>
<td>The day of month as a decimal number. If the result is a single decimal digit, it is prefixed with 0. The modified command <code>%Od</code> produces the locale’s alternative representation.</td>
</tr>
<tr>
<td><code>%D</code></td>
<td>Equivalent to <code>%m/%d/%y</code>.</td>
</tr>
<tr>
<td><code>%e</code></td>
<td>The day of month as a decimal number. If the result is a single decimal digit, it is prefixed with a space. The modified command <code>%Oe</code> produces the locale’s alternative representation.</td>
</tr>
<tr>
<td><code>%f</code></td>
<td>Equivalent to <code>%Y-%m-%d</code>.</td>
</tr>
<tr>
<td><code>%g</code></td>
<td>The last two decimal digits of the calendar year as specified in ISO 8601-1:2019 for the week calendar. If the result is a single digit it is prefixed by 0.</td>
</tr>
<tr>
<td><code>%G</code></td>
<td>The calendar year as a decimal number, as specified in ISO 8601-1:2019 for the week calendar. If the result is less than four digits it is left-padded with 0 to four digits.</td>
</tr>
<tr>
<td><code>%h</code></td>
<td>Equivalent to <code>%b</code>.</td>
</tr>
<tr>
<td><code>%H</code></td>
<td>The hour (24-hour clock) as a decimal number. If the result is a single digit, it is prefixed with 0. The modified command <code>%OH</code> produces the locale’s alternative representation.</td>
</tr>
<tr>
<td><code>%I</code></td>
<td>The hour (12-hour clock) as a decimal number. If the result is a single digit, it is prefixed with 0. The modified command <code>%OI</code> produces the locale’s alternative representation.</td>
</tr>
<tr>
<td><code>%j</code></td>
<td>If the type being formatted is a specialization of <code>duration</code>, the decimal number of <code>days</code> without padding. Otherwise, the day of the year as a decimal number. January 1 is 001. If the result is less than three digits, it is left-padded with 0 to three digits.</td>
</tr>
<tr>
<td><code>%m</code></td>
<td>The month as a decimal number. Jan is 01. If the result is a single digit, it is prefixed with 0. The modified command <code>%Om</code> produces the locale’s alternative representation.</td>
</tr>
<tr>
<td><code>%M</code></td>
<td>The minute as a decimal number. If the result is a single digit, it is prefixed with 0. The modified command <code>%OM</code> produces the locale’s alternative representation.</td>
</tr>
<tr>
<td><code>%n</code></td>
<td>A new-line character.</td>
</tr>
<tr>
<td><code>%p</code></td>
<td>The locale’s equivalent of the AM/PM designations associated with a 12-hour clock.</td>
</tr>
<tr>
<td><code>%q</code></td>
<td>The duration’s unit suffix as specified in 29.5.11.</td>
</tr>
<tr>
<td><code>%Q</code></td>
<td>The duration’s numeric value (as if extracted via <code>.count()</code>).</td>
</tr>
<tr>
<td><code>%r</code></td>
<td>The locale’s 12-hour clock time.</td>
</tr>
<tr>
<td><code>%R</code></td>
<td>Equivalent to <code>%H:%M</code>.</td>
</tr>
</tbody>
</table>
Table 104 — Meaning of conversion specifiers (continued)

<table>
<thead>
<tr>
<th>Specifier</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>%S</td>
<td>Seconds as a decimal number. If the number of seconds is less than 10, the result is prefixed with 0. If the precision of the input cannot be exactly represented with seconds, then the format is a decimal floating-point number with a fixed format and a precision matching that of the precision of the input (or to a microseconds precision if the conversion to floating-point decimal seconds cannot be made within 18 fractional digits). The character for the decimal point is localized according to the locale. The modified command %OS produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%t</td>
<td>A horizontal-tab character.</td>
</tr>
<tr>
<td>%T</td>
<td>Equivalent to %H:%M:%S.</td>
</tr>
<tr>
<td>%u</td>
<td>The calendar day of week as a decimal number (1-7), as specified in ISO 8601-1:2019, where Monday is 1. The modified command %Ou produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%U</td>
<td>The week number of the year as a decimal number. The first Sunday of the year is the first day of week 01. Days of the same year prior to that are in week 00. If the result is a single digit, it is prefixed with 0. The modified command %OU produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%V</td>
<td>The calendar week of year as a decimal number, as specified in ISO 8601-1:2019 for the week calendar. If the result is a single digit, it is prefixed with 0. The modified command %OV produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%w</td>
<td>The weekday as a decimal number (0-6), where Sunday is 0. The modified command %Ow produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%W</td>
<td>The week number of the year as a decimal number. The first Monday of the year is the first day of week 01. Days of the same year prior to that are in week 00. If the result is a single digit, it is prefixed with 0. The modified command %OW produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%x</td>
<td>The locale’s date representation. The modified command %Ex produces the locale’s alternate date representation.</td>
</tr>
<tr>
<td>%X</td>
<td>The locale’s time representation. The modified command %EX produces the locale’s alternate time representation.</td>
</tr>
<tr>
<td>%y</td>
<td>The last two decimal digits of the year. If the result is a single digit it is prefixed by 0. The modified command %Oy produces the locale’s alternative representation. The modified command %Ey produces the locale’s alternative representation of offset from %EC (year only).</td>
</tr>
<tr>
<td>%Y</td>
<td>The year as a decimal number. If the result is less than four digits it is left-padded with 0 to four digits. The modified command %EY produces the locale’s alternative full year representation.</td>
</tr>
<tr>
<td>%z</td>
<td>The offset from UTC as specified in ISO 8601-1:2019, 5.3.4.1. For example -0430 refers to 4 hours 30 minutes behind UTC. If the offset is zero, +0000 is used. The modified commands %EZ and %Oz insert a : between the hours and minutes: -04:30. If the offset information is not available, an exception of type format_error is thrown.</td>
</tr>
<tr>
<td>%Z</td>
<td>The time zone abbreviation. If the time zone abbreviation is not available, an exception of type format_error is thrown.</td>
</tr>
<tr>
<td>%a</td>
<td>A % character.</td>
</tr>
</tbody>
</table>

7 If the chrono-specs is omitted, the chrono object is formatted as if by streaming it to basic_ostringstream<CharT> os with the formatting locale imbued and copying os.str() through the output iterator of the context with additional padding and adjustments as specified by the format specifiers.

    [Example 3:]
    ```cpp
    string s = format("{:=>8}", 42ms); // value of s is "====42ms"
    ```

    — end example]

8 For chrono::duration the library only provides the following specialization of enable_nonlocking_formatter_optimization:
template<class Rep, class Period>
inline constexpr bool enable_nonlocking_formatter_optimization<
    chrono::duration<Rep, Period>> =
    enable_nonlocking_formatter_optimization<Rep>;

For chrono::zoned_time the library only provides the following specialization of enable_nonlocking_formatter_optimization:

template<class Duration>
inline constexpr bool enable_nonlocking_formatter_optimization<
    chrono::zoned_time<Duration, const std::chrono::time_zone*>>> = true;

template<class Duration, class charT>
struct formatter<chrono::sys_time<Duration>, charT>;

Remarks: If %Z is used, it is replaced with STATICALLY-WIDEN<charT>("UTC"). If %z (or a modified variant of %z) is used, an offset of 0min is formatted.

template<class Duration, class charT>
struct formatter<chrono::utc_time<Duration>, charT>;

Remarks: If %Z is used, it is replaced with STATICALLY-WIDEN<charT>("UTC"). If %z (or a modified variant of %z) is used, an offset of 0min is formatted. If the argument represents a time during a positive leap second insertion, and if a seconds field is formatted, the integral portion of that format is STATICALLY-WIDEN<charT>("60").

template<class Duration, class charT>
struct formatter<chrono::tai_time<Duration>, charT>;

Remarks: If %Z is used, it is replaced with STATICALLY-WIDEN<charT>("TAI"). If %z (or a modified variant of %z) is used, an offset of 0min is formatted. The date and time formatted are equivalent to those formatted by a sys_time initialized with

\[
\text{sys\_time}\langle\text{Duration}\rangle\{(\text{tp\_time\_since\_epoch}()) - \\
(\text{sys\_days}\{1970y/January/1\} - \text{sys\_days}\{1958y/January/1\})
\]


template<class Duration, class charT>
struct formatter<chrono::gps_time<Duration>, charT>;

Remarks: If %Z is used, it is replaced with STATICALLY-WIDEN<charT>("GPS"). If %z (or a modified variant of %z) is used, an offset of 0min is formatted. The date and time formatted are equivalent to those formatted by a sys_time initialized with

\[
\text{sys\_time}\langle\text{Duration}\rangle\{(\text{tp\_time\_since\_epoch}()) + \\
(\text{sys\_days}\{1980y/January/Sunday[1]\} - \text{sys\_days}\{1970y/January/1\})
\]


template<class Duration, class charT>
struct formatter<chrono::file_time<Duration>, charT>;

Remarks: If %Z is used, it is replaced with STATICALLY-WIDEN<charT>("UTC"). If %z (or a modified variant of %z) is used, an offset of 0min is formatted. The date and time formatted are equivalent to those formatted by a sys_time initialized with clock_cast<system_clock>(t), or by a utc_time initialized with clock_cast<utc_clock>(t), where t is the first argument to format.

template<class Duration, class charT>
struct formatter<chrono::local_time<Duration>, charT>;

Remarks: If %Z, %z, or a modified version of %z is used, an exception of type format_error is thrown.

template<class Duration>
struct local-time-format-t {
    // exposition only
    local_time<Duration> time;
    // exposition only
    const string* abbrev;
    // exposition only
    const seconds* offset_sec;
};

template<class Duration>
local-time-format-t<Duration>
local_time_format(local_time<Duration> time, const string* abbrev = nullptr,
    const seconds* offset_sec = nullptr);

Returns: {time, abbrev, offset_sec}. 

§ 29.12 ©ISO/IEC 1694
template<class Duration, class charT>
struct formatter<chrono::local-time-format-t<Duration>, charT> {
    Let \( f \) be a local-time-format-t<Duration> object passed to formatter::format.

Remarks: If \( %Z \) is used, it is replaced with \( f.abbrev \) if \( f.abbrev \) is not a null pointer value. If \( %Z \) is used and \( f.abbrev \) is a null pointer value, an exception of type format_error is thrown. If \( %Z \) (or a modified variant of \( %Z \)) is used, it is formatted with the value of \( f.offset_sec \) if \( f.offset_sec \) is not a null pointer value. If \( %Z \) (or a modified variant of \( %Z \)) is used and \( f.offset_sec \) is a null pointer value, then an exception of type format_error is thrown.

template<class Duration, class TimeZonePtr, class charT>
struct formatter<chrono::zoned_time<Duration, TimeZonePtr>, charT> : formatter<chrono::local-time-format-t<Duration>, charT> {

    template<class FormatContext>
    typename FormatContext::iterator
    format(const chrono::zoned_time<Duration, TimeZonePtr>& tp, FormatContext& ctx) const;
};

template<class FormatContext>
typename FormatContext::iterator
format(const chrono::zoned_time<Duration, TimeZonePtr>& tp, FormatContext& ctx) const;

Effects: Equivalent to:

\[
\text{sys_info info = tp.get_info(); return format(const chrono::zoned_time<Duration, TimeZonePtr>& tp, FormatContext& ctx)};\]

29.13 Parsing

[time.parse]

Each parse overload specified in this subclause calls from_stream unqualified, so as to enable argument-dependent lookup (6.5.4). In the following paragraphs, let \( is \) denote an object of type basic_istream<charT, traits> and let \( I \) be basic_istream<charT, traits>&, where charT and traits are template parameters in that context.

Recommended practice: Implementations should make it difficult to accidentally store or use a manipulator that may contain a dangling reference to a format string, for example by making the manipulators produced by parse immovable and preventing stream extraction into an lvalue of such a manipulator type.

template<class charT, class Parsable>
unspecifed
parse(const charT* fmt, Parsable& tp);

template<class charT, class traits, class Alloc, class Parsable>
unspecifed
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp);

Let \( F \) be fmt for the first overload and fmt.c_str() for the second overload. Let traits be char_traits<charT> for the first overload.

Constraints: The expression

\[
\text{from_stream}(\text{declval<basic_istream<charT, traits>&>}(\text{is}), F, \text{tp})
\]

is well-formed when treated as an unevaluated operand (7.2.3).

Returns: A manipulator such that the expression is >> parse(fmt, tp) has type I, has value is, and calls from_stream(is, F, tp).

template<class charT, class traits, class Alloc, class Parsable>
unspecifed
parse(const charT* fmt, Parsable& tp, basic_string<charT, traits, Alloc>& abbrev);

template<class charT, class traits, class Alloc, class Parsable>
unspecifed
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp, basic_string<charT, traits, Alloc>& abbrev);

Let \( F \) be fmt for the first overload and fmt.c_str() for the second overload.

Constraints: The expression
from_stream(declval<basic_istream<charT, traits>&>()(), F, tp, addressof(abbrev))

is well-formed when treated as an unevaluated operand (7.2.3).

Returns: A manipulator such that the expression is >> parse(fmt, tp, abbrev) has type I, has value is, and calls from_stream(is, F, tp, addressof(abbrev)).

template<class charT, class Parsable>
unspecified
parse(const charT* fmt, Parsable& tp, minutes& offset);
template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp, minutes& offset);

Let F be fmt for the first overload and fmt.c_str() for the second overload. Let traits be char_traits<charT> and Alloc be allocator<charT> for the first overload.

Constraints: The expression
from_stream(declval<basic_istream<charT, traits>&>()(), F, tp, declval<basic_string<charT, traits, Alloc>&>()(), &offset)

is well-formed when treated as an unevaluated operand (7.2.3).

Returns: A manipulator such that the expression is >> parse(fmt, tp, offset) has type I, has value is, and calls:
from_stream(is, F, tp, static_cast<basic_string<charT, traits, Alloc>&>()(nullptr), &offset)

template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const charT* fmt, Parsable& tp, basic_string<charT, traits, Alloc>& abbrev, minutes& offset);
template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const basic_string<charT, traits, Alloc>& fmt, Parsable& tp, basic_string<charT, traits, Alloc>& abbrev, minutes& offset);

Let F be fmt for the first overload and fmt.c_str() for the second overload.

Constraints: The expression
from_stream(declval<basic_istream<charT, traits>&>()(), F, tp, addressof(abbrev), &offset)

is well-formed when treated as an unevaluated operand (7.2.3).

Returns: A manipulator such that the expression is >> parse(fmt, tp, abbrev, offset) has type I, has value is, and calls from_stream(is, F, tp, addressof(abbrev), &offset).

All from_stream overloads behave as unformatted input functions, except that they have an unspecified effect on the value returned by subsequent calls to basic_istream::gcount(). Each overload takes a format string containing ordinary characters and flags which have special meaning. Each flag begins with a %. Some flags can be modified by E or O. During parsing each flag interprets characters as parts of date and time types according to Table 105. Some flags can be modified by a width parameter given as a positive decimal integer called out as N below which governs how many characters are parsed from the stream in interpreting the flag. All characters in the format string that are not represented in Table 105, except for whitespace, are parsed unchanged from the stream. A whitespace character matches zero or more whitespace characters in the input stream.

If the type being parsed cannot represent the information that the format flag refers to, is.setstate(ios_base::failbit) is called.

[Example 1: A duration cannot represent a weekday. — end example]
However, if a flag refers to a “time of day” (e.g., %H, %I, %p, etc.), then a specialization of `duration` is parsed as the time of day elapsed since midnight.

17 If the `from_stream` overload fails to parse everything specified by the format string, or if insufficient information is parsed to specify a complete duration, time point, or calendrical data structure, `setstate(ios_base::failbit)` is called on the `basic_istream`.

### Table 105 — Meaning of parse flags

<table>
<thead>
<tr>
<th>Flag</th>
<th>Parsed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%a</td>
<td>The locale’s full or abbreviated case-insensitive weekday name.</td>
</tr>
<tr>
<td>%A</td>
<td>Equivalent to %a.</td>
</tr>
<tr>
<td>%b</td>
<td>The locale’s full or abbreviated case-insensitive month name.</td>
</tr>
<tr>
<td>%B</td>
<td>Equivalent to %b.</td>
</tr>
<tr>
<td>%c</td>
<td>The locale’s date and time representation. The modified command %Ec interprets the locale’s alternate date and time representation.</td>
</tr>
<tr>
<td>%C</td>
<td>The century as a decimal number. The modified command %NC specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %EC interprets the locale’s alternative representation of the century.</td>
</tr>
<tr>
<td>%d</td>
<td>The day of the month as a decimal number. The modified command %Nd specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %Od interprets the locale’s alternative representation of the day of the month.</td>
</tr>
<tr>
<td>%D</td>
<td>Equivalent to %m/%d/%y.</td>
</tr>
<tr>
<td>%e</td>
<td>Equivalent to %d and can be modified like %d.</td>
</tr>
<tr>
<td>%E</td>
<td>Equivalent to %Y-%m-%d. If modified with a width N, the width is applied to only %Y.</td>
</tr>
<tr>
<td>%f</td>
<td>The last two decimal digits of the calendar year, as specified in ISO 8601-1:2019 for the week calendar. The modified command %Ng specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required.</td>
</tr>
<tr>
<td>%g</td>
<td>The calendar year as a decimal number, as specified in ISO 8601-1:2019 for the week calendar. The modified command %Yg specifies the maximum number of characters to read. If N is not specified, the default is 4. Leading zeroes are permitted but not required.</td>
</tr>
<tr>
<td>%h</td>
<td>Equivalent to %b.</td>
</tr>
<tr>
<td>%H</td>
<td>The hour (24-hour clock) as a decimal number. The modified command %NH specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %OH interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%i</td>
<td>The hour (12-hour clock) as a decimal number. The modified command %NI specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %OI interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%j</td>
<td>If the type being parsed is a specialization of <code>duration</code>, a decimal number of days. Otherwise, the day of the year as a decimal number. January 1 is 1. In either case, the modified command %Nj specifies the maximum number of characters to read. If N is not specified, the default is 3. Leading zeroes are permitted but not required.</td>
</tr>
<tr>
<td>%m</td>
<td>The month as a decimal number. January is 1. The modified command %Nm specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %Om interprets the locale’s alternative representation.</td>
</tr>
</tbody>
</table>
| %M   | The minutes as a decimal number. The modified command %Nm specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %OM interprets the locale’s alternative representation.
<table>
<thead>
<tr>
<th>Flag</th>
<th>Parsed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%n</td>
<td>Matches one whitespace character. [Note 1: %n, %t, and a space can be combined to match a wide range of whitespace patterns. For example, &quot;%n &quot; matches one or more whitespace characters, and &quot;%n%t%t&quot; matches one to three whitespace characters. — end note]</td>
</tr>
<tr>
<td>%p</td>
<td>The locale’s equivalent of the AM/PM designations associated with a 12-hour clock.</td>
</tr>
<tr>
<td>%r</td>
<td>The locale’s 12-hour clock time.</td>
</tr>
<tr>
<td>%S</td>
<td>Equivalent to %H:%M.</td>
</tr>
<tr>
<td>%u</td>
<td>The calendar day of week as a decimal number (1-7), as specified in ISO 8601-1:2019, where Monday is 1. The modified command %Nu specifies the maximum number of characters to read. If N is not specified, the default is 1. Leading zeroes are permitted but not required.</td>
</tr>
<tr>
<td>%U</td>
<td>The week number of the year as a decimal number. The first Sunday of the year is the first day of week 01. Days of the same year prior to that are in week 00. The modified command %NU specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %OU interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%V</td>
<td>The calendar week of year as a decimal number, as specified in ISO 8601-1:2019 for the week calendar. The modified command %NV specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required.</td>
</tr>
<tr>
<td>%w</td>
<td>The weekday as a decimal number (0-6), where Sunday is 0. The modified command %wW specifies the maximum number of characters to read. If N is not specified, the default is 1. Leading zeroes are permitted but not required. The modified command %OW interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%W</td>
<td>The week number of the year as a decimal number. The first Monday of the year is the first day of week 01. Days of the same year prior to that are in week 00. The modified command %NW specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified command %OW interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%x</td>
<td>The locale’s date representation. The modified command %Ex interprets the locale’s alternate date representation.</td>
</tr>
<tr>
<td>%X</td>
<td>The locale’s time representation. The modified command %EX interprets the locale’s alternate time representation.</td>
</tr>
<tr>
<td>%y</td>
<td>The last two decimal digits of the year. If the century is not otherwise specified (e.g., with %C), values in the range [69, 99] are presumed to refer to the years 1969 to 1999, and values in the range [00, 68] are presumed to refer to the years 2000 to 2068. The modified command %Ny specifies the maximum number of characters to read. If N is not specified, the default is 2. Leading zeroes are permitted but not required. The modified commands %Ey and %Oy interpret the locale’s alternative representation.</td>
</tr>
<tr>
<td>%Y</td>
<td>The year as a decimal number. The modified command %Yy specifies the maximum number of characters to read. If N is not specified, the default is 4. Leading zeroes are permitted but not required. The modified command %Ey interprets the locale’s alternative representation.</td>
</tr>
</tbody>
</table>
### Table 105 — Meaning of parse flags (continued)

<table>
<thead>
<tr>
<th>Flag</th>
<th>Parsed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%z</td>
<td>The offset from UTC in the format [+</td>
</tr>
<tr>
<td>%Z</td>
<td>The time zone abbreviation or name. A single word is parsed. This word can only contain characters from the basic character set (5.3) that are alphanumeric, or one of '_', '/', '-' or '+'</td>
</tr>
<tr>
<td>%%</td>
<td>A % character is extracted.</td>
</tr>
</tbody>
</table>

### 29.14 Hash support

```cpp
template<class Rep, class Period> struct hash<chrono::duration<Rep, Period>>;
```
1. The specialization `hash<chrono::duration<Rep, Period>>` is enabled (22.10.19) if and only if `hash<Rep>` is enabled. The member functions are not guaranteed to be `noexcept`.

```cpp
template<class Clock, class Duration> struct hash<chrono::time_point<Clock, Duration>>;
```
2. The specialization `hash<chrono::time_point<Clock, Duration>>` is enabled (22.10.19) if and only if `hash<Duration>` is enabled. The member functions are not guaranteed to be `noexcept`.

```cpp
template<> struct hash<chrono::day>;
template<> struct hash<chrono::month>;
template<> struct hash<chrono::year>;
template<> struct hash<chrono::weekday>;
template<> struct hash<chrono::weekday_indexed>;
template<> struct hash<chrono::weekday_last>;
template<> struct hash<chrono::month_day>;
template<> struct hash<chrono::month_day_last>;
template<> struct hash<chrono::month_weekday>;
template<> struct hash<chrono::month_weekday_last>;
template<> struct hash<chrono::year_month>;
template<> struct hash<chrono::year_month_day>;
template<> struct hash<chrono::year_month_day_last>;
template<> struct hash<chrono::year_month_weekday>;
template<> struct hash<chrono::year_month_weekday_last>;
```
3. The specializations are enabled (22.10.19).

[Note 1: All the hash<Key> specializations listed above meet the Cpp17Hash requirements, even when called on objects k of type Key such that k.ok() is false. — end note]

```cpp
template<class Duration, class TimeZonePtr> struct hash<chrono::zoned_time<Duration, TimeZonePtr>>;
```
4. The specialization `hash<chrono::zoned_time<Duration, TimeZonePtr>>` is enabled (22.10.19) if and only if `hash<Duration>` is enabled and `hash<TimeZonePtr>` is enabled. The member functions are not guaranteed to be `noexcept`.

```cpp
template<> struct hash<chrono::leap_second>;
```
5. The specialization is enabled (22.10.19).

### 29.15 Header <ctime> synopsis

```cpp
#define NULL see 17.2.3
#define CLOCKS_PER_SEC see below
#define TIME_UTC see below
```

```
namespace std {
    using size_t = see 17.2.4;
    using clock_t = see below;
    using time_t = see below;
```
struct timespec;
struct tm;

clock_t clock();
double difftime(time_t time1, time_t time0);
time_t mktime(tm* timeptr);
time_t time(time_t* timer);
int timespec_get(timespec* ts, int base);
char* asctime(const tm* timeptr);
char* ctime(const time_t* timer);

2 The functions `asctime`, `ctime`, `gmtime`, and `localtime` are not required to avoid data races (16.4.6.10).

1 The contents of the header `<ctime>` are the same as the C standard library header `<time.h>`.

234 `strftime` supports the C conversion specifiers C, D, e, F, g, h, x, r, t, T, u, V, and z, and the modifiers E and O.

---

234) `strftime` supports the C conversion specifiers C, D, e, F, g, h, x, r, t, T, u, V, and z, and the modifiers E and O.
30 Localization library

30.1 General

This Clause describes components that C++ programs may use to encapsulate (and therefore be more portable when confronting) cultural differences. The locale facility includes internationalization support for character classification and string collation, numeric, monetary, and date/time formatting and parsing, and message retrieval.

The following subclauses describe components for locales themselves, the standard facets, and facilities from the C library, as summarized in Table 106.

Table 106 — Localization library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.3 Locales</td>
<td>&lt;locale&gt;</td>
</tr>
<tr>
<td>30.4 Standard locale categories</td>
<td></td>
</tr>
<tr>
<td>30.5 C library locales</td>
<td>&lt;locale&gt;</td>
</tr>
<tr>
<td>30.6 Text encodings identification</td>
<td>&lt;text_encoding&gt;</td>
</tr>
</tbody>
</table>

30.2 Header <locale> synopsis

```cpp
namespace std {
    // 30.3.1, locale
    class locale;
    template<class facet> const facet& use_facet(const locale&);
    template<class facet> bool has_facet(const locale&) noexcept;

    // 30.3.3, convenience interfaces
    template<class charT> bool isspace(charT c, const locale& loc);
    template<class charT> bool isprint(charT c, const locale& loc);
    template<class charT> bool isctrl(charT c, const locale& loc);
    template<class charT> bool isupper(charT c, const locale& loc);
    template<class charT> bool islower(charT c, const locale& loc);
    template<class charT> bool isalpha(charT c, const locale& loc);
    template<class charT> bool isdigit(charT c, const locale& loc);
    template<class charT> bool ispunct(charT c, const locale& loc);
    template<class charT> bool isxdigit(charT c, const locale& loc);
    template<class charT> bool isalnum(charT c, const locale& loc);
    template<class charT> bool isgraph(charT c, const locale& loc);
    template<class charT> charT toupper(charT c, const locale& loc);
    template<class charT> charT tolower(charT c, const locale& loc);

    // 30.4.2, ctype
    class ctype_base;
    template<class charT> class ctype; // specialization
    template<class charT> class ctype_byname;
    class codecvt_base;
    template<class internT, class externT, class stateT> class codecvt;
    template<class internT, class externT, class stateT> class codecvt_byname;

    // 30.4.3, numeric
    template<class charT, class input_iterator = istreambuf_iterator<charT>>
    class num_get;
    template<class charT, class output_iterator = ostreambuf_iterator<charT>>
    class num_put;
```
The header `<locale>` defines classes and declares functions that encapsulate and manipulate the information peculiar to a locale.\footnote{In this subclause, the type name \texttt{tm} is an incomplete type that is defined in `<ctime>` (29.15).}
// 30.3.1.3, construct/copy/destroy
locale() noexcept;
locale(const locale& other) noexcept;
explicit locale(const char* std_name);
explicit locale(const string& std_name);
locale(const locale& other, const char* std_name, category);
locale(const locale& other, const string& std_name, category);
template<class Facet> locale(const locale& other, Facet* f);
locale(const locale& other, const locale& one, category);
~locale(); // not virtual
const locale& operator=(const locale& other) noexcept;

// 30.3.1.4, locale operations
template<class Facet> locale combine(const locale& other) const;
string name() const;
text_encoding encoding() const;
bool operator==(const locale& other) const;

template<class charT, class traits, class Allocator>
bool operator()(const basic_string<charT, traits, Allocator>& s1,
                const basic_string<charT, traits, Allocator>& s2) const;

// 30.3.1.6, global locale objects
static locale global(const locale&);
static const locale& classic();

1 Class locale implements a type-safe polymorphic set of facets, indexed by facet type. In other words, a facet has a dual role: in one sense, it's just a class interface; at the same time, it's an index into a locale's set of facets.

2 Access to the facets of a locale is via two function templates, use_facet<> and has_facet<>.

[Example 1: An iostream operator<< can be implemented as:\textsuperscript{236}

\begin{verbatim}
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<< (basic_ostream<charT, traits>& s, Date d) {
    typename basic_ostream<charT, traits>::sentry cerberos(s);
    if (cerberos) {
        tm tmbuf; d.extract(tmbuf);
        bool failed =
            use_facet<time_put<charT, ostreambuf_iterator<charT, traits>>>(
                s.getloc()).put(s, s, s.fill(), &tmbuf, 'x').failed();
        if (failed)
            s.setstate(s.badbit); // can throw
    }
    return s;
}
\end{verbatim}

—end example]

4 In the call to use_facet<Facet>(loc), the type argument chooses a facet, making available all members of the named type. If Facet is not present in a locale, it throws the standard exception bad_cast. A C++ program can check if a locale implements a particular facet with the function template has_facet<Facet>(). User-defined facets may be installed in a locale, and used identically as may standard facets.

5 [Note 1: All locale semantics are accessed via use_facet<> and has_facet<>], except that:

\begin{itemize}
\item — A member operator template
\end{itemize}

\begin{verbatim}
operator()(const basic_string<C, T, A>&, const basic_string<C, T, A>&)
\end{verbatim}

is provided so that a locale can be used as a predicate argument to the standard collections, to collate strings.

\textsuperscript{236) Note that in the call to put, the stream is implicitly converted to an ostreambuf_iterator<charT, traits>.
Convenient global interfaces are provided for traditional `ctype` functions such as `isdigit()` and `isspace()`, so that given a locale object `loc` a C++ program can call `isspace(c, loc)`. (This eases upgrading existing extractors (31.7.5.3).)

— end note]

6 Once a facet reference is obtained from a locale object by calling `use_facet<>`, that reference remains usable, and the results from member functions of it may be cached and re-used, as long as some locale object refers to that facet.

7 In successive calls to a locale facet member function on a facet object installed in the same locale, the returned result shall be identical.

8 A `locale` constructed from a name string (such as "POSIX"), or from parts of two named locales, has a name; all others do not. Named locales may be compared for equality; an unnamed locale is equal only to (copies of) itself. For an unnamed locale, `locale::name()` returns the string "."

9 Whether there is one global locale object for the entire program or one global locale object per thread is implementation-defined. Implementations should provide one global locale object per thread. If there is a single global locale object for the entire program, implementations are not required to avoid data races on it (16.4.6.10).

30.3.1.2 Types [locale.types]

30.3.1.2.1 Type `locale::category` [locale.category]

```cpp
using category = int;
```

1 `Valid category` values include the `locale` member bitmask elements `collate`, `ctype`, `monetary`, `numeric`, `time`, and `messages`, each of which represents a single locale category. In addition, `locale` member bitmask constant `none` is defined as zero and represents no category. And `locale` member bitmask constant `all` is defined such that the expression

```
(collate | ctype | monetary | numeric | time | messages | all) == all
```

is true, and represents the union of all categories. Further, the expression `(X | Y)`, where `X` and `Y` each represent a single category, represents the union of the two categories.

2 `locale` member functions expecting a `category` argument require one of the `category` values defined above, or the union of two or more such values. Such a `category` value identifies a set of `locale` categories. Each `locale` category, in turn, identifies a set of `locale` facets, including at least those shown in Table 107.

Table 107 — Locale category facets [tab:locale.category.facets]

<table>
<thead>
<tr>
<th>Category</th>
<th>Includes facets</th>
</tr>
</thead>
<tbody>
<tr>
<td>collate</td>
<td><code>collate&lt;char&gt;</code>, <code>collate&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td>ctype</td>
<td><code>ctype&lt;char&gt;</code>, <code>ctype&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt&lt;char, char, mbstate_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt&lt;wchar_t, char, mbstate_t&gt;</code></td>
</tr>
<tr>
<td>monetary</td>
<td><code>moneypunct&lt;char&gt;</code>, <code>moneypunct&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>moneypunct&lt;char, true&gt;</code>, <code>moneypunct&lt;wchar_t, true&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>money_get&lt;char&gt;</code>, <code>money_get&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>money_put&lt;char&gt;</code>, <code>money_put&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td>numeric</td>
<td><code>numpunct&lt;char&gt;</code>, <code>numpunct&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>num_get&lt;char&gt;</code>, <code>num_get&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>num_put&lt;char&gt;</code>, <code>num_put&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td>time</td>
<td><code>time_get&lt;char&gt;</code>, <code>time_get&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_put&lt;char&gt;</code>, <code>time_put&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td>messages</td>
<td><code>messages&lt;char&gt;</code>, <code>messages&lt;wchar_t&gt;</code></td>
</tr>
</tbody>
</table>

3 For any `locale` `loc` either constructed, or returned by `locale::classic()`, and any facet `Facet` shown in Table 107, `has_facet<Facet>(loc)` is true. Each `locale` member function which takes a `locale::category` argument operates on the corresponding set of facets.

4 An implementation is required to provide those specializations for facet templates identified as members of a category, and for those shown in Table 108.
Table 108 — Required specializations  

<table>
<thead>
<tr>
<th>Category</th>
<th>Includes facets</th>
</tr>
</thead>
<tbody>
<tr>
<td>collate</td>
<td>collate_byname&lt;char&gt;, collate_byname&lt;wchar_t&gt;</td>
</tr>
<tr>
<td>ctype</td>
<td>ctype_byname&lt;char&gt;, ctype_byname&lt;wchar_t&gt;, codecvt_byname&lt;char, char, mbstate_t&gt;, codecvt_byname&lt;wchar_t, char, mbstate_t&gt;</td>
</tr>
<tr>
<td>numeric</td>
<td>numpunct_byname&lt;char&gt;, numpunct_byname&lt;wchar_t&gt;, num_get&lt;C, InputIterator&gt;, num_put&lt;C, OutputIterator&gt;</td>
</tr>
<tr>
<td>time</td>
<td>time_get&lt;char, InputIterator&gt;, time_get_byname&lt;char, InputIterator&gt;, time_get&lt;wchar_t, InputIterator&gt;, time_get_byname&lt;wchar_t, InputIterator&gt;, time_put&lt;char, OutputIterator&gt;, time_put_byname&lt;char, OutputIterator&gt;, time_put&lt;wchar_t, OutputIterator&gt;, time_put_byname&lt;wchar_t, OutputIterator&gt;</td>
</tr>
<tr>
<td>messages</td>
<td>messages_byname&lt;char&gt;, messages_byname&lt;wchar_t&gt;</td>
</tr>
</tbody>
</table>

5 The provided implementation of members of facets num_get<charT> and num_put<charT> calls use_facet<F>(l) only for facet F of types numpunct<charT> and ctype<charT>, and for locale l the value obtained by calling member getloc() on the ios_base& argument to these functions.

6 In declarations of facets, a template parameter with name InputIterator or OutputIterator indicates the set of all possible specializations on parameters that meet the Cpp17InputIterator requirements or Cpp17OutputIterator requirements, respectively (25.3). A template parameter with name C represents the set of types containing char, wchar_t, and any other implementation-defined character container types (3.10) that meet the requirements for a character on which any of the iostream components can be instantiated. A template parameter with name International represents the set of all possible specializations on a bool parameter.

30.3.1.2.2 Class locale::facet  

```
namespace std {
    class locale::facet {
        protected:
            explicit facet(size_t refs = 0);
            virtual ~facet();
            facet(const facet&) = delete;
            void operator=(const facet&) = delete;
        }
    }
```

1 Class facet is the base class for locale feature sets. A class is a facet if it is publicly derived from another facet, or if it is a class derived from locale::facet and contains a publicly accessible declaration as follows:

```
static ::std::locale::id id;
```

2 Template parameters in this Clause which are required to be facets are those named Facet in declarations. A program that passes a type that is not a facet, or a type that refers to a volatile-qualified facet, as an (explicit or deduced) template parameter to a locale function expecting a facet, is ill-formed. A const-qualified facet is a valid template argument to any locale function that expects a Facet template parameter.

237) This is a complete list of requirements; there are no other requirements. Thus, a facet class need not have a public copy constructor, assignment, default constructor, destructor, etc.
The `refs` argument to the constructor is used for lifetime management. For `refs == 0`, the implementation performs `delete static_cast<locale::facet*>(f)` (where `f` is a pointer to the facet) when the last `locale` object containing the facet is destroyed; for `refs == 1`, the implementation never destroys the facet.

Constructors of all facets defined in this Clause take such an argument and pass it along to their `facet` base class constructor. All one-argument constructors defined in this Clause are `explicit`, preventing their participation in implicit conversions.

For some standard facets a standard “..._byname” class, derived from it, implements the virtual function semantics equivalent to that facet of the locale constructed by `locale(const char*)` with the same name. Each such facet provides a constructor that takes a `const char*` argument, which names the locale, and a `refs` argument, which is passed to the base class constructor. Each such facet also provides a constructor that takes a `string` argument `str` and a `refs` argument, which has the same effect as calling the first constructor with the two arguments `str.c_str()` and `refs`. If there is no “..._byname” version of a facet, the base class implements named locale semantics itself by reference to other facets.

### 30.3.1.2.3 Class `locale::id`

```cpp
namespace std {
    class locale::id {
    public:
        id();
        void operator=(const id&) = delete;
        id(const id&) = delete;
    };
}
```

The class `locale::id` provides identification of a locale facet interface, used as an index for lookup and to encapsulate initialization.

[Note 1: Because facets are used by iostreams, potentially while static constructors are running, their initialization cannot depend on programmed static initialization. One initialization strategy is for `locale` to initialize each facet's `id` member the first time an instance of the facet is installed into a locale. This depends only on static storage being zero before constructors run (6.9.3.2). — end note]
template<class Facet> locale(const locale& other, Facet* f);

Effects: Constructs a locale incorporating all facets from the first argument except that of type Facet, and installs the second argument as the remaining facet. If f is null, the resulting object is a copy of other.

Remarks: If f is null, the resulting locale has the same name as other. Otherwise, the resulting locale has no name.

locale(const locale& other, const locale& one, category cats);

Preconditions: cats is a valid category value.

Effects: Constructs a locale incorporating all facets from the first argument except those that implement cats, which are instead incorporated from the second argument.

Remarks: If cats is equal to locale::none, the resulting locale has a name if and only if the first argument has a name. Otherwise, the resulting locale has a name if and only if the first two arguments both have names.

can be localized=(const locale& other) noexcept;

Effects: Creates a copy of other, replacing the current value.

Returns: *this.

30.3.1.4 Members

template<class Facet> locale combine(const locale& other) const;

Effects: Constructs a locale incorporating all facets from *this except for that one facet of other that is identified by Facet.

Returns: The newly created locale.

Throws: runtime_error if has_facet<Facet>(other) is false.

Remarks: The resulting locale has no name.

string name() const;

Returns: The name of *this, if it has one; otherwise, the string ".

text_encoding encoding() const;

Mandates: CHAR_BIT == 8 is true.

Returns: A text_encoding object representing the implementation-defined encoding scheme associated with the locale *this.

30.3.1.5 Operators

bool operator==(const locale& other) const;

Returns: true if both arguments are the same locale, or one is a copy of the other, or each has a name and the names are identical; false otherwise.

template<class charT, class traits, class Allocator>
bool operator()(const basic_string<charT, traits, Allocator>& s1,
const basic_string<charT, traits, Allocator>& s2) const;

Effects: Compares two strings according to the collate<charT> facet.

Returns: 

use_facet<collate<charT>>(*this).compare(s1.data(), s1.data() + s1.size(),
 s2.data(), s2.data() + s2.size()) < 0

Remarks: This member operator template (and therefore locale itself) meets the requirements for a comparator predicate template argument (Clause 27) applied to strings.

[Example 1: A vector of strings v can be collated according to collation rules in locale loc simply by (27.8.2, 24.3.12):

std::sort(v.begin(), v.end(), loc);
—end example]
30.3.1.6 Static members

static locale global(const locale& loc);

Effects: Sets the global locale to its argument. Causes future calls to the constructor locale() to return a copy of the argument. If the argument has a name, does

setlocale(LC_ALL, loc.name().c_str());

otherwise, the effect on the C locale, if any, is implementation-defined.

Returns: The previous value of locale().

Remarks: No library function other than locale::global() affects the value returned by locale().

[Note 1: See 30.5 for data race considerations when setlocale is invoked. — end note]

static const locale& classic();

The "C" locale.

Returns: A locale that implements the classic "C" locale semantics, equivalent to the value locale("C").

Remarks: This locale, its facets, and their member functions, do not change with time.

30.3.2 locale globals

template<class Facet> const Facet& use_facet(const locale& loc);

Mandates: Facet is a facet class whose definition contains the public static member id as defined in 30.3.1.2.2.

Returns: A reference to the corresponding facet of loc, if present.

Throws: bad_cast if has_facet<Facet>(loc) is false.

Remarks: The reference returned remains valid at least as long as any copy of loc exists.

template<class Facet> bool has_facet(const locale& loc) noexcept;

Returns: true if the facet requested is present in loc; otherwise false.

30.3.3 Convenience interfaces

30.3.3.1 Character classification

template<class charT> bool isspace (charT c, const locale& loc);

template<class charT> bool isprint (charT c, const locale& loc);

template<class charT> bool iscntrl (charT c, const locale& loc);

template<class charT> bool isupper (charT c, const locale& loc);

template<class charT> bool islower (charT c, const locale& loc);

template<class charT> bool isalpha (charT c, const locale& loc);

template<class charT> bool isdigit (charT c, const locale& loc);

template<class charT> bool ispunct (charT c, const locale& loc);

template<class charT> bool isxdigit(charT c, const locale& loc);

template<class charT> bool isalnum (charT c, const locale& loc);

template<class charT> bool isgraph (charT c, const locale& loc);

template<class charT> bool isblank (charT c, const locale& loc);

1 Each of these functions is F returns the result of the expression:

use_facet<ctype<charT>>(loc).is(ctype_base::mask, c)

where F is the ctype_base::mask value corresponding to that function (30.4.2).238

30.3.3.2 Character conversions

template<class charT> charT toupper(charT c, const locale& loc);

Returns: use_facet<ctype<charT>>(loc).toupper(c).

template<class charT> charT tolower(charT c, const locale& loc);

Returns: use_facet<ctype<charT>>(loc).tolower(c).

238) When used in a loop, it is faster to cache the ctype<> facet and use it directly, or use the vector form of ctype<>::is.
30.4 Standard locale categories

30.4.1 General

Each of the standard categories includes a family of facets. Some of these implement formatting or parsing of a datum, for use by standard or users’ iostream operators << and >>, as members put() and get(), respectively. Each such member function takes an ios_base& argument whose members flags(), precision(), and width(), specify the format of the corresponding datum (31.5.2). Those functions which need to use other facets call its member getloc() to retrieve the locale imbued there. Formatting facets use the character argument fill to fill out the specified width where necessary.

The put() members make no provision for error reporting. (Any failures of the OutputIterator argument can be extracted from the returned iterator.) The get() members take an ios_base::iostate& argument whose value they ignore, but set to ios_base::failbit in case of a parse error.

Within 30.4 it is unspecified whether one virtual function calls another virtual function.

30.4.2 The ctype category

30.4.2.1 General

namespace std {
    class ctype_base {
        public:
            using mask = see below;

            // numeric values are for exposition only.
            static constexpr mask space = 1 << 0;
            static constexpr mask print = 1 << 1;
            static constexpr mask cntrl = 1 << 2;
            static constexpr mask upper = 1 << 3;
            static constexpr mask lower = 1 << 4;
            static constexpr mask alpha = 1 << 5;
            static constexpr mask digit = 1 << 6;
            static constexpr mask punct = 1 << 7;
            static constexpr mask xdigit = 1 << 8;
            static constexpr mask blank = 1 << 9;
            static constexpr mask alnum = alpha | digit;
            static constexpr mask graph = alnum | punct;
    };
}

1 The type mask is a bitmask type (16.3.3.3.3).

30.4.2.2 Class template ctype

30.4.2.2.1 General

namespace std {
    template<class charT>
    class ctype : public locale::facet, public ctype_base {
        public:
            using char_type = charT;
            explicit ctype(size_t refs = 0);

            bool is(mask m, charT c) const;
            const charT* is(const charT* low, const charT* high, const charT* vec) const;
            const charT* scan_is(mask m, const charT* low, const charT* high) const;
            const charT* scan_not(mask m, const charT* low, const charT* high) const;
            charT toupper(charT c) const;
            const charT* toupper(charT* low, const charT* high) const;
            charT tolower(charT c) const;
            const charT* tolower(charT* low, const charT* high) const;
            charT widen(char c) const;
            const char* widen(const char* low, const char* high, char char_type to) const;
            char narrow(charT c, char dfault) const;
            const charT* narrow(const charT* low, const charT* high, char dfault, char char_type to) const;

§ 30.4.2.2.1 ©ISO/IEC 1709
static locale::id id;

protected:
-ctype();
virtual bool do_is(mask m, charT c) const;
virtual const charT* do_is(const charT* low, const charT* high, mask* vec) const;
virtual const charT* do_scan_is(mask m, const charT* low, const charT* high) const;
virtual const charT* do_scan_not(mask m, const charT* low, const charT* high) const;
virtual charT do_toupper(charT) const;
virtual const charT* do_toupper(charT* low, const charT* high) const;
virtual const charT* do_tolower(charT) const;
virtual const charT* do_tolower(charT* low, const charT* high) const;
virtual charT do_widen(char) const;
virtual const charT* do_widen(const charT* low, const charT* high, charT* dest) const;
virtual char do_narrow(charT, char dfault) const;
virtual const charT* do_narrow(const charT* low, const charT* high, charT* dest, char* dfault) const;
};

1 Class ctype encapsulates the C library <cctype> features. istream members are required to use ctype for character classing during input parsing.

2 The specializations required in Table 107 (30.3.1.2.1), namely ctype<char> and ctype<wchar_t>, implement character classing appropriate to the implementation’s native character set.

30.4.2.2.2 ctype members

bool is(mask m, charT c) const;
const charT* is(const charT* low, const charT* high, mask* vec) const;
Returns: do_is(m, c) or do_is(low, high, vec).

const charT* scan_is(mask m, const charT* low, const charT* high) const;
Returns: do_scan_is(m, low, high).

const charT* scan_not(mask m, const charT* low, const charT* high) const;
Returns: do_scan_not(m, low, high).

certT toupper(charT c) const;
const charT* toupper(charT* low, const charT* high) const;
Returns: do_toupper(c) or do_toupper(low, high).

certT tolower(charT c) const;
const charT* tolower(charT* low, const charT* high) const;
Returns: do_tolower(c) or do_tolower(low, high).

certT widen(char c) const;
const char* widen(const char* low, const char* high, charT* to) const;
Returns: do_widen(c) or do_widen(low, high, to).

cert narrow(charT c, char dfault) const;
const charT* narrow(const charT* low, const charT* high, char dfault, char* to) const;
Returns: do_narrow(c, dfault) or do_narrow(low, high, dfault, to).

30.4.2.2.3 ctype virtual functions

bool do_is(mask m, charT c) const;
const charT* do_is(const charT* low, const charT* high, mask* vec) const;
Effects: Classifies a character or sequence of characters. For each argument character, identifies a value M of type ctype_base::mask. The second form identifies a value M of type ctype_base::mask for each *p where (low <= p && p < high), and places it into vec[p - low].
Returns: The first form returns the result of the expression \((M \& m) \neq 0\); i.e., \texttt{true} if the character has the characteristics specified. The second form returns \texttt{high}.

```cpp
const charT* do_scan_is(mask m, const charT* low, const charT* high) const;
```

Effects: Locates a character in a buffer that conforms to a classification \(m\).

Returns: The smallest pointer \(p\) in the range \([\text{low}, \text{high}]\) such that \(\text{is}(m, *p)\) would return \texttt{true}; otherwise, returns \texttt{high}.

```cpp
const charT* do_scan_not(mask m, const charT* low, const charT* high) const;
```

Effects: Locates a character in a buffer that fails to conform to a classification \(m\).

Returns: The smallest pointer \(p\), if any, in the range \([\text{low}, \text{high}]\) such that \(\text{is}(m, *p)\) would return \texttt{false}; otherwise, returns \texttt{high}.

```cpp
charT do_toupper(charT c) const;
const charT* do_toupper(charT* low, const charT* high) const;
```

Effects: Converts a character or characters to upper case. The second form replaces each character \(*p\) in the range \([\text{low}, \text{high}]\) for which a corresponding upper-case character exists, with that character.

Returns: The first form returns the corresponding upper-case character if it is known to exist, or its argument if not. The second form returns \texttt{high}.

```cpp
charT do_tolower(charT c) const;
const charT* do_tolower(charT* low, const charT* high) const;
```

Effects: Converts a character or characters to lower case. The second form replaces each character \(*p\) in the range \([\text{low}, \text{high}]\) and for which a corresponding lower-case character exists, with that character.

Returns: The first form returns the corresponding lower-case character if it is known to exist, or its argument if not. The second form returns \texttt{high}.

```cpp
char do_narrow(charT c, char dfault) const;
const charT* do_narrow(const charT* low, const charT* high, char* dest) const;
```

Effects: Applies the simplest reasonable transformation from a \texttt{charT} value or sequence of \texttt{charT} values to the corresponding \texttt{char} value or values.\(^{239}\) The only characters for which unique transformations are required are those in the basic character set (5.3).

For any named \texttt{ctype} category with a \texttt{ctype<	exttt{charT}>} facet \(ctc\) and valid \texttt{ctype_base::mask} value \(M\),
\[
(\text{ctc.is}(M, c) \mathbin{|} \mathbin{!}\text{is}(M, \text{do_widen}(c))) \text{ is } \texttt{true}.
\]

The second form transforms each character \(*p\) in the range \([\text{low}, \text{high}]\), placing the result in \(\text{dest}[p - \text{low}]\).

Returns: The first form returns the transformed value. The second form returns \texttt{high}.

```cpp
char do_widen(char c) const;
const char* do_widen(const char* low, const char* high, char* dest) const;
```

Effects: Applies the simplest reasonable transformation from a \texttt{char} value or sequence of \texttt{char} values to the corresponding \texttt{charT} value or values.\(^{239}\) The only characters for which unique transformations are required are those in the basic character set (5.3).

For any character \(c\) in the basic character set (5.3) the transformation is such that \(\text{do_widen}(\text{do_narrow}(c, 0)) == c\)

For any named \texttt{ctype} category with a \texttt{ctype<	exttt{char}>} facet \(ctc\) however, and \texttt{ctype_base::mask} value \(M\),
\[
(\text{is}(M, c) \mathbin{|} \mathbin{!}\text{ctc.is}(M, \text{do_narrow}(c, \text{dfault}))) \text{ is } \texttt{true} \text{ (unless } \text{do_narrow} \text{ returns } \text{dfault}).
\]

In addition, for any digit character \(c\), the expression \((\text{do_narrow}(c, \text{dfault}) - '0')\) evaluates to the digit value of the character. The second form transforms each character \(*p\) in the range \([\text{low}, \text{high}]\), placing the result (or \text{dfault} if no simple transformation is readily available) in \(\text{dest}[p - \text{low}]\).

---

\(^{239}\) The parameter \(c\) of \text{do_widen} is intended to accept values derived from \texttt{character-literals} for conversion to the locale’s encoding.

\(^{240}\) In other words, the transformed character is not a member of any character classification that \(c\) is not also a member of.
Returns: The first form returns the transformed value; or `default` if no mapping is readily available. The second form returns `high`.

### 30.4.2.3 Class template `ctype_byname`

```cpp
namespace std {
    template<class charT>
    class ctype_byname : public ctype<charT> {
        public:
            using mask = typename ctype<charT>::mask;
            explicit ctype_byname(const char*, size_t refs = 0);
            explicit ctype_byname(const string&, size_t refs = 0);

        protected:
            ~ctype_byname();
    }
}
```

### 30.4.2.4 `ctype<char>` specialization

#### 30.4.2.4.1 General

```cpp
namespace std {
    template<class charT>
    class ctype<char> : public locale::facet, public ctype_base {
        public:
            using char_type = char;
            explicit ctype(const mask* tab = nullptr, bool del = false, size_t refs = 0);

            bool is(mask m, char c) const;
            const char* is(const char* low, const char* high, mask* vec) const;
            const char* scan_is (mask m, const char* low, const char* high) const;
            const char* scan_not(mask m, const char* low, const char* high) const;

            char toupper(char c) const;
            const char* toupper(char* low, const char* high) const;
            char tolower(char c) const;
            const char* tolower(char* low, const char* high) const;

            char widen(char c) const;
            const char* widen(const char* low, const char* high, char* to) const;

            char narrow(char c, char dfault) const;
            const char* narrow(const char* low, const char* high, char dfault, char* to) const;

        protected:
            ~ctype();
            virtual char do_toupper(char c) const;
            virtual const char* do_toupper(char* low, const char* high) const;
            virtual char do_tolower(char c) const;
            virtual const char* do_tolower(char* low, const char* high) const;

            virtual char do_widen(char c) const;
            virtual const char* do_widen(const char* low, const char* high, char* to) const;
            virtual char do_narrow(char c, char dfault) const;
            virtual const char* do_narrow(const char* low, const char* high, char dfault, char* to) const;
    }
```
A specialization \( \texttt{ctype}<\texttt{char}> \) is provided so that the member functions on type \texttt{char} can be implemented inline.\(^{241}\) The implementation-defined value of member \texttt{table\_size} is at least 256.

### 30.4.2.4.2 Destructor

\[
\texttt{\textasciitilde\texttt{ctype}()};
\]

**Effects:** If the constructor’s first argument was nonzero, and its second argument was \texttt{true}, does \texttt{delete} \[
[] \texttt{table}().
\]

### 30.4.2.4.3 Members

\[
\begin{align*}
\text{\texttt{\textasciitilde\texttt{ctype}(const mask* tbl = nullptr, bool del = false, size_t refs = 0);}} \\
\text{\texttt{\texttt{bool is(mask m, char c) const;}}} \\
\text{\texttt{const char* is(const char* low, const char* high, mask* vec) const;}} \\
\text{\texttt{const char* scan\_is(mask m, const char* low, const char* high) const;}} \\
\text{\texttt{const char* scan\_not(mask m, const char* low, const char* high) const;}} \\
\text{\texttt{char toupper(char c) const;}} \\
\text{\texttt{const char* toupper(char* low, const char* high) const;}} \\
\text{\texttt{char tolower(char c) const;}} \\
\text{\texttt{const char* tolower(char* low, const char* high) const;}} \\
\text{\texttt{char widen(char c) const;}} \\
\text{\texttt{const char* widen(const char* low, const char* high, char* to) const;}} \\
\text{\texttt{char narrow(char c, char dfault) const;}} \\
\text{\texttt{const char* narrow(const char* low, const char* high, char dfault, char* to) const;}} \\
\end{align*}
\]

**Returns:**

- \texttt{\texttt{\textasciitilde\texttt{ctype}(const mask* tbl = nullptr, bool del = false, size_t refs = 0);}}: The first constructor argument, if it was nonzero, otherwise \texttt{classic\_table()}.
30.4.2.4 Static members

static const mask* classic_table() noexcept;

1 Returns: A pointer to the initial element of an array of size table_size which represents the classifications of characters in the "C" locale.

30.4.2.4.5 Virtual functions

Virtual functions [facet.ctype.char.virtuals]

1 These functions are described identically as those members of the same name in the ctype class template (30.4.2.2.2).

30.4.2.5 Class template codecvt [locale.codecvt]

30.4.2.5.1 General [locale.codecvt.general]

namespace std {
    class codecvt_base {
        public:
            enum result { ok, partial, error, noconv };
    };

    template<class internT, class externT, class stateT>
    class codecvt : public locale::facet, public codecvt_base {
        public:
            using intern_type = internT;
            using extern_type = externT;
            using state_type = stateT;

            explicit codecvt(size_t refs = 0);

            result out(
                stateT& state,
                const internT* from, const internT* from_end, const internT*& from_next,
                externT* to, externT* to_end, externT*& to_next) const;

            result unshift(
                stateT& state,
                externT* to, externT* to_end, externT*& to_next) const;

            result in(
                stateT& state,
                const externT* from, const externT* from_end, const externT*& from_next,
                internT* to, internT* to_end, internT*& to_next) const;

            int encoding() const noexcept;
            bool always_noconv() const noexcept;
            int length(stateT, const externT* from, const externT* end, size_t max) const;
            int max_length() const noexcept;

            static locale::id id;

        protected:
            ~codecvt();

    };

§ 30.4.2.5.1
virtual result do_out(
    stateT& state,
    const internT* from, const internT* from_end, const internT*& from_next,
    externT* to,      externT* to_end,   externT*& to_next) const;
virtual result do_in(
    stateT& state,
    const externT* from, const externT* from_end, const externT*& from_next,
    internT* to,      internT* to_end,   internT*& to_next) const;
virtual result do_unshift(
    stateT& state,
    externT* to,      externT* to_end,   externT*& to_next) const;
virtual int do_encoding() const noexcept;
virtual bool do_always_noconv() const noexcept;
virtual int do_length(stateT&, const externT* from, const externT* end, size_t max) const;
virtual int do_max_length() const noexcept;
}

1 The class codecvt<internT, externT, stateT> is for use when converting from one character encoding to
another, such as from wide characters to multibyte characters or between wide character encodings such as
UTF-32 and EUC.

2 The stateT argument selects the pair of character encodings being mapped between.

3 The specializations required in Table 107 (30.3.1.2.1) convert the implementation-defined native character
set. codecvt<char, char, mbstate_t> implements a degenerate conversion; it does not convert at all.
codecvt<wchar_t, char, mbstate_t> converts between the native character sets for ordinary and wide
characters. Specializations on mbstate_t perform conversion between encodings known to the library
implementer. Other encodings can be converted by specializing on a program-defined stateT type. Objects
of type stateT can contain any state that is useful to communicate to or from the specialized do_in or
do_out members.

30.4.2.5.2 Members

[locale.codecvt.members]
result out(
    stateT& state,
    const internT* from, const internT* from_end, const internT*& from_next,
    externT* to,      externT* to_end,   externT*& to_next) const;
1 Returns: do_out(state, from, from_end, from_next, to, to_end, to_next).

result unshift(stateT& state, externT* to, externT* to_end, externT*& to_next) const;
2 Returns: do_unshift(state, from, from_end, from_next, to, to_end, to_next).

result in(
    stateT& state,
    const externT* from, const externT* from_end, const externT*& from_next,
    internT* to,      internT* to_end,   internT*& to_next) const;
3 Returns: do_in(state, from, from_end, from_next, to, to_end, to_next).

int encoding() const noexcept;
4 Returns: do_encoding().

bool always_noconv() const noexcept;
5 Returns: do_always_noconv().

int length(stateT& state, const externT* from, const externT* from_end, size_t max) const;
6 Returns: do_length(state, from, from_end, max).

int max_length() const noexcept;
7 Returns: do_max_length().

§ 30.4.2.5.2
30.4.2.5.3 Virtual functions

result do_out(
    stateT& state,
    const internT* from, const internT* from_end, const internT*& from_next,
    externT* to, externT* to_end, externT*& to_next) const;

result do_in(
    stateT& state,
    const externT* from, const externT* from_end, const externT*& from_next,
    internT* to, internT* to_end, internT*& to_next) const;

1 Preconditions: (from <= from_end & & to <= to_end) is well-defined and true; state is initialized, if at the beginning of a sequence, or else is equal to the result of converting the preceding characters in the sequence.

2 Effects: Translates characters in the source range [from, from_end), placing the results in sequential positions starting at destination to. Converts no more than (from_end - from) source elements, and stores no more than (to_end - to) destination elements.

3 Stops if it encounters a character it cannot convert. It always leaves the from_next and to_next pointers pointing one beyond the last element successfully converted. If returns noconv, internT and externT are the same type and the converted sequence is identical to the input sequence [from, from_next). to_next is set equal to to, the value of state is unchanged, and there are no changes to the values in [to, to_end).

4 A codecvt facet that is used by basic_filebuf (31.10) shall have the property that if

\[ \text{do_out(state, from, from_end, from_next, to, to_end, to_next) \] would return ok, where from != from_end, then

\[ \text{do_out(state, from, from + 1, from_next, to, to_end, to_next) \]

shall also return ok, and that if

\[ \text{do_in(state, from, from_end, from_next, to, to_end, to_next) \]

would return ok, where to != to_end, then

\[ \text{do_in(state, from, from_end, from_next, to, to + 1, to_next) \]

shall also return ok.242

[Note 1: As a result of operations on state, it can return ok or partial and set from_next == from and to_next != to. —end note]

5 Returns: An enumeration value, as summarized in Table 109.

<table>
<thead>
<tr>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>ok</td>
<td>completed the conversion</td>
</tr>
<tr>
<td>partial</td>
<td>not all source characters converted</td>
</tr>
<tr>
<td>error</td>
<td>encountered a character in [from, from_end) that cannot be converted</td>
</tr>
<tr>
<td>noconv</td>
<td>internT and externT are the same type, and input sequence is identical to converted sequence</td>
</tr>
</tbody>
</table>

A return value of partial, if (from_next == from_end), indicates that either the destination sequence has not absorbed all the available destination elements, or that additional source elements are needed before another destination element can be produced.

Remarks: Its operations on state are unspecified.

[Note 2: This argument can be used, for example, to maintain shift state, to specify conversion options (such as count only), or to identify a cache of seek offsets. —end note]

242) Informally, this means that basic_filebuf assumes that the mappings from internal to external characters is 1 to N: that a codecvt facet that is used by basic_filebuf can translate characters one internal character at a time.
result do_unshift(stateT& state, externT* to, externT* to_end, externT*& to_next) const;

Preconditions: (to <= to_end) is well-defined and true; state is initialized, if at the beginning of a sequence, or else is equal to the result of converting the preceding characters in the sequence.

Effects: Places characters starting at to that should be appended to terminate a sequence when the current stateT is given by state. Stores no more than (to_end - to) destination elements, and leaves the to_next pointer pointing one beyond the last element successfully stored.

Returns: An enumeration value, as summarized in Table 110.

<table>
<thead>
<tr>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>ok</td>
<td>completed the sequence</td>
</tr>
<tr>
<td>partial</td>
<td>space for more than to_end - to destination elements was needed to terminate a sequence given the value of state</td>
</tr>
<tr>
<td>error</td>
<td>an unspecified error has occurred</td>
</tr>
<tr>
<td>noconv</td>
<td>no termination is needed for this state_type</td>
</tr>
</tbody>
</table>

int do_encoding() const noexcept;

Returns: -1 if the encoding of the externT sequence is state-dependent; else the constant number of externT characters needed to produce an internal character; or 0 if this number is not a constant.

bool do_always_noconv() const noexcept;

Returns: true if do_in() and do_out() return noconv for all valid argument values. codecvt<char, char, mbstate_t> returns true.

int do_length(stateT& state, const externT* from, const externT* from_end, size_t max) const;

Preconditions: (from <= from_end) is well-defined and true; state is initialized, if at the beginning of a sequence, or else is equal to the result of converting the preceding characters in the sequence.

Effects: The effect on the state argument is as if it called do_in(state, from, from_end, from, to, to+max, to) for to pointing to a buffer of at least max elements.

Returns: (from_next-from) where from_next is the largest value in the range [from, from_end] such that the sequence of values in the range [from, from_next) represents max or fewer valid complete characters of type internT. The specialization codecvt<char, char, mbstate_t>::do_max_length() returns the lesser of max and (from_end-from).

int do_max_length() const noexcept;

Returns: The maximum value that do_length(state, from, from_end, 1) can return for any valid range [from, from_end) and stateT value state. The specialization codecvt<char, char, mbstate_t>::do_max_length() returns 1.

30.4.2.6 Class template codecvt_byname

namespace std {

template<class internT, class externT, class stateT>
class codecvt_byname : public codecvt<internT, externT, stateT> {

public:
    explicit codecvt_byname(const char*, size_t refs = 0);
    explicit codecvt_byname(const string&, size_t refs = 0);

protected:
    ~codecvt_byname();
};

243) Typically these will be characters to return the state to stateT().

244) If encoding() yields -1, then more than max_length() externT elements can be consumed when producing a single internT character, and additional externT elements can appear at the end of a sequence after those that yield the final internT character.
30.4.3 The numeric category
[category.numeric]

30.4.3.1 General
[category.numeric.general]

1 The classes `num_get<>()` and `num_put<>()` handle numeric formatting and parsing. Virtual functions are provided for several numeric types. Implementations may (but are not required to) delegate extraction of smaller types to extractors for larger types.\(^\text{245}\)

2 All specifications of member functions for `num_put` and `num_get` in the subclauses of 30.4.3 only apply to the specializations required in Tables 107 and 108 (30.3.1.2.1), namely `num_get<char>`, `num_get<wchar_t>`, `num_get<C, InputIterator>`, `num_put<char>`, `num_put<wchar_t>`, and `num_put<C, OutputIterator>`. These specializations refer to the `ios_base&` argument for formatting specifications (30.4), and to its imbued locale for the `numpunct<>` facet to identify all numeric punctuation preferences, and also for the `ctype<>()` facet to perform character classification.

3 Extractor and inserter members of the standard iostreams use `num_get<>()` and `num_put<>()` member functions for formatting and parsing numeric values (31.7.5.3.1, 31.7.6.3.1).

30.4.3.2 Class template `num_get`[locale.num.get]

30.4.3.2.1 General[locale.num.get.general]

```cpp
namespace std {
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
    class num_get : public locale::facet {
        public:
            using char_type = charT;
            using iter_type = InputIterator;
            explicit num_get(size_t refs = 0);
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, bool& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, long& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, long long& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, unsigned short& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, unsigned int& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, unsigned long& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, unsigned long long& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, float& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, double& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, long double& v) const;
            iter_type get(iter_type in, iter_type end, ios_base&,
                          ios_base::iostate& err, void*& v) const;

            static locale::id id;
        
        protected:
            ~num_get();
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, bool& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, long& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, long long& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, short& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, int& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, long& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, long long& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, float& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, double& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, long double& v) const;
            virtual iter_type do_get(iter_type, iter_type, ios_base&,
                                      ios_base::iostate& err, void*& v) const;

    }
```

\(^{245}\) Parsing “-1” correctly into, e.g., an unsigned short requires that the corresponding member `get()` at least extract the sign before delegating.
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, unsigned short& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, unsigned int& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, unsigned long& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, unsigned long long& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, float& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, double& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, long double& v) const;
virtual iter_type do_get(iter_type, iter_type, ios_base&,
    ios_base::iostate& err, void*& v) const;
};

The facet **num_get** is used to parse numeric values from an input sequence such as an istream.

### 30.4.3.2.2 Members

[facet.num.get.members]

```cpp
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, bool& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, long& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, long long& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned short& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned int& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned long& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned long long& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, float& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, double& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, long double& val) const;
iter_type get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, void*& val) const;
```

Returns: do_get(in, end, str, err, val).

### 30.4.3.2.3 Virtual functions

[facet.num.get.virtuals]

```cpp
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, long& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, long long& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned short& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned int& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned long& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, unsigned long long& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, float& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, double& val) const;
```

§ 30.4.3.2.3 © ISO/IEC 1719
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, long double& val) const;
iter_type do_get(iter_type in, iter_type end, ios_base& str,
    ios_base::iostate& err, void*& val) const;

Effects: Reads characters from in, interpreting them according to str.flags(), use_facet<ctype<
charT>>(loc), and use_facet<numpunct<charT>>(loc), where loc is str.getloc().

The details of this operation occur in three stages:

(2.1) — Stage 1: Determine a conversion specifier.
(2.2) — Stage 2: Extract characters from in and determine a corresponding char value for the format
expected by the conversion specification determined in stage 1.
(2.3) — Stage 3: Store results.

The details of the stages are presented below.

Stage 1: The function initializes local variables via
fmtflags flags = str.flags();
fmtflags basefield = (flags & ios_base::basefield);
fmtflags uppercase = (flags & ios_base::uppercase);
fmtflags boolalpha = (flags & ios_base::boolalpha);

For conversion to an integral type, the function determines the integral conversion specifier as
indicated in Table 111. The table is ordered. That is, the first line whose condition is true applies.

Table 111 — Integer conversions

<table>
<thead>
<tr>
<th>State</th>
<th>stdio equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>basefield == oct</td>
<td>%o</td>
</tr>
<tr>
<td>basefield == hex</td>
<td>%X</td>
</tr>
<tr>
<td>basefield == 0</td>
<td>%i</td>
</tr>
<tr>
<td>signed integral type</td>
<td>%d</td>
</tr>
<tr>
<td>unsigned integral type</td>
<td>%u</td>
</tr>
</tbody>
</table>

For conversions to a floating-point type the specifier is %g.
For conversions to void* the specifier is %p.
A length modifier is added to the conversion specification, if needed, as indicated in Table 112.

Table 112 — Length modifier

<table>
<thead>
<tr>
<th>Type</th>
<th>Length modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>short</td>
<td>h</td>
</tr>
<tr>
<td>unsigned short</td>
<td>h</td>
</tr>
<tr>
<td>long</td>
<td>l</td>
</tr>
<tr>
<td>unsigned long</td>
<td>l</td>
</tr>
<tr>
<td>long long</td>
<td>ll</td>
</tr>
<tr>
<td>unsigned long long</td>
<td>ll</td>
</tr>
<tr>
<td>double</td>
<td>L</td>
</tr>
</tbody>
</table>

Stage 2: If in == end then stage 2 terminates. Otherwise a charT is taken from in and local variables
are initialized as if by
char_type ct = *in;
char c = src[find(atoms, atoms + sizeof(src) - 1, ct) - atoms];
if (ct == use_facet<numpunct<charT>>(loc).decimal_point())
c = ".";
bool discard =
c == use_facet<numpunct<charT>>(loc).thousands_sep()
&& use_facet<numpunct<charT>>(loc).grouping().length() != 0;
where the values `src` and `atoms` are defined as if by:

```cpp
static const char src[] = "0123456789abcdefpxABCDEFPX+-";
char_type atoms[sizeof(src)];
use_facet<ctype<charT>>(loc).widen(src, src + sizeof(src), atoms);
```

for this value of `loc`.

If `discard` is `true`, then if `'.'` has not yet been accumulated, then the position of the character is remembered, but the character is otherwise ignored. Otherwise, if `'.'` has already been accumulated, the character is discarded and Stage 2 terminates. If it is not discarded, then a check is made to determine if `c` is allowed as the next character of an input field of the conversion specifier returned by Stage 1. If so, it is accumulated.

If the character is either discarded or accumulated then `in` is advanced by `++in` and processing returns to the beginning of stage 2.

**Example 1:** Given an input sequence of "0xla.bp+07p".

- if the conversion specifier returned by Stage 1 is %d, "0" is accumulated;
- if the conversion specifier returned by Stage 1 is %i, "0xla" are accumulated;
- if the conversion specifier returned by Stage 1 is %g, "0xla.bp+07" are accumulated.

In all cases, the remainder is left in the input. — end example]

**Stage 3:** The sequence of `chars` accumulated in stage 2 (the field) is converted to a numeric value by the rules of one of the functions declared in the header `<cstdlib>`:

- For a signed integer value, the function `strtol`.
- For an unsigned integer value, the function `strtoull`.
- For a `float` value, the function `strtof`.
- For a `double` value, the function `strtod`.
- For a `long double` value, the function `strtold`.

The numeric value to be stored can be one of:

- zero, if the conversion function does not convert the entire field.
- the most positive (or negative) representable value, if the field to be converted to a signed integer type represents a value too large positive (or negative) to be represented in `val`.
- the most positive representable value, if the field to be converted to an unsigned integer type represents a value that cannot be represented in `val`.
- the converted value, otherwise.

The resultant numeric value is stored in `val`. If the conversion function does not convert the entire field, or if the field represents a value outside the range of representable values, `ios_base::failbit` is assigned to `err`.

Digit grouping is checked. That is, the positions of discarded separators are examined for consistency with

```cpp
use_facet<numpunct<charT>>(loc).grouping();
```

If they are not consistent then `ios_base::failbit` is assigned to `err`.

In any case, if stage 2 processing was terminated by the test for `in == end` then `err |= ios_base::eofbit` is performed.

```cpp
iter_type do_get(iter_type in, iter_type end, ios_base& str, 
                 ios_base::iostate& err, bool& val) const;
```

**Effects:** If `(str.flags()&ios_base::boolalpha) == 0` then input proceeds as it would for a `long` except that if a value is being stored into `val`, the value is determined according to the following: If the value to be stored is 0 then `false` is stored. If the value is 1 then `true` is stored. Otherwise `true` is stored and `ios_base::failbit` is assigned to `err`.

Otherwise target sequences are determined “as if” by calling the members `falsename()` and `truename()` of the facet obtained by

```cpp
use_facet<numpunct<charT>>(str.getloc());
```

Successive characters in the range `[in,end)` (see 24.2.4) are obtained and matched against corresponding positions in the target sequences only as necessary to identify a unique match. The input iterator `in` is compared to `end` only when necessary to obtain a character. If a target sequence is uniquely matched, `val` is set to the corresponding value. Otherwise `false` is stored and `ios_base::failbit` is assigned to `err`.

The `in` iterator is always left pointing one position beyond the last character successfully matched. If `val` is set, then `err` is set to `str.goodbit`; or to `str.eofbit` if, when seeking another character to match, it is found that `(in == end)`. If `val` is not set, then `err` is set to `str.failbit`; or to `str.failbit|str.eofbit` if the reason for the failure was that `(in == end)`.
30.4.3.3 Class template num_put

30.4.3.3.1 General

namespace std {
    template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
    class num_put : public locale::facet {
        public:
            using char_type = charT;
            using iter_type = OutputIterator;
            explicit num_put(size_t refs = 0);
            iter_type put(iter_type s, ios_base& f, char_type fill, bool v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, long v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, long long v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, unsigned long v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, unsigned long long v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, double v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, long double v) const;
            iter_type put(iter_type s, ios_base& f, char_type fill, const void* v) const;
            static locale::id id;
    }
}

The facet num_put is used to format numeric values to a character sequence such as an ostream.

30.4.3.3.2 Members

iter_type put(iter_type out, ios_base& str, char_type fill, bool val) const;
iter_type put(iter_type out, ios_base& str, char_type fill, long val) const;
iter_type put(iter_type out, ios_base& str, char_type fill, long long val) const;
iter_type put(iter_type out, ios_base& str, char_type fill, unsigned long val) const;
iter_type put(iter_type out, ios_base& str, char_type fill, unsigned long long val) const;
iter_type put(iter_type out, ios_base& str, char_type fill, double val) const;
iter_type put(iter_type out, ios_base& str, char_type fill, long double val) const;

Returns: do_put(out, str, fill, val).

30.4.3.3.3 Virtual functions

iter_type do_put(iter_type out, ios_base& str, char_type fill, long val) const;
iter_type do_put(iter_type out, ios_base& str, char_type fill, long long val) const;
iter_type do_put(iter_type out, ios_base& str, char_type fill, unsigned long val) const;
iter_type do_put(iter_type out, ios_base& str, char_type fill, unsigned long long val) const;
iter_type do_put(iter_type out, ios_base& str, char_type fill, double val) const;
iter_type do_put(iter_type out, ios_base& str, char_type fill, long double val) const;

©ISO/IEC 1722
iter_type do_put(iter_type out, ios_base& str, char_type fill, const void* val) const;

Effects: Writes characters to the sequence out, formatting val as desired. In the following description, loc names a local variable initialized as

```cpp
locale loc = str.getloc();
```

The details of this operation occur in several stages:

(2.1) — Stage 1: Determine a printf conversion specifier spec and determine the characters that would be printed by printf (31.13) given this conversion specifier for

```cpp
printf(spec, val)
```

assuming that the current locale is the "C" locale.

(2.2) — Stage 2: Adjust the representation by converting each char determined by stage 1 to a charT using a conversion and values returned by members of use_facet<numpunct<charT>>(loc).

(2.3) — Stage 3: Determine where padding is required.

(2.4) — Stage 4: Insert the sequence into the out.

Detailed descriptions of each stage follow.

Returns: out.

Stage 1: The first action of stage 1 is to determine a conversion specifier. The tables that describe this determination use the following local variables

```cpp
fmtflags flags = str.flags();
fmtflags basefield = (flags & (ios_base::basefield));
fmtflags uppercase = (flags & (ios_base::uppercase));
fmtflags floatfield = (flags & (ios_base::floatfield));
fmtflags showpos = (flags & (ios_base::showpos));
fmtflags showbase = (flags & (ios_base::showbase));
fmtflags showpoint = (flags & (ios_base::showpoint));
```

All tables used in describing stage 1 are ordered. That is, the first line whose condition is true applies. A line without a condition is the default behavior when none of the earlier lines apply.

For conversion from an integral type other than a character type, the function determines the integral conversion specifier as indicated in Table 113.

Table 113 — Integer conversions [tab:facet.num.put.int]

<table>
<thead>
<tr>
<th>State</th>
<th>stdio equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>basefield == ios_base::oct</td>
<td>%o</td>
</tr>
<tr>
<td>(basefield == ios_base::hex) &amp; !uppercase</td>
<td>%x</td>
</tr>
<tr>
<td>(basefield == ios_base::hex)</td>
<td>%X</td>
</tr>
<tr>
<td>for a signed integral type</td>
<td>%d</td>
</tr>
<tr>
<td>for an unsigned integral type</td>
<td>%u</td>
</tr>
</tbody>
</table>

For conversion from a floating-point type, the function determines the floating-point conversion specifier as indicated in Table 114.

Table 114 — Floating-point conversions [tab:facet.num.put.fp]

<table>
<thead>
<tr>
<th>State</th>
<th>stdio equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>floatfield == ios_base::fixed</td>
<td>%f</td>
</tr>
<tr>
<td>floatfield == ios_base::scientific &amp; !uppercase</td>
<td>%e</td>
</tr>
<tr>
<td>floatfield == ios_base::scientific</td>
<td>%E</td>
</tr>
<tr>
<td>floatfield == (ios_base::fixed</td>
<td>ios_base::scientific) &amp; !uppercase</td>
</tr>
<tr>
<td>floatfield == (ios_base::fixed</td>
<td>ios_base::scientific)</td>
</tr>
<tr>
<td>!uppercase</td>
<td>%g</td>
</tr>
<tr>
<td>otherwise</td>
<td>%G</td>
</tr>
</tbody>
</table>

For conversions from an integral or floating-point type a length modifier is added to the conversion specifier as indicated in Table 115.
Table 115 — Length modifier  

<table>
<thead>
<tr>
<th>Type</th>
<th>Length modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>long</td>
<td>l</td>
</tr>
<tr>
<td>long long</td>
<td>ll</td>
</tr>
<tr>
<td>unsigned long</td>
<td>l</td>
</tr>
<tr>
<td>unsigned long long</td>
<td>ll</td>
</tr>
<tr>
<td>long double</td>
<td>L</td>
</tr>
<tr>
<td>otherwise</td>
<td>none</td>
</tr>
</tbody>
</table>

The conversion specifier has the following optional additional qualifiers prepended as indicated in Table 116.

Table 116 — Numeric conversions  

<table>
<thead>
<tr>
<th>Type(s)</th>
<th>State</th>
<th>stdio equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>an integral type</td>
<td>showpos</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>showbase</td>
<td>#</td>
</tr>
<tr>
<td>a floating-point type</td>
<td>showpos</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>showpoint</td>
<td>#</td>
</tr>
</tbody>
</table>

For conversion from a floating-point type, if `floatfield != (ios_base::fixed | ios_base::scientific)`, `str.precision()` is specified as precision in the conversion specification. Otherwise, no precision is specified.

For conversion from `void*` the specifier is `%p`.

The representations at the end of stage 1 consists of the `char`s that would be printed by a call of `printf(s, val)` where `s` is the conversion specifier determined above.

Stage 2: Any character `c` other than a decimal point(.) is converted to a `charT` via

```cpp
use_facet<ctype<charT>>((loc).widen(c)
```

A local variable `punct` is initialized via

```cpp
const numpunct<charT>& punct = use_facet<numpunct<charT>>((loc);
```

For arithmetic types, `punct.thousands_sep()` characters are inserted into the sequence as determined by the value returned by `punct.do_grouping()` using the method described in 30.4.4.1.3.

Decimal point characters(.) are replaced by `punct.decimal_point()`.

Stage 3: A local variable is initialized as

```cpp
fmtflags adjustfield = (flags & (ios_base::adjustfield));
```

The location of any padding is determined according to Table 117.

Table 117 — Fill padding  

<table>
<thead>
<tr>
<th>State</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>adjustfield == ios_base::left</td>
<td>pad after</td>
</tr>
<tr>
<td>adjustfield == ios_base::right</td>
<td>pad before</td>
</tr>
<tr>
<td>adjustfield == internal and a sign occurs in the representation</td>
<td>pad after the sign</td>
</tr>
<tr>
<td>adjustfield == internal and representation after stage 1 began with 0x or 0X</td>
<td>pad after x or X</td>
</tr>
<tr>
<td>otherwise</td>
<td>pad before</td>
</tr>
</tbody>
</table>

If `str.width()` is nonzero and the number of `charT`s in the sequence after stage 2 is less than `str.width()`, then enough fill characters are added to the sequence at the position indicated for padding to bring the length of the sequence to `str.width()`.

`str.width(0)` is called.

246) The conversion specification `#o` generates a leading 0 which is not a padding character.
Stage 4: The sequence of charT’s at the end of stage 3 are output via

\[ \text{out}++ = c \]

iter_type do_put(iter_type out, ios_base& str, char_type fill, bool val) const;

Returns: If \((\text{str}.\text{flags}() & \text{ios}_{\text{base}}::\text{boolalpha}) == 0\) returns \(\text{do_put(out, str, fill, (int)val)}\), otherwise obtains a string \(s\) as if by

\[ \text{string	ype} s = \]

\[ \begin{cases} 
\begin{align*}
\text{val} & ? \text{use\_facet<} & \text{numpunct<charT>>(loc).true\_name()} \\
& : \text{use\_facet<} & \text{numpunct<charT>>(loc).false\_name()};
\end{align*}
\end{cases} \]

and then inserts each character \(c\) of \(s\) into \(\text{out}\) via \(\text{out}++ = c\) and returns \(\text{out}\).

30.4.4 The numeric punctuation facet

30.4.4.1 Class template numpunct

30.4.4.1.1 General

namespace std {
    template<class charT>
    class numpunct : public locale::facet {
        public:
            using char_type = charT;
            using string_type = basic_string<charT>;

            explicit numpunct(size_t refs = 0);

            char_type decimal_point() const;
            char_type thousands_sep() const;
            string grouping() const;
            string_type truename() const;
            string_type falsename() const;

            static locale::id id;

        protected:
            ~numpunct(); // virtual
            virtual char_type do_decimal_point() const;
            virtual char_type do_thousands_sep() const;
            virtual string do_grouping() const;
            virtual string_type do_truename() const; // for bool
            virtual string_type do_falsename() const; // for bool
        }
    }

1 numpunct<> specifies numeric punctuation. The specializations required in Table 107 (30.3.1.2.1), namely numpunct<wchar_t> and numpunct<char>, provide classic “C” numeric formats, i.e., they contain information equivalent to that contained in the “C” locale or their wide character counterparts as if obtained by a call to widen.

2 The syntax for number formats is as follows, where digit represents the radix set specified by the \texttt{fmtflags} argument value, and \texttt{thousands-sep} and \texttt{decimal-point} are the results of corresponding numpunct<charT> members. Integer values have the format:

\[
\text{intval:}
\]

\[
\text{sign}_{\text{opt}}, \text{units}
\]

\[
\text{sign:}
\]

\[
\begin{cases} 
\begin{align*}
+ \\
- 
\end{align*}
\end{cases}
\]

\[
\text{units:}
\]

\[
\text{digits}
\]

\[
\text{digits thousands-sep units}
\]

\[
\text{digits:}
\]

\[
\text{digit digits}_{\text{opt}}
\]

and floating-point values have:
where the number of digits between thousands-sep is as specified by `do_grouping()`. For parsing, if the digits portion contains no thousands-separators, no grouping constraint is applied.

### 30.4.4.1.2 Members

```cpp
char_type decimal_point() const;
```

**Returns:** `do_decimal_point()`.

```cpp
char_type thousands_sep() const;
```

**Returns:** `do_thousands_sep()`.

```cpp
string grouping() const;
```

**Returns:** `do_grouping()`.

```cpp
string_type truename() const;
string_type falsename() const;
```

**Returns:** `do_truename()` or `do_falsename()`, respectively.

### 30.4.4.1.3 Virtual functions

```cpp
char_type do_decimal_point() const;
```

**Returns:** A character for use as the decimal radix separator. The required specializations return ‘.’ or L’.’.

```cpp
char_type do_thousands_sep() const;
```

**Returns:** A character for use as the digit group separator. The required specializations return ‘,’ or L’,’.

```cpp
string do_grouping() const;
```

**Returns:** A string `vec` used as a vector of integer values, in which each element `vec[i]` represents the number of digits\(^\text{247}\) in the group at position `i`, starting with position 0 as the rightmost group. If `vec.size() <= i`, the number is the same as group `(i - 1)`; if `(i < 0 || vec[i] <= 0 || vec[i] == CHAR_MAX)`, the size of the digit group is unlimited.

The required specializations return the empty string, indicating no grouping.

```cpp
string_type do_truename() const;
string_type do_falsename() const;
```

**Returns:** A string representing the name of the boolean value `true` or `false`, respectively.

In the base class implementation these names are "true" and "false", or L"true" and L"false".

### 30.4.4.2 Class template numpunct_byname

```cpp
namespace std {
    template<class charT>
    class numpunct_byname : public numpunct<charT> {
        // this class is specialized for char and wchar_t.
        public:
            using char_type = charT;
    }
}
```

\(^{247}\) Thus, the string "\003" specifies groups of 3 digits each, and "3" probably indicates groups of 51 (!) digits each, because 51 is the ASCII value of "3".
using string_type = basic_string<charT>;
explicit numpunct_byname(const char*, size_t refs = 0);
explicit numpunct_byname(const string&, size_t refs = 0);

protected:
- numpunct_byname();
};

30.4.5 The collate category

30.4.5.1 Class template collate

namespace std {
    template<class charT>
    class collate : public locale::facet {
public:
    using char_type = charT;
    using string_type = basic_string<charT>;
    explicit collate(size_t refs = 0);
    int compare(const charT* low1, const charT* high1,
                const charT* low2, const charT* high2) const;
    string_type transform(const charT* low, const charT* high) const;
    long hash(const charT* low, const charT* high) const;
    static locale::id id;
protected:
    -collate();
    virtual int do_compare(const charT* low1, const charT* high1,
                           const charT* low2, const charT* high2) const;
    virtual string_type do_transform(const charT* low, const charT* high) const;
    virtual long do_hash (const charT* low, const charT* high) const;
    
};
}

1 The class collate<charT> provides features for use in the collation (comparison) and hashing of strings. A locale member function template, operator(), uses the collate facet to allow a locale to act directly as the predicate argument for standard algorithms (Clause 27) and containers operating on strings. The specializations required in Table 107 (30.3.1.2.1), namely collate<char> and collate<wchar_t>, apply lexicographical ordering (27.8.11).

2 Each function compares a string of characters *p in the range [low,high).

30.4.5.1.2 Members

int compare(const charT* low1, const charT* high1,
            const charT* low2, const charT* high2) const;

1 Returns: do_compare(low1, high1, low2, high2).

string_type transform(const charT* low, const charT* high) const;

2 Returns: do_transform(low, high).

long hash(const charT* low, const charT* high) const;

3 Returns: do_hash(low, high).

30.4.5.1.3 Virtual functions
int do_compare(const charT* low1, const charT* high1,
    const charT* low2, const charT* high2) const;

Returns: 1 if the first string is greater than the second, -1 if less, zero otherwise. The specializations required in Table 107 (30.3.1.2.1), namely collate<char> and collate<wchar_t>, implement a lexicographical comparison (27.8.11).

string_type do_transform(const charT* low, const charT* high) const;

Returns: A basic_string<charT> value that, compared lexicographically with the result of calling transform() on another string, yields the same result as calling do_compare() on the same two strings. \(^{248}\)

long do_hash(const charT* low, const charT* high) const;

Returns: An integer value equal to the result of calling hash() on any other string for which do_compare() returns 0 (equal) when passed the two strings.

Recommended practice: The probability that the result equals that for another string which does not compare equal should be very small, approaching \(\frac{1.0}{\text{numeric_limits<unsigned long>::max()}}\).

30.4.5.2 Class template collate_byname

namespace std {
    template<class charT>
    class collate_byname : public collate<charT> {
    public:
        using string_type = basic_string<charT>;
        explicit collate_byname(const char*, size_t refs = 0);
        explicit collate_byname(const string&, size_t refs = 0);

    protected:
        ~collate_byname();
    };
}

30.4.6 The time category

30.4.6.1 General

Templates time_get<charT, InputIterator> and time_put<charT, OutputIterator> provide date and time formatting and parsing. All specifications of member functions for time_put and time_get in the subclauses of 30.4.6 only apply to the specializations required in Tables 107 and 108 (30.3.1.2.1). Their members use their ios_base&, ios_base::iostate&, and fill arguments as described in 30.4, and the ctype<> facet, to determine formatting details.

30.4.6.2 Class template time_get

namespace std {
    class time_base {
    public:
        enum dateorder { no_order, dmy, mdy, ymd, ydm };
    }

    template<class charT, class InputIterator = istreambuf_iterator<charT>>
    class time_get : public locale::facet, public time_base {
    public:
        using char_type = charT;
        using iter_type = InputIterator;

        explicit time_get(size_t refs = 0);
    };
}

\(^{248}\) This function is useful when one string is being compared to many other strings.
dateorder date_order() const { return do_date_order(); }  
iter_type get_time(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t) const;  
iter_type get_date(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t) const;  
iter_type get_weekday(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t) const;  
iter_type get_monthname(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t) const;  
iter_type get_year(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t) const;  
iter_type get(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t, char format, char modifier = 0) const;  
iter_type get(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t, const char_type* fmt,  
const char_type* fmtend) const;

static locale::id id;

protected:
~time_get();  
virtual dateorder do_date_order() const;  
virtual iter_type do_get_time(iter_type s, iter_type end, ios_base&,  
ios_base::iostate& err, tm* t) const;  
virtual iter_type do_get_date(iter_type s, iter_type end, ios_base&,  
ios_base::iostate& err, tm* t) const;  
virtual iter_type do_get_weekday(iter_type s, iter_type end, ios_base&,  
ios_base::iostate& err, tm* t) const;  
virtual iter_type do_get_monthname(iter_type s, iter_type end, ios_base&,  
ios_base::iostate& err, tm* t) const;  
virtual iter_type do_get_year(iter_type s, iter_type end, ios_base&,  
ios_base::iostate& err, tm* t) const;  
virtual iter_type do_get(iter_type s, iter_type end, ios_base& f,  
ios_base::iostate& err, tm* t, char format, char modifier) const;

1 time_get is used to parse a character sequence, extracting components of a time or date into a tm object. Each get member parses a format as produced by a corresponding format specifier to time_put<>::put. If the sequence being parsed matches the correct format, the corresponding members of the tm argument are set to the values used to produce the sequence; otherwise either an error is reported or unspecified values are assigned.  

2 If the end iterator is reached during parsing by any of the get() member functions, the member sets ios_base::eofbit in err.

30.4.6.2.2 Members

dateorder date_order() const;  

Returns: do_date_order().  

iter_type get_time(iter_type s, iter_type end, ios_base& str,  
ios_base::iostate& err, tm* t) const;  

Returns: do_get_time(s, end, str, err, t).  

iter_type get_date(iter_type s, iter_type end, ios_base& str,  
ios_base::iostate& err, tm* t) const;  

Returns: do_get_date(s, end, str, err, t).

249) In other words, user confirmation is required for reliable parsing of user-entered dates and times, but machine-generated formats can be parsed reliably. This allows parsers to be aggressive about interpreting user variations on standard formats.
iter_type get_weekday(iter_type s, iter_type end, ios_base& str, 
    ios_base::iostate& err, tm* t) const;
iter_type get_monthname(iter_type s, iter_type end, ios_base& str, 
    ios_base::iostate& err, tm* t) const;

Returns: do_get_weekday(s, end, str, err, t) or do_get_monthname(s, end, str, err, t).

iter_type get_year(iter_type s, iter_type end, ios_base& str, 
    ios_base::iostate& err, tm* t) const;

Returns: do_get_year(s, end, str, err, t).

iter_type get(iter_type s, iter_type end, ios_base& f, ios_base::iostate& err, 
    tm* t, char format, char modifier = 0) const;

Returns: do_get(s, end, f, err, t, format, modifier).

iter_type get(iter_type s, iter_type end, ios_base& f, ios_base::iostate& err, 
    tm* t, const char_type* fmt, const char_type* fmtend) const;

Preconditions: [fmt,fmtend] is a valid range.
Effects: The function starts by evaluating err = ios_base::goodbit. It then enters a loop, reading
zero or more characters from s at each iteration. Unless otherwise specified below, the loop terminates
when the first of the following conditions holds:

8.1 — The expression fmt == fmtend evaluates to true.
8.2 — The expression err == ios_base::goodbit evaluates to false.
8.3 — The expression s == end evaluates to true, in which case the function evaluates err = ios_base::
    eofbit | ios_base::failbit.
8.4 — The next element of fmt is equal to '%', optionally followed by a modifier character, followed by
    a conversion specifier character, format, together forming a conversion specification valid for the
    POSIX function strptime. If the number of elements in the range [fmt,fmtend] is not sufficient
    to unambiguously determine whether the conversion specification is complete and valid, the
    function evaluates err = ios_base::failbit. Otherwise, the function evaluates s = do_get(s, end, 
    f, err, t, format, modifier), where the value of modifier is '0' when the optional
    modifier is absent from the conversion specification. If err == ios_base::goodbit holds after
    the evaluation of the expression, the function increments fmt to point just past the end of the
    conversion specification and continues looping.
8.5 — The expression isspace(*fmt, f.getloc()) evaluates to true, in which case the function first
    increments fmt until fmt == fmtend || !isspace(*fmt, f.getloc()) evaluates to true, then
    advances s until s == end || !isspace(*s, f.getloc()) is true, and finally resumes looping,
8.6 — The next character read from s matches the element pointed to by fmt in a case-insensitive
    comparison, in which case the function evaluates ++fmt, ++s and continues looping. Otherwise,
    the function evaluates err = ios_base::failbit.

9 [Note 1: The function uses the ctype<charT> facet installed in f's locale to determine valid whitespace
    characters. It is unspecified by what means the function performs case-insensitive comparison or whether
    multi-character sequences are considered while doing so. — end note]

Returns: s.

30.4.6.2.3 Virtual functions

dateorder do_date_order() const;

Returns: An enumeration value indicating the preferred order of components for those date formats
that are composed of day, month, and year.250 Returns no_order if the date format specified by 'x'
contains other variable components (e.g., Julian day, week number, week day).

250) This function is intended as a convenience only, for common formats, and can return no_order in valid locales.
iter_type do_get_time(iter_type s, iter_type end, ios_base& str,
   ios_base::iostate& err, tm* t) const;

Effects: Reads characters starting at s until it has extracted those tm members, and remaining format characters, used by time_put<>::put to produce the format specified by "%H:%M:%S", or until it encounters an error or end of sequence.

Returns: An iterator pointing immediately beyond the last character recognized as possibly part of a valid time.

iter_type do_get_date(iter_type s, iter_type end, ios_base& str,
   ios_base::iostate& err, tm* t) const;

Effects: Reads characters starting at s until it has extracted those tm members and remaining format characters used by time_put<>::put to produce one of the following formats, or until it encounters an error. The format depends on the value returned by date_order() as shown in Table 118.

Table 118 — do_get_date effects [tab:locale.time.get.dogetdate]

<table>
<thead>
<tr>
<th>date_order()</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>no_order</td>
<td>&quot;%m%d%y&quot;</td>
</tr>
<tr>
<td>dmy</td>
<td>&quot;%d%m%y&quot;</td>
</tr>
<tr>
<td>mdy</td>
<td>&quot;%m%d%y&quot;</td>
</tr>
<tr>
<td>ymd</td>
<td>&quot;%y%m%d&quot;</td>
</tr>
<tr>
<td>ydm</td>
<td>&quot;%y%d%m&quot;</td>
</tr>
</tbody>
</table>

An implementation may also accept additional implementation-defined formats.

Returns: An iterator pointing immediately beyond the last character recognized as possibly part of a valid date.

iter_type do_get_weekday(iter_type s, iter_type end, ios_base& str,
   ios_base::iostate& err, tm* t) const;
iter_type do_get_monthname(iter_type s, iter_type end, ios_base& str,
   ios_base::iostate& err, tm* t) const;

Effects: Reads characters starting at s until it has extracted the (perhaps abbreviated) name of a weekday or month. If it finds an abbreviation that is followed by characters that can match a full name, it continues reading until it matches the full name or fails. It sets the appropriate tm member accordingly.

Returns: An iterator pointing immediately beyond the last character recognized as part of a valid name.

iter_type do_get_year(iter_type s, iter_type end, ios_base& str,
   ios_base::iostate& err, tm* t) const;

Effects: Reads characters starting at s until it has extracted an unambiguous year identifier. It is implementation-defined whether two-digit year numbers are accepted, and (if so) what century they are assumed to lie in. Sets the t->tm_year member accordingly.

Returns: An iterator pointing immediately beyond the last character recognized as part of a valid year identifier.

iter_type do_get(iter_type s, iter_type end, ios_base& f,
   ios_base::iostate& err, tm* t, char format, char modifier) const;

 Preconditions: t points to an object.

Effects: The function starts by evaluating err = ios_base::goodbit. It then reads characters starting at s until it encounters an error, or until it has extracted and assigned those tm members, and any remaining format characters, corresponding to a conversion specification appropriate for the POSIX function strptime, formed by concatenating '%' and the modifier character, when non-NUL, and the format character. When the concatenation fails to yield a complete valid directive the function leaves the object pointed to by t unchanged and evaluates err |= ios_base::failbit. When s == end evaluates to true after reading a character the function evaluates err |= ios_base::eofbit.
For complex conversion specifications such as `%c`, `%x`, or `%X`, or conversion specifications that involve the optional modifiers `E` or `O`, when the function is unable to unambiguously determine some or all `tm` members from the input sequence `[s, end)`, it evaluates `err |= ios_base::eofbit`. In such cases the values of those `tm` members are unspecified and may be outside their valid range.

Returns: An iterator pointing immediately beyond the last character recognized as possibly part of a valid input sequence for the given `format` and `modifier`.

Remarks: It is unspecified whether multiple calls to `do_get()` with the address of the same `tm` object will update the current contents of the object or simply overwrite its members. Portable programs should zero out the object before invoking the function.

30.4.6.3 Class template `time_get_byname` [locale.time.getbyname]

```cpp
namespace std {
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
    class time_get_byname : public time_get<charT, InputIterator> {
        public:
            using dateorder = time_base::dateorder;
            using iter_type = InputIterator;
            explicit time_get_byname(const char*, size_t refs = 0);
            explicit time_get_byname(const string&, size_t refs = 0);

            protected:
                ~time_get_byname();
        }
    }
}
```

30.4.6.4 Class template `time_put` [locale.time.put]

30.4.6.4.1 General [locale.time.put.general]

```cpp
namespace std {
    template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
    class time_put : public locale::facet {
        public:
            using char_type = charT;
            using iter_type = OutputIterator;
            explicit time_put(size_t refs = 0);

            iter_type put(iter_type s, ios_base& f, char_type fill, const tm* tmb,
                         const charT* pattern, const charT* pat_end) const;
            iter_type put(iter_type s, ios_base& f, char_type fill,
                         const tm* tmb, char format, char modifier = 0) const;

            static locale::id id;

            protected:
                ~time_put();
                virtual iter_type do_put(iter_type s, ios_base&, char_type, const tm* t,
                                         char format, char modifier) const;
        }
    }
}
```

30.4.6.4.2 Members [locale.time.put.members]

```cpp
iter_type put(iter_type s, ios_base& str, char_type fill, const tm* t,
              const charT* pattern, const charT* pat_end) const;
iter_type put(iter_type s, ios_base& str, char_type fill, const tm* t,
              char format, char modifier = 0) const;
```

Effects: The first form steps through the sequence from `pattern` to `pat_end`, identifying characters that are part of a format sequence. Each character that is not part of a format sequence is written to `s` immediately, and each format sequence, as it is identified, results in a call to `do_put`; thus, format
elements and other characters are interleaved in the output in the order in which they appear in the pattern. Format sequences are identified by converting each character c to a char value as if by ct.narrow(c, 0), where ct is a reference to ctype<charT> obtained from str.getloc(). The first character of each sequence is equal to '%', followed by an optional modifier character mod251 and a format specifier character spec as defined for the function strftime. If no modifier character is present, mod is zero. For each valid format sequence identified, calls do_put(s, str, fill, t, spec, mod).

The second form calls do_put(s, str, fill, t, format, modifier).

[Note 1: The fill argument can be used in the implementation-defined formats or by derivations. A space character is a reasonable default for this argument. —end note]

Returns: An iterator pointing immediately after the last character produced.

30.4.6.4.3 Virtual functions

Effects: Formats the contents of the parameter t into characters placed on the output sequence s. Formatting is controlled by the parameters format and modifier, interpreted identically as the format specifiers in the string argument to the standard library function strftime(), except that the sequence of characters produced for those specifiers that are described as depending on the C locale are instead implementation-defined.

[Note 1: Interpretation of the modifier argument is implementation-defined. —end note]

Returns: An iterator pointing immediately after the last character produced.

[Note 2: The fill argument can be used in the implementation-defined formats or by derivations. A space character is a reasonable default for this argument. —end note]

Recommended practice: Interpretation of the modifier should follow POSIX conventions. Implementations should refer to other standards such as POSIX for a specification of the character sequences produced for those specifiers described as depending on the C locale.

30.4.6.5 Class template time_put_byname

namespace std {
  template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
  class time_put_byname : public time_put<charT, OutputIterator> {
    public:
      using char_type = charT;
      using iter_type = OutputIterator;

      explicit time_put_byname(const char*, size_t refs = 0);
      explicit time_put_byname(const string&, size_t refs = 0);

    protected:
      ~time_put_byname();
    }
  }
}

30.4.7 The monetary category

30.4.7.1 General

These templates handle monetary formats. A template parameter indicates whether local or international monetary formats are to be used.

All specifications of member functions for money_put and money_get in the subclasses of 30.4.7 only apply to the specializations required in Tables 107 and 108 (30.3.1.2.1). Their members use their ios_base&, ios_base::iostate&, and fill arguments as described in 30.4, and the moneypunct<> and ctype<> facets, to determine formatting details.

251) Although the C programming language defines no modifiers, most vendors do.
30.4.7.2 Class template money_get

30.4.7.2.1 General

```cpp
namespace std {
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
    class money_get : public locale::facet {
        public:
            using char_type = charT;
            using iter_type = InputIterator;
            using string_type = basic_string<charT>;
            explicit money_get(size_t refs = 0);
            iter_type get(iter_type s, iter_type end, bool intl,
                           ios_base& f, ios_base::iostate& err,
                           long double& units) const;
            iter_type get(iter_type s, iter_type end, bool intl,
                           ios_base& f, ios_base::iostate& err,
                           string_type& digits) const;
            static locale::id id;
        protected:
            ~money_get();
            virtual iter_type do_get(iter_type, iter_type, bool, ios_base&,
                                      ios_base::iostate& err, long double& units) const;
            virtual iter_type do_get(iter_type, iter_type, bool, ios_base&,
                                      ios_base::iostate& err, string_type& digits) const;
    };
}
```

30.4.7.2.2 Members

```cpp
iter_type get(iter_type s, iter_type end, bool intl, ios_base& f,
              ios_base::iostate& err, long double& quant) const;
iter_type get(iter_type s, iter_type end, bool intl, ios_base& f,
              ios_base::iostate& err, string_type& quant) const;
```

Returns: do_get(s, end, intl, f, err, quant).

30.4.7.2.3 Virtual functions

```cpp
iter_type do_get(iter_type s, iter_type end, bool intl, ios_base& str,
                 ios_base::iostate& err, long double& units) const;
iter_type do_get(iter_type s, iter_type end, bool intl, ios_base& str,
                 ios_base::iostate& err, string_type& digits) const;
```

Effects: Reads characters from s to parse and construct a monetary value according to the format specified by a moneypunct<charT, Intl> facet reference mp and the character mapping specified by a ctype<charT> facet reference ct obtained from the locale returned by str.getloc(), and str.flags(). If a valid sequence is recognized, does not change err; otherwise, sets err to (err|str.failbit), or (err|str.failbit|str.eofbit) if no more characters are available, and does not change units or digits. Uses the pattern returned by mp.neg_format() to parse all values. The result is returned as an integral value stored in units or as a sequence of digits possibly preceded by a minus sign (as produced by ct.widen(c) where c is '- ' or in the range from '0' through '9' (inclusive)) stored in digits.

[Example 1: The sequence $1,056.23 in a common United States locale would yield, for units, 105623, or, for digits, "105623". — end example]

If mp.grouping() indicates that no thousands separators are permitted, any such characters are not read, and parsing is terminated at the point where they first appear. Otherwise, thousands separators are optional; if present, they are checked for correct placement only after all format components have been read.

Where money_base::space or money_base::none appears as the last element in the format pattern, no whitespace is consumed. Otherwise, where money_base::space appears in any of the initial elements of
the format pattern, at least one whitespace character is required. Where `money_base::none` appears in any of the initial elements of the format pattern, whitespace is allowed but not required. If `(str.flags() & str.showbase)` is false, the currency symbol is optional and is consumed only if other characters are needed to complete the format; otherwise, the currency symbol is required.

If the first character (if any) in the string `pos` returned by `mp.positive_sign()` or the string `neg` returned by `mp.negative_sign()` is recognized in the position indicated by `sign` in the format pattern, it is consumed and any remaining characters in the string are required after all the other format components.

[Example 2: If `showbase` is off, then for a `neg` value of "("") and a currency symbol of "L", in "(100 L)" the "L" is consumed; but if `neg` is "-", the "L" in "-100 L" is not consumed. — end example]

If `pos` or `neg` is empty, the sign component is optional, and if no sign is detected, the result is given the sign that corresponds to the source of the empty string. Otherwise, the character in the indicated position must match the first character of `pos` or `neg`, and the result is given the corresponding sign. If the first character of `pos` is equal to the first character of `neg`, or if both strings are empty, the result is given a positive sign.

Digits in the numeric monetary component are extracted and placed in `digits`, or into a character buffer `buf1` for conversion to produce a value for `units`, in the order in which they appear, preceded by a minus sign if and only if the result is negative. The value `units` is produced as if by

```cpp
for (int i = 0; i < n; ++i)
    buf2[i] = src[find(atoms, atoms+sizeof(src), buf1[i]) - atoms];
buf2[n] = 0;
sscanf(buf2, "%Lf", &units);
```

where `n` is the number of characters placed in `buf1`, `buf2` is a character buffer, and the values `src` and `atoms` are defined as if by

```cpp
static const char src[] = "0123456789-";
charT atoms[sizeof(src)];
ct.widen(src, src + sizeof(src) - 1, atoms);
```

5

Returns: An iterator pointing immediately beyond the last character recognized as part of a valid monetary quantity.

30.4.7.3 Class template `money_put` [locale.money.put]
30.4.7.3.1 General [locale.money.put.general]

```cpp
namespace std {
    template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
    class money_put : public locale::facet {
    public:
        using char_type = charT;
        using iter_type = OutputIterator;
        using string_type = basic_string<charT>;

        explicit money_put(size_t refs = 0);
        iter_type put(iter_type s, bool intl, ios_base& f,
                      char_type fill, long double units) const;
        iter_type put(iter_type s, bool intl, ios_base& f,
                      const string_type& digits) const;
        static locale::id id;

    protected:
        ~money_put();
        virtual iter_type do_put(iter_type s, bool intl, ios_base& f,
                                 char_type fill, long double units) const;
        virtual iter_type do_put(iter_type s, bool intl, ios_base& f,
                                 const string_type& digits) const;
    };
}
```

252) The semantics here are different from `ct.narrow`. 

§ 30.4.7.3.1
30.4.7.3.2 Members

iter_type put(iter_type s, bool intl, ios_base& f, char_type fill, long double quant) const;
iter_type put(iter_type s, bool intl, ios_base& f, char_type fill, const string_type& quant) const;

Returns: do_put(s, intl, f, loc, quant).

30.4.7.3.3 Virtual functions

iter_type do_put(iter_type s, bool intl, ios_base& str,
char_type fill, long double units) const;
iter_type do_put(iter_type s, bool intl, ios_base& str,
char_type fill, const string_type& digits) const;

Effects: Writes characters to s according to the format specified by a moneypunct<charT, Intl> facet reference mp and the character mapping specified by a ctype<charT> facet reference ct obtained from the locale returned by str.getloc(), and str.flags(). The argument units is transformed into a sequence of wide characters as if by

c.t widen(buf1, buf1 + sprintf(buf1, "%.0Lf", units), buf2)
for character buffers buf1 and buf2. If the first character in digits or buf2 is equal to ct.widen('-'), then the pattern used for formatting is the result of mp.neg_format(); otherwise the pattern is the result of mp.pos_format(). Digit characters are written, interspersed with any thousands separators and decimal point specified by the format, in the order they appear (after the optional leading minus sign) in digits or buf2. In digits, only the optional leading minus sign and the immediately subsequent digit characters (as classified according to ct) are used; any trailing characters (including digits appearing after a non-digit character) are ignored. Calls str.width(0).

Returns: An iterator pointing immediately after the last character produced.

Remarks: The currency symbol is generated if and only if (str.flags() & str.showbase) is nonzero. If the number of characters generated for the specified format is less than the value returned by str.width() on entry to the function, then copies of fill are inserted as necessary to pad to the specified width. For the value af equal to (str.flags() & str.adjustfield), if (af == str.internal) is true, the fill characters are placed where none or space appears in the formatting pattern; otherwise if (af == str.left) is true, they are placed after the other characters; otherwise, they are placed before the other characters.

[Note 1: It is possible, with some combinations of format patterns and flag values, to produce output that cannot be parsed using num_get<>::get. — end note]

30.4.7.4 Class template moneypunct

30.4.7.4.1 General

namespace std {
    class money_base {
    public:
        enum part { none, space, symbol, sign, value };
        struct pattern { char field[4]; };
    };

    template<class charT, bool International = false>
    class moneypunct : public locale::facet, public money_base {
    public:
        using char_type = charT;
        using string_type = basic_string<charT>;

        explicit moneypunct(size_t refs = 0);

        charT decimal_point() const;
        charT thousands_sep() const;
        string grouping() const;
        string_type curr_symbol() const;
        string_type positive_sign() const;
        string_type negative_sign() const;
        int frac_digits() const;
    };
}
The `moneypunct<>` facet defines monetary formatting parameters used by `money_get<>` and `money_put<>`. A monetary format is a sequence of four components, specified by a `pattern` value `p`, such that the `part` value `static_cast<part>(p.field[i])` determines the `i`th component of the format. In the `field` member of a `pattern` object, each value `symbol`, `sign`, `value`, and either `space` or `none` appears exactly once. The value `none`, if present, is not first; the value `space`, if present, is neither first nor last.

Where `none` or `space` appears, whitespace is permitted in the format, except where `none` appears at the end, in which case no whitespace is permitted. The value `space` indicates that at least one space is required at that position. Where `symbol` appears, the sequence of characters returned by `curr_symbol()` is permitted, and can be required. Where `sign` appears, the first (if any) of the sequence of characters returned by `positive_sign()` or `negative_sign()` (respectively as the monetary value is non-negative or negative) is required. Any remaining characters of the sign sequence are required after all other format components. Where `value` appears, the absolute numeric monetary value is required.

The format of the numeric monetary value is a decimal number:

- `value`: `units fractional_opt`  
- `decimal-point digits`
- `fractional`: `decimal-point digits_opt`
- `if frac_digits() returns a positive value, or`
- `value`: `units`
- `otherwise. The symbol decimal-point indicates the character returned by decimal_point()`. The other symbols are defined as follows:

- `units`: `digits`
- `digits thousands-sep units`
- `digits`: `adigit digits_opt`

In the syntax specification, the symbol `adigit` is any of the values `ct.widen(c)` for `c` in the range `'0'` through `'9'` (inclusive) and `ct` is a reference of type `const ctype<charT>&` obtained as described in the definitions of `money_get<>` and `money_put<>`. The symbol `thousands-sep` is the character returned by `thousands_sep()`. The space character used is the value `ct.widen(' ')`. Whitespace characters are those characters `c` for which `ci.is(space, c)` returns `true`. The number of digits required after the decimal point (if any) is exactly the value returned by `frac_digits()`.

The placement of thousands-separator characters (if any) is determined by the value returned by `grouping()`, defined identically as the member `numpunct<>::do_grouping()`.

---

253) An array of `char`, rather than an array of `part`, is specified for `pattern::field` purely for efficiency.
30.4.7.4.2 Members

- charT decimal_point() const;
- charT thousands_sep() const;
- string grouping() const;
- string_type curr_symbol() const;
- string_type positive_sign() const;
- string_type negative_sign() const;
- int frac_digits() const;
- pattern pos_format() const;
- pattern neg_format() const;

Each of these functions \( F \) returns the result of calling the corresponding virtual member function \( \text{do}_F() \).

30.4.7.4.3 Virtual functions

- charT do_decimal_point() const;
  
  Returns: The radix separator to use in case \( \text{do_frac_digits()} \) is greater than zero.

- charT do_thousands_sep() const;
  
  Returns: The digit group separator to use in case \( \text{do_grouping()} \) specifies a digit grouping pattern.

- string do_grouping() const;
  
  Returns: A pattern defined identically as, but not necessarily equal to, the result of \( \text{numpunct<charT>::do_grouping()} \).

- string_type do_curr_symbol() const;
  
  Returns: A string to use as the currency identifier symbol.

[Note 1: For specializations where the second template parameter is \text{true}, this is typically four characters long: a three-letter code as specified by ISO 4217\[1\] followed by a space. — end note]

- string_type do_positive_sign() const;
- string_type do_negative_sign() const;
  
  Returns: \( \text{do_positive_sign()} \) returns the string to use to indicate a positive monetary value; \( \text{do_negative_sign()} \) returns the string to use to indicate a negative value.

- int do_frac_digits() const;
  
  Returns: The number of digits after the decimal radix separator, if any.

- pattern do_pos_format() const;
- pattern do_neg_format() const;
  
  Returns: The specializations required in Table 108 (30.3.1.2.1), namely

  - \( \text{moneypunct<char>} \),
  - \( \text{moneypunct<wchar_t>} \),
  - \( \text{moneypunct<char, true>} \), and
  - \( \text{moneypunct<wchar_t, true>} \),

  return an object of type \( \text{pattern} \) initialized to \{ symbol, sign, none, value \}.

30.4.7.5 Class template moneypunct_byname

```cpp
namespace std {
  template<class charT, bool Intl = false>
  class moneypunct_byname : public moneypunct<charT, Intl> {
  public:
    using pattern = money_base::pattern;
  }
}
```

---

254) In common U.S. locales this is ".".
255) In common U.S. locales this is ",".
256) To specify grouping by 3s, the value is "\003" not "3".
257) This is usually the empty string.
258) In common U.S. locales, this is 2.
259) Note that the international symbol returned by \( \text{do_curr_symbol()} \) usually contains a space, itself; for example, "USD ".

§ 30.4.7.5 ©ISO/IEC 1738
using string_type = basic_string<charT>;

explicit moneypunctbyname(const char*, size_t refs = 0);
explicit moneypunctbyname(const string&, size_t refs = 0);

protected:
- moneypunctbyname();
};

30.4.8 The message retrieval category

30.4.8.1 General

1 Class messages<charT> implements retrieval of strings from message catalogs.

30.4.8.2 Class template messages

30.4.8.2.1 General

namespace std {
    class messages_base {
        public:
            using catalog = unspecified signed integer type;
        }

    template<class charT>
    class messages : public locale::facet, public messages_base {
        public:
            using char_type = charT;
            using string_type = basic_string<charT>;
            explicit messages(size_t refs = 0);
            catalog open(const string& fn, const locale&) const;
            string_type get(catalog c, int set, int msgid,
                const string_type& dfault) const;
            void close(catalog c) const;
            static locale::id id;
        protected:
            ~messages();
            virtual catalog do_open(const string&, const locale&) const;
            virtual string_type do_get(catalog, int set, int msgid,
                const string_type& dfault) const;
            virtual void do_close(catalog) const;
        }
    }

1 Values of type messages_base::catalog usable as arguments to members get and close can be obtained only by calling member open.

30.4.8.2.2 Members

catalog open(const string& name, const locale& loc) const;

1 Returns: do_open(name, loc).

string_type get(catalog cat, int set, int msgid, const string_type& dfault) const;

1 Returns: do_get(cat, set, msgid, dfault).

void close(catalog cat) const;

1 Effects: Calls do_close(cat).
30.4.8.2.3 Virtual functions

```cpp
catalog do_open(const string& name, const locale& loc) const;
```

1. **Returns**: A value that may be passed to `get()` to retrieve a message from the message catalog identified by the string `name` according to an implementation-defined mapping. The result can be used until it is passed to `close()`.

2. Returns a value less than 0 if no such catalog can be opened.

3. **Remarks**: The locale argument `loc` is used for character set code conversion when retrieving messages, if needed.

```cpp
string_type do_get(catalog cat, int set, intmsgid, const string_type& dfault) const;
```

4. **Preconditions**: `cat` is a catalog obtained from `open()` and not yet closed.

5. **Returns**: A message identified by arguments `set`, `msgid`, and `dfault`, according to an implementation-defined mapping. If no such message can be found, returns `dfault`.

```cpp
void do_close(catalog cat) const;
```

6. **Preconditions**: `cat` is a catalog obtained from `open()` and not yet closed.

7. **Effects**: Releases unspecified resources associated with `cat`.

8. **Remarks**: The limit on such resources, if any, is implementation-defined.

30.4.8.3 Class template `messages_byname`

```cpp
namespace std {
  template<class charT>
  class messages_byname : public messages<charT> {
  public:
    using catalog = messages_base::catalog;
    using string_type = basic_string<charT>;
    explicit messages_byname(const char*, size_t refs = 0);
    explicit messages_byname(const string&, size_t refs = 0);
    protected:
      ~messages_byname();
  }
}
```

30.5 C library locales

30.5.1 Header `<locale>` synopsis

```cpp
namespace std {
  struct lconv;
  char* setlocale(int category, const char* locale);
  lconv* localeconv();
}
```

1. The contents and meaning of the header `<locale>` are the same as the C standard library header `<locale.h>`.

30.5.2 Data races

1. Calls to the function `setlocale` may introduce a data race (16.4.6.10) with other calls to `setlocale` or with calls to the functions listed in Table 119.

See also: ISO/IEC 9899:2018, 7.11
Table 119 — Potential setlocale data races

<table>
<thead>
<tr>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>fprintf, isprint, iswdigit, localeconv, tolower</td>
</tr>
<tr>
<td>fscanf, ispunct, iswgraph, mblen, toupper</td>
</tr>
<tr>
<td>isalnum, isspace, iswlower, mbstowcs, towlower</td>
</tr>
<tr>
<td>isalpha, isupper, iswprint, mbtowc, towupper</td>
</tr>
<tr>
<td>isblank, iswalpha, iswpunct, setlocale, wcscoll</td>
</tr>
<tr>
<td>iscntrl, iswalnum, iswxdigit, strcoll, wcstod</td>
</tr>
<tr>
<td>isdigit, iswblank, iswupper, sterror, wcstombs</td>
</tr>
<tr>
<td>isgraph, iswcntrl, iswxdigit, strtod, wcsxfrm</td>
</tr>
<tr>
<td>islower, iswctype, isxdigit, strxfrm, wctomb</td>
</tr>
</tbody>
</table>

30.6 Text encodings identification

30.6.1 Header `<text_encoding>` synopsis

namespace std {
    struct text_encoding;
    
    // 30.6.2.7, hash support
    template<class T> struct hash;
    template<> struct hash<text_encoding>;
}

30.6.2 Class text_encoding

30.6.2.1 Overview

The class `text_encoding` describes an interface for accessing the IANA Character Sets registry[10].

namespace std {
    struct text_encoding {
        static constexpr size_t max_name_length = 63;
        
        // 30.6.2.6, enumeration text_encoding::id
        enum class id : int_least32_t {
            see below
        };
        using enum id;
        
        constexpr text_encoding() = default;
        constexpr explicit text_encoding(string_view enc) noexcept;
        constexpr text_encoding(id i) noexcept;
        
        constexpr id mib() const noexcept;
        constexpr const char* name() const noexcept;
        
        struct aliases_view;
        constexpr aliases_view aliases() const noexcept;
        
        friend constexpr bool operator==(const text_encoding& a,
        const text_encoding& b) noexcept;
        friend constexpr bool operator==(const text_encoding& encoding, id i) noexcept;
        
        static constexpr text_encoding literal() noexcept;
        static text_encoding environment();
        template<id i> static bool environment_is();
    }
}

§ 30.6.2.1
Class `text_encoding` is a trivially copyable type (6.8.1).

### 30.6.2.2 General

A *registered character encoding* is a character encoding scheme in the IANA Character Sets registry.

- **Note 1**: The IANA Character Sets registry uses the term “character sets” to refer to character encodings. — end note

The primary name of a registered character encoding is the name of that encoding specified in the IANA Character Sets registry.

The set of known registered character encodings contains every registered character encoding specified in the IANA Character Sets registry except for the following:

- (2.1) NATS-DANO (33)
- (2.2) NATS-DANO-ADD (34)

Each known registered character encoding is identified by an enumerator in `text_encoding::id`, and has a set of zero or more *aliases*.

The set of aliases of a known registered character encoding is an implementation-defined superset of the aliases specified in the IANA Character Sets registry. The set of aliases for US-ASCII includes “ASCII”. No two aliases or primary names of distinct registered character encodings are equivalent when compared by `text_encoding::comp-name`.

How a `text_encoding` object is determined to be representative of a character encoding scheme implemented in the translation or execution environment is implementation-defined.

An object `e` of type `text_encoding` such that `e.mib() == text_encoding::id::unknown` is false and `e.mib() == text_encoding::id::other` is false maintains the following invariants:

- (6.1) `e.name() == nullptr` is false, and
- (6.2) `e.mib() == text_encoding(e.name()).mib()` is true.

#### Recommended practice:

- (7.1) Implementations should not consider registered encodings to be interchangeable.
- **Example 1**: Shift_JIS and Windows-31J denote different encodings. — end example

- (7.2) Implementations should not use the name of a registered encoding to describe another similar yet different non-registered encoding unless there is a precedent on that implementation.
- **Example 2**: Big5 — end example

### 30.6.2.3 Members

```cpp
constexpr explicit text_encoding(string_view enc) noexcept;
```

- **Preconditions**:
  - (1.1) `enc` represents a string in the ordinary literal encoding consisting only of elements of the basic character set (5.3).
  - (1.2) `enc.size() <= max_name_length` is true.
  - (1.3) `enc.contains('\0')` is false.
- **Postconditions**:
  - (2.1) If there exists a primary name or alias `a` of a known registered character encoding such that `comp-name(a, enc)` is true, `mib_` has the value of the enumerator of `id` associated with that registered character encoding. Otherwise, `mib_ == id::other` is true.
  - (2.2) `enc.compare(name_) == 0` is true.

```cpp
constexpr text_encoding(id i) noexcept;
```

- **Preconditions**: `i` has the value of one of the enumerators of `id`.
- **Postconditions**:
  - (4.1) `mib_ == i` is true.
(4.2) If \( mib_ == \text{id::unknown} \) || \( mib_ == \text{id::other} \) is true, \( \text{strlen(name_)} == 0 \) is true. Otherwise, \( \text{ranges::contains(aliases(), string_view(name_))} \) is true.

```cpp
constexpr id mib() const noexcept;
Returns: mib_.
```

```cpp
constexpr const char* name() const noexcept;
Returns: name_ if \( \text{name_[0]} \neq '\0' \) is true, and nullptr otherwise.
```

**Remarks:** If \( \text{name()} == \text{nullptr} \) is false, \( \text{name()} \) is an NTBS and accessing elements of \( \text{name()} \) outside of the range \( \text{name()} + [0, \text{strlen(name()) + 1}] \) is undefined behavior.

```cpp
constexpr aliases_view aliases() const noexcept;
```

Let \( r \) denote an instance of \( \text{aliases_view} \). If \(*this\) represents a known registered character encoding, then:

1. \( r.\text{front()} \) is the primary name of the registered character encoding,
2. \( r \) contains the aliases of the registered character encoding, and
3. \( r \) does not contain duplicate values when compared with \( \text{strcmp} \).

Otherwise, \( r \) is an empty range.

Each element in \( r \) is a non-null, non-empty NTBS encoded in the literal character encoding and comprising only characters from the basic character set.

**Returns:** \( r \).

**[Note 1: The order of aliases in \( r \) is unspecified. — end note]**

```cpp
static consteval text_encoding literal() noexcept;
Mandates: \( \text{CHAR_BIT} == 8 \) is true.
Returns: A \text{text_encoding} object representing the ordinary character literal encoding (5.3).
```

```cpp
static text_encoding environment();
Mandates: \( \text{CHAR_BIT} == 8 \) is true.
Returns: A \text{text_encoding} object representing the implementation-defined character encoding scheme of the environment. On a POSIX implementation, this is the encoding scheme associated with the POSIX locale denoted by the empty string "".
```

**[Note 2: This function is not affected by calls to setlocale. — end note]**

**Recommended practice:** Implementations should return a value that is not affected by calls to the POSIX function \text{setenv} and other functions which can modify the environment (17.13).

```cpp
template<id i>
static bool environment_is();
Mandates: \( \text{CHAR_BIT} == 8 \) is true.
Returns: \text{environment()} == i.
```

```cpp
static constexpr bool comp-name(string_view a, string_view b);
Returns: true if the two strings \( a \) and \( b \) encoded in the ordinary literal encoding are equal, ignoring, from left-to-right,
1. all elements that are not digits or letters (16.3.3.4.1),
2. character case, and
3. any sequence of one or more 0 characters not immediately preceded by a numeric prefix, where a numeric prefix is a sequence consisting of a digit in the range \([1, 9]\) optionally followed by one or more elements which are not digits or letters,
and false otherwise.
```

**[Note 3: This comparison is identical to the “Charset Alias Matching” algorithm described in the Unicode Technical Standard 22][12]. — end note]**
Example 1:
static_assert(comp-name("UTF-8", "utf8") == true);
static_assert(comp-name("u.t.f-008", "utf8") == true);
static_assert(comp-name("utf8", "utf8") == false);
static_assert(comp-name("utf-80", "utf8") == false);
— end example

30.6.2.4 Comparison functions

friend constexpr bool operator==(const text_encoding& a, const text_encoding& b) noexcept;

Returns: If a.mib_ == id::other && b.mib_ == id::other is true, then comp-name(a.name_,
b.name_). Otherwise, a.mib_ == b.mib_.

friend constexpr bool operator==(const text_encoding& encoding, id i) noexcept;

Returns: encoding.mib_ == i.

Remarks: This operator induces an equivalence relation on its arguments if and only if i != id::other
is true.

30.6.2.5 Class text_encoding::aliases_view

struct text_encoding::aliases_view : ranges::view_interface<text_encoding::aliases_view> {
  constexpr implementation-defined begin() const;
  constexpr implementation-defined end() const;
};

text_encoding::aliases_view models copyable, ranges::view, ranges::random_access_range,
and ranges::borrowed_range.

Both ranges::range_value_t<text_encoding::aliases_view> and ranges::range_reference_t<text_encoding::aliases_view> denote const char*.

ranges::iterator_t<text_encoding::aliases_view> is a constexpr iterator (25.3.1).

30.6.2.6 Enumeration text_encoding::id

namespace std {
enum class text_encoding::id : int_least32_t {
  other = 1,
  unknown = 2,
  ASCII = 3,
  ISOLatin1 = 4,
  ISOLatin2 = 5,
  ISOLatin3 = 6,
  ISOLatin4 = 7,
  ISOLatinCyrillic = 8,
  ISOLatinArabic = 9,
  ISOLatinGreek = 10,
  ISOLatinHebrew = 11,
  ISOLatin5 = 12,
  ISOLatin6 = 13,
  ISUTextComm = 14,
  HalfWidthKatakana = 15,
  JISEncoding = 16,
  Shiftjis = 17,
  EUCPFxdFmtJapanese = 18,
  EUCPFxdWidJapanese = 19,
  ISO4UnitedKingdom = 20,
  ISO15SwedishForNames = 21,
  ISO15Italian = 22,
  ISO17Spanish = 23,
  ISO21German = 24,
  ISO60DanishNorwegian = 25,
  ISO69French = 26,
  ISO10646UTF1 = 27,
  ISO646Basic1983 = 28,
};
NATSEFFI = 31,
KSC56011987 = 36,
ISO2022KR = 37,
EUCKR = 38,
ISO2022JP = 39,
ISO2022JP2 = 40,
ISO13JISC6220jp = 41,
ISO14JISC6220ro = 42,
ISO16Portuguese = 43,
ISO18Greek70ld = 44,
ISO19LatinGreek = 45,
ISO25French = 46,
ISO27LatinGreek1 = 47,
ISO5427Cyrillic = 48,
ISO42JISC62261978 = 49,
ISO47BSViewdata = 50,
ISO49INIS = 51,
ISO50INIS8 = 52,
ISO51INIScyrillic = 53,
ISO54271981 = 54,
ISO5426Greek = 55,
ISO57GB1988 = 56,
ISO58GB231280 = 57,
ISO61Norwegian2 = 58,
ISO70VideotexSupp1 = 59,
ISO84Portuguese2 = 60,
ISO85Spanish2 = 61,
ISO86Hungarian = 62,
ISO87JISX0208 = 63,
ISO88Greek7 = 64,
ISO89ASM0449 = 65,
ISO90 = 66,
ISO91JISC62291984a = 67,
ISO92JISC62991984b = 68,
ISO93JIS62291984badd = 69,
ISO94JIS62291984hand = 70,
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ISO121Canadian1 = 78,
ISO122Canadian2 = 79,
ISO123CSAZ24341985gr = 80,
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ISO88596I = 82,
ISO128T101C2 = 83,
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ISO141JUSIB1002 = 87,
ISO143IECP271 = 88,
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ISO6937Add = 93,
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Amiga1251 = 2104,  
KO17swicthed = 2105,  
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TSCII = 2107,  
CP51932 = 2108,  
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windows1250 = 2250,  
windows1251 = 2251,  
windows1252 = 2252,  
windows1253 = 2253,  
windows1254 = 2254,  
windows1255 = 2255,  
windows1256 = 2256,  
windows1257 = 2257,  
windows1258 = 2258,  
TIS620 = 2259,  
CP60220 = 2260  
};

[Note 1: The text_encoding::id enumeration contains an enumerator for each known registered character encoding. For each encoding, the corresponding enumerator is derived from the alias beginning with “cs”, as follows

— csUnicode is mapped to text_encoding::id::UCS2,
— csIBM904 is mapped to text_encoding::id::IBM94, and
— the “cs” prefix is removed from other names.

—end note]

30.6.2.7 Hash support

30.6.2.7 Hash support

template<> struct hash<text_encoding>;

1 The specialization is enabled (22.10.19).
31 Input/output library

31.1 General

This Clause describes components that C++ programs may use to perform input/output operations.

The following subclauses describe requirements for stream parameters, and components for forward declarations of iostreams, predefined iostreams objects, base iostreams classes, stream buffering, stream formatting and manipulators, string streams, and file streams, as summarized in Table 120.

Table 120 — Input/output library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
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<tbody>
<tr>
<td>31.2</td>
<td>Requirements</td>
</tr>
<tr>
<td>31.3</td>
<td>Forward declarations</td>
</tr>
<tr>
<td>31.4</td>
<td>Standard iostream objects</td>
</tr>
<tr>
<td>31.5</td>
<td>Iostreams base classes</td>
</tr>
<tr>
<td>31.6</td>
<td>Stream buffers</td>
</tr>
<tr>
<td>31.7</td>
<td>Formatting and manipulators</td>
</tr>
<tr>
<td>31.8</td>
<td>String streams</td>
</tr>
<tr>
<td>31.9</td>
<td>Span-based streams</td>
</tr>
<tr>
<td>31.10</td>
<td>File streams</td>
</tr>
<tr>
<td>31.11</td>
<td>Synchronized output streams</td>
</tr>
<tr>
<td>31.12</td>
<td>File systems</td>
</tr>
<tr>
<td>31.13</td>
<td>C library files</td>
</tr>
</tbody>
</table>

31.2 Iostreams requirements

31.2.1 Imbue limitations

No function described in Clause 31 except for ios_base::imbue and basic_filebuf::pubimbue causes any instance of basic_ios::imbue or basic_streambuf::imbue to be called. If any user function called from a function declared in Clause 31 or as an overriding virtual function of any class declared in Clause 31 calls imbue, the behavior is undefined.

31.2.2 Types

using streamoff = implementation-defined;

The type streamoff is a synonym for one of the signed basic integral types of sufficient size to represent the maximum possible file size for the operating system.

using streamsize = implementation-defined;

The type streamsize is a synonym for one of the signed basic integral types. It is used to represent the number of characters transferred in an I/O operation, or the size of I/O buffers.

31.2.3 Positioning type limitations

The classes of Clause 31 with template arguments charT and traits behave as described if traits::pos_type and traits::off_type are streampos and streamoff respectively. Except as noted explicitly below, their behavior when traits::pos_type and traits::off_type are other types is implementation-defined.

[Note 1: For each of the specializations of char_traits defined in 23.2.4, state_type denotes mbstate_t, pos_type denotes fpos<mbstate_t>, and off_type denotes streamoff. — end note]

In the classes of Clause 31, a template parameter with name charT represents a member of the set of types containing char, wchar_t, and any other implementation-defined character container types (3.10) that meet the requirements for a character on which any of the iostream components can be instantiated.

260) Typically long long.
261) Most places where streamsize is used would use size_t in C, or ssize_t in POSIX.
31.2.4 Thread safety

Concurrent access to a stream object (31.8, 31.10), stream buffer object (31.6), or C Library stream (31.13) by multiple threads may result in a data race (6.9.2) unless otherwise specified (31.4).

[Note 1: Data races result in undefined behavior (6.9.2). — end note]

If one thread makes a library call \( a \) that writes a value to a stream and, as a result, another thread reads this value from the stream through a library call \( b \) such that this does not result in a data race, then \( a \)'s write synchronizes with \( b \)'s read.

31.3 Forward declarations

31.3.1 Header `<iosfwd>` synopsis

```cpp
namespace std {
    template<class charT> struct char_traits;
    template<> struct char_traits<char>;
    template<> struct char_traits<char8_t>;
    template<> struct char_traits<char16_t>;
    template<> struct char_traits<char32_t>;
    template<> struct char_traits<wchar_t>;
    template<class T> class allocator;

    template<class charT, class traits = char_traits<charT>>
        class basic_ios;
    template<class charT, class traits = char_traits<charT>>
        class basic_streambuf;
    template<class charT, class traits = char_traits<charT>>
        class basic_istream;
    template<class charT, class traits = char_traits<charT>>
        class basic_ostream;
    template<class charT, class traits = char_traits<charT>,
        class Allocator = allocator<charT>>
        class basic_stringbuf;
    template<class charT, class traits = char_traits<charT>,
        class Allocator = allocator<charT>>
        class basic_istringstream;
    template<class charT, class traits = char_traits<charT>,
        class Allocator = allocator<charT>>
        class basic_ostringstream;
    template<class charT, class traits = char_traits<charT>,
        class Allocator = allocator<charT>>
        class basic_stringstream;
    template<class charT, class traits = char_traits<charT>>
        class basic_spanbuf;
    template<class charT, class traits = char_traits<charT>>
        class basic_ispanstream;
    template<class charT, class traits = char_traits<charT>>
        class basic_ospanstream;
    template<class charT, class traits = char_traits<charT>>
        class basic_spanstream;
    template<class charT, class traits = char_traits<charT>>
        class basic_filebuf;
    template<class charT, class traits = char_traits<charT>>
        class basic_ifstream;
    template<class charT, class traits = char_traits<charT>>
        class basic_ofstream;
    template<class charT, class traits = char_traits<charT>>
        class basic_fstream;
}
```
template<
class charT, class traits = char_traits<charT>,
   class Allocator = allocator<charT>>
class basic_syncbuf;

template<
class charT, class traits = char_traits<charT>,
   class Allocator = allocator<charT>>
class basic_osyncstream;

template<
class charT, class traits = char_traits<charT>>
class istreambuf_iterator;

template<
class charT, class traits = char_traits<charT>>
class ostreambuf_iterator;

using ios = basic_ios<char>;
using wios = basic_ios<wchar_t>;

using streambuf = basic_streambuf<char>;
using istream = basic_istream<char>;
using ostream = basic_ostream<char>;
using iostream = basic_iostream<char>;

using stringbuf = basic_stringbuf<char>;
using istreambuf_iterator = basic_istreambuf_iterator<char>;
using ostringstream = basic_ostringstream<char>;
using spanstream = basic_spanstream<char>;

using filebuf = basic_filebuf<char>;
using ifstream = basic_ifstream<char>;
using ofstream = basic_ofstream<char>;
using fstream = basic_fstream<char>;

using wstreambuf = basic_streambuf<wchar_t>;
using wistream = basic_istream<wchar_t>;
using wostream = basic_ostream<wchar_t>;
using wiostream = basic_iostream<wchar_t>;

using wstringbuf = basic_stringbuf<wchar_t>;
using wistringstream = basic_istringstream<wchar_t>;
using wosystem = basic_ostringstream<wchar_t>;
using wspanstream = basic_spanstream<wchar_t>;

using wfilebuf = basic_filebuf<wchar_t>;
using wifstream = basic_ifstream<wchar_t>;
using wofstream = basic_ofstream<wchar_t>;
using wfstream = basic_fstream<wchar_t>;

template<class state> class fpos;
using streampos = fpos<char_traits<char>::state_type>;
using wstreampos = fpos<char_traits<wchar_t>::state_type>;

§ 31.3.1
using u8streampos = fpos<char_traits<char8_t>::state_type>;
using u16streampos = fpos<char_traits<char16_t>::state_type>;
using u32streampos = fpos<char_traits<char32_t>::state_type>;
}

Default template arguments are described as appearing both in `<iosfwd>` and in the synopsis of other headers but it is well-formed to include both `<iosfwd>` and one or more of the other headers.

### 31.3.2 Overview

The class template specialization `basic_ios<charT, traits>` serves as a virtual base class for the class templates `basic_istream`, `basic_ostream`, and class templates derived from them. `basic_iostream` is a class template derived from both `basic_istream<charT, traits>` and `basic_ostream<charT, traits>`.

The class template specialization `basic_streambuf<charT, traits>` serves as a base class for class templates `basic_stringbuf`, `basic_filebuf`, and `basic_syncbuf`.

The class template specialization `basic_istream<charT, traits>` serves as a base class for class templates `basic_istringstream` and `basic_ifstream`.

The class template specialization `basic_ostream<charT, traits>` serves as a base class for class templates `basic_ostringstream`, `basic_ofstream`, and `basic_osyncstream`.

The class template specialization `basic_iostream<charT, traits>` serves as a base class for class templates `basic_stringstream` and `basic_fstream`.

[Note 1: For each of the class templates above, the program is ill-formed if `traits: :char_type` is not the same type as `charT` (23.2). — end note]

Other `typedef-name`s define instances of class templates specialized for `char` or `wchar_t` types.

Specializations of the class template `fpos` are used for specifying file position information.

[Example 1: The types `streampos` and `wstreampos` are used for positioning streams specialized on `char` and `wchar_t` respectively. — end example]

[Note 2: This synopsis suggests a circularity between `streampos` and `char_traits<char>`. An implementation can avoid this circularity by substituting equivalent types. — end note]

### 31.4 Standard iostream objects

#### 31.4.1 Header `<iostream>` synopsis

```cpp
#include <ios>    // see 31.5.1
#include <streambuf>    // see 31.6.1
#include <iostream>    // see 31.7.1
#include <ostream>    // see 31.7.2

namespace std {
  extern istream cin;
  extern ostream cout;
  extern ostream cerr;
  extern ostream clog;

  extern wistream wcin;
  extern wostream wcout;
  extern wostream wcerr;
  extern wostream wclog;
}
```

#### 31.4.2 Overview

In this Clause, the type name `FILE` refers to the type `FILE` declared in `<cstdio>` (31.13.1).

The header `<iostream>` declares objects that associate objects with the standard C streams provided for by the functions declared in `<cstdio>`, and includes all the headers necessary to use these objects.

---

262) It is the implementation's responsibility to implement headers so that including `<iosfwd>` and other headers does not violate the rules about multiple occurrences of default arguments.
The objects are constructed and the associations are established at some time prior to or during the first
time an object of class `ios_base::Init` is constructed, and in any case before the body of `main` begins execution. The objects are not destroyed during program execution.\(^\text{263}\)

Recommended practice: If it is possible for them to do so, implementations should initialize the objects earlier than required.

The results of including `<iostream>` in a translation unit shall be as if `<iostream>` defined an instance of `ios_base::Init` with static storage duration. Each C++ library module (16.4.2.4) in a hosted implementation shall behave as if it contains an interface unit that defines an unexported `ios_base::Init` variable with

ordered initialization (6.9.3.3).

[Note 1: As a result, the definition of that variable is appearance-ordered before any declaration following the point of importation of a C++ library module. Whether such a definition exists is unobservable by a program that does not reference any of the standard iostream objects. — end note]

Mixing operations on corresponding wide- and narrow-character streams follows the same semantics as mixing such operations on FILEs, as specified in the C standard library.

Concurrent access to a synchronized (31.5.2.5) standard iostream object’s formatted and unformatted input (31.7.5.2) and output (31.7.6.2) functions or a standard C stream by multiple threads does not result in a data race (6.9.2).

[Note 2: Unsynchronized concurrent use of these objects and streams by multiple threads can result in interleaved characters. — end note]

See also: ISO/IEC 9899:2018, 7.21.2

### 31.4.3 Narrow stream objects

```cpp
istream cin;
```

1. The object `cin` controls input from a stream buffer associated with the object `stdin`, declared in `<cstdio>` (31.13.1).

2. After the object `cin` is initialized, `cin.tie()` returns `&cout`. Its state is otherwise the same as required for `basic_ios<char>::init` (31.5.4.2).

```cpp
ostream cout;
```

3. The object `cout` controls output to a stream buffer associated with the object `stdout`, declared in `<cstdio>` (31.13.1).

```cpp
ostream cerr;
```

4. The object `cerr` controls output to a stream buffer associated with the object `stderr`, declared in `<cstdio>` (31.13.1).

5. After the object `cerr` is initialized, `cerr.flags() & unitbuf` is nonzero and `cerr.tie()` returns `&cout`. Its state is otherwise the same as required for `basic_ios<char>::init` (31.5.4.2).

```cpp
ostream clog;
```

6. The object `clog` controls output to a stream buffer associated with the object `stderr`, declared in `<cstdio>` (31.13.1).

### 31.4.4 Wide stream objects

```cpp
wistream wcin;
```

1. The object `wcin` controls input from a stream buffer associated with the object `stdin`, declared in `<cstdio>` (31.13.1).

2. After the object `wcin` is initialized, `wcin.tie()` returns `&wcout`. Its state is otherwise the same as required for `basic_ios<wchar_t>::init` (31.5.4.2).

```cpp
wostream wcout;
```

3. The object `wcout` controls output to a stream buffer associated with the object `stdout`, declared in `<cstdio>` (31.13.1).

\(^{263}\) Constructors and destructors for objects with static storage duration can access these objects to read input from `stdin` or write output to `stdout` or `stderr`.
wostream wcerr;

The object wcerr controls output to a stream buffer associated with the object stderr, declared in <cstdio> (31.13.1).

After the object wcerr is initialized, wcerr.flags() & unitbuf is nonzero and wcerr.tie() returns &wcout. Its state is otherwise the same as required for basic_ios<wchar_t>::init (31.5.4.2).

wostream wclog;

The object wclog controls output to a stream buffer associated with the object stderr, declared in <cstdio> (31.13.1).

31.5 Iostreams base classes

31.5.1 Header <ios> synopsis

#include <iosfwd>  // see 31.3.1

namespace std {

    using streamoff = implementation-defined;
    using streamsize = implementation-defined;

    template<class stateT> class fpos;

    class ios_base;

    template<class charT, class traits = char_traits<charT>>
    class basic_ios;

    ios_base& boolalpha (ios_base& str);
    ios_base& noboolalpha(ios_base& str);

    ios_base& showbase (ios_base& str);
    ios_base& noshowbase (ios_base& str);

    ios_base& showpoint (ios_base& str);
    ios_base& noshowpoint(ios_base& str);

    ios_base& showpos (ios_base& str);
    ios_base& noshowpos (ios_base& str);

    ios_base& skipws (ios_base& str);
    ios_base& noskipws (ios_base& str);

    ios_base& uppercase (ios_base& str);
    ios_base& nouppercase(ios_base& str);

    ios_base& unitbuf (ios_base& str);
    ios_base& nounitbuf (ios_base& str);

    ios_base& internal (ios_base& str);
    ios_base& left (ios_base& str);
    ios_base& right (ios_base& str);

    ios_base& dec (ios_base& str);
    ios_base& hex (ios_base& str);
    ios_base& oct (ios_base& str);

    ios_base& fixed (ios_base& str);

}  // namespace std

§ 31.5.1
ios_base& scientific (ios_base& str);
ios_base& hexfloat (ios_base& str);
ios_base& defaultfloat(isos_base& str);

// 31.5.6, error reporting
enum class io_errc {
    stream = 1
};

namespace std {

    // Class ios_base

    // 31.5.2.2.2, fmtflags
    using fmtflags = T1;
    static constexpr fmtflags boolalpha = unspecified;
    static constexpr fmtflags dec = unspecified;
    static constexpr fmtflags fixed = unspecified;
    static constexpr fmtflags hex = unspecified;
    static constexpr fmtflags internal = unspecified;
    static constexpr fmtflags left = unspecified;
    static constexpr fmtflags oct = unspecified;
    static constexpr fmtflags right = unspecified;
    static constexpr fmtflags scientific = unspecified;
    static constexpr fmtflags showbase = unspecified;
    static constexpr fmtflags showpoint = unspecified;
    static constexpr fmtflags showpos = unspecified;
    static constexpr fmtflags skipws = unspecified;
    static constexpr fmtflags unitbuf = unspecified;
    static constexpr fmtflags uppercase = unspecified;
    static constexpr fmtflags adjustfield = unspecified;
    static constexpr fmtflags basefield = unspecified;
    static constexpr fmtflags floatfield = unspecified;

    // 31.5.2.2.3, iostate
    using iostate = T2;
    static constexpr iostate badbit = unspecified;
    static constexpr iostate eofbit = unspecified;
    static constexpr iostate failbit = unspecified;
    static constexpr iostate goodbit = unspecified;

    // 31.5.2.2.4, openmode
    using openmode = T3;
    static constexpr openmode app = unspecified;
    static constexpr openmode ate = unspecified;
    static constexpr openmode binary = unspecified;
    static constexpr openmode in = unspecified;
    static constexpr openmode noreplace = unspecified;
    static constexpr openmode out = unspecified;
    static constexpr openmode trunc = unspecified;

    // 31.5.2.2.5, seekdir
    using seekdir = T4;
    static constexpr seekdir beg = unspecified;
}
static constexpr seekdir cur = unspecified;
static constexpr seekdir end = unspecified;

class Init;

// 31.5.2.3, fmtflags state
fmtflags flags() const;
fmtflags flags(fmtflags fmtfl);
fmtflags setf(fmtflags fmtfl);
fmtflags setf(fmtflags fmtfl, fmtflags mask);
void unsetf(fmtflags mask);

streamsize precision() const;
streamsize precision(streamsize prec);
streamsize width() const;
streamsize width(streamsize wide);

// 31.5.2.4, locales
locale imbue(const locale& loc);
locale getloc() const;

// 31.5.2.6, storage
static int xalloc();
long& iword(int idx);
void*& pword(int idx);

// destructor
virtual ~ios_base();

// 31.5.2.7, callbacks
enum event { erase_event, imbue_event, copyfmt_event };
using event_callback = void (*)(event, ios_base&, int idx);
void register_callback(event_callback fn, int idx);

ios_base(const ios_base&) = delete;
ios_base& operator=(const ios_base&) = delete;

static bool sync_with_stdio(bool sync = true);

protected:
ios_base();

private:
static int index; // exposition only
long* iarray; // exposition only
void** parray; // exposition only
};

ios_base defines several member types:

(1.1) — a type failure, defined as either a class derived from system_error or a synonym for a class derived from system_error;

(1.2) — a class Init;

(1.3) — three bitmask types, fmtflags, iostate, and openmode;

(1.4) — an enumerated type, seekdir.

It maintains several kinds of data:

(2.1) — state information that reflects the integrity of the stream buffer;

(2.2) — control information that influences how to interpret (format) input sequences and how to generate (format) output sequences;

(2.3) — additional information that is stored by the program for its private use.
Note 1: For the sake of exposition, the maintained data is presented here as:

- `static int index`, specifies the next available unique index for the integer or pointer arrays maintained for the private use of the program, initialized to an unspecified value;
- `long* iarray`, points to the first element of an arbitrary-length `long` array maintained for the private use of the program;
- `void** parray`, points to the first element of an arbitrary-length pointer array maintained for the private use of the program.

— end note —

31.5.2.2 Types

31.5.2.2.1 Class `ios_base::failure`

namespace std {
    class ios_base::failure : public system_error {
    public:
        explicit failure(const string& msg, const error_code& ec = io_errc::stream);
        explicit failure(const char* msg, const error_code& ec = io_errc::stream);
    
    } // class ios_base::failure
}

1 An implementation is permitted to define `ios_base::failure` as a synonym for a class with equivalent functionality to class `ios_base::failure` shown in this subclause.

[Note 1: When `ios_base::failure` is a synonym for another type, that type needs to provide a nested type `failure` to emulate the injected-class-name. — end note]

The class `failure` defines the base class for the types of all objects thrown as exceptions, by functions in the iostreams library, to report errors detected during stream buffer operations.

2 When throwing `ios_base::failure` exceptions, implementations should provide values of `ec` that identify the specific reason for the failure.

[Note 2: Errors arising from the operating system would typically be reported as `system_category()` errors with an error value of the error number reported by the operating system. Errors arising from within the stream library would typically be reported as `error_code(io_errc::stream, iostream_category())`. — end note]

    explicit failure(const string& msg, const error_code& ec = io_errc::stream);

3    explicit failure(const char* msg, const error_code& ec = io_errc::stream);

4 Effects: Constructs the base class with `msg` and `ec`.

31.5.2.2.2 Type `ios_base::fmtflags`

    using fmtflags = T1;

1 The type `fmtflags` is a bitmask type (16.3.3.3.3). Setting its elements has the effects indicated in Table 121.

2 Type `fmtflags` also defines the constants indicated in Table 122.

31.5.2.2.3 Type `ios_base::iostate`

    using iostate = T2;

1 The type `iostate` is a bitmask type (16.3.3.3.3) that contains the elements indicated in Table 123.

2 Type `iostate` also defines the constant:

    — `goodbit`, the value zero.

31.5.2.2.4 Type `ios_base::openmode`

    using openmode = T3;

1 The type `openmode` is a bitmask type (16.3.3.3.3). It contains the elements indicated in Table 124.
### Table 121 — fmtflags effects  
**fmtflags** elements and their effects:

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect(s) if set</th>
</tr>
</thead>
<tbody>
<tr>
<td>boolalpha</td>
<td>insert and extract bool type in alphabetic format</td>
</tr>
<tr>
<td>dec</td>
<td>converts integer input or generates integer output in decimal base</td>
</tr>
<tr>
<td>fixed</td>
<td>generate floating-point output in fixed-point notation</td>
</tr>
<tr>
<td>hex</td>
<td>converts integer input or generates integer output in hexadecimal base</td>
</tr>
<tr>
<td>internal</td>
<td>adds fill characters at a designated internal point in certain generated output, or identical to right if no such point is designated</td>
</tr>
<tr>
<td>left</td>
<td>adds fill characters on the left (initial positions) of certain generated output</td>
</tr>
<tr>
<td>oct</td>
<td>converts integer input or generates integer output in octal base</td>
</tr>
<tr>
<td>right</td>
<td>adds fill characters on the right (final positions) of certain generated output</td>
</tr>
<tr>
<td>scientific</td>
<td>generates floating-point output in scientific notation</td>
</tr>
<tr>
<td>showbase</td>
<td>generates a prefix indicating the numeric base of generated integer output</td>
</tr>
<tr>
<td>shovpoint</td>
<td>generates a decimal-point character unconditionally in generated floating-point output</td>
</tr>
<tr>
<td>showpos</td>
<td>generates a + sign in non-negative generated numeric output</td>
</tr>
<tr>
<td>skipws</td>
<td>skips leading whitespace before certain input operations</td>
</tr>
<tr>
<td>unitbuf</td>
<td>flushes output after each output operation</td>
</tr>
<tr>
<td>uppercase</td>
<td>replaces certain lowercase letters with their uppercase equivalents in generated output</td>
</tr>
</tbody>
</table>

### Table 122 — fmtflags constants  
**fmtflags** constants and their allowable values:

<table>
<thead>
<tr>
<th>Constant</th>
<th>Allowable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>adjustfield</td>
<td>left</td>
</tr>
<tr>
<td>basefield</td>
<td>dec</td>
</tr>
<tr>
<td>floatfield</td>
<td>scientific</td>
</tr>
</tbody>
</table>

### Table 123 — iostate effects  
**iostate** elements and their effects:

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect(s) if set</th>
</tr>
</thead>
<tbody>
<tr>
<td>badbit</td>
<td>indicates a loss of integrity in an input or output sequence (such as an irrecoverable read error from a file);</td>
</tr>
<tr>
<td>eofbit</td>
<td>indicates that an input operation reached the end of an input sequence;</td>
</tr>
<tr>
<td>failbit</td>
<td>indicates that an input operation failed to read the expected characters, or that an output operation failed to generate the desired characters.</td>
</tr>
</tbody>
</table>

### Table 124 — openmode effects  
**openmode** effects:

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect(s) if set</th>
</tr>
</thead>
<tbody>
<tr>
<td>app</td>
<td>seek to end before each write</td>
</tr>
<tr>
<td>ate</td>
<td>open and seek to end immediately after opening</td>
</tr>
<tr>
<td>binary</td>
<td>perform input and output in binary mode (as opposed to text mode)</td>
</tr>
<tr>
<td>in</td>
<td>open for input</td>
</tr>
<tr>
<td>noreplace</td>
<td>open in exclusive mode</td>
</tr>
<tr>
<td>out</td>
<td>open for output</td>
</tr>
<tr>
<td>trunc</td>
<td>truncate an existing stream when opening</td>
</tr>
</tbody>
</table>
31.5.2.2.5 Type ios_base::seekdir

using seekdir = T4;

1 The type seekdir is an enumerated type (16.3.3.3.2) that contains the elements indicated in Table 125.

<table>
<thead>
<tr>
<th>Element</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>beg</td>
<td>request a seek (for subsequent input or output) relative to the beginning of the stream</td>
</tr>
<tr>
<td>cur</td>
<td>request a seek relative to the current position within the sequence</td>
</tr>
<tr>
<td>end</td>
<td>request a seek relative to the current end of the sequence</td>
</tr>
</tbody>
</table>

Table 125 — seekdir effects

31.5.2.2.6 Class ios_base::Init

namespace std {
    class ios_base::Init {
        public:
            Init();
            Init(const Init&) = default;
            ~Init();
            Init& operator=(const Init&) = default;

        private:
            static int init_cnt; // exposition only
    }
}

1 The class Init describes an object whose construction ensures the construction of the eight objects declared in <iostream> (31.4) that associate file stream buffers with the standard C streams provided for by the functions declared in <cstdio> (31.13.1).

2 For the sake of exposition, the maintained data is presented here as:

static int init_cnt, counts the number of constructor and destructor calls for class Init, initialized to zero.

Init();

Effects: Constructs and initializes the objects cin, cout, cerr, clog, wcin, wcout, wcerr, and wclog if they have not already been constructed and initialized.

~Init();

Effects: If there are no other instances of the class still in existence, calls cout.flush(), cerr.flush(), clog.flush(), wcout.flush(), wcerr.flush(), and wclog.flush().

31.5.2.3 State functions

fmtflags flags() const;

Returns: The format control information for both input and output.

fmtflags flags(fmtflags fmtfl);

Postconditions: fmtfl == flags().

Returns: The previous value of flags().

fmtflags setf(fmtflags fmtfl);

Effects: Sets fmtfl in flags().

Returns: The previous value of flags().

fmtflags setf(fmtflags fmtfl, fmtflags mask);

Effects: Clears mask in flags(), sets fmtfl & mask in flags().

Returns: The previous value of flags().
void unsetf(fmtflags mask);
    Effects: Clears mask in flags().
streamsize precision() const;
    Returns: The precision to generate on certain output conversions.
streamsize precision(streamsize prec);
    Postconditions: prec == precision().
    Returns: The previous value of precision().
streamsize width() const;
    Returns: The minimum field width (number of characters) to generate on certain output conversions.
streamsize width(streamsize wide);
    Postconditions: wide == width().
    Returns: The previous value of width().

31.5.2.4 Functions
    [ios.base.locales]
locale imbue(const locale& loc);
    Effects: Calls each registered callback pair (fn, idx) (31.5.2.7) as (*fn)(imbue_event, *this, idx) at such a time that a call to ios_base::getloc() from within fn returns the new locale value loc.
    Postconditions: loc == getloc().
    Returns: The previous value of getloc().
locale getloc() const;
    Returns: If no locale has been imbued, a copy of the global C++ locale, locale(), in effect at the time of construction. Otherwise, returns the imbued locale, to be used to perform locale-dependent input and output operations.

31.5.2.5 Static members
    [ios.members.static]
static bool sync_with_stdio(bool sync = true);
    Effects: If any input or output operation has occurred using the standard streams prior to the call, the effect is implementation-defined. Otherwise, called with a false argument, it allows the standard streams to operate independently of the standard C streams.
    Returns: true if the previous state of the standard iostream objects (31.4) was synchronized and otherwise returns false. The first time it is called, the function returns true.
    Remarks: When a standard iostream object str is synchronized with a standard stdio stream f, the effect of inserting a character c by
        fputc(f, c);
    is the same as the effect of
        str.rdbuf()->sputc(c);
    for any sequences of characters; the effect of extracting a character c by
        c = fgetc(f);
    is the same as the effect of
        c = str.rdbuf()->sbumpc();
    for any sequences of characters; and the effect of pushing back a character c by
        ungetc(c, f);
    is the same as the effect of
        str.rdbuf()->sputbackc(c);
for any sequence of characters.\textsuperscript{264}

31.5.2.6 Storage functions \textsuperscript{[ios.base.storage]}

\begin{verbatim}
static int xalloc();

Returns: index ++.

Remarks: Concurrent access to this function by multiple threads does not result in a data race (6.9.2).

long& ivord(int idx);

Preconditions: idex is a value obtained by a call to xalloc.

Effects: If iarray is a null pointer, allocates an array of long of unspecified size and stores a pointer to its first element in iarray. The function then extends the array pointed at by iarray as necessary to include the element iarray[idx]. Each newly allocated element of the array is initialized to zero. The reference returned is invalid after any other operation on the object.\textsuperscript{265} However, the value of the storage referred to is retained, so that until the next call to copyfmt, calling ivord with the same index yields another reference to the same value. If the function fails\textsuperscript{266} and \&this is a base class subobject of a basic_ios<> object or subobject, the effect is equivalent to calling basic_ios<>::setstate(badbit) on the derived object (which may throw failure).

Returns: On success iarray[idx]. On failure, a valid long& initialized to 0.

void*& pword(int idx);

Preconditions: idex is a value obtained by a call to xalloc.

Effects: If parray is a null pointer, allocates an array of pointers to void of unspecified size and stores a pointer to its first element in parray. The function then extends the array pointed at by parray as necessary to include the element parray[idx]. Each newly allocated element of the array is initialized to a null pointer. The reference returned is invalid after any other operation on the object. However, the value of the storage referred to is retained, so that until the next call to copyfmt, calling pword with the same index yields another reference to the same value. If the function fails\textsuperscript{267} and *this is a base class subobject of a basic_ios<> object or subobject, the effect is equivalent to calling basic_ios<>::setstate(badbit) on the derived object (which may throw failure).

Returns: On success parray[idx]. On failure a valid void*& initialized to 0.

Remarks: After a subsequent call to pword(int) for the same object, the earlier return value may no longer be valid.

31.5.2.7 Callbacks \textsuperscript{[ios.base.callback]}

\begin{verbatim}
void register_callback(event_callback fn, int idx);

Preconditions: The function fn does not throw exceptions.

Effects: Registers the pair (fn, idx) such that during calls to imbue() (31.5.2.4), copyfmt(), or ~ios_base() (31.5.2.8), the function fn is called with argument idx. Functions registered are called when an event occurs, in opposite order of registration. Functions registered while a callback function is active are not called until the next event.

Remarks: Identical pairs are not merged. A function registered twice will be called twice.

31.5.2.8 Constructors and destructor \textsuperscript{[ios.base.cons]}

\begin{verbatim}
ios_base();

Effects: Each ios_base member has an indeterminate value after construction. The object’s members shall be initialized by calling basic_ios::init before the object’s first use or before it is destroyed, whichever comes first; otherwise the behavior is undefined.
\end{verbatim}

\textsuperscript{264} This implies that operations on a standard iostream object can be mixed arbitrarily with operations on the corresponding stdio stream. In practical terms, synchronization usually means that a standard iostream object and a standard stdio object share a buffer.

\textsuperscript{265} An implementation is free to implement both the integer array pointed at by iarray and the pointer array pointed at by parray as sparse data structures, possibly with a one-element cache for each.

\textsuperscript{266} For example, because it cannot allocate space.

\textsuperscript{267} For example, because it cannot allocate space.
Effects: Calls each registered callback pair (fn, idx) (31.5.2.7) as (*fn)(erase_event, *this, idx) at such time that any ios_base member function called from within fn has well-defined results. Then, any memory obtained is deallocated.

31.5.3 Class template fpos

31.5.3.1 General

```cpp
namespace std {
    template<class stateT> class fpos {
        public:
            // 31.5.3.2, members
            stateT state() const;
            void state(stateT);

        private:
            stateT st;    // exposition only
    };
}
```

31.5.3.2 Members

```cpp
void state(stateT s);
```

Effects: Assigns s to st.

```cpp
stateT state() const;
```

Returns: Current value of st.

31.5.3.3 Requirements

An fpos type specifies file position information. It holds a state object whose type is equal to the template parameter stateT. Type stateT shall meet the Cpp17DefaultConstructible (Table 30), Cpp17CopyConstructible (Table 32), Cpp17CopyAssignable (Table 34), and Cpp17Destructible (Table 35) requirements. If is_trivially_copy_constructible_v<stateT> is true, then fpos<stateT> has a trivial copy constructor. If is_trivially_copyAssignable_v<stateT> is true, then fpos<stateT> has a trivial copy assignment operator. If is_trivially_destructible_v<stateT> is true, then fpos<stateT> has a trivial destructor. All specializations of fpos meet the Cpp17DefaultConstructible, Cpp17CopyConstructible, Cpp17CopyAssignable, Cpp17Destructible, and Cpp17EqualityComparable (Table 28) requirements. In addition, the expressions shown in Table 126 are valid and have the indicated semantics. In that table,

1. P refers to a specialization of fpos,
2. p and q refer to values of type P or const P,
3. pl and ql refer to modifiable lvalues of type P,
4. 0 refers to type streamoff, and
5. o and o2 refer to values of type streamoff or const streamoff.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(o)</td>
<td>P</td>
<td>converts from offset</td>
<td>Effects: Value-initializes the state object.</td>
</tr>
<tr>
<td>P p(o);</td>
<td>P</td>
<td></td>
<td>Effects: Value-initializes the state object.</td>
</tr>
<tr>
<td>P p = o;</td>
<td></td>
<td></td>
<td>Postconditions: p == P(o) is true.</td>
</tr>
<tr>
<td>P()</td>
<td>P</td>
<td>P(0)</td>
<td>P(0(p)) == p</td>
</tr>
<tr>
<td>P p;</td>
<td>P</td>
<td>P p(0);</td>
<td></td>
</tr>
<tr>
<td>0(p)</td>
<td>streamoff</td>
<td>converts to offset</td>
<td></td>
</tr>
</tbody>
</table>

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Table 126 — Position type requirements (continued)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note pre-/post-condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>p == q</td>
<td>bool</td>
<td></td>
<td>Remarks: For any two values o and o2, if p is obtained from o converted to P or from a copy of such P value and if q is obtained from o2 converted to P or from a copy of such P value, then p == q is true only if o == o2 is true.</td>
</tr>
<tr>
<td>p != q</td>
<td>bool</td>
<td>!(p == q)</td>
<td>Remarks: With ql = p + o; then: q1 - o == p</td>
</tr>
<tr>
<td>p + o</td>
<td>P</td>
<td>+ offset</td>
<td>Remarks: With ql = p + o; before the +=, then: pl - o == q1</td>
</tr>
<tr>
<td>pl += o</td>
<td>P&amp;</td>
<td>+= offset</td>
<td>Remarks: With ql = pl; before the +=, then: pl - o == q1</td>
</tr>
<tr>
<td>p - o</td>
<td>P</td>
<td>- offset</td>
<td>Remarks: With ql = p - o; then: q1 + o == p</td>
</tr>
<tr>
<td>pl -= o</td>
<td>P&amp;</td>
<td>-= offset</td>
<td>Remarks: With ql = pl; before the -=, then: pl + o == q1</td>
</tr>
<tr>
<td>o + p</td>
<td>convertible to P</td>
<td>p + o</td>
<td>P(o + p) == p + o</td>
</tr>
<tr>
<td>p - q</td>
<td>streamoff</td>
<td>distance</td>
<td>p == q + (p - q)</td>
</tr>
</tbody>
</table>

2 Stream operations that return a value of type traits::pos_type return P(O(-1)) as an invalid value to signal an error. If this value is used as an argument to any istream, ostream, or streambuf member that accepts a value of type traits::pos_type then the behavior of that function is undefined.

31.5.4 Class template basic_ios

31.5.4.1 Overview

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ios : public ios_base {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;

            // 31.5.4.4, flags functions
            explicit operator bool() const;
            bool operator!() const;
            iostate rdstate() const;
            void clear(iostate state = goodbit);
            void setstate(iostate state);
            bool good() const;
            bool eof() const;
            bool fail() const;
            bool bad() const;
            iostate exceptions() const;
            void exceptions(iostate except);

            // 31.5.4.2, constructor/destructor
            explicit basic_ios(basic_streambuf<charT, traits>* sb);
            virtual ~basic_ios();

            // 31.5.4.3, members
            basic_ostream<charT, traits>* tie() const;
            basic_ostream<charT, traits>* tie(basic_ostream<charT, traits>* tiestr);
    }
};
```

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§ 31.5.4.2

31.5.4.2 Constructors

explicit basic_ios(basic_streambuf<charT, traits>* sb);

Effects: Assigns initial values to its member objects by calling init(sb).

basic_ios();

Effects: Leaves its member objects uninitialized. The object shall be initialized by calling basic_ios::init before its first use or before it is destroyed, whichever comes first; otherwise the behavior is undefined.

~basic_ios();

Remarks: The destructor does not destroy rdbuf().

void init(basic_streambuf<charT, traits>* sb);

Postconditions: The postconditions of this function are indicated in Table 127.

Table 127 — basic_ios::init() effects

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdbuf()</td>
<td>sb</td>
</tr>
<tr>
<td>tie()</td>
<td>0</td>
</tr>
<tr>
<td>rdstate()</td>
<td>goodbit if sb is not a null pointer, otherwise badbit.</td>
</tr>
<tr>
<td>exceptions()</td>
<td>goodbit</td>
</tr>
<tr>
<td>flags()</td>
<td>skipws</td>
</tr>
<tr>
<td>width()</td>
<td>0</td>
</tr>
<tr>
<td>precision()</td>
<td>6</td>
</tr>
<tr>
<td>fill()</td>
<td>widen(' ')</td>
</tr>
<tr>
<td>getloc()</td>
<td>a copy of the value returned by locale()</td>
</tr>
<tr>
<td>tarray</td>
<td>a null pointer</td>
</tr>
<tr>
<td>parray</td>
<td>a null pointer</td>
</tr>
</tbody>
</table>


31.5.4.3 Member functions

basic_ostream<charT, traits>* tie() const;

Returns: An output sequence that is tied to (synchronized with) the sequence controlled by the stream buffer.

basic_ostream<charT, traits>* tie(basic_ostream<charT, traits>* tiestr);

Preconditions: If tiestr is not null, tiestr is not reachable by traversing the linked list of tied stream objects starting from tiestr->tie().

Postconditions: tiestr == tie().

Returns: The previous value of tie().

basic_streambuf<charT, traits>* rdbuf() const;

Returns: A pointer to the streambuf associated with the stream.

basic_streambuf<charT, traits>* rdbuf(basic_streambuf<charT, traits>* sb);

Effects: Calls clear().

Postconditions: sb == rdbuf().

Returns: The previous value of rdbuf().

locale imbue(const locale& loc);

Effects: Calls ios_base::imbue(loc) (31.5.2.4) and if rdbuf() != 0 then rdbuf()->pubimbue(loc) (31.6.3.3.1).

Returns: The prior value of ios_base::imbue().

char narrow(char_type c, char dfault) const;

Returns: use_facet<ctype<char_type>>{getloc()}.narrow(c, dfault)

char_type widen(char c) const;

Returns: use_facet<ctype<char_type>>{getloc()}.widen(c)

char_type fill() const;

Returns: The character used to pad (fill) an output conversion to the specified field width.

char_type fill(char_type fillch);

Postconditions: traits::eq(fillch, fill()).

Returns: The previous value of fill().

basic_ios& copyfmt(const basic_ios& rhs);

Effects: If (this == addressof(rhs)) is true does nothing. Otherwise assigns to the member objects of *this the corresponding member objects of rhs as follows:

(16.1) calls each registered callback pair (fn, idx) as (*fn)(erase_event, *this, idx);

(16.2) then, assigns to the member objects of *this the corresponding member objects of rhs, except that

(16.2.1) rdstate(), rdbuf(), and exceptions() are left unchanged;

(16.2.2) the contents of arrays pointed at by pword and iword are copied, not the pointers themselves;\footnote{This suggests an infinite amount of copying, but the implementation can keep track of the maximum element of the arrays that is nonzero.}

(16.2.3) if any newly stored pointer values in *this point at objects stored outside the object rhs and those objects are destroyed when rhs is destroyed, the newly stored pointer values are altered to point at newly constructed copies of the objects;

(16.3) then, calls each callback pair that was copied from rhs as (*fn)(copyfmt_event, *this, idx);

(16.4) then, calls exceptions(rhs.exceptions()).

\footnote{This suggests an infinite amount of copying, but the implementation can keep track of the maximum element of the arrays that is nonzero.}
[Note 1: The second pass through the callback pairs permits a copied pword value to be zeroed, or to have its referent deep copied or reference counted, or to have other special action taken. — end note]

Postconditions: The postconditions of this function are indicated in Table 128.

Table 128 — basic_ios::copyfmt() effects

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdbuf()</td>
<td>unchanged</td>
</tr>
<tr>
<td>tie()</td>
<td>rhs.tie()</td>
</tr>
<tr>
<td>rdstate()</td>
<td>unchanged</td>
</tr>
<tr>
<td>exceptions()</td>
<td>rhs.exceptions()</td>
</tr>
<tr>
<td>flags()</td>
<td>rhs.flags()</td>
</tr>
<tr>
<td>width()</td>
<td>rhs.width()</td>
</tr>
<tr>
<td>precision()</td>
<td>rhs.precision()</td>
</tr>
<tr>
<td>fill()</td>
<td>rhs.fill()</td>
</tr>
<tr>
<td>getloc()</td>
<td>rhs.getloc()</td>
</tr>
</tbody>
</table>

Returns: *this.

void move(basic_ios& rhs);
void move(basic_ios&& rhs);

Postconditions: *this has the state that rhs had before the function call, except that rdbuf() returns nullptr. rhs is in a valid but unspecified state, except that rhs.rdbuf() returns the same value as it returned before the function call, and rhs.tie() returns nullptr.

void swap(basic_ios& rhs) noexcept;

Effects: The states of *this and rhs are exchanged, except that rdbuf() returns the same value as it returned before the function call, and rhs.rdbuf() returns the same value as it returned before the function call.

void set_rdbuf(basic_streambuf<charT, traits>* sb);

Preconditions: sb != nullptr is true.

Effects: Associates the basic_streambuf object pointed to by sb with this stream without calling clear().

Postconditions: rdbuf() == sb is true.

Throws: Nothing.

31.5.4.4 Flags functions

explicit operator bool() const;

Returns: !fail().

bool operator!() const;

Returns: fail().

iostate rdstate() const;

Returns: The error state of the stream buffer.

void clear(iostate state = goodbit);

Effects: If ((state | (rdbuf() ? goodbit : badbit)) & exceptions()) == 0, returns. Otherwise, the function throws an object of class ios_base::failure (31.5.2.2.1), constructed with implementation-defined argument values.

Postconditions: If rdbuf() != 0 then state == rdstate(); otherwise rdstate() == (state | ios_base::badbit).

void setstate(iostate state);
bool good() const;
    \textit{Returns:} \texttt{rdstate() == 0}

bool eof() const;
    \textit{Returns:} true if \texttt{eofbit} is set in \texttt{rdstate}().

bool fail() const;
    \textit{Returns:} true if \texttt{failbit} or \texttt{badbit} is set in \texttt{rdstate}().

bool bad() const;
    \textit{Returns:} true if \texttt{badbit} is set in \texttt{rdstate}().

iostate exceptions() const;
    \textit{Returns:} A mask that determines what elements set in \texttt{rdstate()} cause exceptions to be thrown.

void exceptions(iostate except);
    \textit{Effects:} Calls \texttt{clear(rdstate())}.

\textit{Postconditions:} except == exceptions().

\section*{31.5.5 \texttt{ios} base manipulators\[std.ios.manip]}

\subsection*{31.5.5.1 \texttt{fmtflags} manipulators\[fmtflags.manip]}

Each function specified in this subclause is a designated addressable function (16.4.5.2.1).

\begin{verbatim}
ios_base& boolalpha(ios_base& str);
    \textit{Effects:} Calls \texttt{str.setf(ios_base::boolalpha)}.
    \textit{Returns:} \texttt{str}.

ioe_base& noboolalpha(ios_base& str);
    \textit{Effects:} Calls \texttt{str.unsetf(ios_base::boolalpha)}.
    \textit{Returns:} \texttt{str}.

ios_base& showbase(ios_base& str);
    \textit{Effects:} Calls \texttt{str.setf(ios_base::showbase)}.
    \textit{Returns:} \texttt{str}.

ios_base& noshowbase(ios_base& str);
    \textit{Effects:} Calls \texttt{str.unsetf(ios_base::showbase)}.
    \textit{Returns:} \texttt{str}.

ios_base& showpoint(ios_base& str);
    \textit{Effects:} Calls \texttt{str.setf(ios_base::showpoint)}.
    \textit{Returns:} \texttt{str}.

ios_base& noshowpoint(ios_base& str);
    \textit{Effects:} Calls \texttt{str.unsetf(ios_base::showpoint)}.
    \textit{Returns:} \texttt{str}.

ios_base& showpos(ios_base& str);
    \textit{Effects:} Calls \texttt{str.setf(ios_base::showpos)}.
    \textit{Returns:} \texttt{str}.

ios_base& noshowpos(ios_base& str);
    \textit{Effects:} Calls \texttt{str.unsetf(ios_base::showpos)}.
\end{verbatim}

\footnote{Checking \texttt{badbit} also for \texttt{fail()} is historical practice.}
N4986

17  Returns: str.
    ios_base& skipws(ios_base& str);
18  Effects: Calls str.setf(ios_base::skipws).
19  Returns: str.
    ios_base& noskipws(ios_base& str);
20  Effects: Calls str.unsetf(ios_base::skipws).
21  Returns: str.
    ios_base& uppercase(ios_base& str);
22  Effects: Calls str.setf(ios_base::uppercase).
23  Returns: str.
    ios_base& nouppercase(ios_base& str);
24  Effects: Calls str.unsetf(ios_base::uppercase).
25  Returns: str.
    ios_base& unitbuf(ios_base& str);
26  Effects: Calls str.setf(ios_base::unitbuf).
27  Returns: str.
    ios_base& nounitbuf(ios_base& str);
28  Effects: Calls str.unsetf(ios_base::unitbuf).
29  Returns: str.

31.5.5.2 adjustfield manipulators
[adjustfield.manip]
1 Each function specified in this subclause is a designated addressable function (16.4.5.2.1).
    ios_base& internal(ios_base& str);
2  Effects: Calls str.setf(ios_base::internal, ios_base::adjustfield).
3  Returns: str.
    ios_base& left(ios_base& str);
4  Effects: Calls str.setf(ios_base::left, ios_base::adjustfield).
5  Returns: str.
    ios_base& right(ios_base& str);
6  Effects: Calls str.setf(ios_base::right, ios_base::adjustfield).
7  Returns: str.

31.5.5.3 basefield manipulators
[basefield.manip]
1 Each function specified in this subclause is a designated addressable function (16.4.5.2.1).
    ios_base& dec(ios_base& str);
2  Effects: Calls str.setf(ios_base::dec, ios_base::basefield).
3  Returns: str.  
    ios_base& hex(ios_base& str);
4  Effects: Calls str.setf(ios_base::hex, ios_base::basefield).
5  Returns: str.

270) The function signature dec(ios_base&) can be called by the function signature basic_ostream& stream::operator<<(ios_base& (*)(ios_base&)) to permit expressions of the form cout << dec to change the format flags stored in cout.
31.5.4 floatfield manipulators

Each function specified in this subclause is a designated addressable function (16.4.5.2.1).

ios_base& fixed(ios_base& str);
Effects: Calls str.setf(ios_base::fixed, ios_base::floatfield).
Returns: str.

ios_base& scientific(ios_base& str);
Effects: Calls str.setf(ios_base::scientific, ios_base::floatfield).
Returns: str.

ios_base& hexfloat(ios_base& str);
Effects: Calls str.setf(ios_base::fixed | ios_base::scientific, ios_base::floatfield).
Returns: str.

Note 1: ios_base::hex cannot be used to specify a hexadecimal floating-point format, because it is not part of ios_base::floatfield (Table 122). —end note

ios_base& defaultfloat(ios_base& str);
Effects: Calls str.unsetf(ios_base::floatfield).
Returns: str.

31.5.6 Error reporting

error_code make_error_code(io_errc e) noexcept;
Returns: error_code(static_cast<int>(e), iostream_category()).

error_condition make_error_condition(io_errc e) noexcept;
Returns: error_condition(static_cast<int>(e), iostream_category()).

const error_category& iostream_category() noexcept;
Returns: A reference to an object of a type derived from class error_category.

The object’s default_error_condition and equivalent virtual functions shall behave as specified for the class error_category. The object’s name virtual function shall return a pointer to the string "iostream".

31.6 Stream buffers

31.6.1 Header <streambuf> synopsis

namespace std {
    // 31.6.3, class template basic_streambuf
    template<class charT, class traits = char_traits<charT>>
    class basic_streambuf;
    using streambuf = basic_streambuf<char>;
    using wstreambuf = basic_streambuf<wchar_t>;
}

The header <streambuf> defines types that control input from and output to character sequences.

31.6.2 Stream buffer requirements

Stream buffers can impose various constraints on the sequences they control. Some constraints are:

(1.1) — The controlled input sequence can be not readable.
(1.2) — The controlled output sequence can be not writable.
The controlled sequences can be associated with the contents of other representations for character sequences, such as external files.

The controlled sequences can support operations directly to or from associated sequences.

The controlled sequences can impose limitations on how the program can read characters from a sequence, write characters to a sequence, put characters back into an input sequence, or alter the stream position.

Each sequence is characterized by three pointers which, if non-null, all point into the same charT array object. The array object represents, at any moment, a (sub)sequence of characters from the sequence. Operations performed on a sequence alter the values stored in these pointers, perform reads and writes directly to or from associated sequences, and alter “the stream position” and conversion state as needed to maintain this subsequence relationship. The three pointers are:

- the beginning pointer, or lowest element address in the array (called xbeg here);
- the next pointer, or next element address that is a current candidate for reading or writing (called xnext here);
- the end pointer, or first element address beyond the end of the array (called xend here).

The following semantic constraints shall always apply for any set of three pointers for a sequence, using the pointer names given immediately above:

- If xnext is not a null pointer, then xbeg and xend shall also be non-null pointers into the same charT array, as described above; otherwise, xbeg and xend shall also be null.
- If xnext is not a null pointer and xnext < xend for an output sequence, then a write position is available. In this case, *xnext shall be assignable as the next element to write (to put, or to store a character value, into the sequence).
- If xnext is not a null pointer and xbeg < xnext for an input sequence, then a putback position is available. In this case, xnext[-1] shall have a defined value and is the next (preceding) element to store a character that is put back into the input sequence.
- If xnext is not a null pointer and xnext < xend for an input sequence, then a read position is available. In this case, *xnext shall have a defined value and is the next element to read (to get, or to obtain a character value, from the sequence).

### 31.6.3 Class template basic_streambuf

#### 31.6.3.1 General

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_streambuf {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;

            virtual ~basic_streambuf();

            // 31.6.3.1, locales
            locale pubimbue(const locale& loc);
            locale getloc() const;

            // 31.6.3.2, buffer and positioning
            basic_streambuf* pubsetbuf(char_type* s, streamsize n);
            pos_type pubseekoff(off_type off, ios_base::seekdir way,
                                ios_base::openmode which
                                = ios_base::in | ios_base::out);
            pos_type pubseekpos(pos_type sp,
                                ios_base::openmode which
                                = ios_base::in | ios_base::out);
            int pubsync();
    }
}
```

§ 31.6.3.1 ©ISO/IEC 1770
// get and put areas
// 31.6.3.3, get area
streamsize in_avail();
int_type snextc();
int_type sbumpc();
int_type sgetc();
streamsize sgetn(char_type* s, streamsize n);

// 31.6.3.4, putback
int_type sputbackc(char_type c);
int_type sungetc();

// 31.6.3.5, put area
int_type sputc(char_type c);
streamsize sputn(const char_type* s, streamsize n);

protected:
  basic_streambuf();
  basic_streambuf(const basic_streambuf& rhs);
  basic_streambuf& operator=(const basic_streambuf& rhs);
  void swap(basic_streambuf& rhs);

// 31.6.3.4.2, get area access
char_type* eback() const;
char_type* gptr() const;
char_type* egptr() const;
void gbump(int n);
void setg(char_type* gbeg, char_type* gnext, char_type* gend);

// 31.6.3.4.3, put area access
char_type* pbase() const;
char_type* pptr() const;
char_type* epptr() const;
void pbump(int n);
void setp(char_type* pbeg, char_type* pend);

// 31.6.3.5, virtual functions
// 31.6.3.5.1, locales
virtual void imbue(const locale& loc);

// 31.6.3.5.2, buffer management and positioning
virtual basic_streambuf* setbuf(char_type* s, streamsize n);
virtual pos_type seekoff(off_type off, ios_base::seekdir way,
                           ios_base::openmode which
                           = ios_base::in | ios_base::out);
virtual pos_type seekpos(pos_type sp,
                           ios_base::openmode which
                           = ios_base::in | ios_base::out);
virtual int sync();

// 31.6.3.5.3, get area
virtual streamsize showmanynyc();
virtual streamsize xsgetn(char_type* s, streamsize n);
virtual int_type underflow();
virtual int_type uflow();

// 31.6.3.5.4, putback
virtual int_type pbackfail(int_type c = traits::eof());

// 31.6.3.5.5, put area
virtual streamsize xsputn(const char_type* s, streamsize n);
virtual int_type overflow(int_type c = traits::eof());
The class template basic_streambuf serves as a base class for deriving various stream buffers whose objects each control two character sequences:

(1.1) — a character input sequence;
(1.2) — a character output sequence.

### 31.6.3.2 Constructors

```cpp
basic_streambuf();
```

*Effects:* Initializes:

(1.1) — all pointer member objects to null pointers,
(1.2) — the getloc() member to a copy of the global locale, locale(), at the time of construction.

*Remarks:* Once the getloc() member is initialized, results of calling locale member functions, and of members of facets so obtained, can safely be cached until the next time the member imbue is called.

```cpp
basic_streambuf(const basic_streambuf& rhs);
```

*Postconditions:*

(3.1) — eback() == rhs.eback()
(3.2) — gptr() == rhs.gptr()
(3.3) — egptr() == rhs.egptr()
(3.4) — pbase() == rhs.pbase()
(3.5) — pptr() == rhs.pptr()
(3.6) — epptr() == rhs.epptr()
(3.7) — getloc() == rhs.getloc()

```cpp
~basic_streambuf();
```

*Effects:* None.

### 31.6.3.3 Public member functions

#### 31.6.3.3.1 Locales

```cpp
locale pubimbue(const locale& loc);
```

*Effects:* Calls imbue(loc).

*Postconditions:* loc == getloc().

*Returns:* Previous value of getloc().

```cpp
locale getloc() const;
```

*Returns:* If pubimbue() has ever been called, then the last value of loc supplied, otherwise the current global locale, locale(), in effect at the time of construction. If called after pubimbue() has been called but before pubimbue has returned (i.e., from within the call of imbue()) then it returns the previous value.

#### 31.6.3.3.2 Buffer management and positioning

```cpp
basic_streambuf* pubsetbuf(char_type* s, streamsize n);
```

*Returns:* setbuf(s, n).

```cpp
pos_type pubseekoff(off_type off, ios_base::seekdir way,
                   ios_base::openmode which
                   = ios_base::in | ios_base::out);
```

*Returns:* seekoff(off, way, which).

---

271) The default constructor is protected for class basic_streambuf to assure that only objects for classes derived from this class can be constructed.
pos_type pubseekpos(pos_type sp,
    ios_base::openmode which
    = ios_base::in | ios_base::out);

Returns: seekpos(sp, which).

int pubsync();

Returns: sync().

31.6.3.3 Get area

streamsize in_avail();

Returns: If a read position is available, returns egptr() - gptr(). Otherwise returns showmanyc()
(31.6.3.5.3).

int_type snextc();

Effects: Calls sbumpc().

Returns: If that function returns traits::eof(), returns traits::eof(). Otherwise, returns sgetc().

int_type sbumpc();

Effects: If the input sequence read position is not available, returns uflow(). Otherwise, returns
traits::to_int_type(*gptr()) and increments the next pointer for the input sequence.

int_type sgetc();

Returns: If the input sequence read position is not available, returns underflow(). Otherwise, returns
traits::to_int_type(*gptr()).

streamsize sgetn(char_type* s, streamsize n);

Returns: xsgetn(s, n).

31.6.3.3.4 Putback

int_type sputbackc(char_type c);

Effects: If the input sequence putback position is not available, or if traits::eq(c, gptr()[-1]) is
false, returns pbackfail(traits::to_int_type(c)). Otherwise, decrements the next pointer for
the input sequence and returns traits::to_int_type(*gptr()).

int_type sungetc();

Effects: If the input sequence putback position is not available, returns pbackfail(). Otherwise,
decrements the next pointer for the input sequence and returns traits::to_int_type(*gptr()).

31.6.3.3.5 Put area

int_type sputc(char_type c);

Effects: If the output sequence write position is not available, returns overflow(traits::to_int_type(c)). Otherwise, stores c at the next pointer for the output sequence, increments the pointer, and
returns traits::to_int_type(c).

streamsize sputn(const char_type* s, streamsize n);

Returns: xsputn(s, n).

31.6.3.4 Protected member functions

31.6.3.4.1 Assignment

basic_streambuf& operator=(const basic_streambuf& rhs);

Postconditions:

(1.1) — eback() == rhs.eback()
(1.2) — gptr() == rhs.gptr()
(1.3) — egptr() == rhs.egptr()
— \( pbase() == rhs.pbase() \)
— \( pptr() == rhs.pptr() \)
— \( epptr() == rhs.epptr() \)
— \( getloc() == rhs.getloc() \)

2 \( \text{Returns: } *\text{this.} \)

void swap(basic_streambuf& rhs);
3 \( \text{Effects: Swaps the data members of } rhs \text{ and } *\text{this.} \)

31.6.3.4.2 Get area access \[\text{streambuf.get.area}\]

char_type* eback() const;
1 \( \text{Returns: The beginning pointer for the input sequence.} \)

char_type* gptr() const;
2 \( \text{Returns: The next pointer for the input sequence.} \)

char_type* egptr() const;
3 \( \text{Returns: The end pointer for the input sequence.} \)

void gbump(int n);
4 \( \text{Effects: Adds } n \text{ to the next pointer for the input sequence.} \)

void setg(char_type* gbeg, char_type* gnext, char_type* gend);
5 \( \text{Preconditions: } [\text{gbeg}, \text{gnext}), [\text{gbeg}, \text{gend}), \text{and } [\text{gnext}, \text{gend}) \text{ are all valid ranges.} \)
6 \( \text{Postconditions: } \text{gbeg} == \text{eback}(), \text{gnext} == \text{gptr}(), \text{and } \text{gend} == \text{egptr}() \text{ are all true.} \)

31.6.3.4.3 Put area access \[\text{streambuf.put.area}\]

char_type* pbase() const;
1 \( \text{Returns: The beginning pointer for the output sequence.} \)

char_type* pptr() const;
2 \( \text{Returns: The next pointer for the output sequence.} \)

char_type* epptr() const;
3 \( \text{Returns: The end pointer for the output sequence.} \)

void pbump(int n);
4 \( \text{Effects: Adds } n \text{ to the next pointer for the output sequence.} \)

void setp(char_type* pbeg, char_type* pend);
5 \( \text{Preconditions: } [\text{pbeg}, \text{pend}) \text{ is a valid range.} \)
6 \( \text{Postconditions: } \text{pbeg} == \text{pbase}(), \text{pbeg} == \text{pptr}(), \text{and } \text{pend} == \text{epptr}() \text{ are all true.} \)

31.6.3.5 Virtual functions \[\text{streambuf.virtuals}\]
31.6.3.5.1 Locales \[\text{streambuf.virt.locales}\]

void imbue(const locale&);
1 \( \text{Effects: Change any translations based on locale.} \)

2 \( \text{Remarks: Allows the derived class to be informed of changes in locale at the time they occur. Between} \)
\( \text{invocations of this function a class derived from streambuf can safely cache results of calls to locale} \)
\( \text{functions and to members of facets so obtained.} \)

3 \( \text{Default behavior: Does nothing.} \)
31.6.3.5.2 Buffer management and positioning

basic_streambuf* setbuf(char_type* s, streamsize n);

Effects: Influences stream buffering in a way that is defined separately for each class derived from basic_streambuf in this Clause (31.8.2.5, 31.10.3.5).

Default behavior: Does nothing. Returns this.

pos_type seekoff(off_type off, ios_base::seekdir way, ios_base::openmode which = ios_base::in | ios_base::out);

Effects: Alters the stream positions within one or more of the controlled sequences in a way that is defined separately for each class derived from basic_streambuf in this Clause (31.8.2.5, 31.10.3.5).

Default behavior: Returns pos_type(off_type(-1)).

pos_type seekpos(pos_type sp, ios_base::openmode which = ios_base::in | ios_base::out);

Effects: Alters the stream positions within one or more of the controlled sequences in a way that is defined separately for each class derived from basic_streambuf in this Clause (31.8.2, 31.10.3).

Default behavior: Returns pos_type(off_type(-1)).

int sync();

Effects: Synchronizes the controlled sequences with the arrays. That is, if pbase() is non-null the characters between pbase() and pptr() are written to the controlled sequence. The pointers may then be reset as appropriate.

Returns: -1 on failure. What constitutes failure is determined by each derived class (31.10.3.5).

Default behavior: Returns zero.

31.6.3.5.3 Get area

streamsize showmanyc();

Returns: An estimate of the number of characters available in the sequence, or -1. If it returns a positive value, then successive calls to underflow() will not return traits::eof() until at least that number of characters have been extracted from the stream. If showmanyc() returns -1, then calls to underflow() or uflow() will fail.

Default behavior: Returns zero.

Remarks: Uses traits::eof().

streamsize xsgetn(char_type* s, streamsize n);

Effects: Assigns up to n characters to successive elements of the array whose first element is designated by s. The characters assigned are read from the input sequence as if by repeated calls to sbumpc(). Assigning stops when either n characters have been assigned or a call to sbumpc() would return traits::eof().

Returns: The number of characters assigned.

Remarks: Uses traits::eof().

int_type underflow();

The pending sequence of characters is defined as the concatenation of

(7.1) the empty sequence if gptr() is null, otherwise the characters in [gptr(), egptr()), followed by

(7.2) some (possibly empty) sequence of characters read from the input sequence.

---

272) The morphemes of showmanyc are “es-how-many-see”, not “show-manic”.

273) underflow or uflow can fail by throwing an exception prematurely. The intention is not only that the calls will not return eof() but that they will return “immediately”.

274) Classes derived from basic_streambuf can provide more efficient ways to implement xsgetn() and xsputn() by overriding these definitions from the base class.
The **result character** is the first character of the pending sequence if it is non-empty, otherwise the next character that would be read from the input sequence.

The **backup sequence** is the empty sequence if `eback()` is null, otherwise the characters in `[eback(), gptr())`.

**Effects**: The function sets up the `gptr()` and `egptr()` such that if the pending sequence is non-empty, then `egptr()` is non-null and the characters in `[gptr(), egptr())` are the characters in the pending sequence, otherwise either `gptr()` is null or `gptr() == egptr()`.

If `eback()` and `gptr()` are non-null then the function is not constrained as to their contents, but the “usual backup condition” is that either

1. the backup sequence contains at least `gptr() - eback()` characters, in which case the characters in `[eback(), gptr())` agree with the last `gptr() - egptr()` characters of the backup sequence, or
2. the characters in `[gptr() - n, gptr())` agree with the backup sequence (where `n` is the length of the backup sequence).

**Returns**: `traits::to_int_type(c)`, where `c` is the first character of the pending sequence, without moving the input sequence position past it. If the pending sequence is null then the function returns `traits::eof()` to indicate failure.

**Default behavior**: Returns `traits::eof()`.

**Remarks**: The public members of `basic_streambuf` call this virtual function only if `gptr()` is null or `gptr() >= egptr()`.

```
int_type uflow();
```

**Preconditions**: The constraints are the same as for `underflow()`, except that the result character is transferred from the pending sequence to the backup sequence, and the pending sequence is not empty before the transfer.

**Default behavior**: Calls `underflow()`. If `underflow()` returns `traits::eof()`, returns `traits::eof()`. Otherwise, returns the value of `traits::to_int_type(*gptr())` and increments the value of the next pointer for the input sequence.

**Returns**: `traits::eof()` to indicate failure.

### 31.6.3.5.4 Putback

```
int_type pbackfail(int_type c = traits::eof());
```

**Effects**: The **pending sequence** is defined as for `underflow()`, with the modifications that

1. If `traits::eq_int_type(c, traits::eof())` returns `true`, then the input sequence is backed up one character before the pending sequence is determined.
2. If `traits::eq_int_type(c, traits::eof())` returns `false`, then `c` is prepended. Whether the input sequence is backed up or modified in any other way is unspecified.

**Postconditions**: On return, the constraints of `gptr()`, `eback()`, and `pptr()` are the same as for `underflow()`.

**Returns**: `traits::eof()` to indicate failure. Failure may occur because the input sequence could not be backed up, or if for some other reason the pointers cannot be set consistent with the constraints. `pbackfail()` is called only when put back has really failed.

Returns some value other than `traits::eof()` to indicate success.

**Default behavior**: Returns `traits::eof()`.

**Remarks**: The public functions of `basic_streambuf` call this virtual function only when `gptr()` is null, `gptr() == eback()`, or `traits::eq(traits::to_char_type(c), gptr()[-1])` returns `false`. Other calls shall also satisfy that constraint.

### 31.6.3.5.5 Put area

```
streamsize xsputn(const char_type* s, streamsize n);
```

**Effects**: Writes up to `n` characters to the output sequence as if by repeated calls to `sputc(c)`. The characters written are obtained from successive elements of the array whose first element is designated
by \(s\). Writing stops when either \(n\) characters have been written or a call to \(\text{sputc}(c)\) would return \(\text{traits::eof()}\). It is unspecified whether the function calls \(\text{overflow()}\) when \(\text{pptr()} == \text{epptr()}\) becomes \(\text{true}\) or whether it achieves the same effects by other means.

2 Returns: The number of characters written.

\[
\text{int}_\text{type} \text{overflow}(\text{int}_\text{type} c = \text{traits::eof}());
\]

3 Effects: Consumes some initial subsequence of the characters of the pending sequence. The pending sequence is defined as the concatenation of

(3.1) the empty sequence if \(\text{pbase()}\) is null, otherwise the \(\text{pptr()} - \text{pbase()}\) characters beginning at \(\text{pbase()}\), followed by

(3.2) the empty sequence if \(\text{traits::eq_int_type}(c, \text{traits::eof()})\) returns \(\text{true}\), otherwise the sequence consisting of \(c\).

4 Preconditions: Every overriding definition of this virtual function obeys the following constraints:

(4.1) The effect of consuming a character on the associated output sequence is specified.\(^{275}\)

(4.2) Let \(r\) be the number of characters in the pending sequence not consumed. If \(r\) is nonzero then \(\text{pbase()}\) and \(\text{pptr()}\) are set so that: \(\text{pptr()} - \text{pbase()} == r\) and the \(r\) characters starting at \(\text{pbase()}\) are the associated output stream. In case \(r\) is zero (all characters of the pending sequence have been consumed) then either \(\text{pbase()}\) is set to \(\text{nullptr}\), or \(\text{pbase()}\) and \(\text{pptr()}\) are both set to the same non-null value.

(4.3) The function may fail if either appending some character to the associated output stream fails or if it is unable to establish \(\text{pbase()}\) and \(\text{pptr()}\) according to the above rules.

5 Returns: \(\text{traits::eof()}\) or throws an exception if the function fails. Otherwise, returns some value other than \(\text{traits::eof()}\) to indicate success.\(^{276}\)

6 Default behavior: Returns \(\text{traits::eof()}\).

7 Remarks: The member functions \(\text{sputc()}\) and \(\text{sputn()}\) call this function in case that no room can be found in the put buffer enough to accommodate the argument character sequence.

31.7 Formatting and manipulators

31.7.1 Header <istream> synopsis

 namespace std {
    // 31.7.5.2, class template basic_istream
    template<class charT, class traits = char_traits<charT>>
    class basic_istream;

    using istream = basic_istream<char>;
    using wistream = basic_istream<wchar_t>;

    // 31.7.5.7, class template basic_iostream
    template<class charT, class traits = char_traits<charT>>
    class basic_iostream;

    using iostream = basic_iostream<char>;
    using wiostream = basic_iostream<wchar_t>;

    // 31.7.5.5, standard basic_istream manipulators
    template<class charT, class traits>
    basic_istream<charT, traits>& ws(basic_istream<charT, traits>& is);

    // 31.7.5.6, rvalue stream extraction
    template<class Istream, class T>
    Istream& operator>>(Istream& is, T& x);
}
31.7.2 Header <ostream> synopsis
namespace std {
    // 31.7.6.2, class template basic_ostream
    template<class charT, class traits = char_traits<charT>>
    class basic_ostream;

    using ostream = basic_ostream<char>;
    using wostream = basic_ostream<wchar_t>;

    // 31.7.6.5, standard basic_ostream manipulators
    template<class charT, class traits>
    basic_ostream<charT, traits>& endl(basic_ostream<charT, traits>& os);
    template<class charT, class traits>
    basic_ostream<charT, traits>& ends(basic_ostream<charT, traits>& os);
    template<class charT, class traits>
    basic_ostream<charT, traits>& flush(basic_ostream<charT, traits>& os);
    template<class charT, class traits>
    basic_ostream<charT, traits>& emit_on_flush(basic_ostream<charT, traits>& os);
    template<class charT, class traits>
    basic_ostream<charT, traits>& noemit_on_flush(basic_ostream<charT, traits>& os);
    template<class charT, class traits>
    basic_ostream<charT, traits>& flush_emit(basic_ostream<charT, traits>& os);

    template<class charT, class traits>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const charT& x);

    template<class charT, class traits, class Allocator>
    unspecified quoted(const basic_string<charT, traits, Allocator>& s,
                        charT delim = charT('"'), charT escape = charT('\'));
}

31.7.3 Header <iomanip> synopsis
namespace std {
    // 31.7.7, standard manipulators
    unspecified resetiosflags(ios_base::fmtflags mask);
    unspecified setiosflags (ios_base::fmtflags mask);
    unspecified setbase(int base);
    template<class charT>
    unspecified setfill(charT c);
    unspecified setprecision(int n);
    unspecified setw(int n);

    // 31.7.8, extended manipulators
    template<class moneyT> unspecified get_money(moneyT& mon, bool intl = false);
    template<class moneyT> unspecified put_money(const moneyT& mon, bool intl = false);
    template<class charT> unspecified get_time(tm* tmb, const charT* fmt);
    template<class charT> unspecified put_time(const tm* tmb, const charT* fmt);

    // 31.7.9, quoted manipulators
    template<class charT>
    unspecified quoted(const charT* s, charT delim = charT('"'), charT escape = charT('\\'));
    template<class charT, class traits, class Allocator>
    unspecified quoted(const basic_string<charT, traits, Allocator>& s,
                        charT delim = charT('"'), charT escape = charT('\\'));
}
template<class charT, class traits, class Allocator>
    unspecified quoted(basic_string<charT, traits, Allocator>& s,
        charT delim = charT('"'), charT escape = charT('\'));

template<class charT, class traits>
    unspecified quoted(basic_string_view<charT, traits> s,
        charT delim = charT('"'), charT escape = charT('\'));

31.7.4 Header <print> synopsis

namespace std {
    // 31.7.10, print functions
    template<class... Args>
    void print(format_string<Args...> fmt, Args&&... args);
    template<class... Args>
    void print(FILE* stream, format_string<Args...> fmt, Args&&... args);

    template<class... Args>
    void println(format_string<Args...> fmt, Args&&... args);
    void println();
    template<class... Args>
    void println(FILE* stream, format_string<Args...> fmt, Args&&... args);
    void println(FILE* stream);

    void vprint_unicode(string_view fmt, format_args args);
    void vprint_unicode(FILE* stream, string_view fmt, format_args args);

    void vprint_nonunicode(string_view fmt, format_args args);
    void vprint_nonunicode(FILE* stream, string_view fmt, format_args args);
}

31.7.5 Input streams

31.7.5.1 General

The header <istream> defines two class templates and a function template that control input from a stream
buffer, along with a function template that extracts from stream rvalues.

31.7.5.2 Class template basic_istream

31.7.5.2.1 General

When a function is specified with a type placeholder of extended-floating-point-type, the implementation
provides overloads for all cv-unqualified extended floating-point types (6.8.2) in lieu of extended-floating-
point-type.

namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_istream : virtual public basic_ios<charT, traits> { public:
        // types (inherited from basic_ios (31.5.4))
        using char_type = charT;
        using int_type = typename traits::int_type;
        using pos_type = typename traits::pos_type;
        using off_type = typename traits::off_type;
        using traits_type = traits;

        // 31.7.5.2.2, constructor/destructor
        explicit basic_istream(basic_streambuf<charT, traits>** sb);
        virtual ~basic_istream();

        // 31.7.5.2.4, prefix/suffix
        class sentry;
    }
// 31.7.5.3, formatted input
basic_istream& operator>>(basic_istream& (*pf)(basic_istream&));
basic_istream& operator>>(basic_ios<charT, traits>& (*pf)(basic_ios<charT, traits>&));
basic_istream& operator>>(ios_base& (*pf)(ios_base&));
basic_istream& operator>>(bool& n);
basic_istream& operator>>(short& n);
basic_istream& operator>>(unsigned short& n);
basic_istream& operator>>(int& n);
basic_istream& operator>>(unsigned int& n);
basic_istream& operator>>(long& n);
basic_istream& operator>>(unsigned long& n);
basic_istream& operator>>(long long& n);
basic_istream& operator>>(unsigned long long& n);
basic_istream& operator>>(float& f);
basic_istream& operator>>(double& f);
basic_istream& operator>>(long double& f);
basic_istream& operator>>(extended-floating-point-type& f);
basic_istream& operator>>(void*& p);
basic_istream& operator>>(basic_streambuf<char_type, traits>* sb);

// 31.7.5.4, unformatted input
streamsize gcount() const;
int_type get();
basic_istream& get(char_type& c);
basic_istream& get(char_type* s, streamsize n);
basic_istream& get(char_type* s, streamsize n, char_type delim);
basic_istream& get(basic_streambuf<char_type, traits>& sb);
basic_istream& get(basic_streambuf<char_type, traits>& sb, char_type delim);
basic_istream& getline(char_type* s, streamsize n);
basic_istream& getline(char_type* s, streamsize n, char_type delim);
basic_istream& ignore(streamsize n = 1, int_type delim = traits::eof());
int_type peek();
streamsize read (char_type* s, streamsize n);
streamsize readsome (char_type* s, streamsize n);
basic_istream& putback(char_type c);
basic_istream& unget();
int sync();

pos_type tellg();
basic_istream& seekg(pos_type);
basic_istream& seekg(off_type, ios_base::seekdir);

protected:
// 31.7.5.2.2, copy/move constructor
basic_istream(const basic_istream&) = delete;
basic_istream(basic_istream&& rhs);

// 31.7.5.2.3, assignment and swap
basic_istream& operator=(const basic_istream&); = delete;
basic_istream& operator=(basic_istream&& rhs);
void swap(basic_istream& rhs);
};

// 31.7.5.3.3, character extraction templates
template<class charT, class traits>
    basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>&, charT&);
template<class traits>
    basic_istream<char, traits>& operator>>(basic_istream<char, traits>&, unsigned char&);

§ 31.7.5.2.1
template<class traits>
    basic_istream<char, traits>& operator>>(basic_istream<char, traits>&, signed char&);

template<class charT, class traits, size_t N>
    basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>&, charT(&)[N]);

template<class traits, size_t N>
    basic_istream<char, traits>& operator>>(basic_istream<char, traits>&, unsigned char(&)[N]);

The class template basic_istream defines a number of member function signatures that assist in reading and interpreting input from sequences controlled by a stream buffer.

Two groups of member function signatures share common properties: the formatted input functions (or extractors) and the unformatted input functions. Both groups of input functions are described as if they obtain (or extract) input characters by calling rdbuf()->sgetc() or rdbuf()->sgetc(). They may use other public members of istream.

### 31.7.5.2.2 Constructors

```cpp
explicit basic_istream(basic_streambuf<charT, traits>* sb);
```

**Effects:** Initializes the base class subobject with basic_ios::init(sb) (31.5.4.2).

**Postconditions:** gcount() == 0.

```cpp
basic_istream(basic_istream&& rhs);
```

**Effects:** Default constructs the base class, copies the gcount() from rhs, calls basic_ios<charT, traits>::move(rhs) to initialize the base class, and sets the gcount() for rhs to 0.

**Remarks:** Does not perform any operations of rdbuf().

### 31.7.5.2.3 Assignment and swap

```cpp
basic_istream& operator=(basic_istream&& rhs);
```

**Effects:** Equivalent to swap(rhs).

**Returns:** *this.

```cpp
void swap(basic_istream& rhs);
```

**Effects:** Calls basic_ios<charT, traits>::swap(rhs). Exchanges the values returned by gcount() and rhs.gcount().

### 31.7.5.2.4 Class basic_istream::sentry

```cpp
namespace std {
    template<class charT, class traits>
    class basic_istream<charT, traits>::sentry {
        bool ok_; // exposition only

        public:
            explicit sentry(basic_istream& is, bool noskipws = false);
            ~sentry();
            explicit operator bool() const { return ok_; }
            sentry(const sentry&) = delete;
            sentry& operator=(const sentry&) = delete;
    };
}
```

The class sentry defines a class that is responsible for doing exception safe prefix and suffix operations.

```cpp
explicit sentry(basic_istream& is, bool noskipws = false);
```

**Effects:** If is.good() is false, calls is.setstate(failbit). Otherwise, prepares for formatted or unformatted input. First, if is.tie() is not a null pointer, the function calls is.tie() -> flush()
to synchronize the output sequence with any associated external C stream. Except that this call can be suppressed if the put area of \texttt{is.tie()} is empty. Further an implementation is allowed to defer the call to \texttt{flush} until a call of \texttt{is.rdbuf()->underflow()} occurs. If no such call occurs before the \texttt{sentry} object is destroyed, the call to \texttt{flush} may be eliminated entirely.\footnote{This will be possible only in functions that are part of the library. The semantics of the constructor used in user code is as specified.} If \texttt{noskipws} is zero and \texttt{is.flags()} & \texttt{ios_base::skipws} is nonzero, the function extracts and discards each character as long as the next available input character \texttt{c} is a whitespace character. If \texttt{is.rdbuf()->sbumpc()} or \texttt{is.rdbuf()->sgetc()} returns \texttt{traits::eof()}, the function calls \texttt{setstate(failbit | eofbit)} (which may throw \texttt{ios_base::failure}).

\textbf{Remarks:} The constructor

\begin{verbatim}
explicit sentry(basic_istream& is, bool noskipws = false)
uses the currently imbued locale in \texttt{is}, to determine whether the next input character is whitespace or not.

To decide if the character \texttt{c} is a whitespace character, the constructor performs as if it executes the following code fragment:

\begin{verbatim}
const ctype<charT>& ctype = use_facet<ctype<charT>>(is.getloc());
if (ctype.is(ctype.space, c) != 0)
   // \texttt{c} is a whitespace character.
\end{verbatim}
\end{verbatim}

If, after any preparation is completed, \texttt{is.good()} is \texttt{true}, \texttt{ok_} != \texttt{false} otherwise, \texttt{ok_} == \texttt{false}.

During preparation, the constructor may call \texttt{setstate(failbit)} (which may throw \texttt{ios_base::failure}).\footnote{The \texttt{sentry} constructor and destructor can also perform additional implementation-dependent operations.}

\begin{verbatim}
~sentry();
\end{verbatim}

\textbf{Effects:} None.

\begin{verbatim}
explicit operator bool() const;
\end{verbatim}

\textbf{Returns:} \texttt{ok_}.

\section{Formatted input functions}

\subsection{Common requirements}

Each formatted input function begins execution by constructing an object of type \texttt{ios_base::iostate}, termed the local error state, and initializing it to \texttt{ios_base::goodbit}. It then creates an object of class \texttt{sentry} with the \texttt{noskipws} (second) argument \texttt{false}. If the \texttt{sentry} object returns \texttt{true}, when converted to a value of type \texttt{bool}, the function endeavors to obtain the requested input. Otherwise, if the \texttt{sentry} constructor exits by throwing an exception or if the \texttt{sentry} object produces \texttt{false} when converted to a value of type \texttt{bool}, the function returns without attempting to obtain any input. If \texttt{rdbuf()-&gt;sbumpc()} or \texttt{rdbuf()-&gt;sgetc()} returns \texttt{traits::eof()}, then \texttt{ios_base::eofbit} is set in the local error state and the input function stops trying to obtain the requested input. If an exception is thrown during input then \texttt{ios_base::badbit} is set in the local error state, \texttt{*this}'s error state is set to the local error state, and the exception is rethrown if \texttt{(exceptions() & badbit) != 0}. After extraction is done, the input function calls \texttt{setstate}, which sets \texttt{*this}'s error state to the local error state, and may throw an exception. In any case, the formatted input function destroys the \texttt{sentry} object. If no exception has been thrown, it returns \texttt{*this}.

\subsection{Arithmetic extractors}

\begin{verbatim}
basic_istream& operator&gt;&gt;(unsigned short& val);
basic_istream& operator&gt;&gt;(unsigned int& val);
basic_istream& operator&gt;&gt;(long& val);
basic_istream& operator&gt;&gt;(unsigned long& val);
basic_istream& operator&gt;&gt;(long long& val);
basic_istream& operator&gt;&gt;(float& val);
basic_istream& operator&gt;&gt;(double& val);
basic_istream& operator&gt;&gt;(long double& val);
basic_istream& operator&gt;&gt;(bool& val);
\end{verbatim}
basic_istream& operator>>(void*& val);

1  As in the case of the inserter, these extractors depend on the locale's num_get<> (30.4.3.2) object to perform parsing the input stream data. These extractors behave as formatted input functions (as described in 31.7.5.3.1). After a sentry object is constructed, the conversion occurs as if performed by the following code fragment, where state represents the input function's local error state:

   using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
   use_facet<numget>(loc).get(*this, 0, *this, state, val);

In the above fragment, loc stands for the private member of the basic_ios class.

[Note 1: The first argument provides an object of the istreambuf_iterator class which is an iterator pointed to an input stream. It bypasses istreams and uses streambufs directly. — end note]

Class locale relies on this type as its interface to istream, so that it does not need to depend directly on istream.

basic_istream& operator>>(short& val);

2  The conversion occurs as if performed by the following code fragment (using the same notation as for the preceding code fragment):

   using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
   long lval;
   use_facet<numget>(loc).get(*this, 0, *this, state, lval);
   if (lval < numeric_limits<short>::min()) {
      state |= ios_base::failbit;
      val = numeric_limits<short>::min();
   } else if (numeric_limits<short>::max() < lval) {
      state |= ios_base::failbit;
      val = numeric_limits<short>::max();
   } else
      val = static_cast<short>(lval);

basic_istream& operator>>(int& val);

3  The conversion occurs as if performed by the following code fragment (using the same notation as for the preceding code fragment):

   using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
   long lval;
   use_facet<numget>(loc).get(*this, 0, *this, state, lval);
   if (lval < numeric_limits<int>::min()) {
      state |= ios_base::failbit;
      val = numeric_limits<int>::min();
   } else if (numeric_limits<int>::max() < lval) {
      state |= ios_base::failbit;
      val = numeric_limits<int>::max();
   } else
      val = static_cast<int>(lval);

basic_istream& operator>>(extended-floating-point-type& val);

4  If the floating-point conversion rank of extended-floating-point-type is not less than or equal to that of long double, then an invocation of the operator function is conditionally supported with implementation-defined semantics.

5  Otherwise, let FP be a standard floating-point type:

(5.1)  if the floating-point conversion rank of extended-floating-point-type is less than or equal to that of float, then FP is float,
(5.2)  otherwise, if the floating-point conversion rank of extended-floating-point-type is less than or equal to that of double, then FP is double,
(5.3)  otherwise, FP is long double.

6  The conversion occurs as if performed by the following code fragment (using the same notation as for the preceding code fragment):

   using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
FP fval;
use_facet<numget>(loc).get(*this, 0, *this, state, fval);
if (fval < -numeric_limits<extended-floating-point-type>::max()) {
    state |= ios_base::failbit;
    val = -numeric_limits<extended-floating-point-type>::max();
} else if (numeric_limits<extended-floating-point-type>::max() < fval) {
    state |= ios_base::failbit;
    val = numeric_limits<extended-floating-point-type>::max();
} else {
    val = static_cast<extended-floating-point-type>(fval);
}

[Note 2: When the extended floating-point type has a floating-point conversion rank that is not equal to the rank of any standard floating-point type, then double rounding during the conversion can result in inaccurate results. from_chars can be used in situations where maximum accuracy is important. — end note]

31.7.5.3.3 basic_istream::operator>>

basic_istream& operator>>(basic_istream& (*pf)(basic_istream&));

Effects: None. This extractor does not behave as a formatted input function (as described in 31.7.5.3.1).

Returns: pf(*this).279

basic_istream& operator>>(basic_ios<charT, traits>& (*pf)(basic_ios<charT, traits>&));

Effects: Calls pf(*this). This extractor does not behave as a formatted input function (as described in 31.7.5.3.1).

Returns: *this.

basic_istream& operator>>(ios_base& (*pf)(ios_base&));

Effects: Calls pf(*this).280 This extractor does not behave as a formatted input function (as described in 31.7.5.3.1).

Returns: *this.

template<class charT, class traits, size_t N>
    basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& in, charT (&s)[N]);
template<class traits, size_t N>
    basic_istream<char, traits>& operator>>(basic_istream<char, traits>& in, unsigned char (&s)[N]);
template<class traits, size_t N>
    basic_istream<char, traits>& operator>>(basic_istream<char, traits>& in, signed char (&s)[N]);

Effects: Behaves like a formatted input member (as described in 31.7.5.3.1) of in. After a sentry object is constructed, operator>> extracts characters and stores them into s. If width() is greater than zero, n is min(size_t(width()), N). Otherwise n is N. n is the maximum number of characters stored.

Characters are extracted and stored until any of the following occurs:

(8.1) — n-1 characters are stored;
(8.2) — end of file occurs on the input sequence;
(8.3) — letting ct be use_facet<ctype<charT>>(in.getloc()), ct.is(ct.space, c) is true.

operator>> then stores a null byte (charT()) in the next position, which may be the first position if no characters were extracted. operator>> then calls width(0).

If the function extracted no characters, ios_base::failbit is set in the input function’s local error state before setstate is called.

Returns: in.

template<class charT, class traits>
    basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& in, charT& c);
template<class traits>
    basic_istream<char, traits>& operator>>(basic_istream<char, traits>& in, unsigned char& c);

279) See, for example, the function signature ws(basic_istream&). (31.7.5.5).
280) See, for example, the function signature dec(ios_base&). (31.5.5.3).
template<class traits>
   basic_istream<char, traits>& operator>>(basic_istream<char, traits>& in, signed char& c);

   Effects: Behaves like a formatted input member (as described in 31.7.5.3.1) of in. A character is extracted from in, if one is available, and stored in c. Otherwise, ios_base::failbit is set in the input function’s local error state before setstate is called.

   Returns: in.

basic_istream& operator>>(basic_streambuf<charT, traits>* sb);

   Effects: Behaves as an unformatted input function (31.7.5.4). If sb is null, calls setstate(failbit), which may throw ios_base::failure (31.5.4.4). After a sentry object is constructed, extracts characters from *this and inserts them in the output sequence controlled by sb. Characters are extracted and inserted until any of the following occurs:
   — end-of-file occurs on the input sequence;
   — inserting in the output sequence fails (in which case the character to be inserted is not extracted);
   — an exception occurs (in which case the exception is caught).

If the function extracts no characters, ios_base::failbit is set in the input function’s local error state before setstate is called.

   Returns: *this.

31.7.5.4 Unformatted input functions

Each unformatted input function begins execution by constructing an object of type ios_base::iostate, termed the local error state, and initializing it to ios_base::goodbit. It then creates an object of class sentry with the default argument noskipws (second) argument true. If the sentry object returns true, when converted to a value of type bool, the function endeavors to obtain the requested input. Otherwise, if the sentry constructor exits by throwing an exception or if the sentry object produces false, when converted to a value of type bool, the function returns without attempting to obtain any input. In either case the number of extracted characters is set to 0; unformatted input functions taking a character array of nonzero size as an argument shall also store a null character (using charT()) in the first location of the array.

If rdbuf()->sbumpc() or rdbuf()->sgetc() returns traits::eof(), then ios_base::eofbit is set in the local error state and the input function stops trying to obtain the requested input. If an exception is thrown during input then ios_base::badbit is set in the local error state, *this's error state is set to the local error state, and the exception is rethrown if (exceptions() & badbit) != 0. If no exception has been thrown it stores the number of characters extracted in a member object. After extraction is done, the input function calls setstate, which sets *this’s error state to the local error state, and may throw an exception. In any event the sentry object is destroyed before leaving the unformatted input function.

streamsize gcount() const;

   Effects: None. This member function does not behave as an unformatted input function (as described above).

   Returns: The number of characters extracted by the last unformatted input member function called for the object. If the number cannot be represented, returns numeric_limits<streamsize>::max().

int_type get();

   Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, extracts a character c, if one is available. Otherwise, ios_base::failbit is set in the input function’s local error state before setstate is called.

   Returns: c if available, otherwise traits::eof().

basic_istream& get(char_type& c);

   Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, extracts a character, if one is available, and assigns it to c.281 Otherwise, ios_base::failbit is set in the input function’s local error state before setstate is called.

   Returns: *this.

281) Note that this function is not overloaded on types signed char and unsigned char.
basic_istream& get(char_type* s, streamsize n, char_type delim);

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, extracts characters and stores them into successive locations of an array whose first element is designated by s.\textsuperscript{282} Characters are extracted and stored until any of the following occurs:

1. \( n \) is less than one or \( n - 1 \) characters are stored;
2. end-of-file occurs on the input sequence;
3. \texttt{traits::eq(c, delim)} for the next available input character \( c \) (in which case \( c \) is not extracted).

If the function stores no characters, \texttt{ios_base::failbit} is set in the input function’s local error state before \texttt{setstate} is called. In any case, if \( n \) is greater than zero it then stores a null character into the next successive location of the array.

Returns: \texttt{*this}.

basic_istream& get(char_type* s, streamsize n);

Effects: Calls \texttt{get(s, n, widen('\n'))}.

Returns: Value returned by the call.

basic_istream& get(basic_streambuf<char_type, traits>& sb, char_type delim);

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, extracts characters and inserts them in the output sequence controlled by \( sb \). Characters are extracted and inserted until any of the following occurs:

1. end-of-file occurs on the input sequence;
2. inserting in the output sequence fails (in which case the character to be inserted is not extracted);
3. \texttt{traits::eq(c, delim)} for the next available input character \( c \) (in which case \( c \) is not extracted);
4. an exception occurs (in which case, the exception is caught but not rethrown).

If the function inserts no characters, \texttt{ios_base::failbit} is set in the input function’s local error state before \texttt{setstate} is called.

Returns: \texttt{*this}.

basic_istream& get(basic_streambuf<char_type, traits>& sb);

Effects: Calls \texttt{get(sb, widen('\n'))}.

Returns: Value returned by the call.

basic_istream& getline(char_type* s, streamsize n, char_type delim);

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, extracts characters and stores them into successive locations of an array whose first element is designated by \( s \).\textsuperscript{283} Characters are extracted and stored until one of the following occurs:

1. end-of-file occurs on the input sequence;
2. \texttt{traits::eq(c, delim)} for the next available input character \( c \) (in which case the input character is extracted but not stored);\textsuperscript{284}
3. \( n \) is less than one or \( n - 1 \) characters are stored (in which case the function calls \texttt{setstate( failbit)}).

These conditions are tested in the order shown.\textsuperscript{285}

If the function extracts no characters, \texttt{ios_base::failbit} is set in the input function’s local error state before \texttt{setstate} is called.\textsuperscript{286}

In any case, if \( n \) is greater than zero, it then stores a null character (using \texttt{charT()} into the next successive location of the array.

\textsuperscript{282} Note that this function is not overloaded on types \texttt{signed char} and \texttt{unsigned char}.

\textsuperscript{283} Note that this function is not overloaded on types \texttt{signed char} and \texttt{unsigned char}.

\textsuperscript{284} Since the final input character is “extracted”, it is counted in the \texttt{gcount()}, even though it is not stored.

\textsuperscript{285} This allows an input line which exactly fills the buffer, without setting \texttt{failbit}. This is different behavior than the historical AT&T implementation.

\textsuperscript{286} This implies an empty input line will not cause \texttt{failbit} to be set.
Returns: *this.

[Example 1:]
#include <iostream>

int main() {
    using namespace std;
    const int line_buffer_size = 100;

    char buffer[line_buffer_size];
    int line_number = 0;
    while (cin.getline(buffer, line_buffer_size, '\n') || cin.gcount()) {
        int count = cin.gcount();
        if (cin.eof())
            cout << "Partial final line";  // cin.fail() is false
        else if (cin.fail()) {
            cout << "Partial long line";
            cin.clear(cin.rdstate() & ~ios_base::failbit);
        } else {
            count--;  // Don't include newline in count
            cout << "Line " << ++line_number;
        }
        cout << " (" << count << " chars): " << buffer << endl;
    }
    —end example]

basic_istream& getline(char_type* s, streamsize n);

Returns: getline(s, n, widen(\"\n\")

basic_istream& ignore(streamsize n = 1, int_type delim = traits::eof());

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, extracts characters and discards them. Characters are extracted until any of the following occurs:

(25.1) $n \neq \text{numeric\_limits<streamsize>::max()}$ (17.3.5) and n characters have been extracted so far;

(25.2) end-of-file occurs on the input sequence (in which case the function calls setstate(eofbit), which may throw ios_base::failure (31.5.4.4));

(25.3) traits::eq_int_type(traits::to_int_type(c), delim) for the next available input character c (in which case c is extracted).

[Note 1: The last condition will never occur if traits::eq_int_type(delim, traits::eof()). — end note]

Returns: *this.

int_type peek();

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, reads but does not extract the current input character.

Returns: traits::eof() if good() is false. Otherwise, returns rdbuf()->sgetc().

basic_istream& read(char_type* s, streamsize n);

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, if !good() calls setstate(failbit) which may throw an exception, and return. Otherwise extracts characters and stores them into successive locations of an array whose first element is designated by s. Characters are extracted and stored until either of the following occurs:

(29.1) n characters are stored;

(29.2) end-of-file occurs on the input sequence (in which case the function calls setstate(failbit | eofbit), which may throw ios_base::failure (31.5.4.4)).

Note that this function is not overloaded on types signed char and unsigned char.
Returns: *this.

streamsize readsome(char_type* s, streamsize n);

Effects: Behaves as an unformatted input function (as described above). After constructing a sentry object, if !good() calls setstate(failbit) which may throw an exception, and return. Otherwise extracts characters and stores them into successive locations of an array whose first element is designated by s. If rdbuf()->in_avail() == -1, calls setstate(eofbit) (which may throw ios_base::failure (31.5.4.4)), and extracts no characters;

If rdbuf()->in_avail() == 0, extracts no characters

(31.1)

If rdbuf()->in_avail() > 0, extracts min(rdbuf()->in_avail(), n)).

Returns: The number of characters extracted.

basic_istream& putback(char_type c);

Effects: Behaves as an unformatted input function (as described above), except that the function first clears eofbit. After constructing a sentry object, if !good() calls setstate(failbit) which may throw an exception, and return. If rdbuf() is not null, calls rdbuf()->sputbackc(c). If rdbuf() is null, or if sputbackc returns traits::eof(), calls setstate(badbit) (which may throw ios_base::failure (31.5.4.4)).

[Note 2: This function extracts no characters, so the value returned by the next call to gcount() is 0. — end note]

Returns: *this.

basic_istream& unget();

Effects: Behaves as an unformatted input function (as described above), except that the function first clears eofbit. After constructing a sentry object, if !good() calls setstate(failbit) which may throw an exception, and return. If rdbuf() is null, or if unget() returns traits::eof(), calls setstate(badbit) (which may throw ios_base::failure (31.5.4.4)).

[Note 3: This function extracts no characters, so the value returned by the next call to gcount() is 0. — end note]

Returns: *this.

int sync();

Effects: Behaves as an unformatted input function (as described above), except that it does not count the number of characters extracted and does not affect the value returned by subsequent calls to gcount(). After constructing a sentry object, if rdbuf() is a null pointer, returns -1. Otherwise, calls rdbuf()->pubsync() and, if that function returns -1 calls setstate(badbit) (which may throw ios_base::failure (31.5.4.4)), and returns -1. Otherwise, returns zero.

pos_type tellg();

Effects: Behaves as an unformatted input function (as described above), except that it does not count the number of characters extracted and does not affect the value returned by subsequent calls to gcount(). After constructing a sentry object, if fail() != false, returns pos_type(-1) to indicate failure. Otherwise, returns rdbuf()->pubseekoff(0, cur, in).

basic_istream& seekg(pos_type pos);

Effects: Behaves as an unformatted input function (as described above), except that the function first clears eofbit, it does not count the number of characters extracted, and it does not affect the value returned by subsequent calls to gcount(). After constructing a sentry object, if fail() != true, executes rdbuf()->pubseekpos(pos, ios_base::in). In case of failure, the function calls setstate(failbit) (which may throw ios_base::failure).

Returns: *this.
basic_istream& seekg(off_type off, ios_base::seekdir dir);

42  **Effects:** Behaves as an unformatted input function (as described above), except that the function first clears **eofbit**, does not count the number of characters extracted, and does not affect the value returned by subsequent calls to **gcount()**. After constructing a **sentry** object, if **fail() != true**, executes **rdbuf() -> pubseekoff(off, dir, ios_base::in)**. In case of failure, the function calls **setstate(failbit)** (which may throw **ios_base::failure**).

43  **Returns:** *this.

### 31.7.5.5 Standard basic_istream manipulators

1  Each instantiation of the function template specified in this subclause is a designated addressable function (16.4.5.2.1).

    template<class charT, class traits>
    basic_istream<charT, traits>& ws(basic_istream<charT, traits>& is);

2  **Effects:** Behaves as an unformatted input function (31.7.5.4), except that it does not count the number of characters extracted and does not affect the value returned by subsequent calls to **is.gcount()**. After constructing a **sentry** object extracts characters as long as the next available character c is whitespace or until there are no more characters in the sequence. Whitespace characters are distinguished with the same criterion as used by **sentry::sentry** (31.7.5.2.4). If **ws** stops extracting characters because there are no more available it sets **eofbit**, but not **failbit**.

3  **Returns:** is.

### 31.7.5.6 Rvalue stream extraction

    template<class Istream, class T>
    Istream&& operator>>(Istream&& is, T&& x);

1  **Constraints:** The expression is >> std::forward<T>(x) is well-formed when treated as an unevaluated operand (7.2.3) and **Istream** is publicly and unambiguously derived from **ios_base**.

2  **Effects:** Equivalent to:

    is >> std::forward<T>(x);
    return std::move(is);

### 31.7.5.7 Class template basic_iostream

#### 31.7.5.7.1 General

    namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_iostream
    : public basic_istream<charT, traits>, 
    public basic_ostream<charT, traits> {
    public:
    using char_type  = charT;
    using int_type   = typename traits::int_type;
    using pos_type   = typename traits::pos_type;
    using off_type   = typename traits::off_type;
    using traits_type = traits;

    // 31.7.5.7.2, constructor
    explicit basic_iostream(basic_streambuf<charT, traits>* sb);

    // 31.7.5.7.3, destructor
    virtual ~basic_iostream();

    protected:
    // 31.7.5.7.2, constructor
    basic_iostream(const basic_iostream&) = delete;
    basic_iostream(basic_iostream&& rhs);
    } // basic_iostream

    } // namespace std
The class template `basic_iostream` inherits a number of functions that allow reading input and writing output to sequences controlled by a stream buffer.

### 31.7.5.7.2 Constructors

```cpp
explicit basic_iostream(basic_streambuf<charT, traits>* sb);
```

- **Effects**: Initializes the base class subobjects with `basic_istream<charT, traits>(sb)` (31.7.5.2) and `basic_ostream<charT, traits>(sb)` (31.7.6.2).
- **Postconditions**: `rdbuf() == sb` and `gcount() == 0`.

### 31.7.5.7.3 Destructor

```cpp
virtual ~basic_iostream();
```

- **Remarks**: Does not perform any operations on `rdbuf()`.

### 31.7.5.7.4 Assignment and swap

```cpp
basic_iostream& operator=(basic_iostream&& rhs);
```

- **Effects**: Equivalent to `swap(rhs)`.

```cpp
void swap(basic_iostream& rhs);
```

- **Effects**: Calls `basic_istream<charT, traits>::swap(rhs)`.

### 31.7.6 Output streams

#### 31.7.6.1 General

The header `<ostream>` defines a class template and several function templates that control output to a stream buffer, along with a function template that inserts into stream rvalues.

#### 31.7.6.2 Class template `basic_ostream`

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ostream : virtual public basic_ios<charT, traits> {
        public:
            // types (inherited from basic_ios (31.5.4))
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;

            // 31.7.6.2.2, constructor/destructor
            explicit basic_ostream(basic_streambuf<char_type, traits>* sb);
            virtual ~basic_ostream();

            // 31.7.6.2.4, prefix/suffix
            class sentry;
    }
}
```
// 31.7.6.3, formatted output
basic_ostream& operator<<(basic_ostream& (*pf)(basic_ostream&));
basic_ostream& operator<<(basic_ios<charT, traits>& (*pf)(basic_ios<charT, traits>&));
basic_ostream& operator<<(ios_base& (*pf)(ios_base&));
basic_ostream& operator<<(bool n);
basic_ostream& operator<<(short n);
basic_ostream& operator<<(unsigned short n);
basic_ostream& operator<<(int n);
basic_ostream& operator<<(unsigned int n);
basic_ostream& operator<<(long n);
basic_ostream& operator<<(unsigned long n);
basic_ostream& operator<<(long long n);
basic_ostream& operator<<(unsigned long long n);
basic_ostream& operator<<(float f);
basic_ostream& operator<<(double f);
basic_ostream& operator<<(long double f);
basic_ostream& operator<<(extended-floating-point-type f);
basic_ostream& operator<<(const void* p);
basic_ostream& operator<<(const volatile void* p);
basic_ostream& operator<<(nullptr_t);
basic_ostream& operator<<(basic_streambuf<char_type, traits>* sb);

// 31.7.6.4, unformatted output
basic_ostream& put(char_type c);
basic_ostream& write(const char_type* s, streamsize n);
basic_ostream& flush();

// 31.7.6.2.5, seeks
pos_type tellp();
basic_ostream& seekp(pos_type);
basic_ostream& seekp(off_type, ios_base::seekdir);

protected:
// 31.7.6.2.2, copy/move constructor
basic_ostream(const basic_ostream&) = delete;
basic_ostream(basic_ostream&& rhs);

// 31.7.6.2.3, assignment and swap
basic_ostream& operator=(const basic_ostream&) = delete;
basic_ostream& operator=(basic_ostream&& rhs);
void swap(basic_ostream& rhs);

};

// 31.7.6.3.4, character inserters
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>&, charT);
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>&, char);
template<class traits>
basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>&, wchar_t) = delete;
template<class traits>
basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>&, char8_t) = delete;

§ 31.7.6.2.1
The class template `basic_ostream` defines a number of member function signatures that assist in formatting and writing output to output sequences controlled by a stream buffer.

Two groups of member function signatures share common properties: the formatted output functions (or `inserters`) and the unformatted output functions. Both groups of output functions generate (or `insert`) output characters by actions equivalent to calling `rdbuf()->sputc(int_type)`. They may use other public members of `basic_ostream` except that they shall not invoke any virtual members of `rdbuf()` except `overflow()`, `xsputc()`, and `sync()`.

If one of these called functions throws an exception, then unless explicitly noted otherwise the output function sets `badbit` in the error state. If `badbit` is set in `exceptions()`, the output function rethrows the exception without completing its actions, otherwise it does not throw anything and proceeds as if the called function had returned a failure indication.

[Note 1: The deleted overloads of `operator<<` prevent formatting characters as integers and strings as pointers. — end note]
31.7.6.2.2 Constructors

explicit basic_ostream(basic_streambuf<charT, traits>* sb);
1  Effects: Initializes the base class subobject with basic_ios<charT, traits>::init(sb) (31.5.4.2).
2  Postconditions: rdbuf() == sb.

basic_ostream(basic_ostream&& rhs);
3  Effects: Move constructs from the rvalue rhs. This is accomplished by default constructing the base
class and calling basic_ios<charT, traits>::move(rhs) to initialize the base class.

virtual ~basic_ostream();
4  Remarks: Does not perform any operations on rdbuf().

31.7.6.2.3 Assignment and swap

basic_ostream& operator=(basic_ostream&& rhs);
1  Effects: Equivalent to swap(rhs).
2  Returns: *this.

void swap(basic_ostream& rhs);
3  Effects: Calls basic_ios<charT, traits>::swap(rhs).

31.7.6.2.4 Class basic_ostream::sentry

namespace std {
  template<class charT, class traits>
  class basic_ostream<charT, traits>::sentry {
    bool ok_;  // exposition only

    public:
      explicit sentry(basic_ostream& os);
      ~sentry();
      explicit operator bool() const { return ok_; }

      sentry(const sentry&) = delete;
      sentry& operator=(const sentry&) = delete;
  };
}
1  The class sentry defines a class that is responsible for doing exception safe prefix and suffix operations.

explicit sentry(basic_ostream& os);
2  If os.good() is nonzero, prepares for formatted or unformatted output. If os.tie() is not a null
pointer, calls os.tie()->flush(). 288
3  If, after any preparation is completed, os.good() is true, ok_ == true otherwise, ok_ == false.
During preparation, the constructor may call setstate(failbit) (which may throw ios_base::
failure (31.5.4.4)). 289

~sentry();
4  If (os.flags() & ios_base::unitbuf) && !uncaught_exceptions() && os.good() is true, calls
os.rdbuf()->pubsync(). If that function returns -1, sets badbit in os.rdstate() without propa-
gating an exception.

explicit operator bool() const;
5  Effects: Returns ok_.

288) The call os.tie()->flush() does not necessarily occur if the function can determine that no synchronization is necessary.
289) The sentry constructor and destructor can also perform additional implementation-dependent operations.
31.7.6.2.5 Seek members

Each seek member function begins execution by constructing an object of class `sentry`. It returns by destroying the `sentry` object.

```
pos_type tellp();
```

*Returns*: If `fail()` != false, returns `pos_type(-1)` to indicate failure. Otherwise, returns `rdbuf()->pubseekoff(0, cur, out)`.

```
basic_ostream& seekp(pos_type pos);
```

*Effects*: If `fail()` != true, executes `rdbuf()->pubseekpos(pos, ios_base::out)`. In case of failure, the function calls `setstate(failbit)` (which may throw `ios_base::failure`).

*Returns*: `*this`.

```
basic_ostream& seekp(off_type off, ios_base::seekdir dir);
```

*Effects*: If `fail()` != true, executes `rdbuf()->pubseekoff(off, dir, ios_base::out)`. In case of failure, the function calls `setstate(failbit)` (which may throw `ios_base::failure`).

*Returns*: `*this`.

### 31.7.6.3 Formatted output functions

#### 31.7.6.3.1 Common requirements

Each formatted output function begins execution by constructing an object of class `sentry`. If that object returns true when converted to a value of type bool, the function endeavors to generate the requested output. If the generation fails, then the formatted output function does `setstate(ios_base::failbit)`, which can throw an exception. If an exception is thrown during output, then `ios_base::badbit` is set in `*this`’s error state. If `(exceptions()&badbit) != 0` then the exception is rethrown. Whether or not an exception is thrown, the `sentry` object is destroyed before leaving the formatted output function. If no exception is thrown, the result of the formatted output function is `*this`.

The descriptions of the individual formatted output functions describe how they perform output and do not mention the `sentry` object.

If a formatted output function of a stream `os` determines padding, it does so as follows. Given a `charT` character sequence `seq` where `charT` is the character container type of the stream, if the length of `seq` is less than `os.width()`, then enough copies of `os.fill()` are added to this sequence as necessary to pad to a width of `os.width()` characters. If `(os.flags() & ios_base::adjustfield) == ios_base::left` is true, the fill characters are placed after the character sequence; otherwise, they are placed before the character sequence.

#### 31.7.6.3.2 Arithmetic inserters

```
basic_ostream& operator<<(bool val);
basic_ostream& operator<<(short val);
basic_ostream& operator<<(unsigned short val);
basic_ostream& operator<<(int val);
basic_ostream& operator<<(unsigned int val);
basic_ostream& operator<<(long val);
basic_ostream& operator<<(unsigned long val);
basic_ostream& operator<<(long long val);
basic_ostream& operator<<(unsigned long long val);
basic_ostream& operator<<(float val);
basic_ostream& operator<<(double val);
basic_ostream& operator<<(long double val);
basic_ostream& operator<<(const void* val);
```

*Effects*: The classes `num_get<>` and `num_put<>` handle locale-dependent numeric formatting and parsing. These inserter functions use the imbed locale value to perform numeric formatting. When `val` is of type `bool`, `long`, `unsigned long`, `long long`, `unsigned long long`, `double`, `long double`, or `const void*`, the formatting conversion occurs as if it performed the following code fragment:

---

290) This is done without causing an `ios_base::failure` to be thrown.
bool failed = use_facet<
    num_put<charT, ostream_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(), val).failed();

When val is of type short the formatting conversion occurs as if it performed the following code fragment:

```cpp
ios_base::fmtflags baseflags = ios_base::flags() & ios_base::basefield;
bool failed = use_facet<
    num_put<charT, ostream_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(),
    baseflags == ios_base::oct || baseflags == ios_base::hex
    ? static_cast<long>(static_cast<unsigned short>(val))
    : static_cast<long>(val)).failed();
```

When val is of type int the formatting conversion occurs as if it performed the following code fragment:

```cpp
ios_base::fmtflags baseflags = ios_base::flags() & ios_base::basefield;
bool failed = use_facet<
    num_put<charT, ostream_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(),
    baseflags == ios_base::oct || baseflags == ios_base::hex
    ? static_cast<long>(static_cast<unsigned int>(val))
    : static_cast<long>(val)).failed();
```

When val is of type unsigned short or unsigned int the formatting conversion occurs as if it performed the following code fragment:

```cpp
bool failed = use_facet<
    num_put<charT, ostream_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(),
    static_cast<unsigned long>(val)).failed();
```

When val is of type float the formatting conversion occurs as if it performed the following code fragment:

```cpp
bool failed = use_facet<
    num_put<charT, ostream_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(),
    static_cast<double>(val)).failed();
```

The first argument provides an object of the `ostream_iterator<>` class which is an iterator for class `basic_ostream<>`. It bypasses `ostreams` and uses `streambufs` directly. Class `locale` relies on these types as its interface to iostreams, since for flexibility it has been abstracted away from direct dependence on `ostream`. The second parameter is a reference to the base class subobject of type `ios_base`. It provides formatting specifications such as field width, and a `locale` from which to obtain other facets. If `failed` is `true` then does `setstate(badbit)`, which may throw an exception, and returns.

2 Returns: *this.

3 `basic_ostream` operator<<(const volatile void* p);

4 Effects: Equivalent to: `return operator<<(const_cast<const void*>(p));`

5 `basic_ostream` operator<<(extended-floating-point-type val);

5 Effects: If the floating-point conversion rank of `extended-floating-point-type` is less than or equal to that of `double`, the formatting conversion occurs as if it performed the following code fragment:

```cpp
bool failed = use_facet<
    num_put<charT, ostream_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(),
    static_cast<double>(val)).failed();
```

Otherwise, if the floating-point conversion rank of `extended-floating-point-type` is less than or equal to that of `long double`, the formatting conversion occurs as if it performed the following code fragment:
bool failed = use_facet<
    num_put<charT, ostreambuf_iterator<charT, traits>>
>(getloc()).put(*this, *this, fill(),
    static_cast<long double>(val)).failed();

Otherwise, an invocation of the operator function is conditionally supported with implementation-defined semantics.

If failed is true then does setstate(badbit), which may throw an exception, and returns.

Returns: *this.

31.7.6.3.3 basic_ostream::operator<<

basic_ostream& operator<<(basic_ostream& (*pf)(basic_ostream&));

Effects: None. Does not behave as a formatted output function (as described in 31.7.6.3.1).

Returns: pf(*this).291

basic_ostream& operator<<(basic_ios<charT, traits>& (*pf)(basic_ios<charT, traits>&));

Effects: Calls pf(*this). This inserter does not behave as a formatted output function (as described in 31.7.6.3.1).

Returns: *this.292

basic_ostream& operator<<(ios_base& (*pf)(ios_base&));

Effects: Calls pf(*this). This inserter does not behave as a formatted output function (as described in 31.7.6.3.1).

Returns: *this.

basic_ostream& operator<<(basic_streambuf<charT, traits>* sb);

Effects: Behaves as an unformatted output function (31.7.6.4). After the sentry object is constructed, if sb is null calls setstate(badbit) (which may throw ios_base::failure).

Gets characters from sb and inserts them in *this. Characters are read from sb and inserted until any of the following occurs:

— end-of-file occurs on the input sequence;
— inserting in the output sequence fails (in which case the character to be inserted is not extracted);
— an exception occurs while getting a character from sb.

If the function inserts no characters, it calls setstate(failbit) (which may throw ios_base::failure (31.5.4.4)). If an exception was thrown while extracting a character, the function sets failbit in the error state, and if failbit is set in exceptions() the caught exception is rethrown.

Returns: *this.

basic_ostream& operator<<(nullptr_t);

Effects: Equivalent to:

return *this << s;

where s is an implementation-defined NTCTS (3.35).

31.7.6.3.4 Character inserter function templates

template<class charT, class traits>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, charT c);

template<class charT, class traits>
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, char c);

// specialization

template<class traits>
    basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>& out, char c);

291) See, for example, the function signature endl(basic_ostream&) (31.7.6.5).
292) See, for example, the function signature dec(ios_base&) (31.5.5.3).
template<class traits>
  basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>& out, signed char c);

Effects: Behaves as a formatted output function (31.7.6.3.1) of out. Constructs a character sequence seq. If c has type char and the character container type of the stream is not char, then seq consists of out.widen(c); otherwise seq consists of c. Determines padding for seq as described in 31.7.6.3.1. Inserts seq into out. Calls os.width(0).

Returns: out.

template<class charT, class traits>
  basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, const charT* s);

Effects: Behaves like a formatted inserter (as described in 31.7.6.3.1) of out. Creates a character sequence seq of n characters starting at s, each widened using out.widen() (31.5.4.3), where n is the number that would be computed as if by:

(4.1) traits::length(s) for the overload where the first argument is of type basic_ostream<charT, traits>& and the second is of type const charT*, and also for the overload where the first argument is of type basic_ostream<char, traits>& and the second is of type const char*,

(4.2) char_traits<char>::length(s) for the overload where the first argument is of type basic_ostream<charT, traits>& and the second is of type const char*,

(4.3) traits::length(reinterpret_cast<const char*>(s)) for the other two overloads.

Determines padding for seq as described in 31.7.6.3.1. Inserts seq into out. Calls width(0).

Returns: out.

31.7.6.3.5 Print [ostream.formatted.print]

template<class... Args>
  void print(ostream& os, format_string<Args...> fmt, Args&&... args);

Effects: If the ordinary literal encoding (5.3) is UTF-8, equivalent to:

vprint_unicode(os, fmt.str, make_format_args(args...));

Otherwise, equivalent to:

vprint_nonunicode(os, fmt.str, make_format_args(args...));

template<class... Args>
  void println(ostream& os, format_string<Args...> fmt, Args&&... args);

Effects: Equivalent to:

print(os, "\n", format(fmt, std::forward<Args>(args)...));

void println(ostream& os);

Effects: Equivalent to:

print(os, "\n");

void vprint_unicode(ostream& os, string_view fmt, format_args args);
void vprint_nonunicode(ostream& os, string_view fmt, format_args args);

Effects: Behaves as a formatted output function (31.7.6.3.1) of os, except that:
--- failure to generate output is reported as specified below, and
--- any exception thrown by the call to vformat is propagated without regard to the value of
os.exceptions() and without turning on ios_base::badbit in the error state of os.

After constructing a sentry object, the function initializes an automatic variable via

```c++
string out = vformat(os.getloc(), fmt, args);
```

If the function is vprint_unicode and os is a stream that refers to a terminal capable of displaying Unicode which is determined in an implementation-defined manner, writes out to the terminal using the native Unicode API; if out contains invalid code units, the behavior is undefined and implementations are encouraged to diagnose it. If the native Unicode API is used, the function flushes os before writing out. Otherwise (if os is not such a stream or the function is vprint_nonunicode), inserts the character sequence [out.begin(),out.end()] into os. If writing to the terminal or inserting into os fails, calls os.setstate(ios_base::badbit) (which may throw ios_base::failure).

**Recommended practice:** For vprint_unicode, if invoking the native Unicode API requires transcoding, implementations should substitute invalid code units with \u+00fffd replacement character per the Unicode Standard, Chapter 3.9 u+00fffd Substitution in Conversion.

### 31.7.6.4 Unformatted output functions

1 Each unformatted output function begins execution by constructing an object of class sentry. If that object returns true, while converting to a value of type bool, the function endeavors to generate the requested output. If an exception is thrown during output, then ios_base::badbit is set in *this’s error state. If (exceptions() & badbit) != 0 then the exception is rethrown. In any case, the unformatted output function ends by destroying the sentry object, then, if no exception was thrown, returning the value specified for the unformatted output function.

```c++
basic_ostream& put(char_type c);
```

**Effects:** Behaves as an unformatted output function (as described above). After constructing a sentry object, inserts the character c, if possible.

**Returns:** *this.

```c++
basic_ostream& write(const char_type* s, streamsize n);
```

**Effects:** Behaves as an unformatted output function (as described above). After constructing a sentry object, obtains characters to insert from successive locations of an array whose first element is designated by s. Characters are inserted until either of the following occurs:

- n characters are inserted;
- inserting in the output sequence fails (in which case the function calls setstate(badbit), which may throw ios_base::failure (31.5.4.4)).

**Returns:** *this.

```c++
basic_ostream& flush();
```

**Effects:** Behaves as an unformatted output function (as described above). If rdbuf() is not a null pointer, constructs a sentry object. If that object returns true when converted to a value of type bool the function calls rdbuf()->pubsync(). If that function returns −1 calls setstate(badbit) (which may throw ios_base::failure (31.5.4.4)). Otherwise, if the sentry object returns false, does nothing.

**Returns:** *this.

### 31.7.6.5 Standard basic_ostream manipulators

1 Each instantiation of any of the function templates specified in this subclause is a designated addressable function (16.4.5.2.1).

---

293) This is done without causing an ios_base::failure to be thrown.
294) Note that this function is not overloaded on types signed char and unsigned char.
295) Note that this function is not overloaded on types signed char and unsigned char.
template<class charT, class traits>
    basic_ostream<charT, traits>& endl(basic_ostream<charT, traits>& os);

Effects: Calls os.put(os.widen(\'n\'))\n        , then os.flush().

Returns: os.

template<class charT, class traits>
    basic_ostream<charT, traits>& ends(basic_ostream<charT, traits>& os);

Effects: Inserts a null character into the output sequence: calls os.put(charT()).

Returns: os.

template<class charT, class traits>
    basic_ostream<charT, traits>& flush(basic_ostream<charT, traits>& os);

Effects: Calls os.flush().

Returns: os.

template<class charT, class traits>
    basic_ostream<charT, traits>& emit_on_flush(basic_ostream<charT, traits>& os);

Effects: If os.rdbuf() is a basic_syncbuf<charT, traits, Allocator>*, called buf for the purpose of exposition, calls buf->set_emit_on_sync(true). Otherwise this manipulator has no effect.

[Note 1: To work around the issue that the Allocator template argument cannot be deduced, implementations can introduce an intermediate base class to basic_syncbuf that manages its emit_on_sync flag. — end note]

Returns: os.

template<class charT, class traits>
    basic_ostream<charT, traits>& noemit_on_flush(basic_ostream<charT, traits>& os);

Effects: If os.rdbuf() is a basic_syncbuf<charT, traits, Allocator>*, called buf for the purpose of exposition, calls buf->set_emit_on_sync(false). Otherwise this manipulator has no effect.

Returns: os.

template<class charT, class traits>
    basic_ostream<charT, traits>& flush_emit(basic_ostream<charT, traits>& os);

Effects: Calls os.flush(). Then, if os.rdbuf() is a basic_syncbuf<charT, traits, Allocator>*, called buf for the purpose of exposition, behaves as an unformatted output function (31.7.6.4) of os. After constructing a sentry object, calls buf->emit(). If that call returns false, calls os.setstate(ios_base::badbit).

Returns: os.

31.7.6.6 Rvalue stream insertion

template<class Ostream, class T>
    Ostream&& operator<<(Ostream&& os, const T& x);

Constraints: The expression os << x is well-formed when treated as an unevaluated operand and Ostream is publicly and unambiguously derived from ios_base.

Effects: As if by: os << x;

Returns: std::move(os).

31.7.7 Standard manipulators

The header <iomanip> defines several functions that support extractors and inserters that alter information maintained by class ios_base and its derived classes.

 unspecified resetiosflags(ios_base::fmtflags mask);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << resetiosflags(mask) behaves as if it called f(out, mask), or if
in is an object of type basic_istream<charT, traits> then the expression in >> resetiosflags(mask) behaves as if it called f(in, mask), where the function f is defined as:

```c
void f(ios_base& str, ios_base::fmtflags mask) {
    // reset specified flags
    str.setf(ios_base::fmtflags(0), mask);
}
```

The expression out << resetiosflags(mask) has type basic_ostream<charT, traits>\& and value out. The expression in >> resetiosflags(mask) has type basic_istream<charT, traits>\& and value in.

unspecified resetiosflags(ios_base::fmtflags mask);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << resetiosflags(mask) behaves as if it called f(out, mask), or if in is an object of type basic_istream<charT, traits> then the expression in >> resetiosflags(mask) behaves as if it called f(in, mask), where the function f is defined as:

```c
void f(ios_base& str, ios_base::fmtflags mask) {
    // set specified flags
    str.setf(mask);
}
```

The expression out << setiosflags(mask) has type basic_ostream<charT, traits>\& and value out. The expression in >> setiosflags(mask) has type basic_istream<charT, traits>\& and value in.

unspecified setiosflags(ios_base::fmtflags mask);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setiosflags(mask) behaves as if it called f(out, mask), or if in is an object of type basic_istream<charT, traits> then the expression in >> setiosflags(mask) behaves as if it called f(in, mask), where the function f is defined as:

```c
void f(ios_base& str, ios_base::fmtflags mask) {
    // set specified flags
    str.setf(ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out << setbase(base) has type basic_ostream<charT, traits>\& and value out. The expression in >> setbase(base) has type basic_istream<charT, traits>\& and value in.

unspecified setbase(int base);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.

unspecified setfill(char_type c);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setprecision(n) behaves as if it called f(out, n), or if in is an object of type basic_istream<charT, traits> then the expression in >> setprecision(n) behaves as if it called f(in, n), where the function f is defined as:

```c
void f(ios_base& str, int base) {
    // set basefield
    str.setf(base == 8 ? ios_base::oct :
             base == 10 ? ios_base::dec :
             base == 16 ? ios_base::hex :
             ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out >> setprecision(n) has type basic_istream<charT, traits>\& and value in.

unspecified setprecision(int n);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.

unspecified setfill(char_type c);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setprecision(n) behaves as if it called f(out, n), or if in is an object of type basic_istream<charT, traits> then the expression in >> setprecision(n) behaves as if it called f(in, n), where the function f is defined as:

```c
void f(ios_base& str, int base) {
    // set basefield
    str.setf(base == 8 ? ios_base::oct :
             base == 10 ? ios_base::dec :
             base == 16 ? ios_base::hex :
             ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out >> setprecision(n) has type basic_istream<charT, traits>\& and value in.

unspecified setprecision(int n);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.

unspecified setfill(char_type c);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setprecision(n) behaves as if it called f(out, n), or if in is an object of type basic_istream<charT, traits> then the expression in >> setprecision(n) behaves as if it called f(in, n), where the function f is defined as:

```c
void f(ios_base& str, int base) {
    // set basefield
    str.setf(base == 8 ? ios_base::oct :
             base == 10 ? ios_base::dec :
             base == 16 ? ios_base::hex :
             ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out >> setprecision(n) has type basic_istream<charT, traits>\& and value in.

unspecified setprecision(int n);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.

unspecified setfill(char_type c);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setprecision(n) behaves as if it called f(out, n), or if in is an object of type basic_istream<charT, traits> then the expression in >> setprecision(n) behaves as if it called f(in, n), where the function f is defined as:

```c
void f(ios_base& str, int base) {
    // set basefield
    str.setf(base == 8 ? ios_base::oct :
             base == 10 ? ios_base::dec :
             base == 16 ? ios_base::hex :
             ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out >> setprecision(n) has type basic_istream<charT, traits>\& and value in.

unspecified setprecision(int n);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.

unspecified setfill(char_type c);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setprecision(n) behaves as if it called f(out, n), or if in is an object of type basic_istream<charT, traits> then the expression in >> setprecision(n) behaves as if it called f(in, n), where the function f is defined as:

```c
void f(ios_base& str, int base) {
    // set basefield
    str.setf(base == 8 ? ios_base::oct :
             base == 10 ? ios_base::dec :
             base == 16 ? ios_base::hex :
             ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out >> setprecision(n) has type basic_istream<charT, traits>\& and value in.

unspecified setprecision(int n);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.

unspecified setfill(char_type c);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out << setprecision(n) behaves as if it called f(out, n), or if in is an object of type basic_istream<charT, traits> then the expression in >> setprecision(n) behaves as if it called f(in, n), where the function f is defined as:

```c
void f(ios_base& str, int base) {
    // set basefield
    str.setf(base == 8 ? ios_base::oct :
             base == 10 ? ios_base::dec :
             base == 16 ? ios_base::hex :
             ios_base::fmtflags(0), ios_base::basefield);
}
```

The expression out >> setprecision(n) has type basic_istream<charT, traits>\& and value in.

unspecified setprecision(int n);

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> and c has type charT then the expression out << setfill(c) behaves as if it called f(out, c), where the function f is defined as:

```c
template<class charT, class traits>
void f(basic_ios<charT, traits>& str, charT c) {
    // set fill character
    str.fill(c);
}
```

The expression out << setfill(c) has type basic_ostream<charT, traits>\& and value out.
object of type `basic_istream<charT, traits>` then the expression `in >> setprecision(n)` behaves as if it called f(in, n), where the function f is defined as:

```cpp
void f(ios_base& str, int n) {
    // set precision
    str.precision(n);
}
```

The expression `out << setprecision(n)` has type `basic_ostream<charT, traits>&` and value `out`. The expression `in >> setprecision(n)` has type `basic_istream<charT, traits>&` and value `in`.

`setw(int n);`

Returns: An object of unspecified type such that if `out` is an instance of `basic_ostream<charT, traits>` then the expression `out << setw(n)` behaves as if it called f(out, n), or if `in` is an object of type `basic_istream<charT, traits>` then the expression `in >> setw(n)` behaves as if it called f(in, n), where the function f is defined as:

```cpp
void f(ios_base& str, int n) {
    // set width
    str.width(n);
}
```

The expression `out << setw(n)` has type `basic_ostream<charT, traits>&` and value `out`. The expression `in >> setw(n)` has type `basic_istream<charT, traits>&` and value `in`.

### § 31.7.8 Extended manipulators

The header `<iomanip>` defines several functions that support extractors and inserters that allow for the parsing and formatting of sequences and values for money and time.

```cpp
template<class moneyT> unspecified get_money(moneyT& mon, bool intl = false);
```

Mandates: The type `moneyT` is either `long double` or a specialization of the `basic_string` template (Clause 23).

Effects: The expression `in >> get_money(mon, intl)` described below behaves as a formatted input function (31.7.5.3.1).

Returns: An object of unspecified type such that if `in` is an object of type `basic_istream<charT, traits>` then the expression `in >> get_money(mon, intl)` behaves as if it called f(in, mon, intl), where the function f is defined as:

```cpp
template<class charT, class traits, class moneyT>
void f(basic_ios<charT, traits>& str, moneyT& mon, bool intl) {
    using Iter = istreambuf_iterator<charT, traits>;
    using MoneyGet = money_get<charT, Iter>;
    ios_base::iostate err = ios_base::goodbit;
    const MoneyGet& mg = use_facet<MoneyGet>(str.getloc());
    mg.get(Iter(str.rdbuf()), Iter(), intl, str, err, mon);
    if (ios_base::goodbit != err)
        str.setstate(err);
}
```

The expression `in >> get_money(mon, intl)` has type `basic_istream<charT, traits>&` and value `in`.

```cpp
template<class moneyT> unspecified put_money(const moneyT& mon, bool intl = false);
```

Mandates: The type `moneyT` is either `long double` or a specialization of the `basic_string` template (Clause 23).

Returns: An object of unspecified type such that if `out` is an object of type `basic_ostream<charT, traits>` then the expression `out << put_money(mon, intl)` behaves as a formatted output function (31.7.6.3.1) that calls f(out, mon, intl), where the function f is defined as:
template<class charT, class traits, class moneyT>
void f(basic_ios<charT, traits>& str, const moneyT& mon, bool intl) {
    using Iter = ostreambuf_iterator<charT, traits>;
    using MoneyPut = money_put<charT, Iter>;
    const MoneyPut& mp = use_facet<MoneyPut>(str.getloc());
    const Iter end = mp.put(Iter(str.rdbuf()), intl, str, str.fill(), mon);
    if (end.failed())
        str.setstate(ios_base::badbit);
}

The expression out << put_money(mon, intl) has type basic ostream<charT, traits>& and value out.

template<class charT> unspecified get_time(tm* tmb, const charT* fmt);

7 Preconditions: The argument tmb is a valid pointer to an object of type tm, and [fmt, fmt + char_traits<charT>::length(fmt)] is a valid range.

8 Returns: An object of unspecified type such that if in is an object of type basic istream<charT, traits> then the expression in >> get_time(tmb, fmt) behaves as if it called f(in, tmb, fmt), where the function f is defined as:

template<class charT, class traits>
void f(basic_ios<charT, traits>& str, tm* tmb, const charT* fmt) {
    using Iter = istreambuf_iterator<charT, traits>;
    using TimeGet = time_get<charT, Iter>;
    ios_base::iostate err = ios_base::goodbit;
    const TimeGet& tg = use_facet<TimeGet>(str.getloc());
    tg.get(Iter(str.rdbuf()), Iter(), str, err, tmb,
    fmt, fmt + traits::length(fmt));
    if (err != ios_base::goodbit)
        str.setstate(err);
}

The expression in >> get_time(tmb, fmt) has type basic istream<charT, traits>& and value in.

template<class charT> unspecified put_time(const tm* tmb, const charT* fmt);

9 Preconditions: The argument tmb is a valid pointer to an object of type tm, and [fmt, fmt + char_traits<charT>::length(fmt)] is a valid range.

10 Returns: An object of unspecified type such that if out is an object of type basic ostream<charT, traits> then the expression out << put_time(tmb, fmt) behaves as if it called f(out, tmb, fmt), where the function f is defined as:

template<class charT, class traits>
void f(basic_ios<charT, traits>& str, const tm* tmb, const charT* fmt) {
    using Iter = ostreambuf_iterator<charT, traits>;
    using TimePut = time_put<charT, Iter>;
    const TimePut& tp = use_facet<TimePut>(str.getloc());
    const Iter end = tp.put(Iter(str.rdbuf()), str, str.fill(), tmb,
    fmt, fmt + traits::length(fmt));
    if (end.failed())
        str.setstate(ios_base::badbit);
}

The expression out << put_time(tmb, fmt) has type basic ostream<charT, traits>& and value out.

31.7.9 Quoted manipulators [quoted.manip]
Note 1: Quoted manipulators provide string insertion and extraction of quoted strings (for example, XML and CSV formats). Quoted manipulators are useful in ensuring that the content of a string with embedded spaces remains unchanged if inserted and then extracted via stream I/O. — end note

```
template<class charT>
unspecified quoted(const charT* s, charT delim = charT('"'), charT escape = charT('\\'));
```

```
template<class charT, class traits, class Allocator>
unspecified quoted(const basic_string<charT, traits, Allocator>& s,
charT delim = charT('"'), charT escape = charT('\\'));
```

```
template<class charT, class traits>
unspecified quoted(basic_string_view<charT, traits> s,
charT delim = charT('"'), charT escape = charT('\\'));
```

Returns: An object of unspecified type such that if `out` is an instance of `basic_ostream` with member type `char_type` the same as `charT` and with member type `traits_type`, which in the second and third forms is the same as `traits`, then the expression `out << quoted(s, delim, escape)` behaves as a formatted output function (31.7.6.3.1) of `out`. This forms a character sequence `seq`, initially consisting of the following elements:

1. `delim`.
2. Each character in `s`. If the character to be output is equal to `escape` or `delim`, as determined by `traits_type::eq`, first output `escape`.
3. `delim`.

Let `x` be the number of elements initially in `seq`. Then padding is determined for `seq` as described in 31.7.6.3.1, `seq` is inserted as if by calling `out.rdbuf()->sputn(seq, n)`, where `n` is the larger of `out.width()` and `x`, and `out.width(0)` is called. The expression `out << quoted(s, delim, escape)` has type `basic_ostream<charT, traits>&` and value `out`.

```
template<class charT, class traits, class Allocator>
unspecified quoted(basic_string<charT, traits, Allocator>& s,
charT delim = charT('"'), charT escape = charT('\\'));
```

Returns: An object of unspecified type such that:

1. `delim`.

2. If `in` is an instance of `basic_istream` with member types `char_type` and `traits_type` the same as `charT` and `traits`, respectively, then the expression `in >> quoted(s, delim, escape)` behaves as if it extracts the following characters from `in` using `operator>>(basic_istream<charT, traits>&, charT&)` (31.7.5.3.3) which may throw `ios_base::failure` (31.5.2.2.1):

   1. If the first character extracted is equal to `delim`, as determined by `traits_type::eq`, then:

      1. Turn off the `skipws` flag.
      2. `s.clear()`.
      3. Until an unescaped `delim` character is reached or `!in`, extract characters from `in` and append them to `s`, except that if an `escape` is reached, ignore it and append the next character to `s`.

   2. Discard the final `delim` character.
   3. Restore the `skipws` flag to its original value.
   4. Otherwise, `in >> s`.

3. The expression `in >> quoted(s, delim, escape)` has type `basic_istream<charT, traits>&` and value `in`.

4. The expression `out << quoted(s, delim, escape)` has type `basic_ostream<charT, traits>&` and value `out`.

31.7.10 Print functions [print.fun]
template<class... Args>
void print(format_string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
print(stdout, fmt, std::forward<Args>(args)...);

template<class... Args>
void print(FILE* stream, format_string<Args...> fmt, Args&&... args);

Effects: Let locksafe be (enable_nonlocking_formatter_optimization<remove_cvref_t<Args>>
& ...). If the ordinary literal encoding (5.3) is UTF-8, equivalent to:

locksafe
? vprint_unicode(stream, fmt.str, make_format_args(args...))
: vprint_unicode_buffered(stream, fmt.str, make_format_args(args...));

Otherwise, equivalent to:

locksafe
? vprint_nonunicode(stream, fmt.str, make_format_args(args...))
: vprint_nonunicode_buffered(stream, fmt.str, make_format_args(args...));

template<class... Args>
void println(format_string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
println(stdout, fmt, std::forward<Args>(args)...);

void println();

Effects: Equivalent to:
println(stdout);

template<class... Args>
void println(FILE* stream, format_string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
print(stream, runtime_format(string(fmt.get()) + '\n'), std::forward<Args>(args)...);

void println(FILE* stream);

Effects: Equivalent to:
println(stream, "\n");

void vprint_unicode(string_view fmt, format_args args);

Effects: Equivalent to:
vprint_unicode(stdout, fmt, args);

void vprint_unicode_buffered(FILE* stream, string_view fmt, format_args args);

Effects: Equivalent to:

string out = vformat(fmt, args);
vprint_unicode(stream, "{\}", make_format_args(out));

void vprint_unicode(FILE* stream, string_view fmt, format_args args);

Preconditions: stream is a valid pointer to an output C stream.

Effects: Locks stream. Let out denote the character representation of formatting arguments provided
by args formatted according to specifications given in fmt. If stream refers to a terminal capable of
displaying Unicode, writes out to the terminal using the native Unicode API; if out contains invalid
code units, the behavior is undefined and implementations are encouraged to diagnose it. Otherwise
writes out to stream unchanged. If the native Unicode API is used, the function flushes stream before
writing out. Unconditionally unlocks stream on function exit.


[Note 1: On POSIX and Windows, stream referring to a terminal means that, respectively, isatty(fileno(
stream)) and GetConsoleMode(_get_osfhandle(_fileno(stream)), ...) return nonzero. —end note]
On Windows, the native Unicode API is `WriteConsoleW`. — end note

Throws: Any exception thrown by the call to `vformat` (22.14.3). `system_error` if writing to the terminal or stream fails. May throw `bad_alloc`.

Recommended practice: If invoking the native Unicode API requires transcoding, implementations should substitute invalid code units with U+FFFD REPLACEMENT CHARACTER per the Unicode Standard, Chapter 3.9 U+FFFD Substitution in Conversion.

```c
void vprint_nonunicode(string_view fmt, format_args args);

Effects: Equivalent to:
  vprint_nonunicode(stdout, fmt, args);
```

```c
void vprint_nonunicode_buffered(FILE* stream, string_view fmt, format_args args);

Effects: Equivalent to:
  string out = vformat(fmt, args);
  vprint_nonunicode("{}", make_format_args(out));
```

```c
void vprint_nonunicode(FILE* stream, string_view fmt, format_args args);

Preconditions: stream is a valid pointer to an output C stream.

Effects: While holding the lock on stream, writes the character representation of formatting arguments provided by args formatted according to specifications given in fmt to stream.

Throws: Any exception thrown by the call to `vformat` (22.14.3). `system_error` if writing to stream fails. May throw `bad_alloc`.

31.8 String-based streams

31.8.1 Header `<sstream>` synopsis

```c
namespace std {
  // 31.8.2, class template basic_stringbuf
template<class charT, class traits = char_traits<charT>,
class Allocator = allocator<charT>>
class basic_stringbuf;

  template<class charT, class traits, class Allocator>
  void swap(basic_stringbuf<charT, traits, Allocator>& x,
            basic_stringbuf<charT, traits, Allocator>& y) noexcept(noexcept(x.swap(y)));

  using stringbuf = basic_stringbuf<char>;
  using wstringbuf = basic_stringbuf<wchar_t>;

  // 31.8.3, class template basic_istringstream
  template<class charT, class traits = char_traits<charT>,
class Allocator = allocator<charT>>
class basic_istringstream;

  template<class charT, class traits, class Allocator>
  void swap(basic_istringstream<charT, traits, Allocator>& x,
            basic_istringstream<charT, traits, Allocator>& y);

  using istringstream = basic_istringstream<char>;
  using wistringstream = basic_istringstream<wchar_t>;

  // 31.8.4, class template basic_ostringstream
  template<class charT, class traits = char_traits<charT>,
class Allocator = allocator<charT>>
class basic_ostringstream;

  template<class charT, class traits, class Allocator>
  void swap(basic_ostringstream<charT, traits, Allocator>& x,
            basic_ostringstream<charT, traits, Allocator>& y);
```

§ 31.8.1 © ISO/IEC 1805
using ostringstream = basic_ostringstream<char>;
using wostringstream = basic_ostringstream<wchar_t>;

// 31.8.5, class template basic_stringstream

template<class charT, class traits = char_traits<charT>,
    class Allocator = allocator<charT>>
class basic_stringstream;

template<class charT, class traits, class Allocator>
void swap(basic_stringstream<charT, traits, Allocator>& x,
    basic_stringstream<charT, traits, Allocator>& y);

using stringstream = basic_stringstream<char>;
using wstringstream = basic_stringstream<wchar_t>;

The header `<sstream>` defines four class templates and eight types that associate stream buffers with objects of class `basic_string`, as described in 23.4.

31.8.2 Class template basic_stringbuf

31.8.2.1 General

namespace std {

    template<class charT, class traits = char_traits<charT>,
        class Allocator = allocator<charT>>
    class basic_stringbuf : public basic_streambuf<charT, traits> {
        public:

            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;
            using allocator_type = Allocator;

    // 31.8.2.2, constructors

        basic_stringbuf() : basic_stringbuf(ios_base::in | ios_base::out) {}
        explicit basic_stringbuf(ios_base::openmode which);
        explicit basic_stringbuf(  
            const basic_string<charT, traits, Allocator>& s,
            ios_base::openmode which = ios_base::in | ios_base::out);
        explicit basic_stringbuf(const Allocator& a)  
            : basic_stringbuf(ios_base::in | ios_base::out, a) {}
        basic_stringbuf(ios_base::openmode which, const Allocator& a);
        explicit basic_stringbuf(  
            basic_string<charT, traits, Allocator>&& s,
            ios_base::openmode which = ios_base::in | ios_base::out);
        template<class SAlloc>
        basic_stringbuf(  
            const basic_string<charT, traits, SAlloc>& s,
            const Allocator& a)
            : basic_stringbuf(s, ios_base::in | ios_base::out, a) {}
        template<class SAlloc>
        basic_stringbuf(  
            const basic_string<charT, traits, SAlloc>& s,
            ios_base::openmode which, const Allocator& a);
        template<class SAlloc>
        explicit basic_stringbuf(  
            const basic_string<charT, traits, SAlloc>& s,
            ios_base::openmode which = ios_base::in | ios_base::out);
    template<class T>
        explicit basic_stringbuf(const T& t,
            ios_base::openmode which = ios_base::in | ios_base::out);
    template<class T>
        basic_stringbuf(const T& t, const Allocator& a);
    template<class T>
        basic_stringbuf(const T& t, ios_base::openmode which, const Allocator& a);

    }
basic_stringbuf(const basic_stringbuf&) = delete;
basic_stringbuf(basic_stringbuf&& rhs);
basic_stringbuf(basic_stringbuf&& rhs, const Allocator& a);

// 31.8.2.3, assignment and swap
basic_stringbuf& operator=(const basic_stringbuf&) = delete;
basic_stringbuf& operator=(basic_stringbuf&& rhs);
void swap(basic_stringbuf& rhs) noexcept;

// 31.8.2.4, getters and setters
allocator_type get_allocator() const noexcept;

basic_string<
charT, traits, Allocator> str() const &;
template<class SAlloc>
basic_string<charT, traits, SAlloc> str(const SAlloc& sa) const;
basic_string_view<charT, traits> view() const noexcept;

void str(const basic_string<charT, traits, Allocator>& s);
template<class SAlloc>
void str(const basic_string<charT, traits, SAlloc>& s);
void str(basic_string<charT, traits, Allocator>&& s);
template<class T>
void str(const T& t);

protected:
// 31.8.2.5, overridden virtual functions
int_type underflow() override;
int_type pbackfail(int_type c = traits::eof()) override;
int_type overflow(int_type c = traits::eof()) override;
basic_streambuf<charT, traits>* setbuf(charT*, streamsize) override;
pos_type seekoff(off_type off, ios_base::seekdir way,
ios_base::openmode which = ios_base::in | ios_base::out) override;
pos_type seekpos(pos_type sp,
ios_base::openmode which = ios_base::in | ios_base::out) override;

private:
ios_base::openmode mode;
// exposition only
basic_string<charT, traits, Allocator> buf;
// exposition only
void init_buf_ptrs();
// exposition only
};

1 The class basic_stringbuf is derived from basic_streambuf to associate possibly the input sequence and possibly the output sequence with a sequence of arbitrary characters. The sequence can be initialized from, or made available as, an object of class basic_string.

2 For the sake of exposition, the maintained data and internal pointer initialization is presented here as:

(2.1) — ios_base::openmode mode, has in set if the input sequence can be read, and out set if the output sequence can be written.

(2.2) — basic_string<charT, traits, Allocator> buf contains the underlying character sequence.

(2.3) — init_buf_ptrs() sets the base class’ get area (31.6.3.4.2) and put area (31.6.3.4.3) pointers after initializing, moving from, or assigning to buf accordingly.

31.8.2.2 Constructors

explicit basic_stringbuf(ios_base::openmode which);

Effects: Initializes the base class with basic_streambuf() (31.6.3.2), and mode with which. It is implementation-defined whether the sequence pointers (eback(), gptr(), egptr(), pbase(), pptr(), epptr()) are initialized to null pointers.
2  \textit{Postconditions:} \texttt{str().empty()} is true.

\begin{verbatim}
explicit basic_stringbuf(const basic_string<charT, traits, Allocator>&& s, 
sios_base::openmode which = sios_base::in | sios_base::out);
\end{verbatim}

\begin{verbatim}
  \textit{Effects:} Initializes the base class with \texttt{basic_streambuf() (31.6.3.2)}, mode with which, and buf with s, then calls \texttt{init_buf_ptrs()}. 
\end{verbatim}

3  \sbox{basic_stringbuf}(sios_base::openmode which, const Allocator& a);

\begin{verbatim}
  \textit{Effects:} Initializes the base class with \texttt{basic_streambuf() (31.6.3.2)}, mode with which, and buf with a, then calls \texttt{init_buf_ptrs()}. 
\end{verbatim}

4  \textit{Postconditions:} \texttt{str().empty()} is true.

\begin{verbatim}
explicit basic_stringbuf(basic_string<charT, traits, Allocator>&& s, 
sios_base::openmode which = sios_base::in | sios_base::out);
\end{verbatim}

5  \sbox{Effects:} Initializes the base class with \texttt{basic_streambuf() (31.6.3.2)}, mode with which, and buf with std::move(s), then calls \texttt{init_buf_ptrs()}. 

6  template<class SAlloc>
  \begin{verbatim}
  basic_stringbuf(const basic_string<charT, traits, SAlloc>& s, 
  sios_base::openmode which, const Allocator& a);
  \end{verbatim}

7  \sbox{Effects:} Initializes the base class with \texttt{basic_streambuf() (31.6.3.2)}, mode with which, and buf with \{s,a\}, then calls \texttt{init_buf_ptrs()}. 

8  template<class SAlloc>
  \begin{verbatim}
  explicit basic_stringbuf(const basic_string<charT, traits, SAlloc>& s, 
    sios_base::openmode which = sios_base::in | sios_base::out);
  \end{verbatim}

9  \sbox{Constraints:} \texttt{is_same_v<SAlloc, Allocator>} is false. 

10 template<class T>
    \begin{verbatim}
    explicit basic_stringbuf(const T& t, sios_base::openmode which = sios_base::in | sios_base::out);
    \end{verbatim}

11 \sbox{Effects:} Creates a variable \texttt{sv} as if by \texttt{basic_string_view<charT, traits> sv = t}, then value-initializes the base class, initializes mode with which, and direct-non-list-initializes buf with \texttt{sv}, \texttt{a}, then calls \texttt{init_buf_ptrs()}. 

12 basic_stringbuf(basic_stringbuf&& rhs);

13 basic_stringbuf(basic_stringbuf&& rhs, const Allocator& a);

14 \sbox{Effects:} Copy constructs the base class from \texttt{rhs} and initializes mode with \texttt{rhs.mode}. In the first form buf is initialized from \texttt{std::move(rhs).str()}. In the second form buf is initialized from \{\texttt{std::move(rhs).str()}, \texttt{a}\}. It is implementation-defined whether the sequence pointers in \texttt{*this (eback(), gptr(), egptr(), pbase(), pptr(), epptr())} obtain the values which \texttt{rhs} had. 

15 \sbox{Postconditions:} Let \texttt{rhs_p} refer to the state of \texttt{rhs} just prior to this construction and let \texttt{rhs_a} refer to the state of \texttt{rhs} just after this construction. 

\texttt{- str() == rhs_p.str()}

\texttt{- gptr() - eback() == rhs_p.gptr() - rhs_p.eback()}

\begin{verbatim}
§ 31.8.2.2 ©ISO/IEC 1808
\end{verbatim}
31.8.2.3 Assignment and swap

```cpp
basic_stringbuf& operator=(basic_stringbuf&& rhs);
```

**Effects:** After the move assignment *this has the observable state it would have had if it had been move constructed from rhs (see 31.8.2.2).

**Returns:** *this.

```cpp
void swap(basic_stringbuf& rhs) noexcept;
```

**Preconditions:** allocator_traits<Allocator>::propagate_on_container_swap::value is true or get_allocator() == rhs.get_allocator() is true.

**Effects:** Exchanges the state of *this and rhs.

**Remarks:** The exception specification is equivalent to:

```cpp
allocator_traits<Allocator>::propagate_on_container_swap::value || allocator_traits<Allocator>::is_always_equal::value
```

```cpp
template<class charT, class traits, class Allocator>
void swap(basic_stringbuf<charT, traits, Allocator>& x, basic_stringbuf<charT, traits, Allocator>& y) noexcept(noexcept(x.swap(y)));
```

**Effects:** Equivalent to x.swap(y).

31.8.2.4 Member functions

```cpp
void init_buf_ptrs(); // exposition only
```

**Effects:** Initializes the input and output sequences from buf according to mode.

**Postconditions:**

1. If ios_base::out is set in mode, pbase() points to buf.front() and epptr() >= pbase() + buf.size() is true;
2. in addition, if ios_base::ate is set in mode, pptr() == pbase() + buf.size() is true,
3. otherwise pptr() == pbase() is true.
4. If ios_base::in is set in mode, eback() points to buf.front(), and (gptr() == eback() && egptr() == eback() + buf.size()) is true.

**[Note 1:]** For efficiency reasons, stream buffer operations can violate invariants of buf while it is held encapsulated in the basic_stringbuf, e.g., by writing to characters in the range [buf.data() + buf.size(), buf.data() + buf.capacity()). All operations retrieving a basic_string from buf ensure that the basic_string invariants hold on the returned value. — end note]
allocator_type get_allocator() const noexcept;

Returns: buf.get_allocator().

basic_string<CharT, Traits, Allocator> str() const &;

Effects: Equivalent to:
        return basic_string<CharT, Traits, Allocator>(view(), get_allocator());

template<class SAlloc>
basic_string<CharT, Traits, SAlloc> str(const SAlloc& sa) const;

Constraints: SAlloc is a type that qualifies as an allocator (24.2.2.2).

Effects: Equivalent to:
        return basic_string<CharT, Traits, SAlloc>(view(), sa);

basic_string<CharT, Traits, Allocator> str() &&;

Postconditions: The underlying character sequence buf is empty and pbase(), pptr(), epptr(),
        ebak(), gptr(), and egpstr() are initialized as if by calling init_buf_ptrs() with an empty buf.

Returns: A basic_string<CharT, Traits, Allocator> object move constructed from the basic_stringbuf’s underlying character sequence in buf. This can be achieved by first adjusting buf to have the same content as view().

basic_string_view<CharT, Traits> view() const noexcept;

Let sv be basic_string_view<CharT, Traits>.

Returns: A sv object referring to the basic_stringbuf’s underlying character sequence in buf:

(12.1) If ios_base::out is set in mode, then sv(pbase(), high_mark-pbase()) is returned.
(12.2) Otherwise, if ios_base::in is set in mode, then sv(eback(), egptr()-eback()) is returned.
(12.3) Otherwise, sv() is returned.

[Note 2: Using the returned sv object after destruction or invalidation of the character sequence underlying *this is undefined behavior, unless sv.empty() is true. — end note]

void str(const basic_string<CharT, Traits, Allocator>& s);

Effects: Equivalent to:
        buf = s;
        init_buf_ptrs();

template<class SAlloc>
void str(const basic_string<CharT, Traits, SAlloc>& s);

Constraints: is_same_v<SAlloc, Allocator> is false.

Effects: Equivalent to:
        buf = s;
        init_buf_ptrs();

void str(basic_string<CharT, Traits, Allocator>&& s);

Effects: Equivalent to:
        buf = std::move(s);
        init_buf_ptrs();

template<class T>
void str(const T& t);

Constraints: is_convertible_v<const T&, basic_string_view<CharT, Traits>> is true.

Effects: Equivalent to:
        basic_string_view<CharT, Traits> sv = t;
        buf = sv;
        init_buf_ptrs();
31.8.2.5 Overridden virtual functions

int_type underflow() override;

Returns: If the input sequence has a read position available, returns traits::to_int_type(*gptr()). Otherwise, returns traits::eof(). Any character in the underlying buffer which has been initialized is considered to be part of the input sequence.

int_type pbackfail(int_type c = traits::eof()) override;

Effects: Puts back the character designated by c to the input sequence, if possible, in one of three ways:

(2.1) If traits::eq_int_type(c, traits::eof()) returns false and if the input sequence has a putback position available, and if traits::eq(to_char_type(c), gptr()[-1]) returns true, assigns gptr() - 1 to gptr().

Returns: c.

(2.2) If traits::eq_int_type(c, traits::eof()) returns false and if the input sequence has a putback position available, and if mode & ios_base::out is nonzero, assigns c to *--gptr().

Returns: c.

(2.3) If traits::eq_int_type(c, traits::eof()) returns true and if the input sequence has a putback position available, assigns gptr() - 1 to gptr().

Returns: traits::not_eof(c).

Returns: As specified above, or traits::eof() to indicate failure.

Remarks: If the function can succeed in more than one of these ways, it is unspecified which way is chosen.

int_type overflow(int_type c = traits::eof()) override;

Effects: Appends the character designated by c to the output sequence, if possible, in one of two ways:

(5.1) If traits::eq_int_type(c, traits::eof()) returns false and if either the output sequence has a write position available or the function makes a write position available (as described below), the function calls sputc(c).

Signals success by returning c.

(5.2) If traits::eq_int_type(c, traits::eof()) returns true, there is no character to append.

Signals success by returning a value other than traits::eof().

Returns: As specified above, or traits::eof() to indicate failure.

Remarks: The function can alter the number of write positions available as a result of any call.

The function can make a write position available only if ios_base::out is set in mode. To make a write position available, the function reallocates (or initially allocates) an array object with a sufficient number of elements to hold the current array object (if any), plus at least one additional write position. If ios_base::in is set in mode, the function alters the read end pointer egptr() to point just past the new write position.

pos_type seekoff(off_type off, ios_base::seekdir way, ios_base::openmode which = ios_base::in | ios_base::out) override;

Effects: Alters the stream position within one of the controlled sequences, if possible, as indicated in Table 129.

For a sequence to be positioned, the function determines newoff as indicated in Table 130. If the sequence’s next pointer (either gptr() or pptr()) is a null pointer and newoff is nonzero, the positioning operation fails.

If (newoff + off) < 0, or if newoff + off refers to an uninitialized character (31.8.2.4), the positioning operation fails. Otherwise, the function assigns xbeg + newoff + off to the next pointer xnext.
### Table 129 — seekoff positioning

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>ios_base::in is set in which</td>
<td>positions the input sequence</td>
</tr>
<tr>
<td>ios_base::out is set in which</td>
<td>positions the output sequence</td>
</tr>
<tr>
<td>both ios_base::in and ios_base::out are set in which and either way == ios_base::beg or way == ios_base::end</td>
<td>positions both the input and the output sequences</td>
</tr>
<tr>
<td>Otherwise</td>
<td>the positioning operation fails.</td>
</tr>
</tbody>
</table>

### Table 130 — newoff values

<table>
<thead>
<tr>
<th>Condition</th>
<th>newoff Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>way == ios_base::beg</td>
<td>0</td>
</tr>
<tr>
<td>way == ios_base::cur</td>
<td>the next pointer minus the beginning pointer (xnext - xbeg).</td>
</tr>
<tr>
<td>way == ios_base::end</td>
<td>the high mark pointer minus the beginning pointer (high_mark - xbeg).</td>
</tr>
</tbody>
</table>

12. **Returns:** `pos_type(newoff)`, constructed from the resultant offset `newoff` (of type `off_type`), that stores the resultant stream position, if possible. If the positioning operation fails, or if the constructed object cannot represent the resultant stream position, the return value is `pos_type(off_type(-1))`.

```cpp
pos_type seekpos(pos_type sp,  
    ios_base::openmode which  
    = ios_base::in | ios_base::out) override;
```

13. **Effects:** Equivalent to `seekoff(off_type(sp), ios_base::beg, which)`.

14. **Returns:** `sp` to indicate success, or `pos_type(off_type(-1))` to indicate failure.

```cpp
basic_streambuf<charT, traits>* setbuf(charT* s, streamsize n) override;
```

15. **Effects:** implementation-defined, except that `setbuf(0, 0)` has no effect.

16. **Returns:** `this`.

### 31.8.3 Class template basic_istringstream

31.8.3.1 General

```cpp
namespace std {

    template<class charT, class traits = char_traits<charT>,
    class Allocator = allocator<charT>>
    class basic_istringstream : public basic_istream<charT, traits> {

        public:
        using char_type       = charT;
        using int_type        = typename traits::int_type;
        using pos_type        = typename traits::pos_type;
        using off_type        = typename traits::off_type;
        using traits_type     = traits;
        using allocator_type  = Allocator;

        // 31.8.3.2, constructors
        basic_istringstream() : basic_istringstream(ios_base::in) {};
        explicit basic_istringstream(ios_base::openmode which);
        explicit basic_istringstream(  
            const basic_string<charT, traits, Allocator>& s,  
            ios_base::openmode which = ios_base::in);
        basic_istringstream(ios_base::openmode which, const Allocator& a);
    }
}
```
explicit basic_istringstream(
    basic_string<charT, traits, Allocator>&& s,
    ios_base::openmode which = ios_base::in);
template<class SAlloc>
explicit basic_istringstream(
    const basic_string<charT, traits, SAlloc>& s, const Allocator& a)
    : basic_istringstream(s, ios_base::in, a) {}
template<class SAlloc>
basic_istringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which, const Allocator& a);
template<class SAlloc>
explicit basic_istringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which = ios_base::in);
template<class T>
explicit basic_istringstream(const T& t, ios_base::openmode which = ios_base::in);
template<class T>
basic_istringstream(const T& t, const Allocator& a);
template<class T>
basic_istringstream(const T& t, ios_base::openmode which, const Allocator& a);
basic_istringstream& operator=(const basic_istringstream&) = delete;
basic_istringstream& operator=(basic_istringstream&& rhs);

void swap(basic_istringstream& rhs);

void str(const basic_string<charT, traits, Allocator>& s);
template<class SAlloc>
void str(const basic_string<charT, traits, SAlloc>& s);
void str(basic_string<charT, traits, Allocator>&& s);
template<class T>
void str(const T& t);

private:
    basic_stringbuf<charT, traits, Allocator> sb;  // exposition only
};

The class basic_istringstream<charT, traits, Allocator> supports reading objects of class basic_string<charT, traits, Allocator>. It uses a basic_stringbuf<charT, traits, Allocator> object to control the associated storage. For the sake of exposition, the maintained data is presented here as:

— \( \text{sb} \), the \text{stringbuf} object.

### 31.8.3.2 Constructors

#### [istringstream.cons]

explicit basic_istringstream(ios_base::openmode which);

*Effects:* Initializes the base class with `basic_istream<charT, traits>(\text{addressof(sb)})` \((31.7.5.2)\) and \(\text{sb}\) with `basic_stringbuf<charT, traits, Allocator>(\text{which | ios_base::in})` \((31.8.2.2)\).
explicit basic_istringstream(
    const basic_string<charT, traits, Allocator>& s,
    ios_base::openmode which = ios_base::in);

   Effects: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.5.2)
   and `sb` with `basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::in)` (31.8.2.2).

basic_istringstream(ios_base::openmode which, const Allocator& a);

   Effects: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.5.2)
   and `sb` with `basic_stringbuf<charT, traits, Allocator>(which | ios_base::in, a)` (31.8.2.2).

explicit basic_istringstream(
    basic_string<charT, traits, Allocator>&& s,
    ios_base::openmode which = ios_base::in);

   Effects: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.5.2)
   and `sb` with `basic_stringbuf<charT, traits, Allocator>(std::move(s), which | ios_base::in)` (31.8.2.2).

template<class SAlloc>
basic_istringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which, const Allocator& a);

   Effects: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.5.2)
   and `sb` with `basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::in, a)` (31.8.2.2).

template<class SAlloc>
explicit basic_istringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which = ios_base::in);

   Constraints: `is_same_v<SAlloc, Allocator>` is false.

   Effects: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.5.2)
   and `sb` with `basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::in)` (31.8.2.2).

template<class T>
explicit basic_istringstream(const T& t, ios_base::openmode which = ios_base::in);

   template<class T>
   basic_istringstream(const T& t, const Allocator& a);

   template<class T>
   basic_istringstream(const T& t, ios_base::openmode which, const Allocator& a);

   Let `which` be `ios_base::in` for the overload with no parameter `which`, and `a` be `Allocator()` for the
   overload with no parameter `a`.

   Constraints: `is_convertible_v<const T&, basic_string_view<charT, traits>>` is true.

   Effects: Initializes the base class with `addressof(sb)`, and direct-non-list-initializes `sb` with `t`, which
   `| ios_base::in`, `a`.

basic_istringstream(basic_istringstream&& rhs);

   Effects: Move constructs from the rvalue `rhs`. This is accomplished by move constructing the
   base class, and the contained `basic_stringbuf`. Then calls `basic_istream<charT, traits>::set_rdbuf`(`addressof(sb)`) to install the contained `basic_stringbuf`.

31.8.3.3 Swap

   [stringstream.swap]

void swap(basic_istringstream& rhs);

   Effects: Equivalent to:
   `basic_istream<charT, traits>::swap(rhs);
   sb.swap(rhs.sb);`
template<class charT, class traits, class Allocator>
    void swap(basic_istringstream<charT, traits, Allocator>& x,
              basic_istringstream<charT, traits, Allocator>& y);

    Effects: Equivalent to x.swap(y).

31.8.3.4 Member functions

    basic_stringbuf<charT, traits, Allocator>* rdbuf() const;

1     Returns: const_cast<basic_stringbuf<charT, traits, Allocator>*>(addressof(sb)).

    basic_string<charT, traits, Allocator> str() const &;

2     Effects: Equivalent to: return rdbuf()->str();

template<class SAlloc>
    basic_string<charT, traits, SAlloc> str(const SAlloc& sa) const;

3     Effects: Equivalent to: return rdbuf()->str(sa);

    basic_string<charT, traits, Allocator> str() &&;

4     Effects: Equivalent to: return std::move(*rdbuf()).str();

    basic_string_view<charT, traits> view() const noexcept;

5     Effects: Equivalent to: return rdbuf()->view();

void str(const basic_string<charT, traits, Allocator>& s);

6     Effects: Equivalent to: rdbuf()->str(s);

template<class SAlloc>
    void str(const basic_string<charT, traits, SAlloc>& s);

7     Effects: Equivalent to: rdbuf()->str(s);

    void str(basic_string<charT, traits, Allocator>&& s);

8     Effects: Equivalent to: rdbuf()->str(std::move(s));

    template<class T>
        void str(const T& t);

9     Constraints: is_convertible_v<const T&, basic_string_view<charT, traits>> is true.

10    Effects: Equivalent to: rdbuf()->str(t);

31.8.4 Class template basic_ostringstream

31.8.4.1 General

namespace std {
    template<class charT, class traits = char_traits<charT>,
             class Allocator = allocator<charT>>
    class basic_ostringstream : public basic_ostream<charT, traits> {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;
            using allocator_type = Allocator;

        // 31.8.4.2, constructors
        basic_ostringstream() : basic_ostringstream(ios_base::out) {}
        explicit basic_ostringstream(ios_base::openmode which);
        explicit basic_ostringstream(
            const basic_ostringstream<
                charT, traits, Allocator>& s,
            ios_base::openmode which = ios_base::out);
        basic_ostringstream(ios_base::openmode which, const Allocator& a);
    }
}
explicit basic_ostringstream(
    basic_string<charT, traits, Allocator>&& s,
    ios_base::openmode which = ios_base::out);

template<class SAlloc>
basic_ostringstream(
    const basic_string<charT, traits, SAlloc>& s,
    const Allocator& a)
: basic_ostringstream(s, ios_base::out, a) {}

template<class SAlloc>
basic_ostringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which, const Allocator& a);

template<class SAlloc>
explicit basic_ostringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which = ios_base::out);

template<class T>
explicit basic_ostringstream(const T& t, ios_base::openmode which = ios_base::out);

template<class T>
basic_ostringstream(const T& t, const Allocator& a);

template<class T>
basic_ostringstream(const T& t, ios_base::openmode which, const Allocator& a);

basic_ostringstream& operator=(const basic_ostringstream&) = delete;

basic_ostringstream& operator=(basic_ostringstream&& rhs);

void swap(basic_ostringstream& rhs);

// 31.8.4.3, swap
void swap(basic_ostringstream& rhs);

// 31.8.4.4, members
basic_stringbuf<charT, traits, Allocator>* rdbuf() const;

basic_string<charT, traits, Allocator> str() const &;

template<class SAlloc>
basic_string<charT, traits, SAlloc> str(const SAlloc& sa) const;

basic_string<charT, traits, Allocator> str() &&;

basic_string_view<charT, traits> view() const noexcept;

void str(const basic_string<charT, traits, Allocator>& s);

template<class SAlloc>
void str(const basic_string<charT, traits, SAlloc>& s);

void str(basic_string<charT, traits, Allocator>&& s);

template<class T>
void str(const T& t);

private:
    basic_stringbuf<charT, traits, Allocator> sb;    // exposition only
};

The class basic_ostringstream<charT, traits, Allocator> supports writing objects of class basic_string<charT, traits, Allocator>. It uses a basic_stringbuf object to control the associated storage. For the sake of exposition, the maintained data is presented here as:

sb, the stringbuf object.

31.8.4.2 Constructors [sstream.cons]

explicit basic_ostringstream(ios_base::openmode which);

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.6.2) and sb with basic_stringbuf<charT, traits, Allocator>(which | ios_base::out) (31.8.2.2).
explicit basic_ostringstream(
  const basic_string<charT, traits, Allocator>& s,
  ios_base::openmode which = ios_base::out);

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.6.2) and sb with basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::out) (31.8.2.2).

basic_ostringstream(ios_base::openmode which, const Allocator& a);

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.6.2) and sb with basic_stringbuf<charT, traits, Allocator>(which | ios_base::out, a) (31.8.2.2).

explicit basic_ostringstream(
  basic_string<charT, traits, Allocator>&& s,
  ios_base::openmode which = ios_base::out);

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.6.2) and sb with basic_stringbuf<charT, traits, Allocator>(std::move(s), which | ios_base::out) (31.8.2.2).

template<class SAlloc>
explicit basic_ostringstream(
  const basic_string<charT, traits, SAlloc>& s,
  ios_base::openmode which, const Allocator& a);

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.6.2) and sb with basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::out, a) (31.8.2.2).

template<class SAlloc>
explicit basic_ostringstream(
  basic_string<charT, traits, SAlloc>&& s,
  ios_base::openmode which = ios_base::out);

Constraints: is_same_v<SAlloc, Allocator> is false.

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.6.2) and sb with basic_stringbuf<charT, traits, Allocator>(std::move(s), which | ios_base::out) (31.8.2.2).

template<class T>
explicit basic_ostringstream(const T& t, ios_base::openmode which = ios_base::out);

template<class T>
explicit basic_ostringstream(const T& t, const Allocator& a);

template<class T>
explicit basic_ostringstream(const T& t, ios_base::openmode which, const Allocator& a);

Let which be ios_base::out for the overload with no parameter which, and a be Allocator() for the overload with no parameter a.

Constraints: is_convertible_v<const T&, basic_string_view<charT, traits>> is true.

Effects: Initializes the base class with addressof(sb), and direct-non-list-initializes sb with t, which | ios_base::out, a.

basic_ostringstream(basic_ostringstream&& rhs);

Effects: Move constructs from the rvalue rhs. This is accomplished by move constructing the base class, and the contained basic_stringbuf. Then calls basic_ostream<charT, traits>::set_rdbuf(addressof(sb)) to install the contained basic_stringbuf.

31.8.4.3 Swap

void swap(basic_ostringstream& rhs);

Effects: Equivalent to:

  basic_ostream<charT, traits>::swap(rhs);
  sb.swap(rhs.sb);
template<class charT, class traits, class Allocator>
    void swap(basic_ostringstream<charT, traits, Allocator>& x,
               basic_ostringstream<charT, traits, Allocator>& y);

Effects: Equivalent to x.swap(y).

31.8.4.4 Member functions

basic_stringbuf<charT, traits, Allocator>* rdbuf() const;
Returns: const_cast<basic_stringbuf<charT, traits, Allocator>* >(addressof(sb)).

basic_string<charT, traits, Allocator> str() const &;
Effects: Equivalent to: return rdbuf()->str();

template<class SAlloc>
    basic_string<charT, traits, SAlloc> str(const SAlloc& sa) const;
Effects: Equivalent to: return rdbuf()->str(sa);

basic_string_view<charT, traits> view() const noexcept;
Effects: Equivalent to: return rdbuf()->view();

void str(const basic_string<charT, traits, Allocator>& s);
Effects: Equivalent to: rdbuf()->str(s);

template<class T>
    void str(const T& t);
Effects: Equivalent to: rdbuf()->str(t);

§ 31.8.5.1 General

1818
explicit basic_stringstream(
    basic_string<charT, traits, Allocator>&& s,
    ios_base::openmode which = ios_base::out | ios_base::in);

template<class SAlloc>
basic_stringstream(
    const basic_string<charT, traits, SAlloc>& s,
    const Allocator& a)
    : basic_stringstream(s, ios_base::out | ios_base::in, a) {}

template<class SAlloc>
basic_stringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which, const Allocator& a);

explicit basic_stringstream(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which = ios_base::out | ios_base::in);

template<class T>
explicit basic_stringstream(const T& t,
    ios_base::openmode which = ios_base::out | ios_base::in);

template<class T>
basic_stringstream(const T& t, const Allocator& a);

template<class T>
basic_stringstream(const T& t, ios_base::openmode which, const Allocator& a);

basic_stringstream(const basic_stringstream&) = delete;

basic_stringstream(basic_stringstream&& rhs);

basic_stringstream& operator=(const basic_stringstream&) = delete;

basic_stringstream& operator=(basic_stringstream&& rhs);

// 31.8.5.3, swap
void swap(basic_stringstream& rhs);

// 31.8.5.4, members
basic_stringbuf<charT, traits, Allocator>* rdbuf() const;

basic_string<charT, traits, Allocator> str() const &;

template<class SAlloc>
basic_string<charT, traits, SAlloc> str(const SAlloc& sa) const;

basic_string<charT, traits, Allocator> str() &&;

basic_string_view<charT, traits> view() const noexcept;

void str(const basic_string<charT, traits, Allocator>& s);

template<class SAlloc>
void str(const basic_string<charT, traits, SAlloc>& s);

void str(basic_string<charT, traits, Allocator>&& s);

template<class T>
void str(const T& t);

private:
    basic_stringbuf<charT, traits, Allocator> sb;  // exposition only
};

The class template basic_stringstream<charT, traits> supports reading and writing from objects of
class basic_string<charT, traits, Allocator>. It uses a basic_stringbuf<charT, traits, Allocator>
object to control the associated sequence. For the sake of exposition, the maintained data is presented
here as

(1.1) — sb, the stringbuf object.

31.8.5.2 Constructors

explicit basic_stringstream(ios_base::openmode which);

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2)
and sb with basic_stringbuf<charT, traits, Allocator>(which).
explicit basic_stringstream(  
    const basic_string<charT, traits, Allocator>& s,  
    ios_base::openmode which = ios_base::out | ios_base::in);  

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2)  
and sb with basic_stringbuf<charT, traits, Allocator>(s, which).

basic_stringstream(ios_base::openmode which, const Allocator& a);  

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2)  
and sb with basic_stringbuf<charT, traits, Allocator>(which, a) (31.8.2.2).

explicit basic_stringstream(  
    basic_string<charT, traits, Allocator>&& s,  
    ios_base::openmode which = ios_base::out | ios_base::in);  

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2)  
and sb with basic_stringbuf<charT, traits, Allocator>(std::move(s), which) (31.8.2.2).

template<class SAlloc>  
    basic_stringstream(  
        const basic_string<charT, traits, SAlloc>& s,  
        ios_base::openmode which, const Allocator& a);  

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2)  
and sb with basic_stringbuf<charT, traits, Allocator>(s, which, a) (31.8.2.2).

template<class SAlloc>  
    explicit basic_stringstream(  
        const basic_string<charT, traits, SAlloc>&& s,  
        ios_base::openmode which, const Allocator& a);  

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2)  
and sb with basic_stringbuf<charT, traits, Allocator>(s, which, a) (31.8.2.2).

template<class T>  
    explicit basic_stringstream(const T& t, ios_base::openmode which = ios_base::out | ios_base::in);  

template<class T>  
    basic_stringstream(const T& t, const Allocator& a);  

template<class T>  
    basic_stringstream(const T& t, ios_base::openmode which, const Allocator& a);  

Let which be ios_base::out | ios_base::in for the overload with no parameter which,  
and a be Allocator() for the overload with no parameter a.  

Constraints: is_convertible_v<const T&, basic_string_view<charT, traits>> is true.  

Effects: Initializes the base class with addressof(sb), and direct-non-list-initializes sb with t, which,  
a.

basic_stringstream(basic_stringstream&& rhs);  

Effects: Move constructs from the rvalue rhs. This is accomplished by move constructing  
the base class, and the contained basic_stringbuf. Then calls basic_istream<charT, traits>::set_  
rdbuf(addressof(sb)) to install the contained basic_stringbuf.

31.8.5.3 Swap  

void swap(basic_stringstream& rhs);  

Effects: Equivalent to:  
    basic_iostream<charT,traits>::swap(rhs);  
    sb.swap(rhs.sb);

template<class charT, class traits, class Allocator>  
    void swap(basic_stringstream<charT, traits, Allocator>& x,  
        basic_stringstream<charT, traits, Allocator>& y);  

Effects: Equivalent to x.swap(y).
31.8.5.4 Member functions

basic_stringbuf<charT, traits, Allocator>* rdbuf() const;

Returns: const_cast<basic_stringbuf<charT, traits, Allocator>*>(addressof(sb)).

basic_string<charT, traits, Allocator> str() const &;

Effects: Equivalent to: return rdbuf()->str();

template<class SAlloc>
basic_string<charT,traits,SAlloc> str(const SAlloc& sa) const;

Effects: Equivalent to: return rdbuf()->str(sa);

basic_string<charT,traits,Allocator> str() &&;

Effects: Equivalent to: return std::move(*rdbuf()).str();

basic_string_view<charT, traits> view() const noexcept;

Effects: Equivalent to: return rdbuf()->view();

void str(const basic_string<charT, traits, Allocator>& s);

Effects: Equivalent to: rdbuf()->str(s);

template<class SAlloc>
void str(const basic_string<charT, traits, SAlloc>& s);

Effects: Equivalent to: rdbuf()->str(s);

void str(basic_string<charT, traits, Allocator>&& s);

Effects: Equivalent to: rdbuf()->str(std::move(s));

template<class T>
void str(const T&);

Constraints: is_convertible_v<const T&, basic_string_view<charT, traits>> is true.

Effects: Equivalent to: rdbuf()->str(t);

31.9 Span-based streams

31.9.1 Overview

The header <spanstream> defines class templates and types that associate stream buffers with objects whose types are specializations of span as described in 24.7.2.2.

[Note 1: A user of these classes is responsible for ensuring that the character sequence represented by the given span outlives the use of the sequence by objects of the classes in 31.9. Using multiple basic_spanbuf objects referring to overlapping underlying sequences from different threads, where at least one basic_spanbuf object is used for writing to the sequence, results in a data race. — end note]

31.9.2 Header <spanstream> synopsis

namespace std {
    // 31.9.3, class template basic_spanbuf
    template<class charT, class traits = char_traits<charT>>
        class basic_spanbuf;

    template<class charT, class traits>
        void swap(basic_spanbuf<charT, traits>& x, basic_spanbuf<charT, traits>& y);

    using spanbuf = basic_spanbuf<char>;
    using wspanbuf = basic_spanbuf<wchar_t>;

    // 31.9.4, class template basic_ispanstream
    template<class charT, class traits = char_traits<charT>>
        class basic_ispanstream;
template<class charT, class traits>
void swap(basic_ispanstream<charT, traits>& x, basic_ispanstream<char, traits>& y);

using ispanstream = basic_ispanstream<char>;
using wispanstream = basic_ispanstream<wchar_t>;

// 31.9.5, class template basic_ospanstream
template<class charT, class traits = char_traits<charT>>
class basic_ospanstream;

template<class charT, class traits>
void swap(basic_ospanstream<charT, traits>& x, basic_ospanstream<charT, traits>& y);

using ospanstream = basic_ospanstream<char>;
using wospanstream = basic_ospanstream<wchar_t>;

// 31.9.6, class template basic_spanstream
template<class charT, class traits = char_traits<charT>>
class basic_spanstream;

template<class charT, class traits>
void swap(basic_spanstream<charT, traits>& x, basic_spanstream<charT, traits>& y);

using spanstream = basic_spanstream<char>;
using wspanstream = basic_spanstream<wchar_t>;

31.9.3 Class template basic_spanbuf
[spanbuf]

31.9.3.1 General
[spanbuf.general]
namespace std {
    template<class charT, class traits = char_traits<charT>>
class basic_spanbuf : public basic_streambuf<charT, traits> { 
public:
    using char_type = charT;
    using int_type = typename traits::int_type;
    using pos_type = typename traits::pos_type;
    using off_type = typename traits::off_type;
    using traits_type = traits;

    // 31.9.3.2, constructors
    basic_spanbuf() : basic_spanbuf(ios_base::in | ios_base::out) {} 
    explicit basic_spanbuf(ios_base::openmode which) : basic_spanbuf(std::span<charT>(), which) {} 
    explicit basic_spanbuf(std::span<charT> s, 
                              ios_base::openmode which = ios_base::in | ios_base::out); 
    basic_spanbuf(const basic_spanbuf&) = delete; 
    basic_spanbuf(basic_spanbuf&& rhs); 

    // 31.9.3.3, assignment and swap
    basic_spanbuf& operator=(const basic_spanbuf&) = delete; 
    basic_spanbuf& operator=(basic_spanbuf&& rhs); 
    void swap(basic_spanbuf& rhs); 

    // 31.9.3.4, member functions
    std::span<charT> span() const noexcept; 
    void span(std::span<charT> s) noexcept; 

protected:
    // 31.9.3.5, overridden virtual functions
    basic_streambuf<charT, traits>* setbuf(charT*, streamsize) override; 
    pos_type seekoff(off_type off, ios_base::seekdir way, 
                     ios_base::openmode which = ios_base::in | ios_base::out) override; 
} 
}
pos_type seekpos(pos_type sp,
   ios_base::openmode which = ios_base::in | ios_base::out) override;

private:
   ios_base::openmode mode;       // exposition only
   std::span<charT> buf;          // exposition only

1 The class template basic_spanbuf is derived from basic_streambuf to associate possibly the input sequence
and possibly the output sequence with a sequence of arbitrary characters. The sequence is provided by an
object of class span<charT>.

2 For the sake of exposition, the maintained data is presented here as:

(2.1) — ios_base::openmode mode, has in set if the input sequence can be read, and out set if the output
sequence can be written.

(2.2) — std::span<charT> buf is the view to the underlying character sequence.

31.9.3.2 Constructors

explicit basic_spanbuf(std::span<charT> s,
   ios_base::openmode which = ios_base::in | ios_base::out);

1 Effects: Initializes the base class with basic_streambuf() (31.6.3.2), and mode with which. Initializes
the internal pointers as if calling span(s).

basic_spanbuf(basic_spanbuf&& rhs);

2 Effects: Initializes the base class with std::move(rhs) and mode with std::move(rhs.mode) and buf
with std::move(rhs.buf). The sequence pointers in *this (eback(), gptr(), egptr(), pbase(),
pptr(), epptr()) obtain the values which rhs had. It is implementation-defined whether rhs.buf.
empty() returns true after the move.

Postconditions: Let rhs_p refer to the state of rhs just prior to this construction.

(3.1) — span().data() == rhs_p.span().data()
(3.2) — span().size() == rhs_p.span().size()
(3.3) — eback() == rhs_p.eback()
(3.4) — gptr() == rhs_p.gptr()
(3.5) — egptr() == rhs_p.egptr()
(3.6) — pbase() == rhs_p.pbase()
(3.7) — pptr() == rhs_p.pptr()
(3.8) — epptr() == rhs_p.epptr()
(3.9) — getloc() == rhs_p.getloc()

31.9.3.3 Assignment and swap

basic_spanbuf& operator=(basic_spanbuf&& rhs);

1 Effects: Equivalent to:

   basic_spanbuf tmp(std::move(rhs));
   this->swap(tmp);
   return *this;

void swap(basic_spanbuf& rhs);

2 Effects: Equivalent to:

   basic_streambuf<charT, traits>::swap(rhs);
   std::swap(mode, rhs.mode);
   std::swap(buf, rhs.buf);

§ 31.9.3.3 ©ISO/IEC 1823
template<class charT, class traits>
void swap(basic_spanbuf<charT, traits>& x, basic_spanbuf<charT, traits>& y);

Effects: Equivalent to x.swap(y).

31.9.3.4 Member functions

std::span<charT> span() const noexcept;
Returns: If ios_base::out is set in mode, returns std::span<charT>(pbase(), pptr()), otherwise returns buf.
[Note 1: In contrast to basic_stringbuf, the underlying sequence never grows and is not owned. An owning copy can be obtained by converting the result to basic_string<charT>. — end note]

void span(std::span<charT> s) noexcept;
Effects: buf = s. Initializes the input and output sequences according to mode.
Postconditions:
(3.1) — If ios_base::out is set in mode, pbase() == s.data() && eptr() == pbase() + s.size() is true;
(3.1.1) — in addition, if ios_base::ate is set in mode, pperr() == pbase() + s.size() is true,
(3.1.2) — otherwise pperr() == pbase() is true.
(3.2) — If ios_base::in is set in mode, eback() == s.data() && gperr() == eback() && egperr() == eback() + s.size() is true.

31.9.3.5 Overridden virtual functions

1 [Note 1: Because the underlying buffer is of fixed size, neither overflow, underflow, nor pbackfail can provide useful behavior. — end note]

pos_type seekoff(off_type off, ios_base::seekdir way, ios_base::openmode which = ios_base::in | ios_base::out) override;
Effects: Alters the stream position within one or both of the controlled sequences, if possible, as follows:
(2.1) — If ios_base::in is set in which, positions the input sequence; xnext is gptr(), xbeg is eback().
(2.2) — If ios_base::out is set in which, positions the output sequence; xnext is pptr(), xbeg is pbase().
If both ios_base::in and ios_base::out are set in which and way is ios_base::cur, the positioning operation fails.
For a sequence to be positioned, if its next pointer xnext (either gptr() or pptr()) is a null pointer and the new offset newoff as computed below is nonzero, the positioning operation fails. Otherwise, the function determines baseoff as a value of type off_type as follows:
(4.1) — 0 when way is ios_base::beg;
(4.2) — (pptr() - pbase()) for the output sequence, or (gptr() - eback()) for the input sequence when way is ios_base::cur;
(4.3) — when way is ios_base::end:
(4.3.1) — (pptr() - pbase()) if ios_base::out is set in mode and ios_base::in is not set in mode,
(4.3.2) — buf.size() otherwise.
If baseoff + off would overflow, or if baseoff + off is less than zero, or if baseoff + off is greater than buf.size(), the positioning operation fails. Otherwise, the function computes
off_type newoff = baseoff + off;
and assigns xbeg + newoff to the next pointer xnext.
Returns: pos_type(off_type(-1)) if the positioning operation fails; pos_type(newoff) otherwise.
pos_type seekpos(pos_type sp, ios_base::openmode which = ios_base::in | ios_base::out) override;
Effects: Equivalent to:
return seekoff(off_type(sp), ios_base::beg, which);
basic_streambuf<charT, traits>* setbuf(charT* s, streamsize n) override;

Effects: Equivalent to:
this->span(std::span<charT>(s, n));
return this;

31.9.4 Class template basic_ispanstream

31.9.4.1 General

namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ispanstream
        : public basic_istream<charT, traits> {
public:
    using char_type = charT;
    using int_type = typename traits::int_type;
    using pos_type = typename traits::pos_type;
    using off_type = typename traits::off_type;
    using traits_type = traits;

    // 31.9.4.2, constructors
    explicit basic_ispanstream(std::span<charT> s, ios_base::openmode which = ios_base::in);
    basic_ispanstream(const basic_ispanstream&) = delete;
    basic_ispanstream(basic_ispanstream&& rhs);
    template<class ROS> explicit basic_ispanstream(ROS&& s);
    basic_ispanstream& operator=(const basic_ispanstream&) = delete;
    basic_ispanstream& operator=(basic_ispanstream&& rhs);

    // 31.9.4.3, swap
    void swap(basic_ispanstream& rhs);

    // 31.9.4.4, member functions
    basic_spanbuf<charT, traits>* rdbuf() const noexcept;
    std::span<const charT> span() const noexcept;
    void span(std::span<charT> s) noexcept;
    template<class ROS> void span(ROS&& s) noexcept;

private:
    basic_spanbuf<charT, traits> sb;  // exposition only
};
}

[Note 1: Constructing an ispanstream from a string-literal includes the termination character ‘\0’ in the underlying spanbuf. — end note]

31.9.4.2 Constructors

explicit basic_ispanstream(std::span<charT> s, ios_base::openmode which = ios_base::in);

Effects: Initializes the base class with basic_istream<charT, traits>(addressof(sb)) and sb with basic_spanbuf<charT, traits>(s, which | ios_base::in) (31.9.3.2).

basic_ispanstream(basic_ispanstream&& rhs);

Effects: Initializes the base class with std::move(rhs) and sb with std::move(rhs.sb). Next, basic_istream<charT, traits>::set_rdbuf(addressof(sb)) is called to install the contained basic_spanbuf.

template<class ROS> explicit basic_ispanstream(ROS&& s)

Constraints: ROS models ranges::borrowed_range. !convertible_to<Ros, std::span<charT>> && convertible_to<Ros, std::span<charT const>> is true.

Effects: Let sp be std::span<const charT>(std::forward<Ros>(s)). Equivalent to:

§ 31.9.4.2 ©ISO/IEC 1825
basic_ispanstream(std::span<charT>(const_cast<charT*>(sp.data()), sp.size()))

### 31.9.4.3 Swap

void swap(basic_ispanstream& rhs);

**Effects**: Equivalent to:

basic_istream<charT, traits>::swap(rhs);
sb.swap(rhs.sb);

```cpp
template<class charT, class traits>
void swap(basic_ispanstream<charT, traits>& x, basic_ispanstream<charT, traits>& y);
```

**Effects**: Equivalent to `x.swap(y)`.

### 31.9.4.4 Member functions

```cpp
basic_spanbuf<charT, traits>* rdbuf() const noexcept;
```

**Effects**: Equivalent to:

```cpp
return const_cast<basic_spanbuf<charT, traits>*>(addressof(sb));
```

```cpp
std::span<const charT> span() const noexcept;
```

**Effects**: Equivalent to:

```cpp
return rdbuf()->span();
```

```cpp
void span(std::span<charT> s) noexcept;
```

**Effects**: Equivalent to:

```cpp
rdbuf()->span(s);
```

```cpp
template<class ROS> void span(ROS& s) noexcept;
```

**Constraints**: `ROS` models `ranges::borrowed_range`.

**Effects**: Let `sp` be `std::span<const charT>(std::forward<ROS>(s))`. Equivalent to:

```cpp
this->span(std::span<charT>(const_cast<charT*>(sp.data()), sp.size()));
```

### 31.9.5 Class template basic_ospanstream

#### 31.9.5.1 General

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ospanstream {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;

            // 31.9.5.2, constructors
            explicit basic_ospanstream(std::span<charT> s,
                                         ios_base::openmode which = ios_base::out);
            basic_ospanstream(const basic_ospanstream&) = delete;
            basic_ospanstream(basic_ospanstream&&) = delete;

            basic_ospanstream& operator=(const basic_ospanstream&) = delete;
            basic_ospanstream& operator=(basic_ospanstream&& rhs);

            // 31.9.5.3, swap
            void swap(basic_ospanstream& rhs);

            // 31.9.5.4, member functions
            basic_spanbuf<charT, traits>* rdbuf() const noexcept;
        }
    }
}
```
explicit basic_ospanstream(std::span<charT> s,
ios_base::openmode which = ios_base::out);

Effects: Initializes the base class with
basic_ostream<charT, traits>(addressof(sb)) and sb with
basic_spanbuf<charT, traits>(s, which | ios_base::out) (31.9.3.2).

basic_ospanstream(basic_ospanstream&& rhs) noexcept;

Effects: Initializes the base class with
std::move(rhs) and sb with std::move(rhs.sb). Next, basic_-
ostream<charT, traits>::set_rdbuf(addressof(sb)) is called to install the contained basic_-
spanbuf.

void swap(basic_ospanstream& rhs);

Effects: Equivalent to:

basic_ostream<charT, traits>::swap(rhs);
sb.swap(rhs.sb);

template<class charT, class traits>
void swap(basic_ospanstream<charT, traits>& x, basic_ospanstream<charT, traits>& y);

Effects: Equivalent to x.swap(y).

basic_spanbuf<charT, traits>* rdbuf() const noexcept;

Effects: Equivalent to:

return const_cast<basic_spanbuf<charT, traits>*>(addressof(sb));

std::span<charT> span() const noexcept;

Effects: Equivalent to:

return rdbuf()->span();

void span(std::span<charT> s) noexcept;

Effects: Equivalent to rdbuf()->span(s).

31.9.6 Class template basic_spanstream

31.9.6.1 General

namespace std {

template<Class charT, class traits = char_traits<charT>>
class basic_spanstream
  : public basic_iostream<charT, traits> {
public:
  using char_type = charT;
  using int_type = typename traits::int_type;
  using pos_type = typename traits::pos_type;
  using off_type = typename traits::off_type;
  using traits_type = traits;

  // 31.9.6.2, constructors
  explicit basic_spanstream(std::span<charT> s,
                             ios_base::openmode which = ios_base::out | ios_base::in);
  basic_spanstream(const basic_spanstream&) = delete;
  basic_spanstream(basic_spanstream&& rhs);

} // 31.9.6.1

31.9.5.2 Constructors

basic_spanstream& operator=(const basic_spanstream&) = delete;
basic_spanstream& operator=(basic_spanstream&& rhs);

// 31.9.6.3, swap
void swap(basic_spanstream& rhs);

// 31.9.6.4, members
basic_spanbuf<charT, traits>* rdbuf() const noexcept;
std::span<charT> span() const noexcept;
void span(std::span<charT> s) noexcept;

private:
basic_spanbuf<charT, traits> sb;    // exposition only
};

31.9.6.2 Constructors

explicit basic_spanstream(std::span<charT> s,
  ios_base::openmode which = ios_base::out | ios_base::in);

1 Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) and sb
  with basic_spanbuf<charT, traits>(s, which) (31.9.3.2).

basic_spanstream(basic_spanstream&& rhs);

2 Effects: Initializes the base class with std::move(rhs) and sb with std::move(rhs.sb). Next,
basic_iostream<charT, traits>::set_rdbuf(addressof(sb)) is called to install the contained
basic_spanbuf.

31.9.6.3 Swap

void swap(basic_spanstream& rhs);

1 Effects: Equivalent to:
  basic_iostream<charT, traits>::swap(rhs);
  sb.swap(rhs.sb);

template<class charT, class traits>
void swap(basic_spanstream<charT, traits>& x, basic_spanstream<charT, traits>& y);

2 Effects: Equivalent to x.swap(y).

31.9.6.4 Member functions

basic_spanbuf<charT, traits>* rdbuf() const noexcept;

1 Effects: Equivalent to:
  return const_cast<basic_spanbuf<charT, traits>*>(addressof(sb));

std::span<charT> span() const noexcept;

2 Effects: Equivalent to: return rdbuf()->span();

void span(std::span<charT> s) noexcept;

3 Effects: Equivalent to rdbuf()->span(s).

31.10 File-based streams

31.10.1 Header <fstream> synopsis

namespace std {

};
The header `<fstream>` defines four class templates and eight types that associate stream buffers with files and assist reading and writing files.

1. The header `<fstream>` defines four class templates and eight types that associate stream buffers with files and assist reading and writing files.

2. [Note 1: The class template `basic_filebuf` treats a file as a source or sink of bytes. In an environment that uses a large character set, the file typically holds multibyte character sequences and the `basic_filebuf` object converts those multibyte sequences into wide character sequences. —end note]

3. In subclause 31.10, member functions taking arguments of `const filesystem::path::value_type*` are only provided on systems where `filesystem::path::value_type` is not `char`.

[Note 2: These functions enable class path support for systems with a wide native path character type, such as `wchar_t`. —end note]

### 31.10.2 Native handles

Several classes described in 31.10 have a member `native_handle_type`.

The type `native_handle_type` represents a platform-specific native handle to a file. It is trivially copyable and models `semiregular`.

[Note 1: For operating systems based on POSIX, `native_handle_type` is `int`. For Windows-based operating systems, `native_handle_type` is `HANDLE`. —end note]

### 31.10.3 Class template basic_filebuf

#### 31.10.3.1 General

```cpp
namespace std {

    template<class charT, class traits = char_traits<charT>>
    class basic_filebuf : public basic_streambuf<charT, traits> {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
    }
```
using traits_type = traits;
using native_handle_type = implementation-defined; // see 31.10.2

// 31.10.3.2, constructors/destructor
basic_filebuf();
basic_filebuf(const basic_filebuf&) = delete;
basic_filebuf(basic_filebuf&& rhs);
virtual ~basic_filebuf();

// 31.10.3.3, assignment and swap
basic_filebuf& operator=(const basic_filebuf&) = delete;
basic_filebuf& operator=(basic_filebuf&& rhs);
void swap(basic_filebuf& rhs);

// 31.10.3.4, members
bool is_open() const;
basic_filebuf* open(const char* s, ios_base::openmode mode);
basic_filebuf* open(const filesystem::path::value_type* s,
    ios_base::openmode mode); // wide systems only; see 31.10.1
basic_filebuf* open(const string& s, ios_base::openmode mode);
basic_filebuf* open(const filesystem::path& s, ios_base::openmode mode);
basic_filebuf* close();
native_handle_type native_handle() const noexcept;

protected:
// 31.10.3.5, overridden virtual functions
streamsize showmanyc() override;
int_type underflow() override;
int_type uflow() override;
int_type pbackfail(int_type c = traits::eof()) override;
int_type overflow (int_type c = traits::eof()) override;
basic_streambuf<charT, traits>* setbuf(char_type* s, streamsize n) override;

pos_type seekoff(off_type off, ios_base::seekdir way,
    ios_base::openmode which = ios_base::in | ios_base::out) override;
pos_type seekpos(pos_type sp,
    ios_base::openmode which = ios_base::in | ios_base::out) override;

int sync() override;
void imbue(const locale& loc) override;
};

1 The class basic_filebuf<charT, traits> associates both the input sequence and the output sequence with a file.

2 The restrictions on reading and writing a sequence controlled by an object of class basic_filebuf<charT,
traits> are the same as for reading and writing with the C standard library FILEs.

3 In particular:

(3.1) — If the file is not open for reading the input sequence cannot be read.

(3.2) — If the file is not open for writing the output sequence cannot be written.

(3.3) — A joint file position is maintained for both the input sequence and the output sequence.

4 An instance of basic_filebuf behaves as described in 31.10.3 provided traits::pos_type is fpos<traits::
state_type>. Otherwise the behavior is undefined.

5 The file associated with a basic_filebuf has an associated value of type native_handle_type, called the
native handle (31.10.2) of that file. This native handle can be obtained by calling the member function
native_handle.

6 For any opened basic_filebuf f, the native handle returned by f.native_handle() is invalidated when
f.close() is called, or f is destroyed.
In order to support file I/O and multibyte/wide character conversion, conversions are performed using members of a facet, referred to as \texttt{a_codecvt} in following subclauses, obtained as if by

\begin{verbatim}
const codecvt<charT, char, typename traits::state_type>& a_codecvt = use_facet<codecvt<charT, char, typename traits::state_type>>(getloc());
\end{verbatim}

### 31.10.3.2 Constructors

[\texttt{filebuf.cons}]

\begin{verbatim}
basic_filebuf();
\end{verbatim}

1. \textit{Effects}: Initializes the base class with \texttt{basic_streambuf<charT, traits>()} (31.6.3.2).

2. \textit{Postconditions}: \texttt{is\_open()} == \texttt{false}.

\begin{verbatim}
basic_filebuf(basic_filebuf&& rhs);
\end{verbatim}

3. \textit{Effects}: It is implementation-defined whether the sequence pointers in \texttt{*this (eback(), gptr(), egptr(), pbase(), pptr(), eptr())} obtain the values which \texttt{rhs} had. Whether they do or not, \texttt{*this} and \texttt{rhs} reference separate buffers (if any at all) after the construction. Additionally \texttt{*this} references the file which \texttt{rhs} did before the construction, and \texttt{rhs} references no file after the construction. The openmode, locale and any other state of \texttt{rhs} is also copied.

4. \textit{Postconditions}: Let \texttt{rhs\_p} refer to the state of \texttt{rhs} just prior to this construction and let \texttt{rhs\_a} refer to the state of \texttt{rhs} just after this construction.

\begin{verbatim}
— is\_open() == rhs\_p.is\_open()
— rhs\_a.is\_open() == false
— gptr() - eback() == rhs\_p.gptr() - rhs\_p.eback()
— egptr() - eback() == rhs\_p.egptr() - rhs\_p.eback()
— pptr() - pbase() == rhs\_p.pptr() - rhs\_p.pbase()
— eptr() - pbase() == rhs\_p.eptr() - rhs\_p.pbase()
— if (eback()) eback() != rhs\_a.eback()
— if (gptr()) gptr() != rhs\_a.gptr()
— if (egptr()) egptr() != rhs\_a.egptr()
— if (pbase()) pbase() != rhs\_a.pbase()
— if (pptr()) pptr() != rhs\_a.pptr()
— if (eptr()) eptr() != rhs\_a.eptr()
\end{verbatim}

\begin{verbatim}
virtual ~basic_filebuf();
\end{verbatim}

5. \textit{Effects}: Calls \texttt{close()}. If an exception occurs during the destruction of the object, including the call to \texttt{close()}, the exception is caught but not rethrown (see 16.4.6.13).

### 31.10.3.3 Assignment and swap

[\texttt{filebuf.assign}]

\begin{verbatim}
basic_filebuf& operator=(basic_filebuf&& rhs);
\end{verbatim}

1. \textit{Effects}: Calls \texttt{close()} then move assigns from \texttt{rhs}. After the move assignment \texttt{*this} has the observable state it would have had if it had been move constructed from \texttt{rhs} (see 31.10.3.2).

2. \textit{Returns}: \texttt{*this}.

\begin{verbatim}
void swap(basic_filebuf& rhs);
\end{verbatim}

3. \textit{Effects}: Exchanges the state of \texttt{*this} and \texttt{rhs}.

\begin{verbatim}
template<class charT, class traits>
  void swap(basic_filebuf<charT, traits>& x, basic_filebuf<charT, traits>& y);
\end{verbatim}

4. \textit{Effects}: Equivalent to \texttt{x.swap(y)}.

### 31.10.3.4 Member functions

[\texttt{filebuf.members}]

\section*{§ 31.10.3.4}
bool is_open() const;

Returns: true if a previous call to open succeeded (returned a non-null value) and there has been no intervening call to close.

basic_filebuf* open(const char* s, ios_base::openmode mode);
basic_filebuf* open(const filesystem::path::value_type* s, ios_base::openmode mode); // wide systems only; see 31.10.1

Preconditions: s points to a NTCTS (3.35).

Effects: If is_open() != false, returns a null pointer. Otherwise, initializes the filebuf as required. It then opens the file to which s resolves, if possible, as if by a call to fopen with the second argument determined from mode & ~ios_base::ate as indicated in Table 131. If mode is not some combination of flags shown in the table then the open fails.

<table>
<thead>
<tr>
<th>ios_base flag combination</th>
<th>stdio equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>binary in out trunc app noreplace</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>&quot;w&quot;</td>
</tr>
<tr>
<td>+</td>
<td>&quot;wx&quot;</td>
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<td>&quot;a+s&quot;</td>
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<td>&quot;a+b&quot;</td>
</tr>
<tr>
<td>+ + + +</td>
<td>&quot;a+b&quot;</td>
</tr>
</tbody>
</table>

If the open operation succeeds and ios_base::ate is set in mode, positions the file to the end (as if by calling fseek(file, 0, SEEK_END), where file is the pointer returned by calling fopen).\(^\text{297}\)

If the repositioning operation fails, calls close() and returns a null pointer to indicate failure.

Returns: this if successful, a null pointer otherwise.

basic_filebuf* open(const string& s, ios_base::openmode mode);
basic_filebuf* open(const filesystem::path& s, ios_base::openmode mode);

Returns: open(s.c_str(), mode);

\(^{297}\) The macro SEEK_END is defined, and the function signatures fopen(const char*, const char*) and fseek(FILE*, long, int) are declared, in <cstdio> (31.13.1).
basic_filebuf* close();

Effects: If is_open() == false, returns a null pointer. If a put area exists, calls overflow(traits::
eof()) to flush characters. If the last virtual member function called on *this (between underflow,
overflow, seekoff, and seekpos) was overflow then calls a_codecvt.unshift (possibly several
times) to determine a termination sequence, inserts those characters and calls overflow(traits::
eof()) again. Finally, regardless of whether any of the preceding calls fails or throws an exception,
the function closes the file (as if by calling fclose(file)). If any of the calls made by the function,
including fclose, fails, close fails by returning a null pointer. If one of these calls throws an exception,
the exception is caught and rethrown after closing the file.

Postconditions: is_open() == false.

Returns: this on success, a null pointer otherwise.

native_handle_type native_handle() const noexcept;

Preconditions: is_open() is true.

Returns: The native handle associated with *this.

31.10.3.5 Overridden virtual functions

streamsize showmanyc() override;

Effects: Behaves the same as basic_streambuf::showmanyc() (31.6.3.5).

Remarks: An implementation may provide an overriding definition for this function signature if it can
determine whether more characters can be read from the input sequence.

int_type underflow() override;

Effects: Behaves according to the description of basic_streambuf<charT, traits>::underflow(),
with the specialization that a sequence of characters is read from the input sequence as if by reading
from the associated file into an internal buffer (extern_buf) and then as if by doing:

char extern_buf[XSIZE];
char* extern_end;
charT intern_buf[ISIZE];
charT* intern_end;
codecvt_base::result r =
a_codecvt.in(state, extern_buf, extern_buf+XSIZE, extern_end,
intern_buf, intern_buf+ISIZE, intern_end);

This shall be done in such a way that the class can recover the position (fpos_t) corresponding to each
character between intern_buf and intern_end. If the value of r indicates that a_codecvt.in() ran
out of space in intern_buf, retry with a larger intern_buf.

int_type uflow() override;

Effects: Behaves according to the description of basic_streambuf<charT, traits>::uflow(), with
the specialization that a sequence of characters is read from the input with the same method as used
by underflow.

int_type pbackfail(int_type c = traits::eof()) override;

Effects: Puts back the character designated by c to the input sequence, if possible, in one of three ways:

(1) If traits::eq_int_type(c, traits::eof()) returns false and if the function makes a putback
position available and if traits::eq(to_char_type(c), gptr()[-1]) returns true, decrements
the next pointer for the input sequence, gptr().

Returns: c.

(2) If traits::eq_int_type(c, traits::eof()) returns false and if the function makes a putback
position available and if the function is permitted to assign to the putback position, decrements
the next pointer for the input sequence, and stores c there.

Returns: c.
— If traits::eq_int_type(c, traits::eof()) returns true, and if either the input sequence has a putback position available or the function makes a putback position available, decrements the next pointer for the input sequence, gptr().

Returns: traits::not_eof(c).

Returns: As specified above, or traits::eof() to indicate failure.

Remarks: If is_open() == false, the function always fails.

The function does not put back a character directly to the input sequence.

If the function can succeed in more than one of these ways, it is unspecified which way is chosen. The function can alter the number of putback positions available as a result of any call.

### 6

Returns: As specified above, or traits::eof() to indicate failure.

### 7

Remarks: If is_open() == false, the function always fails.

### 8

The function does not put back a character directly to the input sequence.

### 9

If the function can succeed in more than one of these ways, it is unspecified which way is chosen. The function can alter the number of putback positions available as a result of any call.

### 10

Effects: Behaves according to the description of basic_streambuf<charT, traits>::overflow(c), except that the behavior of “consuming characters” is performed by first converting as if by:

```cpp
charT* b = pbase();
charT* p = pptr();
char* end;
char xbuf[XSIZE];
char* xbuf_end;
codecvt_base::result r =
a_codecvt.out(state, b, p, end, xbuf, xbuf+XSIZE, xbuf_end);
```

and then

10.1 — If r == codecvt_base::error then fail.

10.2 — If r == codecvt_base::noconv then output characters from b up to (and not including) p.

10.3 — If r == codecvt_base::partial then output to the file characters from xbuf up to xbuf_end, and repeat using characters from end to p. If output fails, fail (without repeating).

10.4 — Otherwise output from xbuf to xbuf_end, and fail if output fails. At this point if b != p and b == end (xbuf isn’t large enough) then increase XSIZE and repeat from the beginning.

Returns: traits::not_eof(c) to indicate success, and traits::eof() to indicate failure. If is_open() == false, the function always fails.

### 11

basic_streambuf* setbuf(char_type* s, streamsize n) override;

Effects: If setbuf(0, 0) is called on a stream before any I/O has occurred on that stream, the stream becomes unbuffered. Otherwise the results are implementation-defined. “Unbuffered” means that pbase() and pptr() always return null and output to the file should appear as soon as possible.

### 12

Effects: If setbuf(0, 0) is called on a stream before any I/O has occurred on that stream, the stream becomes unbuffered. Otherwise the results are implementation-defined. “Unbuffered” means that pbase() and pptr() always return null and output to the file should appear as soon as possible.

pos_type seekoff(off_type off, ios_base::seekdir way,
ios_base::openmode which = ios_base::in | ios_base::out) override;

Effects: Let width denote a_codecvt.encoding(). If is_open() == false, or off != 0 & width <= 0, then the positioning operation fails. Otherwise, if way != basic_ios::cur or off != 0, and if the last operation was output, then update the output sequence and write any unshift sequence. Next, seek to the new position: if width > 0, call fseek(file, width * off, whence), otherwise call fseek(file, 0, whence).

Returns: A newly constructed pos_type object that stores the resultant stream position, if possible. If the positioning operation fails, or if the object cannot represent the resultant stream position, returns pos_type(off_type(-1)).

Remarks: “The last operation was output” means either the last virtual operation was overflow or the put buffer is non-empty. “Write any unshift sequence” means, if width is less than zero then call a_codecvt.unshift(state, xbuf, xbuf+XSIZE, xbuf_end) and output the resulting unshift sequence. The function determines one of three values for the argument whence, of type int, as indicated in Table 132.

pos_type seekpos(pos_type sp,
ios_base::openmode which

§ 31.10.3.5 ©ISO/IEC 1834
Table 132 — seekoff effects

<table>
<thead>
<tr>
<th>way</th>
<th>Value</th>
<th>stdio Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic_ios::beg</td>
<td>SEEK_SET</td>
<td></td>
</tr>
<tr>
<td>basic_ios::cur</td>
<td>SEEK_CUR</td>
<td></td>
</tr>
<tr>
<td>basic_ios::end</td>
<td>SEEK_END</td>
<td></td>
</tr>
</tbody>
</table>

Alters the file position, if possible, to correspond to the position stored in \( sp \) (as described below). Altering the file position performs as follows:

1. If \( (om & \text{ios\_base::out}) \neq 0 \), then update the output sequence and write any unshift sequence;
2. Set the file position to \( sp \) as if by a call to \text{fsetpos};
3. If \( (om & \text{ios\_base::in}) \neq 0 \), then update the input sequence;

where \( om \) is the open mode passed to the last call to \text{open()}. The operation fails if \text{is\_open()} returns \text{false}.

If \( sp \) is an invalid stream position, or if the function positions neither sequence, the positioning operation fails. If \( sp \) has not been obtained by a previous successful call to one of the positioning functions (\text{seekoff} or \text{seekpos}) on the same file the effects are undefined.

Returns: \( sp \) on success. Otherwise returns \text{pos\_type(off\_type(-1))}.

```cpp
int sync() override;
```

Effects: If a put area exists, calls \text{filebuf::overflow} to write the characters to the file, then flushes the file as if by calling \text{fflush(file)}. If a get area exists, the effect is implementation-defined.

```cpp
void imbue(const locale& loc) override;
```

Preconditions: If the file is not positioned at its beginning and the encoding of the current locale as determined by \text{a\_codecvt\_encoding()} is state-dependent (30.4.2.5.3) then that facet is the same as the corresponding facet of \( loc \).

Effects: Causes characters inserted or extracted after this call to be converted according to \( loc \) until another call of \text{imbue}.

Remarks: This may require reconversion of previously converted characters. This in turn may require the implementation to be able to reconstruct the original contents of the file.

### 31.10.4 Class template basic\_ifstream

#### 31.10.4.1 General

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ifstream : public basic_istream<charT, traits> {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;
            using native_handle_type = typename basic_filebuf<charT, traits>::native_handle_type;

            // 31.10.4.2, constructors
            basic_ifstream();
            explicit basic_ifstream(const char* s,
                                     ios_base::openmode mode = ios_base::in);
            explicit basic_ifstream(const filesystem::path::value_type* s,
                                     ios_base::openmode mode = ios_base::in); // wide systems only; see 31.10.1
            explicit basic_ifstream(const string& s,
                                     ios_base::openmode mode = ios_base::in);
    }
}
```

© ISO/IEC 1835
The class `basic_ifstream<charT, traits>` supports reading from named files. It uses a `basic_filebuf<charT, traits>` object to control the associated sequence. For the sake of exposition, the maintained data is presented here as:

1. `sb`, the `filebuf` object.

31.10.4.2 Constructors [ifstream.cons]

```
template<class T>
    explicit basic_ifstream(const T& s, ios_base::openmode mode = ios_base::in);
basic_ifstream(const basic_ifstream&) = delete;
basic_ifstream(basic_ifstream&& rhs);

basic_ifstream& operator=(const basic_ifstream&) = delete;
basic_ifstream& operator=(basic_ifstream&& rhs);

// 31.10.4.3, swap
void swap(basic_ifstream& rhs);

// 31.10.4.4, members
basic_filebuf<charT, traits>* rdbuf() const;
native_handle_type native_handle() const noexcept;

bool is_open() const;
void open(const char* s, ios_base::openmode mode = ios_base::in);
void open(const filesystem::path::value_type* s,
        ios_base::openmode mode = ios_base::in); // wide systems only; see 31.10.1
void open(const string& s, ios_base::openmode mode = ios_base::in);
void open(const filesystem::path& s, ios_base::openmode mode = ios_base::in);
void close();
```

---

1 The class `basic_ifstream<charT, traits>` supports reading from named files. It uses a `basic_filebuf<charT, traits>` object to control the associated sequence. For the sake of exposition, the maintained data is presented here as:

1. `sb`, the `filebuf` object.

---

2 Effects: Initializes the base class with `basic_istream<charT, traits>(addressof(sb)) (31.7.5.2.2)` and `sb` with `basic_filebuf<charT, traits>() (31.10.3.2)`.

3 Effects: Equivalent to `basic_ifstream(s.c_str(), mode)`.

4 Constraints: `is_same_v<T, filesystem::path>` is true.

5 Effects: Equivalent to `basic_ifstream(s.c_str(), mode)`.

6 Effects: Move constructs the base class, and the contained `basic_filebuf`. Then calls `basic_istream<charT, traits>::set_rdbuf(addressof(sb))` to install the contained `basic_filebuf`.

---

§ 31.10.4.2 © ISO/IEC 1836
N4986

31.10.4.3 Swap

void swap(basic_ifstream& rhs);

Effects: Exchanges the state of *this and rhs by calling basic_istream<
charT, traits>::swap(rhs) and sb.swap(rhs.sb).

template<class charT, class traits>
void swap(basic_ifstream<
charT, traits>& x, basic_ifstream<
charT, traits>& y);

Effects: Equivalent to x.swap(y).

31.10.4.4 Member functions

basic_filebuf<
charT, traits>* rdbuf() const;

Returns: const_cast<
basic_filebuf<
charT, traits>*>(addressof(sb)).

native_handle_type
native_handle() const

noexcept;

Effects: Equivalent to: return rdbuf()->native_handle();

bool is_open() const;

Returns: rdbuf()->is_open().

void open(const char* s, ios_base::openmode mode = ios_base::in);

void open(const filesystem::path::value_type* s,
ios_base::openmode mode = ios_base::in); // wide systems only; see 31.10.1

Effects: Calls rdbuf()->open(s, mode | ios_base::in). If that function does not return a null
pointer calls clear(), otherwise calls setstate(failbit) (which may throw ios_base::failure)
(31.5.4.4).

void open(const string& s, ios_base::openmode mode = ios_base::in);

void open(const filesystem::path& s, ios_base::openmode mode = ios_base::in);

Effects: Calls open(s.c_str(), mode).

void close();

Effects: Calls rdbuf()->close() and, if that function returns a null pointer, calls
setstate(failbit) (which may throw ios_base::failure) (31.5.4.4).

31.10.5 Class template basic_ofstream

31.10.5.1 General

namespace std {

template<class charT, class traits = char_traits<charT>>
class basic_ofstream : public basic_ostream<
charT, traits> {

public:

using char_type = charT;

using int_type = typename traits::int_type;

using pos_type = typename traits::pos_type;

using off_type = typename traits::off_type;

using traits_type = traits;

using native_handle_type =
typename basic_filebuf<
charT, traits>::native_handle_type;

// 31.10.5.2, constructors

basic_ofstream();

explicit basic_ofstream(const char* s,
ios_base::openmode mode = ios_base::out);

explicit basic_ofstream(const filesystem::path::value_type* s, // wide systems only; see 31.10.1
ios_base::openmode mode = ios_base::out);

explicit basic_ofstream(const string& s,
ios_base::openmode mode = ios_base::out);

explicit basic_ofstream(const T& s, ios_base::openmode mode = ios_base::out);

basic_ofstream(const basic_ofstream&) = delete;

basic_ofstream(basic_ofstream&& rhs);

§ 31.10.5.1 ©ISO/IEC 1837
The class `basic_ofstream<charT, traits>` supports writing to named files. It uses a `basic_filebuf<charT, traits>` object to control the associated sequence. For the sake of exposition, the maintained data is presented here as:

\[(1.1) \quad \text{sb, the filebuf object.}\]

### 31.10.5.2 Constructors

[ofstream.cons]

#### basic_ofstream();

\[\text{Effects: Initializes the base class with } \text{basic_ostream}<\text{charT, traits}>(\text{addressof(sb)}) \text{ (}31.7.6.2.2\text{)} \text{ and sb with } \text{basic_filebuf}<\text{charT, traits}>(); \text{ (}31.10.3.2\text{).}\]

#### explicit basic_ofstream(const char* s, ios_base::openmode mode = ios_base::out);

\[\text{Effects: Initializes the base class with } \text{basic_ostream}<\text{charT, traits}>(\text{addressof(sb)}) \text{ (}31.7.6.2.2\text{)} \text{ and sb with } \text{basic_filebuf}<\text{charT, traits}>(); \text{ (}31.10.3.2\text{).}\]

#### explicit basic_ofstream(const filesystem::path::value_type* s, ios_base::openmode mode = ios_base::out); \[\text{Effects: Initializes the base class with } \text{basic_ostream}<\text{charT, traits}>(\text{addressof(sb)}) \text{ (}31.7.6.2.2\text{)} \text{ and sb with } \text{basic_filebuf}<\text{charT, traits}>(); \text{ (}31.10.3.2\text{), then calls } \text{rdbuf()->open(s, mode | ios_base::out)}. \text{ If that function returns a null pointer, calls } \text{setstate(failbit).}\]

#### explicit basic_ofstream(const string& s, ios_base::openmode mode = ios_base::out);

\[\text{Effects: Equivalent to } \text{basic_ofstream(s.c_str(), mode).}\]

#### template<class T> explicit basic_ofstream(const T& s, ios_base::openmode mode = ios_base::out);

\[\text{Constraints: } \text{is_same_v<T, filesystem::path> is true.}\]

\[\text{Effects: Equivalent to } \text{basic_ofstream(s.c_str(), mode).}\]

#### basic_ofstream(basic_ofstream&& rhs);

\[\text{Effects: Move constructs the base class, and the contained } \text{basic_filebuf}. \text{ Then calls } \text{basic_ostream}<\text{charT, traits}>::\text{set_rdbuf(addressof(sb))} \text{ to install the contained } \text{basic_filebuf}.\]

### 31.10.5.3 Swap

[ofstream.swap]

#### void swap(basic_ofstream& rhs);

\[\text{Effects: Exchanges the state of } *\text{this and rhs by calling } \text{basic_ostream}<\text{charT, traits}>::\text{swap(rhs)} \text{ and sb.swap(rhs.sb).}\]
template<class charT, class traits>
void swap(basic_ofstream<charT, traits>& x, basic_ofstream<charT, traits>& y);

Effects: Equivalent to x.swap(y).

31.10.5.4 Member functions

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>basic_filebuf&lt;charT, traits&gt;* rdbuf() const;</td>
<td>Returns: const_cast&lt;basic_filebuf&lt;charT, traits&gt;*&gt;(addressof(sb)).</td>
</tr>
<tr>
<td>2</td>
<td>native_handle_type native_handle() const noexcept;</td>
<td>Effects: Equivalent to: return rdbuf()-&gt;native_handle();</td>
</tr>
<tr>
<td>3</td>
<td>bool is_open() const;</td>
<td>Returns: rdbuf()-&gt;is_open().</td>
</tr>
<tr>
<td>4</td>
<td>void open(const char* s, ios_base::openmode mode = ios_base::out); void open(const filesystem::path::value_type* s, ios_base::openmode mode = ios_base::in</td>
<td>ios_base::out); // wide systems only; see 31.10.1</td>
</tr>
<tr>
<td>5</td>
<td>void close();</td>
<td>Effects: Calls rdbuf()-&gt;close() and, if that function fails (returns a null pointer), calls setstate(failbit) (which may throw ios_base::failure) (31.5.4.4).</td>
</tr>
<tr>
<td>6</td>
<td>void open(const string&amp; s, ios_base::openmode mode = ios_base::out); void open(const filesystem::path&amp; s, ios_base::openmode mode = ios_base::out);</td>
<td>Effects: Calls open(s.c_str(), mode).</td>
</tr>
</tbody>
</table>

31.10.6 Class template basic_fstream

31.10.6.1 General

namespace std {
  template<class charT, class traits = char_traits<charT>>
  class basic_fstream : public basic_iostream<charT, traits> { public:
    using char_type = charT;
    using int_type = typename traits::int_type;
    using pos_type = typename traits::pos_type;
    using off_type = typename traits::off_type;
    using traits_type = traits;
    using native_handle_type = typename basic_filebuf<charT, traits>::native_handle_type;

    // 31.10.6.2, constructors
    basic_fstream();
    explicit basic_fstream( const char* s, ios_base::openmode mode = ios_base::in | ios_base::out); explicit basic_fstream( const filesystem::path::value_type* s, ios_base::openmode mode = ios_base::in|ios_base::out); // wide systems only; see 31.10.1
    explicit basic_fstream( const string& s, ios_base::openmode mode = ios_base::in | ios_base::out); template<class T> explicit basic_fstream(const T& s, ios_base::openmode mode = ios_base::in | ios_base::out); basic_fstream(const basic_fstream&) = delete;
    basic_fstream(basic_fstream&& rhs); basic_fstream& operator=(const basic_fstream&) = delete;
    basic_fstream& operator=(basic_fstream&& rhs);
  }"
// 31.10.6.3, swap
void swap(basic_fstream& rhs);

// 31.10.6.4, members
basic_filebuf<charT, traits>* rdbuf() const;
native_handle_type native_handle() const noexcept;
bool is_open() const;
void open(
    const char* s,
    ios_base::openmode mode = ios_base::in | ios_base::out);
void open(
    const filesystem::path::value_type* s,
    ios_base::openmode mode = ios_base::in | ios_base::out); // wide systems only; see 31.10.1
void open(
    const string& s,
    ios_base::openmode mode = ios_base::in | ios_base::out);
void close();

private:
    basic_filebuf<charT, traits> sb; // exposition only
};

The class template basic_fstream<charT, traits> supports reading and writing from named files. It uses a basic_filebuf<charT, traits> object to control the associated sequences. For the sake of exposition, the maintained data is presented here as:

— sb, the basic_filebuf object.

31.10.6.2 Constructors [fstream.cons]

basic_fstream();

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2) and sb with basic_filebuf<charT, traits>().

explicit basic_fstream(
    const char* s,
    ios_base::openmode mode = ios_base::in | ios_base::out);

explicit basic_fstream(
    const filesystem::path::value_type* s,
    ios_base::openmode mode = ios_base::in | ios_base::out); // wide systems only; see 31.10.1

Effects: Initializes the base class with basic_iostream<charT, traits>(addressof(sb)) (31.7.5.7.2) and sb with basic_filebuf<charT, traits>(). Then calls rdbuf()->open(s, mode). If that function returns a null pointer, calls setstate(failbit).

explicit basic_fstream(
    const string& s,
    ios_base::openmode mode = ios_base::in | ios_base::out);

Effects: Equivalent to basic_fstream(s.c_str(), mode).

template<class T>
explicit basic_fstream(const T& s, ios_base::openmode mode = ios_base::in | ios_base::out);

Constraints: is_same_v<T, filesystem::path> is true.

Effects: Equivalent to basic_fstream(s.c_str(), mode).

basic_fstream(basic_fstream&& rhs);

Effects: Move constructs the base class, and the contained basic_filebuf. Then calls basic_istream<charT, traits>::set_rdbuf(addressof(sb)) to install the contained basic_filebuf.
31.10.6.3 Swap

void swap(basic_fstream& rhs);

Effects: Exchanges the state of this and rhs by calling basic_iostream<charT, traits>::swap(rhs)
and sb.swap(rhs.sb).

template<class charT, class traits>
void swap(basic_fstream<charT, traits>& x,
           basic_fstream<charT, traits>& y);

Effects: Equivalent to x.swap(y).

31.10.6.4 Member functions

basic_filebuf<charT, traits>* rdbuf() const;
Returns: const_cast<basic_filebuf<charT, traits>*>(addressof(sb)).

native_handle_type native_handle() const noexcept;
Effects: Equivalent to: return rdbuf()->native_handle();

bool is_open() const;
Returns: rdbuf()->is_open().

void open(
    const char* s,
    ios_base::openmode mode = ios_base::in | ios_base::out);
void open(
    const filesystem::path::value_type* s,
    ios_base::openmode mode = ios_base::in | ios_base::out); // wide systems only; see 31.10.1
Effects: Calls rdbuf()->open(s, mode). If that function does not return a null pointer
calls clear(), otherwise calls setstate(failbit) (which may throw ios_base::failure) (31.5.4.4).

void open(
    const string& s,
    ios_base::openmode mode = ios_base::in | ios_base::out);
void open(
    const filesystem::path& s,
    ios_base::openmode mode = ios_base::in | ios_base::out);
Effects: Calls open(s.c_str(), mode).

void close();
Effects: Calls rdbuf()->close() and, if that function returns a null pointer, calls setstate(failbit)
(which may throw ios_base::failure) (31.5.4.4).

31.11 Synchronized output streams

31.11.1 Header <syncstream> synopsis

#include <ostream> // see 31.7.2
namespace std {
    // 31.11.2, class template basic_syncbuf
    template<class charT, class traits = char_traits<charT>, class Allocator = allocator<charT>>
    class basic_syncbuf;

    // 31.11.2.6, specialized algorithms
    template<class charT, class traits, class Allocator>
    void swap(basic_syncbuf<charT, traits, Allocator>&, basic_syncbuf<charT, traits, Allocator>&);

    using syncbuf = basic_syncbuf<char>;
    using wsyncbuf = basic_syncbuf<wchar_t>;

§ 31.11.1
The header `<syncstream>` provides a mechanism to synchronize execution agents writing to the same stream.

### 31.11.2 Class template `basic_syncbuf` [syncstream.syncbuf]

#### 31.11.2.1 Overview [syncstream.syncbuf.overview]

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>, class Allocator = allocator<charT>>
    class basic_syncbuf : public basic_streambuf<charT, traits> {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;
            using allocator_type = Allocator;
            using streambuf_type = basic_streambuf<charT, traits>;

            using streambuf_type = basic_streambuf<charT, traits>;

            // 31.11.2.2, construction and destruction
            basic_syncbuf() : basic_syncbuf(nullptr) {}  
            explicit basic_syncbuf(streambuf_type* obuf) : basic_syncbuf(obuf, Allocator()) {}  
            basic_syncbuf(streambuf_type*, const Allocator&);  
            basic_syncbuf(basic_syncbuf&&);  
            ~basic_syncbuf();

            // 31.11.2.3, assignment and swap
            basic_syncbuf& operator=(basic_syncbuf&&); 
            void swap(basic_syncbuf&);

            // 31.11.2.4, member functions           
            bool emit(); 
            streambuf_type* get_wrapped() const noexcept;  
            allocator_type get_allocator() const noexcept;  
            void set_emit_on_sync(bool) noexcept;

            protected:
                // 31.11.2.5, overridden virtual functions
                int sync() override;

            private:
                streambuf_type* wrapped;  // exposition only
                bool emit_on_sync{};      // exposition only
    };
```

Class template `basic_syncbuf` stores character data written to it, known as the associated output, into internal buffers allocated using the object's allocator. The associated output is transferred to the wrapped stream buffer object `*wrapped` when `emit()` is called or when the `basic_syncbuf` object is destroyed. Such transfers are atomic with respect to transfers by other `basic_syncbuf` objects with the same wrapped stream buffer object.

#### 31.11.2.2 Construction and destruction [syncstream.syncbuf.cons]

```cpp
basic_syncbuf(streambuf_type* obuf, const Allocator& allocator);
```

**Effects:** Sets `wrapped` to `obuf`. 

1 Class template `basic_syncbuf` stores character data written to it, known as the associated output, into internal buffers allocated using the object's allocator. The associated output is transferred to the wrapped stream buffer object `*wrapped` when `emit()` is called or when the `basic_syncbuf` object is destroyed. Such transfers are atomic with respect to transfers by other `basic_syncbuf` objects with the same wrapped stream buffer object.
Postconditions: \( \text{get\_wrapped()} \) == \( \text{obuf} \) and \( \text{get\_allocator()} \) == \( \text{allocator} \) are true.

Throws: Nothing unless an exception is thrown by the construction of a mutex or by memory allocation.

Remarks: A copy of \( \text{allocator} \) is used to allocate memory for internal buffers holding the associated output.

\[
\text{basic\_syncbuf(basic\_syncbuf\&\& other)};
\]

Postconditions: The value returned by \( \text{this}\rightarrow\text{get\_wrapped()} \) is the value returned by \( \text{other}\cdot\text{get\_wrapped()} \) prior to calling this constructor. Output stored in \( \text{other} \) prior to calling this constructor will be stored in \( \ast\text{this} \) afterwards. \( \text{other}\cdot\text{pbase()} \) == \( \text{other}\cdot\text{pptr()} \) and \( \text{other}\cdot\text{get\_wrapped()} \) == \( \text{nullptr} \) are true.

Remarks: This constructor disassociates \( \text{other} \) from its wrapped stream buffer, ensuring destruction of \( \text{other} \) produces no output.

\[
\text{~basic\_syncbuf();}
\]

Effects: Calls \( \text{emit()} \).

Throws: Nothing. If an exception is thrown from \( \text{emit()} \), the destructor catches and ignores that exception.

### 31.11.2.3 Assignment and swap

\[
\text{basic\_syncbuf\& operator=(basic\_syncbuf\&\& rhs)};
\]

Effects: Calls \( \text{emit()} \) then move assigns from \( \text{rhs} \). After the move assignment \( \ast\text{this} \) has the observable state it would have had if it had been move constructed from \( \text{rhs} \) (31.11.2.2).

Postconditions:

1. \( \text{rhs}\cdot\text{get\_wrapped()} \) == \( \text{nullptr} \) is true.
2. \( \text{this}\rightarrow\text{get\_allocator()} \) == \( \text{rhs}\cdot\text{get\_allocator()} \) is true when
   
   \[
   \text{allocator\_traits<Allocator>::propagate\_on\_container\_move\_assignment::value is true};
   \]
   
   otherwise, the allocator is unchanged.

Returns: \( \ast\text{this} \).

Remarks: This assignment operator disassociates \( \text{rhs} \) from its wrapped stream buffer, ensuring destruction of \( \text{rhs} \) produces no output.

\[
\text{void swap(basic\_syncbuf\& other)};
\]

Preconditions: Either \( \text{allocator\_traits<Allocator>::propagate\_on\_container\_swap::value is true} \) or \( \text{this}\rightarrow\text{get\_allocator()} \) == \( \text{other}\cdot\text{get\_allocator()} \) is true.

Effects: Exchanges the state of \( \ast\text{this} \) and \( \text{other} \).

### 31.11.2.4 Member functions

\[
\text{bool emit();}
\]

Effects: Atomically transfers the associated output of \( \ast\text{this} \) to the stream buffer \( \ast\text{wrapped} \), so that it appears in the output stream as a contiguous sequence of characters. \( \text{wrapped}\rightarrow\text{pubsync()} \) is called if and only if a call was made to \( \text{sync()} \) since the most recent call to \( \text{emit()} \), if any.

Synchronization: All \( \text{emit()} \) calls transferring characters to the same stream buffer object appear to execute in a total order consistent with the “happens before” relation (6.9.2.2), where each \( \text{emit()} \) call synchronizes with subsequent \( \text{emit()} \) calls in that total order.

Postconditions: On success, the associated output is empty.

Returns: true if all of the following conditions hold; otherwise false:

1. \( \text{wrapped} \) == \( \text{nullptr} \) is false.
2. All of the characters in the associated output were successfully transferred.
3. The call to \( \text{wrapped}\rightarrow\text{pubsync()} \) (if any) succeeded.

Remarks: May call member functions of \( \text{wrapped} \) while holding a lock uniquely associated with \( \text{wrapped} \).
streambuf_type* get_wrapped() const noexcept;

Returns: wrapped.

allocator_type get_allocator() const noexcept;

Returns: A copy of the allocator that was set in the constructor or assignment operator.

void set_emit_on_sync(bool b) noexcept;

Effects: emit_on_sync = b.

31.11.2.5 Overridden virtual functions

int sync() override;

Effects: Records that the wrapped stream buffer is to be flushed. Then, if emit_on_sync is true, calls emit().

[Note 1: If emit_on_sync is false, the actual flush is delayed until a call to emit(). — end note]

Returns: If emit() was called and returned false, returns -1; otherwise 0.

31.11.2.6 Specialized algorithms

template<class charT, class traits, class Allocator>
void swap(basic_syncbuf<charT, traits, Allocator>& a,
        basic_syncbuf<charT, traits, Allocator>& b);

Effects: Equivalent to a.swap(b).

31.11.3 Class template basic_osyncstream

31.11.3.1 Overview

namespace std {
    template<class charT, class traits = char_traits<charT>, class Allocator = allocator<charT>>
    class basic_osyncstream : public basic_ostream<charT, traits> {
        public:
            using char_type = charT;
            using int_type = typename traits::int_type;
            using pos_type = typename traits::pos_type;
            using off_type = typename traits::off_type;
            using traits_type = traits;
            using allocator_type = Allocator;
            using streambuf_type = basic_streambuf<charT, traits>;
            using syncbuf_type = basic_syncbuf<charT, traits, Allocator>;

        // 31.11.3.2, construction and destruction
        basic_osyncstream(streambuf_type*, const Allocator&);
        explicit basic_osyncstream(streambuf_type* obuf) :
        basic_osyncstream(obuf, Allocator()) {}
        basic_osyncstream(basic_ostream<charT, traits>& os, const Allocator& allocator)
        basic_osyncstream(os.rdbuf(), allocator) {}
        explicit basic_osyncstream(basic_ostream<charT, traits>&& os)
        basic_osyncstream(os, Allocator()) {}
        basic_osyncstream(basic_osyncstream&&) noexcept;
        ~basic_osyncstream();

        // assignment
        basic_osyncstream& operator=(basic_osyncstream&);

        // 31.11.3.3, member functions
        void emit();
        streambuf_type* get_wrapped() const noexcept;
        syncbuf_type* rdbuf() const noexcept {
            return const_cast<syncbuf_type*>(addressof(sb));
        }
    }
}
private:
    syncbuf_type sb; // exposition only
};

Allocator shall meet the Cpp17Allocator requirements (16.4.4.6.1).

[Example 1: A named variable can be used within a block statement for streaming.]
{
    osyncstream bout(cout);
    bout << "Hello, ";
    bout << "World!";
    bout << endl; // flush is noted
    bout << "and more!\n";
} // characters are transferred and cout is flushed
— end example

[Example 2: A temporary object can be used for streaming within a single statement.]

    osyncstream(cout) << "Hello, " << "World!" << '\n';

In this example, cout is not flushed. — end example]

31.11.3.2 Construction and destruction [synostream.osyncstream.cons]

basic_osyncstream(streambuf_type* buf, const Allocator& allocator);

Effects: Initializes sb from buf and allocator. Initializes the base class with basic_ostream<charT, traits>(addressof(sb)).

Postconditions: get_wrapped() == buf is true.

basic_osyncstream(basic_osyncstream&& other) noexcept;

Effects: Move constructs the base class and sb from the corresponding subobjects of other, and calls basic_ostream<charT, traits>::set_rdbuf(addressof(sb)).

Postconditions: The value returned by get_wrapped() is the value returned by other.get_wrapped() prior to calling this constructor. nullptr == other.get_wrapped() is true.

31.11.3.3 Member functions [synostream.osyncstream.members]

void emit();

Effects: Behaves as an unformatted output function (31.7.6.4). After constructing a sentry object, calls sb.emit(). If that call returns false, calls setstate(ios_base::badbit).

[Example 1: A flush on a basic_osyncstream does not flush immediately:]
{
    osyncstream bout(cout);
    bout << "Hello," " \n"; // no flush
    bout.emit(); // characters transferred; cout not flushed
    bout << "World!" << endl; // flush noted; cout not flushed
    bout.emit(); // characters transferred; cout flushed
    bout << "Greetings," " \n"; // no flush
} // characters transferred; cout not flushed
— end example

[Example 2: The function emit() can be used to handle exceptions from operations on the underlying stream.]
{
    osyncstream bout(cout);
    bout << "Hello, " << "World!" << '\n';
    try {
        bout.emit();
    }
-- end example]
streambuf_type* get_wrapped() const noexcept;

Returns: sb.get_wrapped().

[Example 3: Obtaining the wrapped stream buffer with get_wrapped() allows wrapping it again with an
osyncstream. For example,
{
    osyncstream bout1(cout);
bout1 << "Hello, ";
    {
        osyncstream(bout1.get_wrapped()) << "Goodbye, " << "Planet!" << '\n';
    }
bout1 << "World!" << '\n';
}
produces the uninterleaved output
Goodbye, Planet!
Hello, World!
-- end example]

31.12 File systems [filesystems]
31.12.1 General [fs.general]
1 Subclause 31.12 describes operations on file systems and their components, such as paths, regular files, and
directories.
2 A file system is a collection of files and their attributes.
3 A file is an object within a file system that holds user or system data. Files can be written to, or read from,
or both. A file has certain attributes, including type. File types include regular files and directories. Other
types of files, such as symbolic links, may be supported by the implementation.
4 A directory is a file within a file system that acts as a container of directory entries that contain information
about other files, possibly including other directory files. The parent directory of a directory is the directory that
both contains a directory entry for the given directory and is represented by the dot-dot filename (31.12.6.2)
in the given directory. The parent directory of other types of files is a directory containing a directory entry
for the file under discussion.
5 A link is an object that associates a filename with a file. Several links can associate names with the same file.
A hard link is a link to an existing file. Some file systems support multiple hard links to a file. If the last
hard link to a file is removed, the file itself is removed.
[Note 1: A hard link can be thought of as a shared-ownership smart pointer to a file. — end note]
A symbolic link is a type of file with the property that when the file is encountered during pathname
resolution (31.12.6), a string stored by the file is used to modify the pathname resolution.
[Note 2: Symbolic links are often called symlinks. A symbolic link can be thought of as a raw pointer to a file. If the
file pointed to does not exist, the symbolic link is said to be a “dangling” symbolic link. — end note]

31.12.2 Conformance [fs.conformance]
31.12.2.1 General [fs.conformance.general]
1 Conformance is specified in terms of behavior. Ideal behavior is not always implementable, so the conformance
subclauses take that into account.
31.12.2.2 POSIX conformance [fs.conform.9945]
1 Some behavior is specified by reference to POSIX. How such behavior is actually implemented is unspecified.
[Note 1: This constitutes an “as if” rule allowing implementations to call native operating system or other APIs.
— end note]
Implementations should provide such behavior as it is defined by POSIX. Implementations shall document any behavior that differs from the behavior defined by POSIX. Implementations that do not support exact POSIX behavior should provide behavior as close to POSIX behavior as is reasonable given the limitations of actual operating systems and file systems. If an implementation cannot provide any reasonable behavior, the implementation shall report an error as specified in 31.12.5.

[Note 2: This allows users to rely on an exception being thrown or an error code being set when an implementation cannot provide any reasonable behavior. — end note]

Implementations are not required to provide behavior that is not supported by a particular file system.

[Example 1: The FAT file system used by some memory cards, camera memory, and floppy disks does not support hard links, symlinks, and many other features of more capable file systems, so implementations are not required to support those features on the FAT file system but instead are required to report an error as described above. — end example]

31.12.2.3 Operating system dependent behavior conformance

Behavior that is specified as being operating system dependent is dependent upon the behavior and characteristics of an operating system. The operating system an implementation is dependent upon is implementation-defined.

31.12.2.4 File system race behavior

A file system race is the condition that occurs when multiple threads, processes, or computers interleave access and modification of the same object within a file system. Behavior is undefined if calls to functions provided by subclause 31.12 introduce a file system race.

If the possibility of a file system race would make it unreliable for a program to test for a precondition before calling a function described herein, Preconditions: is not specified for the function.

[Note 1: As a design practice, preconditions are not specified when it is unreasonable for a program to detect them prior to calling the function. — end note]

31.12.3 Requirements

Throughout subclause 31.12, char, wchar_t, char8_t, char16_t, and char32_t are collectively called encoded character types.

Functions with template parameters named EcharT shall not participate in overload resolution unless EcharT is one of the encoded character types.

Template parameters named InputIterator shall meet the Cpp17InputIterator requirements (25.3.5.3) and shall have a value type that is one of the encoded character types.

[Note 1: Use of an encoded character type implies an associated character set and encoding. Since signed char and unsigned char have no implied character set and encoding, they are not included as permitted types. — end note]

Template parameters named Allocator shall meet the Cpp17Allocator requirements (16.4.4.6.1).

31.12.4 Header <filesystem> synopsis

```cpp
#include <compare> // see 17.11.1

namespace std::filesystem {
    // 31.12.6, paths
    class path;

    // 31.12.6.8, path non-member functions
    void swap(path& lhs, path& rhs) noexcept;
    size_t hash_value(const path& p) noexcept;

    // 31.12.7, filesystem errors
    class filesystem_error;

    // 31.12.10, directory entries
    class directory_entry;
```

§ 31.12.4 ©ISO/IEC 1847
// 31.12.11, directory iterators
class directory_iterator;

// 31.12.11.3, range access for directory iterators
directory_iterator begin(directory_iterator iter) noexcept;
directory_iterator end(directory_iterator) noexcept;

// 31.12.12, recursive directory iterators
class recursive_directory_iterator;

// 31.12.12.3, range access for recursive directory iterators
recursive_directory_iterator begin(recursive_directory_iterator iter) noexcept;
recursive_directory_iterator end(recursive_directory_iterator) noexcept;

// 31.12.9, file status
class file_status;

struct space_info {
  uintmax_t capacity;
  uintmax_t free;
  uintmax_t available;

  friend bool operator==(const space_info&, const space_info&) = default;
};

// 31.12.8, enumerations
enum class file_type;
enum class perms;
enum class perm_options;
enum class copy_options;
enum class directory_options;

using file_time_type = chrono::time_point<chrono::file_clock>;

// 31.12.13, filesystem operations
path absolute(const path& p);
path absolute(const path& p, error_code& ec);

path canonical(const path& p);
path canonical(const path& p, error_code& ec);

void copy(const path& from, const path& to);
void copy(const path& from, const path& to, error_code& ec);
void copy(const path& from, const path& to, copy_options options);
void copy(const path& from, const path& to, copy_options options,
          error_code& ec);

bool copy_file(const path& from, const path& to);
bool copy_file(const path& from, const path& to, error_code& ec);
bool copy_file(const path& from, const path& to, copy_options option);
bool copy_file(const path& from, const path& to, copy_options option,
               error_code& ec);

void copy_symlink(const path& existing_symlink, const path& new_symlink);
void copy_symlink(const path& existing_symlink, const path& new_symlink,
                  error_code& ec) noexcept;

bool create_directories(const path& p);
bool create_directories(const path& p, error_code& ec);

bool create_directory(const path& p);
bool create_directory(const path& p, error_code& ec) noexcept;
bool create_directory(const path& p, const path& attributes);
bool create_directory(const path& p, const path& attributes, error_code& ec) noexcept;

void create_directory_symlink(const path& to, const path& new_symlink);
void create_directory_symlink(const path& to, const path& new_symlink, error_code& ec) noexcept;

void create_hard_link(const path& to, const path& new_hard_link);
void create_hard_link(const path& to, const path& new_hard_link, error_code& ec) noexcept;

void create_symlink(const path& to, const path& new_symlink);
void create_symlink(const path& to, const path& new_symlink, error_code& ec) noexcept;

path current_path();
path current_path(error_code& ec);
void current_path(const path& p);
void current_path(const path& p, error_code& ec) noexcept;

bool equivalent(const path& p1, const path& p2);
bool equivalent(const path& p1, const path& p2, error_code& ec) noexcept;

bool exists(file_status s) noexcept;
bool exists(const path& p);
bool exists(const path& p, error_code& ec) noexcept;

uintmax_t file_size(const path& p);
uintmax_t file_size(const path& p, error_code& ec) noexcept;

uintmax_t hard_link_count(const path& p);
uintmax_t hard_link_count(const path& p, error_code& ec) noexcept;

bool is_block_file(file_status s) noexcept;
bool is_block_file(const path& p);
bool is_block_file(const path& p, error_code& ec) noexcept;

bool is_character_file(file_status s) noexcept;
bool is_character_file(const path& p);
bool is_character_file(const path& p, error_code& ec) noexcept;

bool is_directory(file_status s) noexcept;
bool is_directory(const path& p);
bool is_directory(const path& p, error_code& ec) noexcept;

bool is_empty(const path& p);
bool is_empty(const path& p, error_code& ec);

bool is_fifo(file_status s) noexcept;
bool is_fifo(const path& p);
bool is_fifo(const path& p, error_code& ec) noexcept;

bool is_other(file_status s) noexcept;
bool is_other(const path& p);
bool is_other(const path& p, error_code& ec) noexcept;

bool is_regular_file(file_status s) noexcept;
bool is_regular_file(const path& p);
bool is_regular_file(const path& p, error_code& ec) noexcept;

bool is_socket(file_status s) noexcept;
bool is_socket(const path& p);
bool is_socket(const path& p, error_code& ec) noexcept;
namespace std {

// 31.12.6.9, formatting support
template<class charT> struct formatter<filesystem::path, charT>;

// 31.12.6.10, hash support
template<class T> struct hash;
template<> struct hash<filesystem::path>;

} // std

§ 31.12.4

bool is_symlink(file_status s) noexcept;
bool is_symlink(const path& p);
bool is_symlink(const path& p, error_code& ec) noexcept;

file_time_type last_write_time(const path& p);
file_time_type last_write_time(const path& p, error_code& ec) noexcept;
void last_write_time(const path& p, file_time_type new_time);
void last_write_time(const path& p, file_time_type new_time,
                     error_code& ec) noexcept;

void permissions(const path& p, perms prms, perm_options opts=perm_options::replace);
void permissions(const path& p, perms prms, error_code& ec) noexcept;
void permissions(const path& p, perms prms, perm_options opts, error_code& ec);

path proximate(const path& p, error_code& ec);
path proximate(const path& p, const path& base = current_path());
path proximate(const path& p, const path& base, error_code& ec);

path read_symlink(const path& p);
path read_symlink(const path& p, error_code& ec);

path relative(const path& p, error_code& ec);
path relative(const path& p, const path& base = current_path());
path relative(const path& p, const path& base, error_code& ec);

bool remove(const path& p);
bool remove(const path& p, error_code& ec) noexcept;

uintmax_t remove_all(const path& p);
uintmax_t remove_all(const path& p, error_code& ec);

void rename(const path& from, const path& to);
void rename(const path& from, const path& to, error_code& ec) noexcept;

void resize_file(const path& p, uintmax_t size);
void resize_file(const path& p, uintmax_t size, error_code& ec) noexcept;

space_info space(const path& p);
space_info space(const path& p, error_code& ec) noexcept;

file_status status(const path& p);
file_status status(const path& p, error_code& ec) noexcept;

bool status_known(file_status s) noexcept;

file_status symlink_status(const path& p);
file_status symlink_status(const path& p, error_code& ec) noexcept;

path temp_directory_path();
path temp_directory_path(error_code& ec);

path weakly_canonical(const path& p);
path weakly_canonical(const path& p, error_code& ec);
namespace std::ranges {
    template<>
    inline constexpr bool enable_borrowed_range<filesystem::directory_iterator> = true;
    template<>
    inline constexpr bool enable_borrowed_range<filesystem::recursive_directory_iterator> = true;
    template<>
    inline constexpr bool enable_view<filesystem::directory_iterator> = true;
    template<>
    inline constexpr bool enable_view<filesystem::recursive_directory_iterator> = true;
}

Implementations should ensure that the resolution and range of file_time_type reflect the operating system dependent resolution and range of file time values.

31.12.5 Error reporting

1 Filesystem library functions often provide two overloads, one that throws an exception to report file system errors, and another that sets an error_code.

[Note 1: This supports two common use cases:
(1.1) Uses where file system errors are truly exceptional and indicate a serious failure. Throwing an exception is an appropriate response.
(1.2) Uses where file system errors are routine and do not necessarily represent failure. Returning an error code is the most appropriate response. This allows application specific error handling, including simply ignoring the error. —end note]

2 Functions not having an argument of type error_code& handle errors as follows, unless otherwise specified:
(2.1) When a call by the implementation to an operating system or other underlying API results in an error that prevents the function from meeting its specifications, an exception of type filesystem_error shall be thrown. For functions with a single path argument, that argument shall be passed to the filesystem_error constructor with a single path argument. For functions with two path arguments, the first of these arguments shall be passed to the filesystem_error constructor as the path1 argument, and the second shall be passed as the path2 argument. The filesystem_error constructor’s error_code argument is set as appropriate for the specific operating system dependent error.
(2.2) Failure to allocate storage is reported by throwing an exception as described in 16.4.6.13.
(2.3) Destructors throw nothing.

3 Functions having an argument of type error_code& handle errors as follows, unless otherwise specified:
(3.1) If a call by the implementation to an operating system or other underlying API results in an error that prevents the function from meeting its specifications, the error_code& argument is set as appropriate for the specific operating system dependent error. Otherwise, clear() is called on the error_code& argument.

31.12.6 Class path

31.12.6.1 General

An object of class path represents a path and contains a pathname. Such an object is concerned only with the lexical and syntactic aspects of a path. The path does not necessarily exist in external storage, and the pathname is not necessarily valid for the current operating system or for a particular file system.

[Note 1: Class path is used to support the differences between the string types used by different operating systems to represent pathnames, and to perform conversions between encodings when necessary. —end note]

A path is a sequence of elements that identify the location of a file within a filesystem. The elements are the root-name_opt, root-directory_opt, and an optional sequence of filenames (31.12.6.2). The maximum number of elements in the sequence is operating system dependent (31.12.2.3).

An absolute path is a path that unambiguously identifies the location of a file without reference to an additional starting location. The elements of a path that determine if it is absolute are operating system dependent. A relative path is a path that is not absolute, and as such, only unambiguously identifies the location of a file when resolved relative to an implied starting location. The elements of a path that determine if it is relative are operating system dependent.
A pathname is a character string that represents the name of a path. Pathnames are formatted according to the generic pathname format grammar (31.12.6.2) or according to an operating system dependent native pathname format accepted by the host operating system.

Pathname resolution is the operating system dependent mechanism for resolving a pathname to a particular file in a file hierarchy. There may be multiple pathnames that resolve to the same file. 

Example 1: For POSIX-based operating systems, this mechanism is specified in POSIX, section 4.12, Pathname resolution. — end example

namespace std::filesystem {
    class path {
    public:
        using value_type = see below;
        using string_type = basic_string<value_type>;
        static constexpr value_type preferred_separator = see below;

        // 31.12.8.1, enumeration format
        enum format;

        // 31.12.5.1, constructors and destructor
        path() noexcept;
        path(const path& p);
        path(path&& p) noexcept;
        path(string_type& source, format fmt = auto_format);
        template<class Source>
            path(const Source& source, format fmt = auto_format);
        template<class InputIterator>
            path(InputIterator first, InputIterator last, format fmt = auto_format);
        template<class Source>
            path(const Source& source, const locale& loc, format fmt = auto_format);
        template<class InputIterator>
            path(InputIterator first, InputIterator last, const locale& loc, format fmt = auto_format);
        ~path();

        // 31.12.5.2, assignments
        path& operator=(const path& p);
        path& operator=(path&& p) noexcept;
        path& operator=(string_type& source);
        template<class Source>
            path& operator=(const Source& source);
        template<class InputIterator>
            path& operator=(InputIterator first, InputIterator last);

        // 31.12.5.3, appends
        path& operator/=(const path& x);
        template<class Source>
            path& operator/=(const Source& x);
        template<class string_type>
            path& operator/=(const string_type& source);
        template<class InputIterator>
            path& append(InputIterator first, InputIterator last);

        // 31.12.5.4, concatenation
        path& operator+=(const path& x);
        path& operator+=(const string_type& x);
        path& operator+=(basic_string_view<value_type> x);
        path& operator+=(const value_type* x);
        path& operator+=(value_type x);
        template<class Source>
            path& operator+=(const Source& x);
}
template<class EcharT>
  path& operator+=(EcharT x);

template<class Source>
  path& concat(const Source& x);

template<class InputIterator>
  path& concat(InputIterator first, InputIterator last);

// 31.12.6.5, modifiers
void clear() noexcept;
path& make_preferred();
path& remove_filename();
path& replace_filename(const path& replacement);
path& replace_extension(const path& replacement = path());
void swap(path& rhs) noexcept;

// 31.12.6.8, non-member operators
friend bool operator==(const path& lhs, const path& rhs) noexcept;
friend strong_ordering operator<=>(const path& lhs, const path& rhs) noexcept;

friend path operator/(const path& lhs, const path& rhs);

// 31.12.6.5.6, native format observers
const string_type& native() const noexcept;
const value_type* c_str() const noexcept;
operator string_type() const;

template<class EcharT, class traits = char_traits<EcharT>,
class Allocator = allocator<EcharT>>
  basic_string<EcharT, traits, Allocator>
    string(const Allocator& a = Allocator()) const;

std::string string() const;
std::wstring wstring() const;
std::u8string u8string() const;
std::u16string u16string() const;
std::u32string u32string() const;

// 31.12.6.5.7, generic format observers
template<class EcharT, class traits = char_traits<EcharT>,
class Allocator = allocator<EcharT>>
  generic_string(const Allocator& a = Allocator()) const;

std::string generic_string() const;
std::wstring generic_wstring() const;
std::u8string generic_u8string() const;
std::u16string generic_u16string() const;
std::u32string generic_u32string() const;

// 31.12.6.5.8, compare
int compare(const path& p) const noexcept;
int compare(const string_type& s) const;
int compare(basic_string_view<value_type> s) const;
int compare(const value_type* s) const;

// 31.12.6.5.9, decomposition
path root_name() const;
path root_directory() const;
path root_path() const;
path relative_path() const;
path parent_path() const;
path filename() const;
path stem() const;
path extension() const;

§ 31.12.6.1
value_type is a typedef for the operating system dependent encoded character type used to represent pathnames.

The value of the preferred_separator member is the operating system dependent preferred-separator character (31.12.6.2).

[Example 2: For POSIX-based operating systems, value_type is char and preferred_separator is the slash character (/). For Windows-based operating systems, value_type is wchar_t and preferred_separator is the backslash character (L'\'). — end example]

31.12.6.2 Generic pathname format

pathname:
   root-name_opt root-directory_opt relative-path

root-name:
   operating system dependent sequences of characters
   implementation-defined sequences of characters

root-directory:
   directory-separator

relative-path:
   filename
   filename directory-separator relative-path
   an empty path

filename:
   non-empty sequence of characters other than directory-separator characters

directory-separator:
   preferred-separator directory-separator_opt
   fallback-separator directory-separator_opt
preferred-separator:
  operating system dependent directory separator character

fallback-separator:
  /, if preferred-separator is not /

A filename is the name of a file. The dot and dot-dot filenames, consisting solely of one and two period characters respectively, have special meaning. The following characteristics of filenames are operating system dependent:

1. The permitted characters.
   
   [Example 1: Some operating systems prohibit the ASCII control characters (0x00 – 0x1F) in filenames. — end example]

   [Note 1: Wider portability can be achieved by limiting filename characters to the POSIX Portable Filename Character Set:
   A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
   a b c d e f g h i j k l m n o p q r s t u v w x y z
   0 1 2 3 4 5 6 7 8 9 . _ - — end note]

2. The maximum permitted length.

3. Filenames that are not permitted.

4. Filenames that have special meaning.

5. Case awareness and sensitivity during path resolution.

6. Special rules that may apply to file types other than regular files, such as directories.

Except in a root-name, multiple successive directory-separator characters are considered to be the same as one directory-separator character.

The dot filename is treated as a reference to the current directory. The dot-dot filename is treated as a reference to the parent directory. What the dot-dot filename refers to relative to root-directory is implementation-defined. Specific filenames may have special meanings for a particular operating system.

A root-name identifies the starting location for pathname resolution (31.12.6). If there are no operating system dependent root-names, at least one implementation-defined root-name is required.

[Note 2: Many operating systems define a name beginning with two directory-separator characters as a root-name that identifies network or other resource locations. Some operating systems define a single letter followed by a colon as a drive specifier — a root-name identifying a specific device such as a disk drive. — end note]

If a root-name is otherwise ambiguous, the possibility with the longest sequence of characters is chosen.

[Note 3: On a POSIX-like operating system, it is impossible to have a root-name and a relative-path without an intervening root-directory element. — end note]

Normalization of a generic format pathname means:

1. If the path is empty, stop.
2. Replace each slash character in the root-name with a preferred-separator.
3. Replace each directory-separator with a preferred-separator.
   
   [Note 4: The generic pathname grammar defines directory-separator as one or more slashes and preferred-separators. — end note]
4. Remove each dot filename and any immediately following directory-separator.
5. As long as any appear, remove a non-dot-dot filename immediately followed by a directory-separator and a dot-dot filename, along with any immediately following directory-separator.
6. If there is a root-directory, remove all dot-dot filenames and any directory-separators immediately following them.
   
   [Note 5: These dot-dot filenames attempt to refer to nonexistent parent directories. — end note]
7. If the last filename is dot-dot, remove any trailing directory-separator.
8. If the path is empty, add a dot.

The result of normalization is a path in normal form, which is said to be normalized.
### 31.12.6.3 Conversions

#### 31.12.6.3.1 Argument format conversions

1. [Note 1: The format conversions described in this subclause are not applied on POSIX-based operating systems because on these systems:]
   - The generic format is acceptable as a native path.
   - There is no need to distinguish between native format and generic format in function arguments.
   - Paths for regular files and paths for directories share the same syntax.
     
     — end note

2. Several functions are defined to accept detected-format arguments, which are character sequences. A detected-format argument represents a path using either a path name in the generic format (31.12.6.2) or a path name in the native format (31.12.6). Such an argument is taken to be in the generic format if and only if it matches the generic format and is not acceptable to the operating system as a native path.

3. [Note 2: Some operating systems have no unambiguous way to distinguish between native format and generic format arguments. This is by design as it simplifies use for operating systems that do not require disambiguation. It is possible that an implementation for an operating system where disambiguation is needed distinguishes between the formats. — end note]

4. Pathnames are converted as needed between the generic and native formats in an operating-system-dependent manner. Let \( G(n) \) and \( N(g) \) in a mathematical sense be the implementation’s functions that convert native-to-generic and generic-to-native formats respectively. If \( g = G(n) \) for some \( n \), then \( G(N(g)) = g \); if \( n = N(g) \) for some \( g \), then \( N(G(n)) = n \).

   [Note 3: Neither \( G \) nor \( N \) need be invertible. — end note]

5. If the native format requires paths for regular files to be formatted differently from paths for directories, the path shall be treated as a directory path if its last element is a directory-separator, otherwise it shall be treated as a path to a regular file.

6. [Note 4: A path stores a native format pathname (31.12.6.5.6) and acts as if it also stores a generic format pathname, related as given below. The implementation can generate the generic format pathname based on the native format pathname (and possibly other information) when requested. — end note]

7. When a path is constructed from or is assigned a single representation separate from any path, the other representation is selected by the appropriate conversion function \( (G \ or \ N) \).

8. When the (new) value \( p \) of one representation of a path is derived from the representation of that or another path, a value \( q \) is chosen for the other representation. The value \( q \) converts to \( p \) (by \( G \ or \ N \) as appropriate) if any such value does so; \( q \) is otherwise unspecified.

   [Note 5: If \( q \) is the result of converting any path at all, it is the result of converting \( p \). — end note]

### 31.12.6.3.2 Type and encoding conversions

The native encoding of an ordinary character string is the operating system dependent current encoding for pathnames (31.12.6). The native encoding for wide character strings is the implementation-defined execution wide-character set encoding (16.3.3.3.4).

2. For member function arguments that take character sequences representing paths and for member functions returning strings, value type and encoding conversion is performed if the value type of the argument or return value differs from \texttt{path::value_type}. For the argument or return value, the method of conversion and the encoding to be converted to is determined by its value type:

   (2.1) \texttt{char}: The encoding is the native ordinary encoding. The method of conversion, if any, is operating system dependent.

   [Note 1: For POSIX-based operating systems \texttt{path::value_type} is \texttt{char} so no conversion from \texttt{char} value type arguments or to \texttt{char} value type return values is performed. For Windows-based operating systems, the native ordinary encoding is determined by calling a Windows API function. — end note]

   [Note 2: This results in behavior identical to other C and C++ standard library functions that perform file operations using ordinary character strings to identify paths. Changing this behavior would be surprising and error-prone. — end note]

   (2.2) \texttt{wchar_t}: The encoding is the native wide encoding. The method of conversion is unspecified.

   [Note 3: For Windows-based operating systems \texttt{path::value_type} is \texttt{wchar_t} so no conversion from \texttt{wchar_t} value type arguments or to \texttt{wchar_t} value type return values is performed. — end note]
— **char8_t**: The encoding is UTF-8. The method of conversion is unspecified.
— **char16_t**: The encoding is UTF-16. The method of conversion is unspecified.
— **char32_t**: The encoding is UTF-32. The method of conversion is unspecified.

3 If the encoding being converted to has no representation for source characters, the resulting converted characters, if any, are unspecified. Implementations should not modify member function arguments if already of type path::value_type.

### 31.12.6.4 Requirements  
[fs.path.req]

1 In addition to the requirements (31.12.3), function template parameters named **Source** shall be one of:

1. **basic_string<EcharT, traits, Allocator>**. A function argument const Source& source shall have an effective range [source.begin(), source.end()).
2. **basic_string_view<EcharT, traits>**. A function argument const Source& source shall have an effective range [source.begin(), source.end()).
3. A type meeting the Cpp17InputIterator requirements that iterates over a NTCTS. The value type shall be an encoded character type. A function argument const Source& source shall have an effective range [source.begin(), source.end()) where end is the first iterator value with an element value equal to iterator_traits<Source>::value_type().
4. A character array that after array-to-pointer decay results in a pointer to the start of a NTCTS. The value type shall be an encoded character type. A function argument const Source& source shall have an effective range [source, end) where end is the first iterator value with an element value equal to iterator_traits<decay_t<Source>>::value_type().

2 Functions taking template parameters named **Source** shall not participate in overload resolution unless **Source** denotes a type other than path, and either

1. **Source** is a specialization of basic_string or basic_string_view, or
2. the qualified-id iterator_traits<decay_t<Source>>::value_type is valid and denotes a possibly const encoded character type (13.10.3).

3 [Note 1: See path conversions (31.12.6.3) for how the value types above and their encodings convert to path::value_type and its encoding. — end note]

4 Arguments of type **Source** shall not be null pointers.

### 31.12.6.5 Members  
[fs.path.member]

### 31.12.6.5.1 Constructors  
[fs.path.construct]

- **path() noexcept;**  
  Postconditions: empty() is true.
- **path(const path& p);**
- **path(path&& p) noexcept;**  
  **Effects**: Constructs an object of class path having the same pathname in the native and generic formats, respectively, as the original value of p. In the second form, p is left in a valid but unspecified state.
- **path(string_type&& source, format fmt = auto_format);**  
  **Effects**: Constructs an object of class path for which the pathname in the detected-format of source has the original value of source (31.12.6.3.1), converting format if required (31.12.6.3.1). source is left in a valid but unspecified state.
- **template<class Source> path(const Source& source, format fmt = auto_format);**
- **template<class InputIterator> path(InputIterator first, InputIterator last, format fmt = auto_format);**  
  **Effects**: Let s be the effective range of source (31.12.6.4) or the range [first, last), with the encoding converted if required (31.12.6.3). Finds the detected-format of s (31.12.6.3.1) and constructs an object of class path for which the pathname in that format is s.
template<class Source>
    path(const Source& source, const locale& loc, format fmt = auto_format);

template<class InputIterator>
    path(InputIterator first, InputIterator last, const locale& loc, format fmt = auto_format);

Mandates: The value type of Source and InputIterator is char.

Effects: Let s be the effective range of source or the range [first, last), after converting the encoding as follows:

(6.1) — If value_type is wchar_t, converts to the native wide encoding (31.12.6.3.2) using the codecvt<wchar_t, char, mbstate_t> facet of loc.

(6.2) — Otherwise a conversion is performed using the codecvt<wchar_t, char, mbstate_t> facet of loc, and then a second conversion to the current ordinary encoding.

Finds the detected-format of s (31.12.6.3.1) and constructs an object of class path for which the pathname in that format is s.

[Example 1: A string is to be read from a database that is encoded in ISO/IEC 8859-1, and used to create a directory:
	namespace fs = std::filesystem;
	std::string latin1_string = read_latin1_data();

codecvt_8859_1<wchar_t> latin1_facet;

td::locale latin1_locale(std::locale(), latin1_facet);

fs::create_directory(fs::path(latin1_string, latin1_locale));

For POSIX-based operating systems, the path is constructed by first using latin1_facet to convert ISO/IEC 8859-1 encoded latin1_string to a wide character string in the native wide encoding (31.12.6.3.2). The resulting wide string is then converted to an ordinary character pathname string in the current native ordinary encoding. If the native wide encoding is UTF-16 or UTF-32, and the current native ordinary encoding is UTF-8, all of the characters in the ISO/IEC 8859-1 character set will be converted to their Unicode representation, but for other native ordinary encodings some characters may have no representation.

For Windows-based operating systems, the path is constructed by using latin1_facet to convert ISO/IEC 8859-1 encoded latin1_string to a UTF-16 encoded wide character pathname string. All of the characters in the ISO/IEC 8859-1 character set will be converted to their Unicode representation. — end example]

§ 31.12.6.5.2 Assignments

path& operator=(const path& p);

Effects: If *this and p are the same object, has no effect. Otherwise, sets both respective pathnames of *this to the respective pathnames of p.

Returns: *this.

path& operator=(path&& p) noexcept;

Effects: If *this and p are the same object, has no effect. Otherwise, sets both respective pathnames of *this to the respective pathnames of p. p is left in a valid but unspecified state.

[Note 1: A valid implementation is swap(p). — end note]

Returns: *this.

path& operator=(string_type&& source);
path assign(string_type&& source);

Effects: Sets the pathname in the detected-format of source to the original value of source. source is left in a valid but unspecified state.

Returns: *this.
N4986

template<class InputIterator>
path& assign(InputIterator first, InputIterator last);

Effects: Let s be the effective range of source (31.12.6.4) or the range [first, last), with the encoding converted if required (31.12.6.3). Finds the detected-format of s (31.12.6.3.1) and sets the pathname in that format to s.

Returns: *this.

31.12.6.5.3 Appends

The append operations use operator/= to denote their semantic effect of appending preferred-separator when needed.

path& operator/=(const path& p);

Effects: If p.is_absolute() || (p.has_root_name() & p.root_name() != root_name()), then operator=(p).

Otherwise, modifies *this as if by these steps:

(3.1) — If p.has_root_directory(), then removes any root directory and relative path from the generic format pathname. Otherwise, if !has_root_directory() && is_absolute() is true or if has_filename() is true, then appends path::preferred_separator to the generic format pathname.

(3.2) — Then appends the native format pathname of p, omitting any root-name from its generic format pathname, to the native format pathname.

Example 1: Even if //host is interpreted as a root-name, both of the paths path("//host")/"foo" and path("//host/")/"foo" equal "//host/foo" (although the former might use backslash as the preferred separator).

Expression examples:

// On POSIX,
path("foo") /= path(""); // yields path("foo/")
path("foo") /= path("/bar"); // yields path("/bar")

// On Windows,
path("foo") /= path(""); // yields path("foo\")
path("foo") /= path("/bar"); // yields path("/bar")
path("foo") /= path("c:/bar"); // yields path("c:/bar")
path("foo") /= path("c:"); // yields path("c:")
path("c:" /= path("")); // yields path("c:")
path("c:foo") /= path("/bar"); // yields path("c:/bar")
path("c:foo") /= path("c:bar"); // yields path("c:foo\bar")

—end example]

Returns: *this.

template<class Source>
path& operator/=(const Source& source);

template<class Source>
path& append(const Source& source);

Effects: Equivalent to: return operator/=(path(source));

template<class InputIterator>
path& append(InputIterator first, InputIterator last);

Effects: Equivalent to: return operator/=(path(first, last));

31.12.6.5.4 Concatenation

path& operator+=(const path& x);
path& operator+=(const string_type& x);
path& operator+=(basic_string_view<value_type> x);
path& operator+=(const value_type* x);

template<class Source>
path& operator+=(const Source& x);
template<class Source>
path& concat(const Source& x);

Effects: Appends path(x).native() to the pathname in the native format.

[Note 1: This directly manipulates the value of native(), which is not necessarily portable between operating systems. — end note]

Returns: *this.

path& operator+=(value_type x);

Effects: Equivalent to: return *this += basic_string_view(&x, 1);

template<class EcharT>
path& operator+=(EcharT x);

Effects: Equivalent to: return *this += basic_string_view(&x, 1);

template<class InputIterator>
path& concat(InputIterator first, InputIterator last);

Effects: Equivalent to: return *this += path(first, last);

31.12.6.5.5 Modifiers
[fs.path.modifiers]

void clear() noexcept;

Postconditions: empty() is true.

path& make_preferred();

Effects: Each directory-separator of the pathname in the generic format is converted to preferred-separator.

Returns: *this.

[Example 1:

    path p("foo/bar");
    std::cout << p << 'n';
    p.make_preferred();
    std::cout << p << 'n';
]

On an operating system where preferred-separator is a slash, the output is:

"foo/bar"
"foo/bar"

On an operating system where preferred-separator is a backslash, the output is:

"foo/bar"
"foo\bar"

— end example]

path& remove_filename();

Effects: Remove the generic format pathname of filename() from the generic format pathname.

Postconditions: !has_filename().

Returns: *this.

[Example 2:

    path("foo/bar").remove_filename(); // yields "foo/"
    path("foo/").remove_filename(); // yields "foo/"
    path("/foo").remove_filename(); // yields "/
    path("/").remove_filename(); // yields "/"
]

— end example]

path& replace_filename(const path& replacement);

Effects: Equivalent to:

    remove_filename();
    operator/=(replacement);

Returns: *this.
Example 3:

```cpp
path("/foo").replace_filename("bar"); // yields "/bar" on POSIX
path("/").replace_filename("bar"); // yields "/bar" on POSIX
— end example
```

```cpp
path& replace_extension(const path& replacement = path());
```

**Effects:**

- Any existing `extension()` (31.12.6.5.9) is removed from the pathname in the generic format, then
- If `replacement` is not empty and does not begin with a dot character, a dot character is appended to the pathname in the generic format, then
- `operator+=(replacement);`

```cpp
void swap(path& rhs) noexcept;
```

**Effects:** Swaps the contents (in all formats) of the two paths.

**Complexity:** Constant time.

31.12.6.5.6 Native format observers [fs.path.native.obs]

The string returned by all native format observers is in the native pathname format (31.12.6).

```cpp
const string_type& native() const noexcept;
```

**Returns:** The pathname in the native format.

```cpp
const value_type* c_str() const noexcept;
```

**Effects:** Equivalent to: `return native().c_str();`

```cpp
operator string_type() const;
```

**Returns:** `native()`.

```cpp
template<class EcharT, class traits = char_traits<EcharT>,
class Allocator = allocator<EcharT>>
basic_string<EcharT, traits, Allocator>
string(const Allocator& a = Allocator()) const;
```

**Returns:** `native()`.

**Remarks:** All memory allocation, including for the return value, shall be performed by `a`. Conversion, if any, is specified by 31.12.6.3.

```cpp
std::string string() const;
std::wstring wstring() const;
std::u8string u8string() const;
std::u16string u16string() const;
std::u32string u32string() const;
```

**Returns:** `native()`.

**Remarks:** Conversion, if any, is performed as specified by 31.12.6.3.

31.12.6.5.7 Generic format observers [fs.path.generic.obs]

Generic format observer functions return strings formatted according to the generic pathname format (31.12.6.2). A single slash (`'/'`) character is used as the directory-separator.

Example 1: On an operating system that uses backslash as its preferred-separator,

```cpp
path("foo\bar").generic_string()
```

returns "foo/bar". — end example]
template<class EcharT, class traits = char_traits<EcharT>,
class Allocator = allocator<EcharT>>
basic_string<EcharT, traits, Allocator>
generic_string(const Allocator& a = Allocator()) const;

Returns: The pathname in the generic format.
Remarks: All memory allocation, including for the return value, shall be performed by a. Conversion, if any, is specified by 31.12.6.3.

std::string generic_string() const;
std::wstring generic_wstring() const;
std::u8string generic_u8string() const;
std::u16string generic_u16string() const;
std::u32string generic_u32string() const;

Returns: The pathname in the generic format.
Remarks: Conversion, if any, is specified by 31.12.6.3.

31.12.6.5.8 Compare

int compare(const path& p) const noexcept;

Returns:
(1.1) — Let rootNameComparison be the result of this->root_name().native().compare(p.root_name().native()). If rootNameComparison is not 0, rootNameComparison.
(1.2) — Otherwise, if !this->has_root_directory() and p.has_root_directory(), a value less than 0.
(1.3) — Otherwise, if this->has_root_directory() and !p.has_root_directory(), a value greater than 0.
(1.4) — Otherwise, if native() for the elements of this->relative_path() are lexicographically less than native() for the elements of p.relative_path(), a value less than 0.
(1.5) — Otherwise, if native() for the elements of this->relative_path() are lexicographically greater than native() for the elements of p.relative_path(), a value greater than 0.
(1.6) — Otherwise, 0.

int compare(const string_type& s) const;
int compare(basic_string_view<value_type> s) const;
int compare(const value_type* s) const;

Effects: Equivalent to: return compare(path(s));

31.12.6.5.9 Decomposition

path root_name() const;

Returns: root-name, if the pathname in the generic format includes root-name, otherwise path().

path root_directory() const;

Returns: root-directory, if the pathname in the generic format includes root-directory, otherwise path().

path root_path() const;

Returns: root_name() / root_directory().

path relative_path() const;

Returns: A path composed from the pathname in the generic format, if empty() is false, beginning with the first filename after root_path(). Otherwise, path().

path parent_path() const;

Returns: *this if has_relative_path() is false, otherwise a path whose generic format pathname is the longest prefix of the generic format pathname of *this that produces one fewer element in its iteration.
path filename() const;

Returns: relative_path().empty() ? path() : *--end().

[Example 1:
  path("/foo/bar.txt").filename();  // yields "bar.txt"
  path("/foo/bar").filename();     // yields "bar"
  path("/foo/bar/").filename();    // yields ""
  path("/").filename();           // yields ""
  path("//host").filename();       // yields ""
  path(".").filename();           // yields "."
  path("..").filename();          // yields ".."
  — end example]

path stem() const;

Returns: Let $f$ be the generic format pathname of filename(). Returns a path whose pathname in the generic format is

- if it contains no periods other than a leading period or consists solely of one or two periods;
- otherwise, the prefix of $f$ ending before its last period.

[Example 2:
  std::cout << path("/foo/bar.txt").stem();  // outputs "bar"
  path p = "foo.bar.baz.tar";
  for (; !p.extension().empty(); p = p.stem())
     std::cout << p.extension() << '
     // outputs: .tar
     // .baz
     // .bar
  — end example]

path extension() const;

Returns: A path whose pathname in the generic format is the suffix of filename() not included in stem().

[Example 3:
  path("/foo/bar.txt").extension();       // yields ".txt" and stem() is "bar"
  path("/foo/bar").extension();           // yields "" and stem() is "bar"
  path("/foo/.").extension();             // yields "" and stem() is ".
  path("./bar").extension();             // yields "." and stem() is "bar"
  path("./bar").extension();             // yields ".bar" and stem() is ".
  — end example]

[Note 1: The period is included in the return value so that it is possible to distinguish between no extension and an empty extension. — end note]

[Note 2: On non-POSIX operating systems, for a path $p$, it is possible that $p.stem() + p.extension() == p.filename()$ is false, even though the generic format pathnames are the same. — end note]

31.12.6.5.10 Query

[[nodiscard]] bool empty() const noexcept;

Returns: true if the pathname in the generic format is empty, otherwise false.

bool has_root_path() const;

Returns: !root_path().empty().

bool has_root_name() const;

Returns: !root_name().empty().

bool has_root_directory() const;

Returns: !root_directory().empty().
bool has_relative_path() const;
Returns: !relative_path().empty().

bool has_parent_path() const;
Returns: !parent_path().empty().

bool has_filename() const;
Returns: !filename().empty().

bool has_stem() const;
Returns: !stem().empty().

bool has_extension() const;
Returns: !extension().empty().

bool is_absolute() const;
Returns: true if the pathname in the native format contains an absolute path (31.12.6), otherwise false.

[Example 1: path("/").is_absolute() is true for POSIX-based operating systems, and false for Windows-based operating systems. — end example]

bool is_relative() const;
Returns: !is_absolute().

31.12.6.5.11 Generation
path lexically_normal() const;
Returns: A path whose pathname in the generic format is the normal form (31.12.6.2) of the pathname in the generic format of *this.

[Example 1:
assert(path("foo/./bar/..").lexically_normal() == "foo/");
assert(path("foo///bar///").lexically_normal() == "foo/");
The above assertions will succeed. On Windows, the returned path’s directory-separator characters will be backslashes rather than slashes, but that does not affect path equality. — end example]

path lexically_relative(const path& base) const;
Effects: If:
— root_name() != base.root_name() is true, or
— is_absolute() != base.is_absolute() is true, or
— !has_root_directory() && base.has_root_directory() is true, or
— any filename in relative_path() or base.relative_path() can be interpreted as a root-name, returns path().

[Note 1: On a POSIX implementation, no filename in a relative-path is acceptable as a root-name. — end note]
Determines the first mismatched element of *this and base as if by:
auto [a, b] = mismatch(begin(), end(), base.begin(), base.end());
Then,
— if a == end() and b == base.end(), returns path("."); otherwise
— let n be the number of filename elements in [b, base.end()) that are not dot or dot-dot or empty, minus the number that are dot-dot. If n<0, returns path(); otherwise
— if n == 0 and (a == end() || a->empty()), returns path("."); otherwise
— returns an object of class path that is default-constructed, followed by
— application of operator/=(path("..")) n times, and then
— application of operator/= for each element in [a, end()).
N4986

Returns: *this made relative to base. Does not resolve (31.12.6) symlinks. Does not first normalize (31.12.6.2) *this or base.

[Example 2:]
assert(path("/a/d").lexically_relative("/a/b/c") == "../../d");
assert(path("/a/b/c").lexically_relative("/a/d") == ".../b/c");
assert(path("a/b/c").lexically_relative("a") == "b/c");
assert(path("a/b/c").lexically_relative("a/b/c/x/y") == ".../..");
assert(path("a/b/c").lexically_relative("a/b/c") == ".");
assert(path("a/b") .lexically_relative("c/d") == ".../a/b");

The above assertions will succeed. On Windows, the returned path's directory-separator characters will be backslashes rather than slashes, but that does not affect path equality. — end example]

[Note 2: If symlink following semantics are desired, use the operational function relative(). — end note]

[Note 3: If normalization (31.12.6.2) is needed to ensure consistent matching of elements, apply lexically_normal() to *this, base, or both. — end note]

path lexically_proximate(const path& base) const;

Returns: If the value of lexically_relative(base) is not an empty path, return it. Otherwise return *this.

[Note 4: If symlink following semantics are desired, use the operational function proximate(). — end note]

[Note 5: If normalization (31.12.6.2) is needed to ensure consistent matching of elements, apply lexically_normal() to *this, base, or both. — end note]

31.12.6.6 Iterators

Path iterators iterate over the elements of the pathname in the generic format (31.12.6.2).

A path::iterator is a constant iterator meeting all the requirements of a bidirectional iterator (25.3.5.6) except that, for dereferenceable iterators a and b of type path::iterator with a == b, there is no requirement that *a and *b are bound to the same object. Its value_type is path.

Calling any non-const member function of a path object invalidates all iterators referring to elements of that object.

For the elements of the pathname in the generic format, the forward traversal order is as follows:

(4.1) — The root-name element, if present.

(4.2) — The root-directory element, if present.

[Note 1: It is possible that the use of the generic format is needed to ensure correct lexicographical comparison. — end note]

(4.3) — Each successive filename element, if present.

(4.4) — An empty element, if a trailing non-root directory-separator is present.

The backward traversal order is the reverse of forward traversal.

iterator begin() const;

Returns: An iterator for the first present element in the traversal list above. If no elements are present, the end iterator.

iterator end() const;

Returns: The end iterator.

31.12.6.7 Inserter and extractor

template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const path& p);

Effects: Equivalent to os << quoted(p.string<charT, traits>())

[Note 1: The quoted function is described in 31.7.9. — end note]

Returns: os.

§ 31.12.6.7 © ISO/IEC 1865
template<class charT, class traits>
friend basic_istream<charT, traits>&
    operator>>(basic_istream<charT, traits>& is, path& p);

Effects: Equivalent to:
    basic_string<charT, traits> tmp;
    is >> quoted(tmp);
    p = tmp;

Returns: is.

31.12.6.8 Non-member functions

void swap(path& lhs, path& rhs) noexcept;

Effects: Equivalent to lhs.swap(rhs).

size_t hash_value(const path& p) noexcept;

Returns: A hash value for the path p. If for two paths, p1 == p2 then hash_value(p1) == hash_value(p2).

friend bool operator==(const path& lhs, const path& rhs) noexcept;

Returns: lhs.compare(rhs) == 0.

[Note 1: Path equality and path equivalence have different semantics.
(4.1) — Equality is determined by the path non-member operator==, which considers the two paths' lexical representations only.
[Example 1: path("foo") == "bar" is never true. — end example]
(4.2) — Equivalence is determined by the equivalent() non-member function, which determines if two paths resolve (31.12.6) to the same file system entity.
[Example 2: equivalent("foo", "bar") will be true when both paths resolve to the same file. — end example]
— end note]

friend strong_ordering operator<=>(const path& lhs, const path& rhs) noexcept;

Returns: lhs.compare(rhs) <=> 0.

friend path operator/(const path& lhs, const path& rhs);

Effects: Equivalent to: return path(lhs) /= rhs;

31.12.6.9 Formatting support

31.12.6.9.1 Formatting support overview

namespace std {
    template<class charT> struct formatter<filesystem::path, charT> {
        constexpr void set_debug_format();

        constexpr typename basic_format_parse_context<charT>::iterator
            parse(basic_format_parse_context<charT>& ctx);

        template<class FormatContext>
            typename FormatContext::iterator
                format(const filesystem::path& path, FormatContext& ctx) const;
    };
}

31.12.6.9.2 Formatting support functions

Formatting of paths uses formatting specifiers of the form

path-format-spec:
    fill-and-align^opt width^opt ?^opt g^opt

where the productions fill-and-align and width are described in 22.14.2. If the ? option is used then the path is formatted as an escaped string (22.14.6.5).
constexpr void set_debug_format();

Effects: Modifies the state of the formatter to be as if the path-format-spec parsed by the last call to parse contained the ? option.

constexpr typename basic_format_parse_context<charT>::iterator parse(basic_format_parse_context<charT>& ctx);

Effects: Parses the format specifier as a path-format-spec and stores the parsed specifiers in *this.

Returns: An iterator past the end of the path-format-spec.

template<class FormatContext>
typename FormatContext::iterator format(const filesystem::path& p, FormatContext& ctx) const;

Effects: Let s be p.generic_string<filesystem::path::value_type>() if the g option is used, otherwise p.native(). Writes s into ctx.out(), adjusted according to the path-format-spec. If charT is char, path::value_type is wchar_t, and the literal encoding is UTF-8, then the escaped path is transcoded from the native encoding for wide character strings to UTF-8 with maximal subparts of ill-formed subsequences substituted with $\text{U+FFFD}$ replacement character per the Unicode Standard, Chapter 3.9 $\text{U+FFFD}$ Substitution in Conversion. If charT and path::value_type are the same then no transcoding is performed. Otherwise, transcoding is implementation-defined.

Returns: An iterator past the end of the output range.

31.12.6.10 Hash support

```cpp
template<> struct hash<filesystem::path>;
```

For an object p of type filesystem::path, hash<filesystem::path>()(p) evaluates to the same result as filesystem::hash_value(p).

31.12.7 Class filesystem_error

31.12.7.1 General

namespace std::filesystem {

```cpp
class filesystem_error : public system_error {
public:
    filesystem_error(const string& what_arg, error_code ec);
    filesystem_error(const string& what_arg,
                     const path& p1, error_code ec);
    filesystem_error(const string& what_arg,
                     const path& p1, const path& p2, error_code ec);

    const path& path1() const noexcept;
    const path& path2() const noexcept;
    const char* what() const noexcept override;
};
```

} // namespace std::filesystem

The class filesystem_error defines the type of objects thrown as exceptions to report file system errors from functions described in subclause 31.12.

31.12.7.2 Members

Constructors are provided that store zero, one, or two paths associated with an error.

```cpp
filesystem_error(const string& what_arg, error_code ec);
```

Postconditions:

1. code() == ec is true,
2. path1().empty() is true,
3. path2().empty() is true, and
4. string_view(what()).find(what_arg.c_str()) != string_view::npos is true.

§ 31.12.7.2 © ISO/IEC

1867
filesystem_error(const string& what_arg, const path& p1, error_code ec);

**Postconditions:**

- code() == ec is true,
- path1() returns a reference to the stored copy of p1,
- path2().empty() is true, and
- string_view(what()).find(what_arg.c_str()) != string_view::npos is true.

filesystem_error(const string& what_arg, const path& p1, const path& p2, error_code ec);

**Postconditions:**

- code() == ec,
- path1() returns a reference to the stored copy of p1,
- path2() returns a reference to the stored copy of p2, and
- string_view(what()).find(what_arg.c_str()) != string_view::npos.

const path& path1() const noexcept;

**Returns:** A reference to the copy of p1 stored by the constructor, or, if none, an empty path.

const path& path2() const noexcept;

**Returns:** A reference to the copy of p2 stored by the constructor, or, if none, an empty path.

const char* what() const noexcept override;

**Returns:** An 
ntbs that incorporates the what_arg argument supplied to the constructor. The exact format is unspecified. Implementations should include the system_error::what() string and the pathnames of path1 and path2 in the native format in the returned string.

### 31.12.8 Enumerations

#### 31.12.8.1 Enum path::format

This enum specifies constants used to identify the format of the character sequence, with the meanings listed in Table 133.

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>native_format</td>
<td>The native pathname format.</td>
</tr>
<tr>
<td>generic_format</td>
<td>The generic pathname format.</td>
</tr>
<tr>
<td>auto_format</td>
<td>The interpretation of the format of the character sequence is implement-</td>
</tr>
<tr>
<td></td>
<td>ation-defined. The implementation may inspect the content of the charac-</td>
</tr>
<tr>
<td></td>
<td>ter sequence to determine the format.</td>
</tr>
<tr>
<td></td>
<td><strong>Recommended practice:</strong> For POSIX-based systems, native and</td>
</tr>
<tr>
<td></td>
<td>generic formats are equivalent and the character sequence should</td>
</tr>
<tr>
<td></td>
<td>always be interpreted in the same way.</td>
</tr>
</tbody>
</table>

#### 31.12.8.2 Enum class file_type

This enum class specifies constants used to identify file types, with the meanings listed in Table 134. The values of the constants are distinct.

#### 31.12.8.3 Enum class copy_options

The enum class type copy_options is a bitmask type (16.3.3.3.3) that specifies bitmask constants used to control the semantics of copy operations. The constants are specified in option groups with the meanings listed in Table 135. The constant none represents the empty bitmask, and is shown in each option group for purposes of exposition; implementations shall provide only a single definition. Every other constant in the table represents a distinct bitmask element.
### Table 134 — Enum class `file_type`  

<table>
<thead>
<tr>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>none</code></td>
<td>The type of the file has not been determined or an error occurred while trying to determine the type.</td>
</tr>
<tr>
<td><code>not_found</code></td>
<td>Pseudo-type indicating the file was not found. [Note 1: The file not being found is not considered an error while determining the type of a file. — end note]</td>
</tr>
<tr>
<td><code>regular</code></td>
<td>Regular file</td>
</tr>
<tr>
<td><code>directory</code></td>
<td>Directory file</td>
</tr>
<tr>
<td><code>symlink</code></td>
<td>Symbolic link file</td>
</tr>
<tr>
<td><code>block</code></td>
<td>Block special file</td>
</tr>
<tr>
<td><code>character</code></td>
<td>Character special file</td>
</tr>
<tr>
<td><code>fifo</code></td>
<td>FIFO or pipe file</td>
</tr>
<tr>
<td><code>socket</code></td>
<td>Socket file</td>
</tr>
<tr>
<td><code>implementation-defined</code></td>
<td>Implementations that support file systems having file types in addition to the above <code>file_type</code> types shall supply implementation-defined <code>file_type</code> constants to separately identify each of those additional file types</td>
</tr>
<tr>
<td><code>unknown</code></td>
<td>The file exists but the type cannot be determined</td>
</tr>
</tbody>
</table>

### Table 135 — Enum class `copy_options`  

<table>
<thead>
<tr>
<th>Option group controlling <code>copy_file</code> function effects for existing target files</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>none</code></td>
<td>(Default) Error; file already exists.</td>
<td></td>
</tr>
<tr>
<td><code>skip_existing</code></td>
<td>Do not overwrite existing file, do not report an error.</td>
<td></td>
</tr>
<tr>
<td><code>overwrite_existing</code></td>
<td>Overwrite the existing file.</td>
<td></td>
</tr>
<tr>
<td><code>update_existing</code></td>
<td>Overwrite the existing file if it is older than the replacement file.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option group controlling <code>copy</code> function effects for subdirectories</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>none</code></td>
<td>(Default) Do not copy subdirectories.</td>
<td></td>
</tr>
<tr>
<td><code>recursive</code></td>
<td>Recursively copy subdirectories and their contents.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option group controlling <code>copy</code> function effects for symbolic links</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>none</code></td>
<td>(Default) Follow symbolic links.</td>
<td></td>
</tr>
<tr>
<td><code>copy_symlinks</code></td>
<td>Copy symbolic links as symbolic links rather than copying the files that they point to.</td>
<td></td>
</tr>
<tr>
<td><code>skip_symlinks</code></td>
<td>Ignore symbolic links.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option group controlling <code>copy</code> function effects for choosing the form of copying</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>none</code></td>
<td>(Default) Copy content.</td>
<td></td>
</tr>
<tr>
<td><code>directories_only</code></td>
<td>Copy directory structure only, do not copy non-directory files.</td>
<td></td>
</tr>
<tr>
<td><code>create_symlinks</code></td>
<td>Make symbolic links instead of copies of files. The source path shall be an absolute path unless the destination path is in the current directory.</td>
<td></td>
</tr>
<tr>
<td><code>create_hard_links</code></td>
<td>Make hard links instead of copies of files.</td>
<td></td>
</tr>
</tbody>
</table>
31.12.8.4 Enum class perms

The `enum` type `perms` is a bitmask type (16.3.3.3.3) that specifies bitmask constants used to identify file permissions, with the meanings listed in Table 136.

Table 136 — Enum class perms

<table>
<thead>
<tr>
<th>Name</th>
<th>Value (octal)</th>
<th>POSIX macro</th>
<th>Definition or notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>0</td>
<td></td>
<td>There are no permissions set for the file.</td>
</tr>
<tr>
<td>owner_read</td>
<td>0400</td>
<td>S_IRUSR</td>
<td>Read permission, owner</td>
</tr>
<tr>
<td>owner_write</td>
<td>0200</td>
<td>S_IWUSR</td>
<td>Write permission, owner</td>
</tr>
<tr>
<td>owner_exec</td>
<td>0100</td>
<td>S_IXUSR</td>
<td>Execute/search permission, owner</td>
</tr>
<tr>
<td>owner_all</td>
<td>0700</td>
<td>S_IRWXU</td>
<td>Read, write, execute/search by owner; owner_read</td>
</tr>
<tr>
<td>group_read</td>
<td>040</td>
<td>S_IRGRP</td>
<td>Read permission, group</td>
</tr>
<tr>
<td>group_write</td>
<td>020</td>
<td>S_IWGRP</td>
<td>Write permission, group</td>
</tr>
<tr>
<td>group_exec</td>
<td>010</td>
<td>S_IXGRP</td>
<td>Execute/search permission, group</td>
</tr>
<tr>
<td>group_all</td>
<td>070</td>
<td>S_IRWXG</td>
<td>Read, write, execute/search by group; group_read</td>
</tr>
<tr>
<td>others_read</td>
<td>04</td>
<td>S_IROTH</td>
<td>Read permission, others</td>
</tr>
<tr>
<td>others_write</td>
<td>02</td>
<td>S_IWOTH</td>
<td>Write permission, others</td>
</tr>
<tr>
<td>others_exec</td>
<td>01</td>
<td>S_IXOTH</td>
<td>Execute/search permission, others</td>
</tr>
<tr>
<td>others_all</td>
<td>07</td>
<td>S_IRWXO</td>
<td>Read, write, execute/search by others; others_read</td>
</tr>
<tr>
<td>all</td>
<td>0777</td>
<td></td>
<td>owner_all</td>
</tr>
<tr>
<td>set_uid</td>
<td>04000</td>
<td>S_ISUID</td>
<td>Set-user-ID on execution</td>
</tr>
<tr>
<td>set_gid</td>
<td>02000</td>
<td>S_ISGID</td>
<td>Set-group-ID on execution</td>
</tr>
<tr>
<td>sticky_bit</td>
<td>01000</td>
<td>S_ISVTX</td>
<td>Operating system dependent.</td>
</tr>
<tr>
<td>mask</td>
<td>07777</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>unknown</td>
<td>0xFFFF</td>
<td></td>
<td>The permissions are not known, such as when a file_status object is created without specifying the permissions</td>
</tr>
</tbody>
</table>

31.12.8.5 Enum class perm_options

The `enum` type `perm_options` is a bitmask type (16.3.3.3.3) that specifies bitmask constants used to control the semantics of permissions operations, with the meanings listed in Table 137. The bitmask constants are bitmask elements. In Table 137 `perm` denotes a value of type `perms` passed to `permissions`.

Table 137 — Enum class perm_options

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>replace</td>
<td>permissions shall replace the file’s permission bits with perm</td>
</tr>
<tr>
<td>add</td>
<td>permissions shall replace the file’s permission bits with the bitwise OR of perm and the file’s current permission bits.</td>
</tr>
<tr>
<td>remove</td>
<td>permissions shall replace the file’s permission bits with the bitwise AND of the complement of perm and the file’s current permission bits.</td>
</tr>
<tr>
<td>follow</td>
<td>permissions shall change the permissions of a symbolic link itself rather than the permissions of the file the link resolves to.</td>
</tr>
</tbody>
</table>

31.12.8.6 Enum class directory_options

The `enum` type `directory_options` is a bitmask type (16.3.3.3.3) that specifies bitmask constants used to identify directory traversal options, with the meanings listed in Table 138. The constant `none` represents the empty bitmask; every other constant in the table represents a distinct bitmask element.
Table 138 — Enum class directory_options

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>(Default) Skip directory symlinks, permission denied is an error.</td>
</tr>
<tr>
<td>follow_directory_symlink</td>
<td>Follow rather than skip directory symlinks.</td>
</tr>
<tr>
<td>skip_permission_denied</td>
<td>Skip directories that would otherwise result in permission denied.</td>
</tr>
</tbody>
</table>

31.12.9 Class file_status

31.12.9.1 General

namespace std::filesystem {
  class file_status {
    public:
      // 31.12.9.2, constructors and destructor
      file_status() noexcept : file_status(file_type::none) {}  
      explicit file_status(file_type ft, 
          perms prms = perms::unknown) noexcept;  
      file_status(const file_status&) noexcept = default;
      file_status(file_status&&) noexcept = default;
      ~file_status();  

      // assignments
      file_status& operator=(const file_status&) noexcept = default;
      file_status& operator=(file_status&&) noexcept = default;

      // 31.12.9.4, modifiers
      void type(file_type ft) noexcept;  
      void permissions(perms prms) noexcept;

      // 31.12.9.3, observers
      file_type type() const noexcept;  
      perms permissions() const noexcept;

      friend bool operator==(const file_status& lhs, const file_status& rhs) noexcept  
      { return lhs.type() == rhs.type() && lhs.permissions() == rhs.permissions(); }  
    }
  }
}

1 An object of type file_status stores information about the type and permissions of a file.

31.12.9.2 Constructors

explicit file_status(file_type ft, perms prms = perms::unknown) noexcept;

1 Postconditions: type() == ft and permissions() == prms.

31.12.9.3 Observers

file_type type() const noexcept;

1 Returns: The value of type() specified by the postconditions of the most recent call to a constructor, 
operator=, or type(file_type) function.

perms permissions() const noexcept;

2 Returns: The value of permissions() specified by the postconditions of the most recent call to a 
constructor, operator=, or permissions(perms) function.

31.12.9.4 Modifiers

void type(file_type ft) noexcept;

1 Postconditions: type() == ft.
void permissions(perms prms) noexcept;

2  \textit{Postconditions:} permissions() == prms.

31.12.10  Class directory_entry

31.12.10.1  General

\begin{verbatim}
namespace std::filesystem {
    class directory_entry {
        public:
            // 31.12.10.2, constructors and destructor
            directory_entry() noexcept = default;
            directory_entry(const directory_entry&) = default;
            directory_entry(directory_entry&&) noexcept = default;
            explicit directory_entry(const filesystem::path& p);
            directory_entry(const filesystem::path& p, error_code& ec);
            ~directory_entry();

            // assignments
            directory_entry& operator=(const directory_entry&) = default;
            directory_entry& operator=(directory_entry&&) noexcept = default;

            // 31.12.10.3, modifiers
            void assign(const filesystem::path& p);
            void assign(const filesystem::path& p, error_code& ec);
            void replace_filename(const filesystem::path& p);
            void replace_filename(const filesystem::path& p, error_code& ec);
            void refresh();
            void refresh(error_code& ec) noexcept;

            // 31.12.10.4, observers
            const filesystem::path& path() const noexcept;
            operator const filesystem::path&() const noexcept;
            bool exists() const;
            bool exists(error_code& ec) const noexcept;
            bool is_block_file() const;
            bool is_block_file(error_code& ec) const noexcept;
            bool is_character_file() const;
            bool is_character_file(error_code& ec) const noexcept;
            bool is_directory() const;
            bool is_directory(error_code& ec) const noexcept;
            bool is_fifo() const;
            bool is_fifo(error_code& ec) const noexcept;
            bool is_other() const;
            bool is_other(error_code& ec) const noexcept;
            bool is_regular_file() const;
            bool is_regular_file(error_code& ec) const noexcept;
            bool is_socket() const;
            bool is_socket(error_code& ec) const;
            bool is_symlink() const;
            bool is_symlink(error_code& ec) const noexcept;
            uintmax_t file_size() const;
            uintmax_t file_size(error_code& ec) const noexcept;
            uintmax_t hard_link_count() const;
            uintmax_t hard_link_count(error_code& ec) const noexcept;
            file_time_type last_write_time() const;
            file_time_type last_write_time(error_code& ec) const noexcept;
            file_status status() const;
            file_status status(error_code& ec) const noexcept;
            file_status symlink_status() const;
            file_status symlink_status(error_code& ec) const noexcept;

            bool operator==(const directory_entry& rhs) const noexcept;
            strong_ordering operator<=>(const directory_entry& rhs) const noexcept;
    }
}
\end{verbatim}

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1872
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const directory_entry& d);

private:
filesystem::path pathobject;     // exposition only
friend class directory_iterator; // exposition only

};

A `directory_entry` object stores a `path` object and may store additional objects for file attributes such as hard link count, status, symlink status, file size, and last write time.

Implementations should store such additional file attributes during directory iteration if their values are available and storing the values would allow the implementation to eliminate file system accesses by `directory_entry` observer functions (31.12.13). Such stored file attribute values are said to be `cached`.

[Note 1: For purposes of exposition, class `directory_iterator` (31.12.11) is shown above as a friend of class `directory_entry`. Friendship allows the `directory_iterator` implementation to cache already available attribute values directly into a `directory_entry` object without the cost of an unneeded call to `refresh()`—end note]

[Example 1:]
using namespace std::filesystem;

```cpp
// use possibly cached last write time to minimize disk accesses
for (auto& x : directory_iterator("."))
{
    std::cout << x.path() << " " << x.last_write_time() << std::endl;
}

// call refresh() to refresh a stale cache
for (auto& x : directory_iterator("."))
{
    lengthy_function(x.path());   // cache becomes stale
    x.refresh();
    std::cout << x.path() << " " << x.last_write_time() << std::endl;
}
```

On implementations that do not cache the last write time, both loops will result in a potentially expensive call to the `std::filesystem::last_write_time` function. On implementations that do cache the last write time, the first loop will use the cached value and so will not result in a potentially expensive call to the `std::filesystem::last_write_time` function. The code is portable to any implementation, regardless of whether or not it employs caching.—end example]

31.12.10.2 Constructors

```cpp
explicit directory_entry(const filesystem::path& p);
directory_entry(const filesystem::path& p, error_code& ec);
```

1 Effects: Calls `refresh()` or `refresh(ec)`, respectively.
2 Postconditions: `path() == p` if no error occurs, otherwise `path() == filesystem::path()`.
3 Throws: As specified in 31.12.5.

31.12.10.3 Modifiers

```cpp
void assign(const filesystem::path& p);
void assign(const filesystem::path& p, error_code& ec);
```

1 Effects: Equivalent to `pathobject = p`, then `refresh()` or `refresh(ec)`, respectively. If an error occurs, the values of any cached attributes are unspecified.
2 Throws: As specified in 31.12.5.

```cpp
void replace_filename(const filesystem::path& p);
```
void replace_filename(const filesystem::path& p, error_code& ec);

Effects: Equivalent to pathobject.replace_filename(p), then refresh() or refresh(ec), respectively. If an error occurs, the values of any cached attributes are unspecified.

Throws: As specified in 31.12.5.

void refresh();
void refresh(error_code& ec) noexcept;

Effects: Stores the current values of any cached attributes of the file p resolves to. If an error occurs, an error is reported (31.12.5) and the values of any cached attributes are unspecified.

Throws: As specified in 31.12.5.

[Note 1: Implementations of directory_iterator (31.12.11) are prohibited from directly or indirectly calling the refresh function as described in 31.12.11.1. — end note]

31.12.10.4 Observers [fs.dir.entry.obs]

Unqualified function names in the Returns: elements of the directory_entry observers described below refer to members of the std::filesystem namespace.

const filesystem::path& path() const noexcept;
operator const filesystem::path&() const noexcept;

Returns: pathobject.

bool exists() const;
bool exists(error_code& ec) const noexcept;

Returns: exists(this->status()) or exists(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_block_file() const;
bool is_block_file(error_code& ec) const noexcept;

Returns: is_block_file(this->status()) or is_block_file(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_character_file() const;
bool is_character_file(error_code& ec) const noexcept;

Returns: is_character_file(this->status()) or is_character_file(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_directory() const;
bool is_directory(error_code& ec) const noexcept;

Returns: is_directory(this->status()) or is_directory(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_fifo() const;
bool is_fifo(error_code& ec) const noexcept;

Returns: is_fifo(this->status()) or is_fifo(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_other() const;
bool is_other(error_code& ec) const noexcept;

Returns: is_other(this->status()) or is_other(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_regular_file() const;
bool is_regular_file(error_code& ec) const noexcept;

Returns: is_regular_file(this->status()) or is_regular_file(this->status(ec)), respectively.
Throws: As specified in 31.12.5.

bool is_socket() const;
bool is_socket(error_code& ec) const noexcept;

Returns: is_socket(this->status()) or is_socket(this->status(ec)), respectively.

Throws: As specified in 31.12.5.

bool is_symlink() const;
bool is_symlink(error_code& ec) const noexcept;

Returns: is_symlink(this->symlink_status()) or is_symlink(this->symlink_status(ec)), respectively.

Throws: As specified in 31.12.5.

uintmax_t file_size() const;
uintmax_t file_size(error_code& ec) const noexcept;

Returns: If cached, the file size attribute value. Otherwise, file_size(path()) or file_size(path(), ec), respectively.

Throws: As specified in 31.12.5.

uintmax_t hard_link_count() const;
uintmax_t hard_link_count(error_code& ec) const noexcept;

Returns: If cached, the hard link count attribute value. Otherwise, hard_link_count(path()) or hard_link_count(path(), ec), respectively.

Throws: As specified in 31.12.5.

file_time_type last_write_time() const;
file_time_type last_write_time(error_code& ec) const noexcept;

Returns: If cached, the last write time attribute value. Otherwise, last_write_time(path()) or last_write_time(path(), ec), respectively.

Throws: As specified in 31.12.5.

file_status status() const;
file_status status(error_code& ec) const noexcept;

Returns: If cached, the status attribute value. Otherwise, status(path()) or status(path(), ec), respectively.

Throws: As specified in 31.12.5.

file_status symlink_status() const;
file_status symlink_status(error_code& ec) const noexcept;

Returns: If cached, the symlink status attribute value. Otherwise, symlink_status(path()) or symlink_status(path(), ec), respectively.

Throws: As specified in 31.12.5.

bool operator==(const directory_entry& rhs) const noexcept;

Returns: pathobject == rhs.pathobject.

strong_ordering operator<=>(const directory_entry& rhs) const noexcept;

Returns: pathobject <=> rhs.pathobject.

31.12.10.5 Inserter

```cpp
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const directory_entry& d);
```

Effects: Equivalent to: return os << d.path();
31.12.11 Class directory_iterator  

31.12.11.1 General

1 An object of type directory_iterator provides an iterator for a sequence of directory_entry elements representing the path and any cached attribute values (31.12.10) for each file in a directory or in an implementation-defined directory-like file type.

[Note 1: For iteration into subdirectories, see class recursive_directory_iterator (31.12.12). — end note]

namespace std::filesystem {
    class directory_iterator {
    public:
        using iterator_category = input_iterator_tag;
        using value_type = directory_entry;
        using difference_type = ptrdiff_t;
        using pointer = const directory_entry*;
        using reference = const directory_entry&;

        // 31.12.11.2, member functions
        directory_iterator() noexcept;
        explicit directory_iterator(const path& p);
        directory_iterator(const path& p, directory_options options);
        directory_iterator(const path& p, error_code& ec);
        directory_iterator(const path& p, directory_options options,
                          error_code& ec);
        directory_iterator(const directory_iterator& rhs);
        directory_iterator(directory_iterator&& rhs) noexcept;
        ~directory_iterator();

        directory_iterator& operator=(const directory_iterator& rhs);
        directory_iterator& operator=(directory_iterator&& rhs) noexcept;

        const directory_entry& operator*() const;
        const directory_entry* operator->() const;
        directory_iterator& operator++();
        directory_iterator& increment(error_code& ec);

        bool operator==(default_sentinel_t) const noexcept {
            return *this == directory_iterator();
        }

    } // other members as required by 25.3.5.3, input iterators
};

2 directory_iterator meets the Cpp17InputIterator requirements (25.3.5.3).

3 If an iterator of type directory_iterator reports an error or is advanced past the last directory element, that iterator shall become equal to the end iterator value. The directory_iterator default constructor shall create an iterator equal to the end iterator value, and this shall be the only valid iterator for the end condition.

4 The end iterator is not dereferenceable.

5 Two end iterators are always equal. An end iterator shall not be equal to a non-end iterator.

6 The result of calling the path() member of the directory_entry object obtained by dereferencing a directory_iterator is a reference to a path object composed of the directory argument from which the iterator was constructed with the filename of the directory entry appended as if by operator/=

7 Directory iteration shall not yield directory entries for the current (dot) and parent (dot-dot) directories.

8 The order of directory entries obtained by dereferencing successive increments of a directory_iterator is unspecified.

9 Constructors and non-const directory_iterator member functions store the values of any cached attributes (31.12.10) in the directory_entry element returned by operator*(). directory_iterator member functions shall not directly or indirectly call any directory_entry refresh function.
Note 2: The exact mechanism for storing cached attribute values is not exposed to users. For exposition, class directory_iterator is shown in 31.12.10 as a friend of class directory_entry. — end note

Note 3: A path obtained by dereferencing a directory iterator might not actually exist; it could be a symbolic link to a non-existent file. Recursively walking directory trees for purposes of removing and renaming entries might invalidate symbolic links that are being followed. — end note

Note 4: If a file is removed from or added to a directory after the construction of a directory_iterator for the directory, it is unspecified whether or not subsequently incrementing the iterator will ever result in an iterator referencing the removed or added directory entry. See POSIX readdir. — end note

### 31.12.11.2 Members

directory_iterator() noexcept;

*Effects*: Constructs the end iterator.

directory_iterator(const path& p);
directory_iterator(const path& p, directory_options options);
directory_iterator(const path& p, error_code& ec);
directory_iterator(const path& p, directory_options options, error_code& ec);

*Effects*: For the directory that p resolves to, constructs an iterator for the first element in a sequence of directory_entry elements representing the files in the directory, if any; otherwise the end iterator. However, if

(options & directory_options::skip_permission_denied) != directory_options::none

and construction encounters an error indicating that permission to access p is denied, constructs the end iterator and does not report an error.

*Throws*: As specified in 31.12.5.

[Note 1: To iterate over the current directory, use directory_iterator(“.”) rather than directory_iterator(“”). — end note]

directory_iterator(const directory_iterator& rhs);
directory_iterator(directory_iterator&& rhs) noexcept;

*Postconditions*: *this has the original value of rhs.

directory_iterator& operator=(const directory_iterator& rhs);
directory_iterator& operator=(directory_iterator&& rhs) noexcept;

*Effects*: If *this and rhs are the same object, the member has no effect.

*Postconditions*: *this has the original value of rhs.

*Returns*: *this.

directory_iterator& operator++();
directory_iterator& increment(error_code& ec);

*Effects*: As specified for the prefix increment operation of Input iterators (25.3.5.3).

*Returns*: *this.

*Throws*: As specified in 31.12.5.

### 31.12.11.3 Non-member functions

These functions enable range access for directory_iterator.

directory_iterator begin(directory_iterator iter) noexcept;

*Returns*: iter.

directory_iterator end(directory_iterator) noexcept;

*Returns*: directory_iterator().
31.12.12 Class recursive_directory_iterator

An object of type `recursive_directory_iterator` provides an iterator for a sequence of `directory_entry` elements representing the files in a directory or in an implementation-defined directory-like file type, and its subdirectories.

```cpp
namespace std::filesystem {
    class recursive_directory_iterator {
        public:
            using iterator_category = input_iterator_tag;
            using value_type = directory_entry;
            using difference_type = ptrdiff_t;
            using pointer = const directory_entry*;
            using reference = const directory_entry&;

            // 31.12.12.2, constructors and destructor
            recursive_directory_iterator() noexcept;
            explicit recursive_directory_iterator(const path& p);
            recursive_directory_iterator(const path& p, directory_options options);
            recursive_directory_iterator(const path& p, directory_options options,
                                           error_code& ec);
            recursive_directory_iterator(const path& p, error_code& ec);
            recursive_directory_iterator(const recursive_directory_iterator& rhs);
            recursive_directory_iterator(recursive_directory_iterator&& rhs) noexcept;
            ~recursive_directory_iterator();

            // 31.12.12.2, observers
            directory_options options() const;
            int depth() const;
            bool recursion_pending() const;

            // other members as required by 25.3.5.3, input iterators
    }
};
```

2 Calling `options`, `depth`, `recursion_pending`, `pop` or `disable_recursion_pending` on an iterator that is not dereferenceable results in undefined behavior.

3 The behavior of a `recursive_directory_iterator` is the same as a `directory_iterator` unless otherwise specified.

4 [Note 1: If the directory structure being iterated over contains cycles then it is possible that the end iterator is unreachable. — end note]
31.12.12.2 Members

recursive_directory_iterator() noexcept;

Effects: Constructs the end iterator.

explicit recursive_directory_iterator(const path& p);
recursive_directory_iterator(const path& p, directory_options options);
recursive_directory_iterator(const path& p, directory_options options, error_code& ec);
recursive_directory_iterator(const path& p, error_code& ec);

Effects: Constructs an iterator representing the first entry in the directory to which p resolves, if any; otherwise, the end iterator. However, if
(options & directory_options::skip_permission_denied) != directory_options::none
and construction encounters an error indicating that permission to access p is denied, constructs the end iterator and does not report an error.

Postconditions: options() == options for the signatures with a directory_options argument, otherwise options() == directory_options::none.

Throws: As specified in 31.12.5.

[Note 1: Use recursive_directory_iterator(".") rather than recursive_directory_iterator("") to iterate over the current directory. —end note]

recursive_directory_iterator(const recursive_directory_iterator& rhs);

Postconditions:
(7.1) — options() == rhs.options()
(7.2) — depth() == rhs.depth()
(7.3) — recursion_pending() == rhs.recursion_pending()

recursive_directory_iterator(recursive_directory_iterator&& rhs) noexcept;

Postconditions: options(), depth(), and recursion_pending() have the values that rhs.options(), rhs.depth(), and rhs.recursion_pending(), respectively, had before the function call.

recursive_directory_iterator& operator=(const recursive_directory_iterator& rhs);

Effects: If *this and rhs are the same object, the member has no effect.

Postconditions:
(10.1) — options() == rhs.options()
(10.2) — depth() == rhs.depth()
(10.3) — recursion_pending() == rhs.recursion_pending()

Returns: *this.

recursive_directory_iterator& operator=(recursive_directory_iterator&& rhs) noexcept;

Effects: If *this and rhs are the same object, the member has no effect.

Postconditions: options(), depth(), and recursion_pending() have the values that rhs.options(), rhs.depth(), and rhs.recursion_pending(), respectively, had before the function call.

Returns: *this.

directory_options options() const;

Returns: The value of the argument passed to the constructor for the options parameter, if present, otherwise directory_options::none.

Throws: Nothing.

int depth() const;

Returns: The current depth of the directory tree being traversed.
bool recursion_pending() const;

Returns: true if disable_recursion_pending() has not been called subsequent to the prior construction or increment operation, otherwise false.

Throws: Nothing.

recursive_directory_iterator& operator++();
recursive_directory_iterator& increment(error_code& ec);

Effects: As specified for the prefix increment operation of Input iterators (25.3.5.3), except that:

(21.1) — If there are no more entries at the current depth, then if depth() != 0 iteration over the parent directory resumes; otherwise *this = recursive_directory_iterator().

(21.2) — Otherwise if

recursion_pending() && !is_directory(*this)->status() || (!is_symlink(*this)->symlink_status()) ||
(options() & directory_options::follow_directory_symlink) != directory_options::none

then either directory (*this)->path() is recursively iterated into or, if

(options() & directory_options::skip_permission_denied) != directory_options::none

and an error occurs indicating that permission to access directory (*this)->path() is denied, then directory (*this)->path() is treated as an empty directory and no error is reported.

Returns: *this.

Throws: As specified in 31.12.5.

void pop();
void pop(error_code& ec);

Effects: If depth() == 0, set *this to recursive_directory_iterator(). Otherwise, cease iteration of the directory currently being iterated over, and continue iteration over the parent directory.

Throws: As specified in 31.12.5.

Remarks: Any copies of the previous value of *this are no longer required to be dereferenceable nor to be in the domain of ==.

void disable_recursion_pending();

Postconditions: recursion_pending() == false.

[Note 4: disable_recursion_pending() is used to prevent unwanted recursion into a directory. — end note]
path filesystem::absolute(const path& p, error_code& ec);

Effects: Composes an absolute path referencing the same file system location as p according to the operating system (31.12.2.3).

Returns: The composed path. The signature with argument ec returns path() if an error occurs.

[Note 1: For the returned path, rp, rp.is_absolute() is true unless an error occurs. — end note]

Throws: As specified in 31.12.5.

[Note 2: To resolve symlinks or perform other sanitization that can involve queries to secondary storage, such as hard disks, consider canonical (31.12.13.3). — end note]

[Note 3: Implementations are strongly encouraged to not query secondary storage, and not consider !exists(p) an error. — end note]

[Example 1: For POSIX-based operating systems, absolute(p) is simply current_path()/p. For Windows-based operating systems, absolute might have the same semantics as GetFullPathNameW. — end example]

31.12.13.3 Canonical

path filesystem::canonical(const path& p);

path filesystem::canonical(const path& p, error_code& ec);

Effects: Converts p to an absolute path that has no symbolic link, dot, or dot-dot elements in its pathname in the generic format.

Returns: A path that refers to the same file system object as absolute(p). The signature with argument ec returns path() if an error occurs.

Throws: As specified in 31.12.5.

Remarks: !exists(p) is an error.

31.12.13.4 Copy

void filesystem::copy(const path& from, const path& to);

void filesystem::copy(const path& from, const path& to, error_code& ec);

Effects: Equivalent to copy(from, to, copy_options::none).

void filesystem::copy(const path& from, const path& to, copy_options options);

void filesystem::copy(const path& from, const path& to, copy_options options, error_code& ec);

Preconditions: At most one element from each option group (31.12.8.3) is set in options.

Effects: Before the first use of f and t:

(4.1) If

(options & copy_options::create_symlinks) != copy_options::none ||
(options & copy_options::skip_symlinks) != copy_options::none

then auto f = symlink_status(from) and if needed auto t = symlink_status(to).

(4.2) Otherwise, if

(options & copy_options::copy_symlinks) != copy_options::none

then auto f = symlink_status(from) and if needed auto t = status(to).

(4.3) Otherwise, auto f = status(from) and if needed auto t = status(to).

Effects are then as follows:

(4.4) If f.type() or t.type() is an implementation-defined file type (31.12.8.2), then the effects are implementation-defined.

(4.5) Otherwise, an error is reported as specified in 31.12.5 if

(4.5.1) exists(f) is false, or

(4.5.2) equivalent(from, to) is true, or

(4.5.3) is_other(f) || is_other(t) is true, or
is_directory(f) && is_regular_file(t) is true.

Otherwise, if is_symlink(f), then:

- If (options & copy_options::skip_symlinks) != copy_options::none then return.
- Otherwise if !exists(t) && (options & copy_options::copy_symlinks) != copy_options::none then copy_symlink(from, to).
- Otherwise report an error as specified in 31.12.5.

Otherwise, if is_regular_file(f), then:

- If (options & copy_options::directories_only) != copy_options::none, then return.
- Otherwise, if (options & copy_options::create_symlinks) != copy_options::none, then create a symbolic link to the source file.
- Otherwise, if (options & copy_options::create_hard_links) != copy_options::none, then create a hard link to the source file.
- Otherwise, if is_directory(t), then copy_file(from, to/from.filename(), options).
- Otherwise, copy_file(from, to, options).

Otherwise, if

\[
\text{is_directory(f) \&\& (options \& copy_options::create_symlinks) \neq \text{copy_options::none}}
\]

then report an error with an error_code argument equal to make_error_code(errc::is_a_directory).

Otherwise, if

\[
\text{is_directory(f) \&\& ((options \& copy_options::recursive) \neq \text{copy_options::none})}
\]

- If exists(t) is false, then create_directory(to, from).
- Then, iterate over the files in from, as if by

\[
\text{for (const directory_entry& x : directory_iterator(from))}
\]

\[
\text{copy(x.path(), to/x.path().filename(), options | copy_options::in-recursive-copy);}
\]

where in-recursive-copy is a bitmask element of copy_options that is not one of the elements in 31.12.8.3.

Otherwise, for the signature with argument ec, ec.clear().

Otherwise, no effects.

Throws: As specified in 31.12.5.

Remarks: For the signature with argument ec, any library functions called by the implementation shall have an error_code argument if applicable.

[Example 1: Given this directory structure:

\[
\text{/dir1}
\]

\[
\text{file1}
\]

\[
\text{file2}
\]

\[
\text{dir2}
\]

\[
\text{file3}
\]

Calling copy("/dir1", "/dir3") would result in:

\[
\text{/dir1}
\]

\[
\text{file1}
\]

\[
\text{file2}
\]

\[
\text{dir2}
\]

\[
\text{file3}
\]

\[
\text{/dir3}
\]
Alternatively, calling `copy("/dir1", "/dir3", copy_options::recursive)` would result in:

```
/dir1
  file1
  file2
dir2
  file3
/dir3
  file1
  file2
dir2
  file3
```

— end example

### 31.12.13.5 Copy file

```cpp
bool filesystem::copy_file(const path& from, const path& to);
bool filesystem::copy_file(const path& from, const path& to, error_code& ec);
```

1. **Returns**: `copy_file(from, to, copy_options::none)` or `copy_file(from, to, copy_options::none, ec)`, respectively.
2. **Throws**: As specified in 31.12.5.
3. **Preconditions**: At most one element from each option group (31.12.8.3) is set in `options`.
4. **Effects**: As follows:
   1. Report an error as specified in 31.12.5 if
      1.1. `is_regular_file(from)` is false, or
      1.2. `exists(to)` is true and `is_regular_file(to)` is false, or
      1.3. `exists(to)` is true and `equivalent(from, to)` is true, or
      1.4. `exists(to)` is true and
         ```cpp
         (options & (copy_options::skip_existing |
                     copy_options::overwrite_existing |
                     copy_options::update_existing)) == copy_options::none
         ```
   2. Otherwise, copy the contents and attributes of the file from resolves to, to the file to resolves to, if
      2.1. `exists(to)` is false, or
      2.2. `(options & copy_options::overwrite_existing) != copy_options::none, or
      2.3. `(options & copy_options::update_existing) != copy_options::none and from is more recent than to, determined as if by use of the `last_write_time` function (31.12.13.26).
   3. Otherwise, no effects.
5. **Returns**: `true` if the from file was copied, otherwise `false`. The signature with argument `ec` returns `false` if an error occurs.
6. **Throws**: As specified in 31.12.5.
7. **Complexity**: At most one direct or indirect invocation of `status(to)`.

### 31.12.13.6 Copy symlink

```cpp
void filesystem::copy_symlink(const path& existing_symlink, const path& new_symlink);
```
void filesystem::copy_symlink(const path& existing_symlink, const path& new_symlink, error_code& ec) noexcept;

Effects: Equivalent to function (read_symlink(existing_symlink), new_symlink) or function (read_symlink(existing_symlink, ec), new_symlink, ec), respectively, where in each case function is create_symlink or create_directory_symlink as appropriate.

Throws: As specified in 31.12.5.

31.12.13.7 Create directories [fs.op.create.directories]

bool filesystem::create_directories(const path& p);
bool filesystem::create_directories(const path& p, error_code& ec);

Effects: Calls create_directory() for each element of p that does not exist.

Returns: true if a new directory was created for the directory p resolves to, otherwise false.

Throws: As specified in 31.12.5.

Complexity: $\theta(n)$ where n is the number of elements of p.

31.12.13.8 Create directory [fs.op.create.directory]

bool filesystem::create_directory(const path& p);
bool filesystem::create_directory(const path& p, error_code& ec) noexcept;

Effects: Creates the directory p resolves to, as if by POSIX mkdir with a second argument of static_cast<int>({perms::all}). If mkdir fails because p resolves to an existing directory, no error is reported. Otherwise on failure an error is reported.

Returns: true if a new directory was created, otherwise false.

Throws: As specified in 31.12.5.

bool filesystem::create_directory(const path& p, const path& existing_p);
bool filesystem::create_directory(const path& p, const path& existing_p, error_code& ec) noexcept;

Effects: Creates the directory p resolves to, with attributes copied from directory existing_p. The set of attributes copied is operating system dependent. If mkdir fails because p resolves to an existing directory, no error is reported. Otherwise on failure an error is reported.

[Note 1: For POSIX-based operating systems, the attributes are those copied by native API stat(existing_p.c_str(), &attributes_stat) followed by mkdir(p.c_str(), attributes_stat.st_mode). For Windows-based operating systems, the attributes are those copied by native API CreateDirectoryExW(existing_p.c_str(), p.c_str(), 0). —end note]

Returns: true if a new directory was created with attributes copied from directory existing_p, otherwise false.

Throws: As specified in 31.12.5.

31.12.13.9 Create directory symlink [fs.op.create.dir.symlink]

void filesystem::create_directory_symlink(const path& to, const path& new_symlink);
void filesystem::create_directory_symlink(const path& to, const path& new_symlink, error_code& ec) noexcept;

Effects: Establishes the postcondition, as if by POSIX symlink().

Postconditions: new_symlink resolves to a symbolic link file that contains an unspecified representation of to.

Throws: As specified in 31.12.5.

[Note 1: Some operating systems require symlink creation to identify that the link is to a directory. Thus, create_symlink() (instead of create_directory_symlink()) cannot be used reliably to create directory symlinks. —end note]

[Note 2: Some operating systems do not support symbolic links at all or support them only for regular files. Some file systems (such as the FAT file system) do not support symbolic links regardless of the operating system. —end note]
31.12.13.10 Create hard link

void filesystem::create_hard_link(const path& to, const path& new_hard_link);
void filesystem::create_hard_link(const path& to, const path& new_hard_link,
  error_code& ec) noexcept;
1 Effects: Establishes the postcondition, as if by POSIX link().
2 Postconditions:
3   — exists(to) && exists(new_hard_link) && equivalent(to, new_hard_link)
4   — The contents of the file or directory to resolves to are unchanged.
5 Throws: As specified in 31.12.5.
6 [Note 1: Some operating systems do not support hard links at all or support them only for regular files. Some
7   file systems (such as the FAT file system) do not support hard links regardless of the operating system. Some
8   file systems limit the number of links per file. — end note]

31.12.13.11 Create symlink

void filesystem::create_symlink(const path& to, const path& new_symlink);
void filesystem::create_symlink(const path& to, const path& new_symlink,
  error_code& ec) noexcept;
1 Effects: Establishes the postcondition, as if by POSIX symlink().
2 Postconditions:
3   new_symlink resolves to a symbolic link file that contains an unspecified representation of to.
4 Throws: As specified in 31.12.5.
5 [Note 1: Some operating systems do not support symbolic links at all or support them only for regular files. Some
6   file systems (such as the FAT file system) do not support symbolic links regardless of the operating system.
7   — end note]

31.12.13.12 Current path

path filesystem::current_path();
path filesystem::current_path(error_code& ec);
1 Returns: The absolute path of the current working directory, whose pathname in the native format is
2 obtained as if by POSIX getcwd(). The signature with argument ec returns path() if an error occurs.
3 Throws: As specified in 31.12.5.
4 Remarks: The current working directory is the directory, associated with the process, that is used as
5 the starting location in pathname resolution for relative paths.
6 [Note 1: The current_path() name was chosen to emphasize that the returned value is a path, not just a
7   single directory name. — end note]
7 [Note 2: The current path as returned by many operating systems is a dangerous global variable and can be
8   changed unexpectedly by third-party or system library functions, or by another thread. — end note]

void filesystem::current_path(const path& p);
void filesystem::current_path(const path& p, error_code& ec) noexcept;
6 Effects: Establishes the postcondition, as if by POSIX chdir().
7 Postconditions: equivalent(p, current_path()).
8 Throws: As specified in 31.12.5.
9 [Note 3: The current path for many operating systems is a dangerous global state and can be changed
10   unexpectedly by third-party or system library functions, or by another thread. — end note]

31.12.13.13 Equivalent

bool filesystem::equivalent(const path& p1, const path& p2);
bool filesystem::equivalent(const path& p1, const path& p2, error_code& ec) noexcept;
1 Two paths are considered to resolve to the same file system entity if two candidate entities reside on
2 the same device at the same location.
Returns: \texttt{true}, if \texttt{p1} and \texttt{p2} resolve to the same file system entity, otherwise \texttt{false}. The signature with argument \texttt{ec} returns \texttt{false} if an error occurs.

Throws: As specified in 31.12.5.

Remarks: \texttt{!exists(p1) || !exists(p2)} is an error.

31.12.13.14 Exists

\begin{verbatim}
bool filesystem::exists(file_status s) noexcept;

Returns: \texttt{status_known(s) \&\& s.type() \!== \texttt{file_type::not_found.}}

bool filesystem::exists(const path& p);
bool filesystem::exists(const path& p, error_code& ec) noexcept;

Let \texttt{s} be a \texttt{file_status}, determined as if by \texttt{status(p)} or \texttt{status(p, ec)}, respectively.

Effects: The signature with argument \texttt{ec} calls \texttt{ec.clear()} if \texttt{status_known(s)}.

Returns: \texttt{exists(s)}.

 Throws: As specified in 31.12.5.
\end{verbatim}

31.12.13.15 File size

\begin{verbatim}
uintmax_t filesystem::file_size(const path& p);
uintmax_t filesystem::file_size(const path& p, error_code& ec) noexcept;

Effects: If \texttt{exists(p)} is \texttt{false}, an error is reported (31.12.5).

Returns:

\begin{enumerate}
\item If \texttt{is_regular_file(p)}, the size in bytes of the file \texttt{p} resolves to, determined as if by the value of the POSIX \texttt{stat} class member \texttt{st_size} obtained as if by POSIX \texttt{stat(}).
\item Otherwise, the result is implementation-defined.
\end{enumerate}

The signature with argument \texttt{ec} returns \texttt{static_cast<uintmax_t>(-1)} if an error occurs.

Throws: As specified in 31.12.5.
\end{verbatim}

31.12.13.16 Hard link count

\begin{verbatim}
uintmax_t filesystem::hard_link_count(const path& p);
uintmax_t filesystem::hard_link_count(const path& p, error_code& ec) noexcept;

Returns: The number of hard links for \texttt{p}. The signature with argument \texttt{ec} returns \texttt{static_cast<uintmax_t>(-1)} if an error occurs.

Throws: As specified in 31.12.5.
\end{verbatim}

31.12.13.17 Is block file

\begin{verbatim}
bool filesystem::is_block_file(file_status s) noexcept;

Returns: \texttt{s.type() \!== \texttt{file_type::block.}}

bool filesystem::is_block_file(const path& p);
bool filesystem::is_block_file(const path& p, error_code& ec) noexcept;

Returns: \texttt{is_block_file(status(p)) \!or \texttt{is_block_file(status(p, ec))}}, respectively. The signature with argument \texttt{ec} returns \texttt{false} if an error occurs.

Throws: As specified in 31.12.5.
\end{verbatim}

31.12.13.18 Is character file

\begin{verbatim}
bool filesystem::is_character_file(file_status s) noexcept;

Returns: \texttt{s.type() \!== \texttt{file_type::character.}}
\end{verbatim}
bool filesystem::is_character_file(const path& p);
bool filesystem::is_character_file(const path& p, error_code& ec) noexcept;

Returns: is_character_file(status(p)) or is_character_file(status(p, ec)), respectively. The signature with argument ec returns false if an error occurs.

Throws: As specified in 31.12.5.

31.12.13.19 Is directory [fs.op.is.directory]
bool filesystem::is_directory(file_status s) noexcept;

Returns: s.type() == file_type::directory.

bool filesystem::is_directory(const path& p);
bool filesystem::is_directory(const path& p, error_code& ec) noexcept;

Returns: is_directory(status(p)) or is_directory(status(p, ec)), respectively. The signature with argument ec returns false if an error occurs.

Throws: As specified in 31.12.5.

31.12.13.20 Is empty [fs.op.is.empty]
bool filesystem::is_empty(const path& p);
bool filesystem::is_empty(const path& p, error_code& ec);

Effects:
(1.1) — Determine file_status s, as if by status(p) or status(p, ec), respectively.
(1.2) — For the signature with argument ec, return false if an error occurred.
(1.3) — Otherwise, if is_directory(s):
  (1.3.1) — Create a variable itr, as if by directory_iterator itr(p) or directory_iterator itr(p, ec), respectively.
  (1.3.2) — For the signature with argument ec, return false if an error occurred.
  (1.3.3) — Otherwise, return itr == directory_iterator().
(1.4) — Otherwise:
  (1.4.1) — Determine uintmax_t sz, as if by file_size(p) or file_size(p, ec), respectively.
  (1.4.2) — For the signature with argument ec, return false if an error occurred.
  (1.4.3) — Otherwise, return sz == 0.

Throws: As specified in 31.12.5.

31.12.13.21 Is fifo [fs.op.is.fifo]
bool filesystem::is_fifo(file_status s) noexcept;

Returns: s.type() == file_type::fifo.

bool filesystem::is_fifo(const path& p);
bool filesystem::is_fifo(const path& p, error_code& ec) noexcept;

Returns: is_fifo(status(p)) or is_fifo(status(p, ec)), respectively. The signature with argument ec returns false if an error occurs.

Throws: As specified in 31.12.5.

31.12.13.22 Is other [fs.op.is.other]
bool filesystem::is_other(file_status s) noexcept;

Returns: exists(s) && !is_regular_file(s) && !is_directory(s) && !is_symlink(s).

bool filesystem::is_other(const path& p);
bool filesystem::is_other(const path& p, error_code& ec) noexcept;

Returns: is_other(status(p)) or is_other(status(p, ec)), respectively. The signature with argument ec returns false if an error occurs.
Throws: As specified in 31.12.5.

31.12.13.23 Is regular file

bool filesystem::is_regular_file(file_status s) noexcept;

Returns: s.type() == file_type::regular.

bool filesystem::is_regular_file(const path& p);

Returns: is_regular_file(status(p)).

Throws: filesystem_error if status(p) would throw filesystem_error.

bool filesystem::is_regular_file(const path& p, error_code& ec) noexcept;

Effects: Sets ec as if by status(p, ec).

[Note 1: file_type::none, file_type::not_found and file_type::unknown cases set ec to error values. To distinguish between cases, call the status function directly. — end note]

Returns: is_regular_file(status(p, ec)). Returns false if an error occurs.

31.12.13.24 Is socket

bool filesystem::is_socket(file_status s) noexcept;

Returns: s.type() == file_type::socket.

bool filesystem::is_socket(const path& p);

Returns: is_socket(status(p)) or is_socket(status(p, ec)), respectively. The signature with argument ec returns false if an error occurs.

Throws: As specified in 31.12.5.

31.12.13.25 Is symlink

bool filesystem::is_symlink(file_status s) noexcept;

Returns: s.type() == file_type::symlink.

bool filesystem::is_symlink(const path& p);

Returns: is_symlink(symlink_status(p)) or is_symlink(symlink_status(p, ec)), respectively. The signature with argument ec returns false if an error occurs.

Throws: As specified in 31.12.5.

31.12.13.26 Last write time

file_time_type filesystem::last_write_time(const path& p);

file_time_type filesystem::last_write_time(const path& p, error_code& ec) noexcept;

Returns: The time of last data modification of p, determined as if by the value of the POSIX stat class member st_mtime obtained as if by POSIX stat(). The signature with argument ec returns file_time_type::min() if an error occurs.

Throws: As specified in 31.12.5.

void filesystem::last_write_time(const path& p, file_time_type new_time);

void filesystem::last_write_time(const path& p, file_time_type new_time, error_code& ec) noexcept;

Effects: Sets the time of last data modification of the file resolved to by p to new_time, as if by POSIX futimens().

Throws: As specified in 31.12.5.

[Note 1: A postcondition of last_write_time(p) == new_time is not specified because it does not necessarily hold for file systems with coarse time granularity. — end note]
31.12.13.27 Permissions

```cpp
void filesystem::permissions(const path& p, perms prms, perm_options opts=perm_options::replace);
void filesystem::permissions(const path& p, perms prms, error_code& ec) noexcept;
void filesystem::permissions(const path& p, perms prms, perm_options opts, error_code& ec);
```

**Preconditions:** Exactly one of the `perm_options` constants `replace`, `add`, or `remove` is present in `opts`.

**Effects:** Applies the action specified by `opts` to the file `p` resolves to, or to file `p` itself if `p` is a symbolic link and `perm_options::nofollow` is set in `opts`. The action is applied as if by POSIX `fchmodat()`.

*Note 1:* Conceptually permissions are viewed as bits, but the actual implementation can use some other mechanism. — end note

**Throws:** As specified in 31.12.5.

**Remarks:** The second signature behaves as if it had an additional parameter `perm_options opts` with an argument of `perm_options::replace`.

31.12.13.28 Proximate

```cpp
path filesystem::proximate(const path& p, error_code& ec);
```

**Returns:** `proximate(p, current_path(), ec)`.

**Throws:** As specified in 31.12.5.

```cpp
path filesystem::proximate(const path& p, const path& base = current_path());
path filesystem::proximate(const path& p, const path& base, error_code& ec);
```

**Returns:** For the first form:

weakly_canonical(p).lexically_proximate(weakly_canonical(base));

For the second form:

weakly_canonical(p, ec).lexically_proximate(weakly_canonical(base, ec));

or `path()` at the first error occurrence, if any.

**Throws:** As specified in 31.12.5.

31.12.13.29 Read symlink

```cpp
path filesystem::read_symlink(const path& p);
path filesystem::read_symlink(const path& p, error_code& ec);
```

**Returns:** If `p` resolves to a symbolic link, a `path` object containing the contents of that symbolic link. The signature with argument `ec` returns `path()` if an error occurs.

**Throws:** As specified in 31.12.5.

*Note 1:* It is an error if `p` does not resolve to a symbolic link. — end note

31.12.13.30 Relative

```cpp
path filesystem::relative(const path& p, error_code& ec);
```

**Returns:** `relative(p, current_path(), ec)`.

**Throws:** As specified in 31.12.5.

```cpp
path filesystem::relative(const path& p, const path& base = current_path());
path filesystem::relative(const path& p, const path& base, error_code& ec);
```

**Returns:** For the first form:

weakly_canonical(p).lexically_relative(weakly_canonical(base));

For the second form:

weakly_canonical(p, ec).lexically_relative(weakly_canonical(base, ec));

or `path()` at the first error occurrence, if any.

**Throws:** As specified in 31.12.5.
### 31.12.13.31 Remove

```cpp
bool filesystem::remove(const path& p);
bool filesystem::remove(const path& p, error_code& ec) noexcept;
```

**Effects:** If `exists(symlink_status(p, ec))`, the file `p` is removed as if by POSIX `remove()`.

[Note 1: A symbolic link is itself removed, rather than the file it resolves to. — end note]

**Postconditions:** `exists(symlink_status(p))` is false.

**Returns:** false if `p` did not exist, otherwise true. The signature with argument `ec` returns false if an error occurs.

**Throws:** As specified in 31.12.5.

### 31.12.13.32 Remove all

```cpp
uintmax_t filesystem::remove_all(const path& p);
uintmax_t filesystem::remove_all(const path& p, error_code& ec);
```

**Effects:** Recursively deletes the contents of `p` if it exists, then deletes file `p` itself, as if by POSIX `remove()`.

[Note 1: A symbolic link is itself removed, rather than the file it resolves to. — end note]

**Postconditions:** `exists(symlink_status(p))` is false.

**Returns:** The number of files removed. The signature with argument `ec` returns `static_cast<uintmax_t>(-1)` if an error occurs.

**Throws:** As specified in 31.12.5.

### 31.12.13.33 Rename

```cpp
void filesystem::rename(const path& old_p, const path& new_p);
void filesystem::rename(const path& old_p, const path& new_p, error_code& ec) noexcept;
```

**Effects:** Renames `old_p` to `new_p`, as if by POSIX `rename()`.

[Note 1:
(1.1) — If `old_p` and `new_p` resolve to the same existing file, no action is taken.
(1.2) — Otherwise, the rename can include the following effects:
(1.2.1) — if `new_p` resolves to an existing non-directory file, `new_p` is removed; otherwise,
(1.2.2) — if `new_p` resolves to an existing directory, `new_p` is removed if empty on POSIX compliant operating systems but might be an error on other operating systems.

A symbolic link is itself renamed, rather than the file it resolves to. — end note]

**Throws:** As specified in 31.12.5.

### 31.12.13.34 Resize file

```cpp
void filesystem::resize_file(const path& p, uintmax_t new_size);
void filesystem::resize_file(const path& p, uintmax_t new_size, error_code& ec) noexcept;
```

**Effects:** Causes the size that would be returned by `file_size(p)` to be equal to `new_size`, as if by POSIX `truncate()`.

**Throws:** As specified in 31.12.5.

### 31.12.13.35 Space

```cpp
space_info filesystem::space(const path& p);
space_info filesystem::space(const path& p, error_code& ec) noexcept;
```

**Returns:** An object of type `space_info`. The value of the `space_info` object is determined as if by using POSIX `statvfs` to obtain a POSIX `struct statvfs`, and then multiplying its `f_blocks`, `f_bfree`, and `f_bavail` members by its `f_frsize` member, and assigning the results to the `capacity`, `free`, and `available` members respectively. Any members for which the value cannot be determined shall be set to `static_cast<uintmax_t>(-1)`. For the signature with argument `ec`, all members are set to `static_cast<uintmax_t>(-1)` if an error occurs.
Throws: As specified in 31.12.5.

Remarks: The value of member `space_info::available` is operating system dependent.

[Note 1: `available` might be less than `free`. — end note]

### 31.12.13.36 Status

```cpp
file_status filesystem::status(const path& p);
```

**Effects:** As if by:

```cpp
error_code ec;
file_status result = status(p, ec);
if (result.type() == file_type::none)
    throw filesystem_error(implementation-supplied-message, p, ec);
return result;
```

**Returns:** See above.

**Throws:** `filesystem_error`.

[Note 1: `result` values of `file_status(file_type::not_found)` and `file_status(file_type::unknown)` are not considered failures and do not cause an exception to be thrown. — end note]

```cpp
file_status filesystem::status(const path& p, error_code& ec) noexcept;
```

**Effects:** If possible, determines the attributes of the file `p` resolves to, as if by using POSIX `stat()` to obtain a POSIX `struct stat`. If, during attribute determination, the underlying file system API reports an error, sets `ec` to indicate the specific error reported. Otherwise, `ec.clear()`.

[Note 2: This allows users to inspect the specifics of underlying API errors even when the value returned by `status()` is not `file_status(file_type::none)`. — end note]

Let `prms` denote the result of `(m & perms::mask)`, where `m` is determined as if by converting the `st_mode` member of the obtained `struct stat` to the type `perms`.

**Returns:**

1. If `ec != error_code()`:
   1. If the specific error indicates that `p` cannot be resolved because some element of the path does not exist, returns `file_status(file_type::not_found)`.  
   2. Otherwise, if the specific error indicates that `p` can be resolved but the attributes cannot be determined, returns `file_status(file_type::unknown)`.  
   3. Otherwise, returns `file_status(file_type::none)`.

[Note 3: These semantics distinguish between `p` being known not to exist, `p` existing but not being able to determine its attributes, and there being an error that prevents even knowing if `p` exists. These distinctions are important to some use cases. — end note]

2. Otherwise,
   1. If the attributes indicate a regular file, as if by POSIX `S_ISREG`, returns `file_status(file_type::regular, prms)`.  
      [Note 4: `file_type::regular` implies appropriate `<fstream>` operations would succeed, assuming no hardware, permission, access, or file system race errors. Lack of `file_type::regular` does not necessarily imply `<fstream>` operations would fail on a directory. — end note]
   2. Otherwise, if the attributes indicate a directory, as if by POSIX `S_ISDIR`, returns `file_status(file_type::directory, prms)`.  
      [Note 5: `file_type::directory` implies that calling `directory_iterator(p)` would succeed. — end note]
   3. Otherwise, if the attributes indicate a block special file, as if by POSIX `S_ISBLK`, returns `file_status(file_type::block, prms)`.  
   4. Otherwise, if the attributes indicate a character special file, as if by POSIX `S_ISCHR`, returns `file_status(file_type::character, prms)`.  
   5. Otherwise, if the attributes indicate a fifo or pipe file, as if by POSIX `S_ISFIFO`, returns `file_status(file_type::fifo, prms)`.  

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— Otherwise, if the attributes indicate a socket, as if by POSIX `S_ISSOCK`, returns `file_status(file_type::socket, prms)`.

— Otherwise, if the attributes indicate an implementation-defined file type (31.12.8.2), returns `file_status(file_type::A, prms)`, where `A` is the constant for the implementation-defined file type.

— Otherwise, returns `file_status(file_type::unknown, prms)`.

Remarks: If a symbolic link is encountered during pathname resolution, pathname resolution continues using the contents of the symbolic link.

31.12.13.37 Status known

bool filesystem::status_known(file_status s) noexcept;

Returns: `s.type() != file_type::none`.

31.12.13.38 Symlink status

file_status filesystem::symlink_status(const path& p);
file_status filesystem::symlink_status(const path& p, error_code& ec) noexcept;

Effects: Same as `status()`, above, except that the attributes of `p` are determined as if by using POSIX `lstat()` to obtain a POSIX struct stat.

Let `prms` denote the result of `(m & perms::mask)`, where `m` is determined as if by converting the `st_mode` member of the obtained struct stat to the type `perms`.

Returns: Same as `status()`, above, except that if the attributes indicate a symbolic link, as if by POSIX `S_ISLNK`, returns `file_status(file_type::symlink, prms)`.

The signature with argument `ec` returns `file_status(file_type::none)` if an error occurs.

Throws: As specified in 31.12.5.

Remarks: Pathname resolution terminates if `p` names a symbolic link.

31.12.13.39 Temporary directory path

path filesystem::temp_directory_path();
path filesystem::temp_directory_path(error_code& ec);

Let `p` be an unspecified directory path suitable for temporary files.

Effects: If `exists(p)` is `false` or `is_directory(p)` is `false`, an error is reported (31.12.5).

Returns: The path `p`. The signature with argument `ec` returns `path()` if an error occurs.

Throws: As specified in 31.12.5.

[Example 1: For POSIX-based operating systems, an implementation might return the path supplied by the first environment variable found in the list `TMPDIR`, `TMP`, `TEMP`, `TEMPDIR`, or if none of these are found, "~/tmp".

For Windows-based operating systems, an implementation might return the path reported by the Windows GetTempPath API function. — end example]
31.13 C library files

31.13.1 Header <cstdio> synopsis

```c
namespace std {
    using size_t = see 17.2.4;
    using FILE = see below;
    using fpos_t = see below;
}

#define NULL see 17.2.3
#define _IOFBF see below
#define _IOLBF see below
#define _IONBF see below
#define BUFSIZ see below
#define EOF see below
#define FOPEN_MAX see below
#define FILENAME_MAX see below
#define L_tmpnam see below
#define SEEK_CUR see below
#define SEEK_END see below
#define SEEK_SET see below
#define TMP_MAX see below
#define stderr see below
#define stdin see below
#define stdout see below
namespace std {
    int remove(const char* filename);
    int rename(const char* old_p, const char* new_p);
    FILE* tmpfile();
    char* tmpnam(char* s);
    int fclose(FILE* stream);
    int fflush(FILE* stream);
    FILE* fopen(const char* filename, const char* mode);
    FILE* freopen(const char* filename, const char* mode, FILE* stream);
    void setbuf(FILE* stream, char* buf);
    int setvbuf(FILE* stream, char* buf, int mode, size_t size);
    int fprintf(FILE* stream, const char* format, ...);
    int fscanf(FILE* stream, const char* format, ...);
    int printf(const char* format, ...);
    int scanf(const char* format, ...);
    int snprintf(char* s, size_t n, const char* format, ...);
    int sprintf(char* s, const char* format, ...);
    int sscanf(const char* s, const char* format, ...);
    int vfprintf(FILE* stream, const char* format, va_list arg);
    int vfscanf(FILE* stream, const char* format, va_list arg);
    int vprintf(const char* format, va_list arg);
    int vscanf(const char* format, va_list arg);
    int vsnprintf(char* s, size_t n, const char* format, va_list arg);
    int vsprintf(char* s, const char* format, va_list arg);
    int vsscanf(const char* s, const char* format, va_list arg);
    int fgetc(FILE* stream);
    char* fgets(char* s, int n, FILE* stream);
    int fputc(int c, FILE* stream);
    int fputs(const char* s, FILE* stream);
    int getc(FILE* stream);
    int getchar();
    int putc(int c, FILE* stream);
    int putchar(int c);
    int puts(const char* s);
    int ungetc(int c, FILE* stream);
    size_t fread(void* ptr, size_t size, size_t nmemb, FILE* stream);
    size_t fwrite(const void* ptr, size_t size, size_t nmemb, FILE* stream);
    int fgetpos(FILE* stream, fpos_t* pos);
}
```
int fseek(FILE* stream, long int offset, int whence);
int fsetpos(FILE* stream, const fpos_t* pos);
long int ftell(FILE* stream);
void rewind(FILE* stream);
void clearerr(FILE* stream);
int feof(FILE* stream);
int ferror(FILE* stream);
void perror(const char* s);

1 The contents and meaning of the header `<cstdio>` are the same as the C standard library header `<stdio.h>`.

2 Calls to the function `tmpnam` with an argument that is a null pointer value may introduce a data race (16.4.6.10) with other calls to `tmpnam` with an argument that is a null pointer value.

See also: ISO/IEC 9899:2018, 7.21

31.13.2 Header `<cinttypes>` synopsis

```c
#include <cstdint>  // see 17.4.1

namespace std {
    using imaxdiv_t = see below;

    constexpr intmax_t imaxabs(intmax_t j);
    constexpr imaxdiv_t imaxdiv(intmax_t numerator, intmax_t denominator);
    intmax_t strtoimax(const char* nptr, char** endptr, int base);
    uintmax_t strtouimax(const char* nptr, char** endptr, int base);
    intmax_t wcstol(const wchar_t* nptr, wchar_t** endptr, int base);
    uintmax_t wcstoul(const wchar_t* nptr, wchar_t** endptr, int base);
    constexpr intmax_t abs(intmax_t);
    // optional, see below
    constexpr imaxdiv_t div(intmax_t numerator, intmax_t denominator);
    // optional, see below
    constexpr intmax_t t abs(intmax_t);
    constexpr imaxdiv_t t div(intmax_t, intmax_t);  // optional, see below
}
```

#define PRIdN see below
#define PRIiN see below
#define PRIoN see below
#define PRIuN see below
#define PRIxN see below
#define PRIxNLAST see below
#define PRIxFAST see below
#define PRIxNLAST see below
#define PRIxFAST see below
#define SCNdN see below
#define SCNiN see below
#define SCNoN see below
#define SCNuN see below
#define SCNxN see below
#define SCNdN see below
#define SCNdNLAST see below
#define SCNdFAST see below
#define SCNdNLAST see below
#define SCNdFAST see below
#define PRIdLEAST see below
#define PRIiLEAST see below
#define PRIoLEAST see below
#define PRIuLEAST see below
#define PRIxLEAST see below
#define SCNdLEAST see below
#define SCNdNLAST see below
#define SCNdFAST see below
#define SCNdNLAST see below
#define SCNdFAST see below
#define PRIdFAST see below
#define PRIiFAST see below
#define PRIoFAST see below
#define PRIuFAST see below
#define PRIxFAST see below
#define PRIxFAST see below
#define SCNdFAST see below
#define SCNdFAST see below
#define SCNdFAST see below
The contents and meaning of the header `<inttypes>` are the same as the C standard library header `<inttypes.h>`, with the following changes:

(1.1) The header `<inttypes>` includes the header `<cstdint>` (17.4.1) instead of `<stdint.h>`, and

(1.2) `intmax_t` and `uintmax_t` are not required to be able to represent all values of extended integer types wider than `long long` and `unsigned long long`, respectively, and

(1.3) if and only if the type `intmax_t` designates an extended integer type (6.8.2), the following function signatures are added:

```c
constexpr intmax_t abs(intmax_t);
constexpr imaxdiv_t div(intmax_t, intmax_t);
```

which shall have the same semantics as the function signatures `constexpr intmax_t imaxabs(intmax_t)` and `constexpr imaxdiv_t imaxdiv(intmax_t, intmax_t)`, respectively.

See also: ISO/IEC 9899:2018, 7.8

Each of the PRI macros listed in this subclause is defined if and only if the implementation defines the corresponding `typedef-name` in 17.4.1. Each of the SCN macros listed in this subclause is defined if and only if the implementation defines the corresponding `typedef-name` in 17.4.1 and has a suitable `fscanf` length modifier for the type.
32 Regular expressions library [re]

32.1 General [re.general]
1 This Clause describes components that C++ programs may use to perform operations involving regular expression matching and searching.

2 The following subclauses describe a basic regular expression class template and its traits that can handle char-like (23.1) template arguments, two specializations of this class template that handle sequences of char and wchar_t, a class template that holds the result of a regular expression match, a series of algorithms that allow a character sequence to be operated upon by a regular expression, and two iterator types for enumerating regular expression matches, as summarized in Table 139.

Table 139 — Regular expressions library summary [tab:re.summary]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.2 Requirements</td>
<td></td>
</tr>
<tr>
<td>32.4 Constants</td>
<td>&lt;regex&gt;</td>
</tr>
<tr>
<td>32.5 Exception type</td>
<td></td>
</tr>
<tr>
<td>32.6 Traits</td>
<td></td>
</tr>
<tr>
<td>32.7 Regular expression template</td>
<td></td>
</tr>
<tr>
<td>32.8 Submatches</td>
<td></td>
</tr>
<tr>
<td>32.9 Match results</td>
<td></td>
</tr>
<tr>
<td>32.10 Algorithms</td>
<td></td>
</tr>
<tr>
<td>32.11 Iterators</td>
<td></td>
</tr>
<tr>
<td>32.12 Grammar</td>
<td></td>
</tr>
</tbody>
</table>

3 The ECMAScript Language Specification described in Standard Ecma-262 is called ECMA-262 in this Clause.

32.2 Requirements [re.req]
1 This subclause defines requirements on classes representing regular expression traits.

[Note 1: The class template regex_traits, defined in 32.6, meets these requirements. — end note]

2 The class template basic_regex, defined in 32.7, needs a set of related types and functions to complete the definition of its semantics. These types and functions are provided as a set of member typedef-names and functions in the template parameter traits used by the basic_regex class template. This subclause defines the semantics of these members.

3 To specialize class template basic_regex for a character container CharT and its related regular expression traits class Traits, use basic_regex<CharT, Traits>.

4 In the following requirements,

- X denotes a traits class defining types and functions for the character container type charT;
- u is an object of type X;
- v is an object of type const X;
- p is a value of type const charT*;
- I1 and I2 are input iterators (25.3.5.3);
- F1 and F2 are forward iterators (25.3.5.5);
- c is a value of type const charT;
- s is an object of type X::string_type;
- cs is an object of type const X::string_type;
- b is a value of type bool;
- I is a value of type int;
— \( c_1 \) is an object of type \( X::\text{char\_class\_type} \); and

— \( \text{loc} \) is an object of type \( X::\text{locale\_type} \).

A traits class \( X \) meets the regular expression traits requirements if the following types and expressions are well-formed and have the specified semantics.

\[
\begin{align*}
\text{typename } X::\text{char\_type} \\
\text{Result: } \text{charT}, \text{ the character container type used in the implementation of class template } \text{basic\_regex}.
\end{align*}
\]

\[
\begin{align*}
\text{typename } X::\text{string\_type} \\
\text{Result: } \text{basic\_string}<\text{charT}>
\end{align*}
\]

\[
\begin{align*}
\text{typename } X::\text{locale\_type} \\
\text{Result: } \text{A copy constructible type that represents the locale used by the traits class.}
\end{align*}
\]

\[
\begin{align*}
\text{typename } X::\text{char\_class\_type} \\
\text{Result: } \text{A bitmask type (16.3.3.3.3) representing a particular character classification.}
\end{align*}
\]

\[
\begin{align*}
X::\text{length}(p) \\
\text{Result: } \text{size\_t} \\
\text{Returns: } \text{The smallest } i \text{ such that } p[i] == 0. \\
\text{Complexity: } \text{Linear in } i.
\end{align*}
\]

\[
\begin{align*}
v.\text{translate}(c) \\
\text{Result: } X::\text{char\_type} \\
\text{Returns: } \text{A character such that for any character } d \text{ that is to be considered equivalent to } c \text{ then } v.\text{translate}(c) == v.\text{translate}(d).
\end{align*}
\]

\[
\begin{align*}
v.\text{translate\_nocase}(c) \\
\text{Result: } X::\text{char\_type} \\
\text{Returns: } \text{For all characters } C \text{ that are to be considered equivalent to } c \text{ when comparisons are to be performed without regard to case, then } v.\text{translate\_nocase}(c) == v.\text{translate\_nocase}(C).
\end{align*}
\]

\[
\begin{align*}
v.\text{transform}(F1, F2) \\
\text{Result: } X::\text{string\_type} \\
\text{Returns: } \text{A sort key for the character sequence designated by the iterator range } [F1, F2) \text{ such that if the character sequence } [G1, G2) \text{ sorts before the character sequence } [H1, H2) \text{ then } v.\text{transform}(G1, G2) < v.\text{transform}(H1, H2).
\end{align*}
\]

\[
\begin{align*}
v.\text{transform\_primary}(F1, F2) \\
\text{Result: } X::\text{string\_type} \\
\text{Returns: } \text{A sort key for the character sequence designated by the iterator range } [F1, F2) \text{ such that if the character sequence } [G1, G2) \text{ sorts before the character sequence } [H1, H2) \text{ when character case is not considered then } v.\text{transform\_primary}(G1, G2) < v.\text{transform\_primary}(H1, H2).
\end{align*}
\]

\[
\begin{align*}
v.\text{lookup\_collatename}(F1, F2) \\
\text{Result: } X::\text{string\_type} \\
\text{Returns: } \text{A sequence of characters that represents the collating element consisting of the character sequence designated by the iterator range } [F1, F2). \text{ Returns an empty string if the character sequence is not a valid collating element.}
\end{align*}
\]

\[
\begin{align*}
v.\text{lookup\_classname}(F1, F2, b) \\
\text{Result: } X::\text{char\_class\_type} \\
\text{Returns: } \text{Converts the character sequence designated by the iterator range } [F1, F2) \text{ into a value of a bitmask type that can subsequently be passed to } \text{isctype}. \text{ Values returned from } v.\text{lookup\_classname} \text{ can be bitwise OR’ed together; the resulting value represents membership in either of the corresponding}
\end{align*}
\]
character classes. If \( b \) is \texttt{true}, the returned bitmask is suitable for matching characters without regard to their case. Returns 0 if the character sequence is not the name of a character class recognized by \( X \). The value returned shall be independent of the case of the characters in the sequence.

\[ v.\text{isctype}(c, cl) \]
\[ \text{Result: bool} \]
\[ \text{Returns: Returns } \texttt{true} \text{ if character } c \text{ is a member of one of the character classes designated by } cl, \texttt{false} \text{ otherwise.} \]

\[ v.\text{value}(c, I) \]
\[ \text{Result: int} \]
\[ \text{Returns: Returns the value represented by the digit } c \text{ in base } I \text{ if the character } c \text{ is a valid digit in base } I; \text{otherwise returns } -1. \]
\[ \text{[Note 2: The value of } I \text{ will only be 8, 10, or 16. — end note]} \]

\[ u.\text{imbue}(loc) \]
\[ \text{Result: } X::\text{locale_type} \]
\[ \text{Effects: Imbues } u \text{ with the locale } loc \text{ and returns the previous locale used by } u \text{ if any.} \]

\[ v.\text{getloc}() \]
\[ \text{Result: } X::\text{locale_type} \]
\[ \text{Returns: Returns the current locale used by } v \text{, if any.} \]

\[ \text{[Note 3: Class template } \texttt{regex_traits} \text{ meets the requirements for a regular expression traits class when it is specialized for } \texttt{char} \text{ or } \texttt{wchar_t}. \text{ This class template is described in the header } <\texttt{regex}>, \text{ and is described in 32.6. — end note]} \]

### 32.3 Header \(<\texttt{regex}>\) synopsis

```
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
  // 32.4, regex constants
  namespace regex_constants {
    using syntax_option_type = T1;
    using match_flag_type = T2;
    using error_type = T3;
  }

  // 32.5, class regex_error
  class regex_error;

  // 32.6, class template regex_traits
  template<class charT> struct regex_traits;

  // 32.7, class template basic_regex
  template<class charT, class traits = regex_traits<charT>> class basic_regex;
  using regex = basic_regex<char>;
  using wregex = basic_regex<wchar_t>;

  // 32.7.6, basic_regex swap
  template<class charT, class traits>
  void swap(basic_regex<charT, traits>& e1, basic_regex<charT, traits>& e2);

  // 32.8, class template sub_match
  template<class BidirectionalIterator>
  class sub_match;
  using csub_match = sub_match<const char*>
  using wcsub_match = sub_match<const wchar_t*>;
```
using ssub_match = sub_match<string::const_iterator>;
using wssub_match = sub_match<wstring::const_iterator>;

// 32.8.3, sub_match non-member operators
template<class BiIter>
  bool operator==(const sub_match<BiIter>& lhs, const sub_match<BiIter>& rhs);
template<class BiIter>
  auto operator<=>(const sub_match<BiIter>& lhs, const sub_match<BiIter>& rhs);

template<class BiIter, class ST, class SA>
  bool operator==(const sub_match<BiIter>& lhs,
                  const basic_string<typename iterator_traits<BiIter>::value_type, ST, SA>& rhs);
template<class BiIter, class ST, class SA>
  auto operator<=>(const sub_match<BiIter>& lhs,
                   const basic_string<typename iterator_traits<BiIter>::value_type, ST, SA>& rhs);

template<class BiIter>
  bool operator==(const sub_match<BiIter>& lhs,
                  const typename iterator_traits<BiIter>::value_type* rhs);
template<class BiIter>
  auto operator<=>(const sub_match<BiIter>& lhs,
                   const typename iterator_traits<BiIter>::value_type* rhs);

template<class BiIter>
  bool operator==(const sub_match<BiIter>& lhs,
                  const typename iterator_traits<BiIter>::value_type& rhs);
template<class BiIter>
  auto operator<=>(const sub_match<BiIter>& lhs,
                   const typename iterator_traits<BiIter>::value_type& rhs);

template<class charT, class ST, class BiIter>
  basic_ostream<charT, ST>&
    operator<<(basic_ostream<charT, ST>& os, const sub_match<BiIter>& m);

// 32.9, class template match_results
template<class BidirectionalIterator,
         class Allocator = allocator<sub_match<BidirectionalIterator>>> class match_results;

template<class BidirectionalIterator, class Allocator = allocator<sub_match<BidirectionalIterator>>> class match_results;

using cmatch = match_results<const char*>;
using wcmatch = match_results<const wchar_t*>;
using smatch = match_results<string::const_iterator>;
using wsmatch = match_results<wstring::const_iterator>;

// match_results comparisons
template<class BidirectionalIterator, class Allocator>
  bool operator==(const match_results<BidirectionalIterator, Allocator>& m1,
                  const match_results<BidirectionalIterator, Allocator>& m2);

// 32.9.8, match_results swap
template<class BidirectionalIterator, class Allocator>
  void swap(match_results<BidirectionalIterator, Allocator>& m1,
            match_results<BidirectionalIterator, Allocator>& m2);

// 32.10.2, function template regex_match
template<class BidirectionalIterator, class Allocator, class charT, class traits>
  bool regex_match(BidirectionalIterator first, BidirectionalIterator last,
                   match_results<BidirectionalIterator, Allocator>& m,
                   const basic_regex<charT, traits>& e,
                   regex_constants::match_flag_type flags = regex_constants::match_default);
template<class BidirectionalIterator, class charT, class traits>
bool regex_match(BidirectionalIterator first, BidirectionalIterator last,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

// 32.10.3, function template regex_search
template<class BidirectionalIterator, class Allocator, class charT, class traits>
bool regex_search(BidirectionalIterator first, BidirectionalIterator last,
match_results<BidirectionalIterator, Allocator>& m,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

template<class charT, class Allocator, class charT, class traits>
bool regex_match(const charT* str, match_results<const charT*, Allocator>& m,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

// § 32.3
= regex_constants::match_default) = delete;

// 32.10.4, function template regex_replace
template<class OutputIterator, class BidirectionalIterator,
         class traits, class charT, class ST, class SA>
OutputIterator regex_replace(OutputIterator out,
   BidirectionalIterator first, BidirectionalIterator last,
   const basic_regex<charT, traits>& e,
   const basic_string<charT, ST, SA>& fmt,
   regex_constants::match_flag_type flags = regex_constants::match_default);

template<class OutputIterator, class BidirectionalIterator, class traits, class charT>
OutputIterator regex_replace(OutputIterator out,
   BidirectionalIterator first, BidirectionalIterator last,
   const basic_regex<charT, traits>& e,
   const charT* fmt,
   regex_constants::match_flag_type flags = regex_constants::match_default);

template<class traits, class charT, class ST, class SA, class FST, class FSA>
basic_string<charT, ST, SA>
regex_replace(const basic_string<charT, ST, SA>& s,
   const basic_regex<charT, traits>& e,
   const basic_string<charT, FST, FSA>& fmt,
   regex_constants::match_flag_type flags = regex_constants::match_default);

template<class traits, class charT, class ST, class SA>
basic_string<charT, ST, SA>
regex_replace(const charT* s,
   const basic_regex<charT, traits>& e,
   const basic_string<charT, ST, SA>& fmt,
   regex_constants::match_flag_type flags = regex_constants::match_default);

// 32.11.1, class template regex_iterator
template<class BidirectionalIterator,
         class charT = typename iterator_traits<BidirectionalIterator>::value_type,
         class traits = regex_traits<charT>>
class regex_iterator;

using cregex_iterator = regex_iterator<const char*>;
using wcregex_iterator = regex_iterator<const wchar_t*>;
using sregex_iterator = regex_iterator<string::const_iterator>
using wsregex_iterator = regex_iterator<wstring::const_iterator>

// 32.11.2, class template regex_token_iterator
template<class BidirectionalIterator,
         class charT = typename iterator_traits<BidirectionalIterator>::value_type,
         class traits = regex_traits<charT>>
class regex_token_iterator;

using cregex_token_iterator = regex_token_iterator<const char*>;
using wcregex_token_iterator = regex_token_iterator<const wchar_t*>;
using sregex_token_iterator = regex_token_iterator<string::const_iterator>
using wsregex_token_iterator = regex_token_iterator<wstring::const_iterator>;
namespace pmr {
  template<class BidirectionalIterator>
  using match_results =
    std::match_results<BidirectionalIterator,
    polymorphic_allocator<sub_match<BidirectionalIterator>>>;

  using cmatch = match_results<const char*>;
  using wcmatch = match_results<const wchar_t*>;
  using smatch = match_results<string::const_iterator>;
  using wsmatch = match_results<wstring::const_iterator>;
}

32.4 Namespace std::regex_constants

32.4.1 General

The namespace std::regex_constants holds symbolic constants used by the regular expression library. This namespace provides three types, syntax_option_type, match_flag_type, and error_type, along with several constants of these types.

32.4.2 Bitmask type syntax_option_type

namespace std::regex_constants {
  using syntax_option_type = T1;
  inline constexpr syntax_option_type icase = unspecified;
  inline constexpr syntax_option_type nosubs = unspecified;
  inline constexpr syntax_option_type optimize = unspecified;
  inline constexpr syntax_option_type collate = unspecified;
  inline constexpr syntax_option_type ECMAScript = unspecified;
  inline constexpr syntax_option_type basic = unspecified;
  inline constexpr syntax_option_type extended = unspecified;
  inline constexpr syntax_option_type awk = unspecified;
  inline constexpr syntax_option_type grep = unspecified;
  inline constexpr syntax_option_type egrep = unspecified;
  inline constexpr syntax_option_type multiline = unspecified;
}

The type syntax_option_type is an implementation-defined bitmask type (16.3.3.3.3). Setting its elements has the effects listed in Table 140. A valid value of type syntax_option_type shall have at most one of the grammar elements ECMAScript, basic, extended, awk, grep, egrep, set. If no grammar element is set, the default grammar is ECMAScript.

32.4.3 Bitmask type match_flag_type

namespace std::regex_constants {
  using match_flag_type = T2;
  inline constexpr match_flag_type match_default = {};
  inline constexpr match_flag_type match_not_bol = unspecified;
  inline constexpr match_flag_type match_not_eol = unspecified;
  inline constexpr match_flag_type match_not_bow = unspecified;
  inline constexpr match_flag_type match_not_eow = unspecified;
  inline constexpr match_flag_type match_any = unspecified;
  inline constexpr match_flag_type match_not_null = unspecified;
  inline constexpr match_flag_type match_continuous = unspecified;
  inline constexpr match_flag_type match_prev_avail = unspecified;
  inline constexpr match_flag_type format_default = {};
  inline constexpr match_flag_type format_sed = unspecified;
  inline constexpr match_flag_type format_no_copy = unspecified;
  inline constexpr match_flag_type format_first_only = unspecified;
}

The type match_flag_type is an implementation-defined bitmask type (16.3.3.3.3). The constants of that type, except for match_default and format_default, are bitmask elements. The match_default and format_default constants are empty bitmasks. Matching a regular expression against a sequence of characters [first,last) proceeds according to the rules of the grammar specified for the regular expression object, modified according to the effects listed in Table 141 for any bitmask elements set.
Table 140 — syntax_option_type effects  [tab:re.synopt]

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect(s) if set</th>
</tr>
</thead>
<tbody>
<tr>
<td>icase</td>
<td>Specifies that matching of regular expressions against a character container sequence shall be performed without regard to case.</td>
</tr>
<tr>
<td>nosubs</td>
<td>Specifies that no sub-expressions shall be considered to be marked, so that when a regular expression is matched against a character container sequence, no sub-expression matches shall be stored in the supplied match_results object.</td>
</tr>
<tr>
<td>optimize</td>
<td>Specifies that the regular expression engine should pay more attention to the speed with which regular expressions are matched, and less to the speed with which regular expression objects are constructed. Otherwise it has no detectable effect on the program output.</td>
</tr>
<tr>
<td>collate</td>
<td>Specifies that character ranges of the form &quot;[a-b]&quot; shall be locale sensitive.</td>
</tr>
<tr>
<td>ECMAScript</td>
<td>Specifies that the grammar recognized by the regular expression engine shall be that used by ECMAScript in ECMA-262, as modified in 32.12. See also: ECMA-262 15.10</td>
</tr>
<tr>
<td>basic</td>
<td>Specifies that the grammar recognized by the regular expression engine shall be that used by basic regular expressions in POSIX. See also: POSIX, Base Definitions and Headers, Section 9.3</td>
</tr>
<tr>
<td>extended</td>
<td>Specifies that the grammar recognized by the regular expression engine shall be that used by extended regular expressions in POSIX. See also: POSIX, Base Definitions and Headers, Section 9.4</td>
</tr>
<tr>
<td>awk</td>
<td>Specifies that the grammar recognized by the regular expression engine shall be that used by the utility awk in POSIX.</td>
</tr>
<tr>
<td>grep</td>
<td>Specifies that the grammar recognized by the regular expression engine shall be that used by the utility grep in POSIX.</td>
</tr>
<tr>
<td>egrep</td>
<td>Specifies that the grammar recognized by the regular expression engine shall be that used by the utility grep when given the -E option in POSIX.</td>
</tr>
<tr>
<td>multiline</td>
<td>Specifies that ^ shall match the beginning of a line and $ shall match the end of a line, if the ECMAScript engine is selected.</td>
</tr>
</tbody>
</table>

Table 141 — regex_constants::match_flag_type effects when obtaining a match against a character container sequence [first, last).  [tab:re.matchflag]

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect(s) if set</th>
</tr>
</thead>
<tbody>
<tr>
<td>match_not_bol</td>
<td>The first character in the sequence [first, last) shall be treated as though it is not at the beginning of a line, so the character ^ in the regular expression shall not match [first, first).</td>
</tr>
<tr>
<td>match_not_eol</td>
<td>The last character in the sequence [first, last) shall be treated as though it is not at the end of a line, so the character &quot;$&quot; in the regular expression shall not match [last, last).</td>
</tr>
<tr>
<td>match_not_bow</td>
<td>The expression \b shall not match the sub-sequence [first, first).</td>
</tr>
<tr>
<td>match_not_eow</td>
<td>The expression \b shall not match the sub-sequence [last, last).</td>
</tr>
<tr>
<td>match_any</td>
<td>If more than one match is possible then any match is an acceptable result.</td>
</tr>
<tr>
<td>match_not_null</td>
<td>The expression shall not match an empty sequence.</td>
</tr>
<tr>
<td>match_continuous</td>
<td>The expression shall only match a sub-sequence that begins at first.</td>
</tr>
<tr>
<td>match_prev_avail</td>
<td>--first is a valid iterator position. When this flag is set the flags match_not_bol and match_not_bow shall be ignored by the regular expression algorithms (32.10) and iterators (32.11).</td>
</tr>
</tbody>
</table>
Table 141 — regex::match_flag_type effects when obtaining a match against a character container sequence [first, last]. (continued)

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect(s) if set</th>
</tr>
</thead>
<tbody>
<tr>
<td>format_default</td>
<td>When a regular expression match is to be replaced by a new string, the new string shall be constructed using the rules used by the ECMAScript replace function in ECMA-262, part 15.5.4.11 String.prototype.replace. In addition, during search and replace operations all non-overlapping occurrences of the regular expression shall be located and replaced, and sections of the input that did not match the expression shall be copied unchanged to the output string.</td>
</tr>
<tr>
<td>format_sed</td>
<td>When a regular expression match is to be replaced by a new string, the new string shall be constructed using the rules used by the sed utility in POSIX.</td>
</tr>
<tr>
<td>format_no_copy</td>
<td>During a search and replace operation, sections of the character container sequence being searched that do not match the regular expression shall not be copied to the output string.</td>
</tr>
<tr>
<td>format_first_only</td>
<td>When specified during a search and replace operation, only the first occurrence of the regular expression shall be replaced.</td>
</tr>
</tbody>
</table>

32.4.4 Implementation-defined error_type

```cpp
namespace std::regex_constants {
   using error_type = T3;
   inline constexpr error_type error_collate = unspecified;
   inline constexpr error_type error ctype = unspecified;
   inline constexpr error_type error escape = unspecified;
   inline constexpr error_type error_backref = unspecified;
   inline constexpr error_type error_brack = unspecified;
   inline constexpr error_type error paren = unspecified;
   inline constexpr error_type error brac = unspecified;
   inline constexpr error_type error_badbrace = unspecified;
   inline constexpr error_type error range = unspecified;
   inline constexpr error_type error space = unspecified;
   inline constexpr error_type error_badrepeat = unspecified;
   inline constexpr error_type error complexity = unspecified;
   inline constexpr error_type error stack = unspecified;
}
```

1 The type `error_type` is an implementation-defined enumerated type (16.3.3.3.2). Values of type `error_type` represent the error conditions described in Table 142:

Table 142 — error_type values in the C locale [tab:re.err]

<table>
<thead>
<tr>
<th>Value</th>
<th>Error condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>error_collate</td>
<td>The expression contains an invalid collating element name.</td>
</tr>
<tr>
<td>error ctype</td>
<td>The expression contains an invalid character class name.</td>
</tr>
<tr>
<td>error escape</td>
<td>The expression contains an invalid escaped character, or a trailing escape.</td>
</tr>
<tr>
<td>error backref</td>
<td>The expression contains an invalid back reference.</td>
</tr>
<tr>
<td>error brack</td>
<td>The expression contains mismatched [ and ].</td>
</tr>
<tr>
<td>error paren</td>
<td>The expression contains mismatched ( and ).</td>
</tr>
<tr>
<td>error brac</td>
<td>The expression contains mismatched { and }</td>
</tr>
<tr>
<td>error badbrac</td>
<td>The expression contains an invalid range in a {} expression.</td>
</tr>
<tr>
<td>error range</td>
<td>The expression contains an invalid character range, such as [b~a] in most encodings.</td>
</tr>
<tr>
<td>error space</td>
<td>There is insufficient memory to convert the expression into a finite state machine.</td>
</tr>
<tr>
<td>error badrepeat</td>
<td>One of *?+{ is not preceded by a valid regular expression.</td>
</tr>
<tr>
<td>error complexity</td>
<td>The complexity of an attempted match against a regular expression exceeds a pre-set level.</td>
</tr>
</tbody>
</table>
32.5 Class regex_error

```cpp
namespace std {
    class regex_error : public runtime_error {
    public:
        explicit regex_error(regex_constants::error_type ecode);
        regex_constants::error_type code() const;
    };
}
```

1 The class `regex_error` defines the type of objects thrown as exceptions to report errors from the regular expression library.

2 `regex_error(regex_constants::error_type ecode);`

3 Postconditions: `ecode == code()`.

32.6 Class template regex_traits

```cpp
namespace std {
    template<class charT>
    struct regex_traits {
        using char_type = charT;
        using string_type = basic_string<char_type>;
        using locale_type = locale;
        using char_class_type = bitmask_type;

        regex_traits();
        static size_t length(const char_type* p);
        charT translate(charT c) const;
        charT translate_nocase(charT c) const;
        template<class ForwardIterator>
        string_type transform(ForwardIterator first, ForwardIterator last) const;
        template<class ForwardIterator>
        string_type transform_primary(ForwardIterator first, ForwardIterator last) const;
        template<class ForwardIterator>
        string_type lookup_collatename(ForwardIterator first, ForwardIterator last) const;
        template<class ForwardIterator>
        char_class_type lookup_classname(ForwardIterator first, ForwardIterator last, bool icase = false) const;
        bool isctype(charT c, char_class_type f) const;
        int value(charT ch, int radix) const;
        locale_type imbue(locale_type l); locale_type getloc() const;
    };
}
```

1 The specializations `regex_traits<char>` and `regex_traits<wchar_t>` meet the requirements for a regular expression traits class (32.2).

2 The type `char_class_type` is used to represent a character classification and is capable of holding an implementation specific set returned by `lookup_classname`. 

---

Table 142 — error_type values in the C locale (continued)

<table>
<thead>
<tr>
<th>Value</th>
<th>Error condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>error_stack</td>
<td>There is insufficient memory to determine whether the regular expression matches the specified character sequence.</td>
</tr>
</tbody>
</table>
static size_t length(const char_type* p);
Returns: char_traits<charT>::length(p).

charT translate(charT c) const;
Returns: c.

ccharT translate_nocase(charT c) const;
Returns: use_facet<ctype<charT>>().tolower(c).

template<class ForwardIterator>
string_type transform(ForwardIterator first, ForwardIterator last) const;
Effects: As if by:
    string_type str(first, last);
    return use_facet<collate<charT>>()
        (getloc()).transform(str.data(), str.data() + str.length());

template<class ForwardIterator>
string_type transform_primary(ForwardIterator first, ForwardIterator last) const;
Effects: If
    typeid(use_facet<collate<charT>>) == typeid(collate_byname<charT>)
and the form of the sort key returned by collate_byname<charT>::transform(first, last) is
known and can be converted into a primary sort key then returns that key, otherwise returns an empty
string.

template<class ForwardIterator>
string_type lookup_collatename(ForwardIterator first, ForwardIterator last) const;
Returns: A sequence of one or more characters that represents the collating element consisting of the
character sequence designated by the iterator range [first, last). Returns an empty string if the
character sequence is not a valid collating element.

template<class ForwardIterator>
char_class_type lookup_classname(
    ForwardIterator first, ForwardIterator last, bool icase = false) const;
Returns: An unspecified value that represents the character classification named by the character
sequence designated by the iterator range [first, last). If the parameter icase is true then the
returned mask identifies the character classification without regard to the case of the characters being
matched, otherwise it does honor the case of the characters being matched. The value returned shall
be independent of the case of the characters in the character sequence. If the name is not recognized
then returns char_class_type().
Remarks: For regex_traits<char>, at least the narrow character names in Table 143 shall be
recognized. For regex_traits<wchar_t>, at least the wide character names in Table 143 shall be
recognized.

bool isctype(charT c, char_class_type f) const;
Effects: Determines if the character c is a member of the character classification represented by f.
Returns: Given the following function declaration:
    // for exposition only
    template<class C>
    ctype_base::mask convert(typename regex_traits<C>::char_class_type f);
that returns a value in which each ctype_base::mask value corresponding to a value in f named in
Table 143 is set, then the result is determined as if by:
    ctype_base::mask m = convert<charT>(f);
    const ctype<charT>& ct = use_facet<ctype<charT>>().getloc());

298) For example, if the parameter icase is true then [[:lower:]] is the same as [[:alpha:]].
if (ct.is(m, c)) {
    return true;
} else if (c == ct.widen('_')) {
    charT w[1] = { ct.widen('w') };  
    char_class_type x = lookup_classname(w, w+1);  
    return (f&x) == x;  
} else {  
    return false;  
}

[Example 1:]
    regex_traits<char> t;  
    string d("d");  
    string u("upper");  
    regex_traits<char>::char_class_type f;  
    f = t.lookup_classname(d.begin(), d.end());  
    f |= t.lookup_classname(u.begin(), u.end());  
    ctype_base::mask m = convert<char>(f);  // m == ctype_base::digit|ctype_base::upper  
    — end example]

[Example 2:]
    regex_traits<char> t;  
    string w("w");  
    regex_traits<char>::char_class_type f;  
    f = t.lookup_classname(w.begin(), w.end());  
    t.isctype('A', f);  // returns true  
    t.isctype('_', f);  // returns true  
    t.isctype(' ', f);  // returns false  
    — end example]

int value(charT ch, int radix) const;

Preconditions: The value of radial is 8, 10, or 16.

Returns: The value represented by the digit ch in base radial if the character ch is a valid digit in base radial; otherwise returns -1.

locale_type imbue(locale_type loc);

Effects: Imbues *this with a copy of the locale loc.

[Note 1: Calling imbue with a different locale than the one currently in use invalidates all cached data held by *this. — end note]

Postconditions: getloc() == loc.

Returns: If no locale has been previously imbued then a copy of the global locale in effect at the time of construction of *this, otherwise a copy of the last argument passed to imbue.

locale_type getloc() const;

Returns: If no locale has been imbued then a copy of the global locale in effect at the time of construction of *this, otherwise a copy of the last argument passed to imbue.

32.7 Class template basic_regex [re.regex]

32.7.1 General [re.regex.general]

For a char-like type charT, specializations of class template basic_regex represent regular expressions constructed from character sequences of charT characters. In the rest of 32.7, charT denotes a given char-like type. Storage for a regular expression is allocated and freed as necessary by the member functions of class basic_regex.

Objects of type specialization of basic_regex are responsible for converting the sequence of charT objects to an internal representation. It is not specified what form this representation takes, nor how it is accessed by algorithms that operate on regular expressions.

[Note 1: Implementations will typically declare some function templates as friends of basic_regex to achieve this. — end note]
Table 143 — Character class names and corresponding ctype masks

<table>
<thead>
<tr>
<th>Narrow character name</th>
<th>Wide character name</th>
<th>Corresponding ctype_base::mask value</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;alnum&quot;</td>
<td>L&quot;alnum&quot;</td>
<td>ctype_base::alnum</td>
</tr>
<tr>
<td>&quot;alpha&quot;</td>
<td>L&quot;alpha&quot;</td>
<td>ctype_base::alpha</td>
</tr>
<tr>
<td>&quot;blank&quot;</td>
<td>L&quot;blank&quot;</td>
<td>ctype_base::blank</td>
</tr>
<tr>
<td>&quot;cntrl&quot;</td>
<td>L&quot;cntrl&quot;</td>
<td>ctype_base::cntrl</td>
</tr>
<tr>
<td>&quot;digit&quot;</td>
<td>L&quot;digit&quot;</td>
<td>ctype_base::digit</td>
</tr>
<tr>
<td>&quot;d&quot;</td>
<td>L&quot;d&quot;</td>
<td>ctype_base::digit</td>
</tr>
<tr>
<td>&quot;graph&quot;</td>
<td>L&quot;graph&quot;</td>
<td>ctype_base::graph</td>
</tr>
<tr>
<td>&quot;lower&quot;</td>
<td>L&quot;lower&quot;</td>
<td>ctype_base::lower</td>
</tr>
<tr>
<td>&quot;print&quot;</td>
<td>L&quot;print&quot;</td>
<td>ctype_base::print</td>
</tr>
<tr>
<td>&quot;punct&quot;</td>
<td>L&quot;punct&quot;</td>
<td>ctype_base::punct</td>
</tr>
<tr>
<td>&quot;space&quot;</td>
<td>L&quot;space&quot;</td>
<td>ctype_base::space</td>
</tr>
<tr>
<td>&quot;s&quot;</td>
<td>L&quot;s&quot;</td>
<td>ctype_base::space</td>
</tr>
<tr>
<td>&quot;upper&quot;</td>
<td>L&quot;upper&quot;</td>
<td>ctype_base::upper</td>
</tr>
<tr>
<td>&quot;w&quot;</td>
<td>L&quot;w&quot;</td>
<td>ctype_base::alnum</td>
</tr>
<tr>
<td>&quot;xdigit&quot;</td>
<td>L&quot;xdigit&quot;</td>
<td>ctype_base::xdigit</td>
</tr>
</tbody>
</table>

3 The functions described in 32.7 report errors by throwing exceptions of type regex_error.

```c
namespace std {
    template<class charT, class traits = regex_traits<charT>>
    class basic_regex {
    public:
        // types
        using value_type = charT;
        using traits_type = traits;
        using string_type = typename traits::string_type;
        using flag_type = regex_constants::syntax_option_type;
        using locale_type = typename traits::locale_type;

        // 32.4.2, constants
        static constexpr flag_type icase = regex_constants::icase;
        static constexpr flag_type nosubs = regex_constants::nosubs;
        static constexpr flag_type optimize = regex_constants::optimize;
        static constexpr flag_type collate = regex_constants::collate;
        static constexpr flag_type ECMAScript = regex_constants::ECMAScript;
        static constexpr flag_type basic = regex_constants::basic;
        static constexpr flag_type extended = regex_constants::extended;
        static constexpr flag_type awk = regex_constants::awk;
        static constexpr flag_type grep = regex_constants::grep;
        static constexpr flag_type egrep = regex_constants::egrep;
        static constexpr flag_type multiline = regex_constants::multiline;

        // 32.7.2, construct/copy/destroy
        basic_regex();
        explicit basic_regex(const charT* p, flag_type f = regex_constants::ECMAScript);
        basic_regex(const charT* p, size_t len, flag_type f = regex_constants::ECMAScript);
        basic_regex(const basic_regex&) noexcept;
        template<class ST, class SA>
            explicit basic_regex(const basic_string<charT, ST, SA>& s,
                flag_type f = regex_constants::ECMAScript);
        template<class ForwardIterator>
        basic_regex(ForwardIterator first, ForwardIterator last,
            flag_type f = regex_constants::ECMAScript);
        basic_regex(initializer_list<charT> il, flag_type f = regex_constants::ECMAScript);
        ~basic_regex();
    }
} // namespace std
```
32.7.2 Constructors

basic_regex();

Postconditions: *this does not match any character sequence.

explicit basic_regex(const charT* p, flag_type f = regex_constants::ECMAScript);

Preconditions: [p, p + char_traits<charT>::length(p)) is a valid range.

Effects: The object’s internal finite state machine is constructed from the regular expression contained in the sequence of characters [p, p + char_traits<charT>::length(p)), and interpreted according to the flags f.

Postconditions: flags() returns f. mark_count() returns the number of marked sub-expressions within the expression.

Throws: regex_error if [p, p + char_traits<charT>::length(p)) is not a valid regular expression.

basic_regex(const charT* p, size_t len, flag_type f = regex_constants::ECMAScript);

Preconditions: [p, p + len) is a valid range.

Effects: The object’s internal finite state machine is constructed from the regular expression contained in the sequence of characters [p, p + len), and interpreted according the flags specified in f.

Postconditions: flags() returns f. mark_count() returns the number of marked sub-expressions within the expression.

Throws: regex_error if [p, p + len) is not a valid regular expression.
basic_regex(const basic_regex& e);

Postconditions: flags() and mark_count() return e.flags() and e.mark_count(), respectively.

basic_regex(basic_regex&& e) noexcept;

Postconditions: flags() and mark_count() return the values that e.flags() and e.mark_count(), respectively, had before construction.

template<class ST, class SA>
explicit basic_regex(const basic_string<charT, ST, SA>& s,
flag_type f = regex_constants::ECMAScript);

Effects: The object’s internal finite state machine is constructed from the regular expression contained in the string s, and interpreted according to the flags specified in f.

Postconditions: flags() returns f. mark_count() returns the number of marked sub-expressions within the expression.

Throws: regex_error if s is not a valid regular expression.

template<class ForwardIterator>
basic_regex(ForwardIterator first, ForwardIterator last,
flag_type f = regex_constants::ECMAScript);

Effects: The object’s internal finite state machine is constructed from the regular expression contained in the sequence of characters [first, last), and interpreted according to the flags specified in f.

Postconditions: flags() returns f. mark_count() returns the number of marked sub-expressions within the expression.

Throws: regex_error if the sequence [first, last) is not a valid regular expression.

basic_regex(initializer_list<charT> il, flag_type f = regex_constants::ECMAScript);

Effects: Same as basic_regex(il.begin(), il.end(), f).

32.7.3 Assignment [re.regex.assign]

basic_regex& operator=(const basic_regex& e);

Postconditions: flags() and mark_count() return e.flags() and e.mark_count(), respectively.

basic_regex& operator=(basic_regex&& e) noexcept;

Postconditions: flags() and mark_count() return the values that e.flags() and e.mark_count(), respectively, had before assignment. e is in a valid state with unspecified value.

basic_regex& operator=(const charT* p);

Effects: Equivalent to: return assign(p);

basic_regex& operator=(initializer_list<charT> il);

Effects: Equivalent to: return assign(il.begin(), il.end());

template<class ST, class SA>
basic_regex& operator=(const basic_string<charT, ST, SA>& s);

Effects: Equivalent to: return assign(s);

basic_regex& assign(const basic_regex& e);

Effects: Equivalent to: return *this = e;

basic_regex& assign(basic_regex&& e) noexcept;

Effects: Equivalent to: return *this = std::move(e);

basic_regex& assign(const charT* p, flag_type f = regex_constants::ECMAScript);

Effects: Equivalent to: return assign(string_type(p), f);

basic_regex& assign(const charT* p, size_t len, flag_type f = regex_constants::ECMAScript);

Effects: Equivalent to: return assign(string_type(p, len), f);
template<class ST, class SA>
  basic_regex& assign(const basic_string<charT, ST, SA>& s,
          flag_type f = regex_constants::ECMAScript);

  **Effects:** Assigns the regular expression contained in the string `s`, interpreted according the flags specified in `f`. If an exception is thrown, `*this` is unchanged.

  **Postconditions:** If no exception is thrown, `flags()` returns `f` and `mark_count()` returns the number of marked sub-expressions within the expression.

  **Returns:** `*this`.

  **Throws:** `regex_error` if `s` is not a valid regular expression.

template<class InputIterator>
  basic_regex& assign(InputIterator first, InputIterator last,
          flag_type f = regex_constants::ECMAScript);

  **Effects:** Equivalent to: return assign(string_type(first, last), f);

basic_regex& assign(initializer_list<charT> il,
          flag_type f = regex_constants::ECMAScript);

  **Effects:** Equivalent to: return assign(il.begin(), il.end(), f);

### 32.7.4 Constant operations

```cpp
unsigned mark_count() const;
```

  **Effects:** Returns the number of marked sub-expressions within the regular expression.

```cpp
flag_type flags() const;
```

  **Effects:** Returns a copy of the regular expression syntax flags that were passed to the object’s constructor or to the last call to `assign`.

### 32.7.5 Locale

```cpp
locale_type imbue(locale_type loc);
```

  **Effects:** Returns the result of `traits_inst.imbue(loc)` where `traits_inst` is a (default-initialized) instance of the template type argument `traits` stored within the object. After a call to `imbue` the `basic_regex` object does not match any character sequence.

```cpp
locale_type getloc() const;
```

  **Effects:** Returns the result of `traits_inst.getloc()` where `traits_inst` is a (default-initialized) instance of the template parameter `traits` stored within the object.

### 32.7.6 Swap

```cpp
void swap(basic_regex& e);
```

  **Effects:** Swaps the contents of the two regular expressions.

  **Postconditions:** `*this` contains the regular expression that was in `e`, `e` contains the regular expression that was in `*this`.

  **Complexity:** Constant time.

### 32.7.7 Non-member functions

```cpp
template<class charT, class traits>
  void swap(basic_regex<charT, traits>& lhs, basic_regex<charT, traits>& rhs);
```

  **Effects:** Calls `lhs.swap(rhs)`.

### 32.8 Class template sub_match

#### 32.8.1 General

Class template `sub_match` denotes the sequence of characters matched by a particular marked sub-expression.
namespace std {

    template<class BidirectionalIterator>
    class sub_match : public pair<BidirectionalIterator, BidirectionalIterator> {
        public:
            using value_type = typename iterator_traits<BidirectionalIterator>::value_type;
            using difference_type = typename iterator_traits<BidirectionalIterator>::difference_type;
            using iterator = BidirectionalIterator;
            using string_type = basic_string<value_type>;

            bool matched;

            constexpr sub_match();

            difference_type length() const;
            operator string_type() const;
            string_type str() const;

            int compare(const sub_match& s) const;
            int compare(const string_type& s) const;
            int compare(const value_type* s) const;

            void swap(sub_match& s) noexcept;
    };
}

32.8.2 Members

constexpr sub_match();
1  Effects: Value-initializes the pair base class subobject and the member matched.

difference_type length() const;
2  Returns: matched ? distance(first, second) : 0.

operator string_type() const;
3  Returns: matched ? string_type(first, second) : string_type().

string_type str() const;
4  Returns: matched ? string_type(first, second) : string_type().

int compare(const sub_match& s) const;
5  Returns: str().compare(s.str()).

int compare(const string_type& s) const;
6  Returns: str().compare(s).

int compare(const value_type* s) const;
7  Returns: str().compare(s).

void swap(sub_match& s) noexcept(see below);
8  Preconditions: BidirectionalIterator meets the Cpp17Swappable requirements (16.4.4.3).
9  Effects: Equivalent to:
    this->pair<BidirectionalIterator, BidirectionalIterator>::swap(s);
10 std::swap(matched, s.matched);
11  Remarks: The exception specification is equivalent to is_nothrow_swappable_v<BidirectionalIterator>.

32.8.3 Non-member operators

Let SM-CAT(I) be

§ 32.8.3
template<class BiIter>
bool operator==(const sub_match<BiIter>& lhs, const sub_match<BiIter>& rhs);

Returns: lhs.compare(rhs) == 0.

template<class BiIter>
auto operator<=>(const sub_match<BiIter>& lhs, const sub_match<BiIter>& rhs);

Returns: static_cast<SM-CAT(BiIter)>(lhs.compare(rhs) <=> 0).

template<class BiIter, class ST, class SA>
bool operator==(const sub_match<BiIter>& lhs, const basic_string<typename iterator_traits<BiIter>::value_type, ST, SA>& rhs);

Returns:
lhs.compare(typename sub_match<BiIter>::string_type(rhs.data(), rhs.size())) == 0

template<class BiIter, class ST, class SA>
auto operator<=>(const sub_match<BiIter>& lhs, const basic_string<typename iterator_traits<BiIter>::value_type, ST, SA>& rhs);

Returns:
static_cast<SM-CAT(BiIter)>(lhs.compare(typename sub_match<BiIter>::string_type(rhs.data(), rhs.size())) <=> 0)

template<class BiIter>
bool operator==(const sub_match<BiIter>& lhs, const typename iterator_traits<BiIter>::value_type* rhs);

Returns: lhs.compare(rhs) == 0.

template<class BiIter>
auto operator<=>(const sub_match<BiIter>& lhs, const typename iterator_traits<BiIter>::value_type* rhs);

Returns: static_cast<SM-CAT(BiIter)>(lhs.compare(rhs) <=> 0).

template<class BiIter>
bool operator==(const sub_match<BiIter>& lhs, const typename iterator_traits<BiIter>::value_type& rhs);

Returns: lhs.compare(typename sub_match<BiIter>::string_type(1, rhs)) == 0.

template<class BiIter>
auto operator<=>(const sub_match<BiIter>& lhs, const typename iterator_traits<BiIter>::value_type& rhs);

Returns:
static_cast<SM-CAT(BiIter)>(lhs.compare(typename sub_match<BiIter>::string_type(1, rhs)) <=> 0)

template<class charT, class ST, class BiIter>
basic_ostream<charT, ST>& operator<<(basic_ostream<charT, ST>& os, const sub_match<BiIter>& m);

Returns: os << m.str().

§ 32.8.3
32.9 Class template match_results

32.9.1 General

Class template match_results denotes a collection of character sequences representing the result of a regular expression match. Storage for the collection is allocated and freed as necessary by the member functions of class template match_results.

The class template match_results meets the requirements of an allocator-aware container (24.2.2.5) and of a sequence container (24.2.2, 24.2.4) except that only copy assignment, move assignment, and operations defined for const-qualified sequence containers are supported and that the semantics of the comparison operator functions are different from those required for a container.

A default-constructed match_results object has no fully established result state. A match result is ready when, as a consequence of a completed regular expression match modifying such an object, its result state becomes fully established. The effects of calling most member functions from a match_results object that is not ready are undefined.

The sub_match object stored at index 0 represents sub-expression 0, i.e., the whole match. In this case the sub_match member matched is always true. The sub_match object stored at index n denotes what matched the marked sub-expression n within the matched expression. If the sub-expression n participated in a regular expression match then the sub_match member matched evaluates to true, and members first and second denote the range of characters [first,second) which formed that match. Otherwise matched is false, and members first and second point to the end of the sequence that was searched.

Note 1: The sub_match objects representing different sub-expressions that did not participate in a regular expression match need not be distinct. — end note

namespace std {
    template<class BidirectionalIterator,
             class Allocator = allocator<sub_match<BidirectionalIterator>>> class match_results {
        public:
            using value_type = sub_match<BidirectionalIterator>;
            using const_reference = const value_type&;
            using reference = value_type&;
            using const_iterator = implementation-defined;
            using iterator = const_iterator;
            using difference_type =
                typename iterator_traits<BidirectionalIterator>::difference_type;
            using size_type = typename allocator_traits<Allocator>::size_type;
            using allocator_type = Allocator;
            using char_type =
                typename iterator_traits<BidirectionalIterator>::value_type;
            using string_type = basic_string<char_type>;

            // 32.9.2, construct/copy/destroy
            match_results() : match_results(Allocator()) {}
            explicit match_results(const Allocator& a);
            match_results(const match_results& m);
            match_results(const match_results& m, const Allocator& a);
            match_results(match_results&& m) noexcept;
            match_results(match_results&& m, const Allocator& a);
            match_results& operator=(const match_results& m);
            match_results& operator=(match_results&& m);
            ~match_results();

            // 32.9.3, state
            bool ready() const;

            // 32.9.4, size
            size_type size() const;
            size_type max_size() const;
            [[nodiscard]] bool empty() const;

            // 32.9.5, element access
            difference_type length(size_type sub = 0) const;

        } // class
    } // namespace

difference_type position(size_type sub = 0) const;
string_type str(size_type sub = 0) const;
const_reference operator[](size_type n) const;

const_reference prefix() const;
const_reference suffix() const;
const_iterator begin() const;
const_iterator end() const;
const_iterator cbegin() const;
const_iterator cend() const;

// 32.9.6, format
template<class OutputIter>
OutputIter
format(OutputIter out,
const char_type* fmt_first, const char_type* fmt_last,
regex_constants::match_flag_type flags = regex_constants::format_default) const;

template<class OutputIter, class ST, class SA>
OutputIter
format(OutputIter out,
const basic_string<char_type, ST, SA>& fmt,
regex_constants::match_flag_type flags = regex_constants::format_default) const;

template<class ST, class SA>
basic_string<char_type, ST, SA>
format(const basic_string<char_type, ST, SA>& fmt,
regex_constants::match_flag_type flags = regex_constants::format_default) const;

string_type
format(const char_type* fmt,
regex_constants::match_flag_type flags = regex_constants::format_default) const;

// 32.9.7, allocator
allocator_type get_allocator() const;

// 32.9.8, swap
void swap(match_results& that);
}

32.9.2 Constructors

Table 144 lists the postconditions of match_results copy/move constructors and copy/move assignment operators. For move operations, the results of the expressions depending on the parameter m denote the values they had before the respective function calls.

explicit match_results(const Allocator& a);

Effects: The stored Allocator value is constructed from a.

Postconditions: ready() returns false. size() returns 0.

match_results(const match_results& m);
match_results(const match_results& m, const Allocator& a);

Effects: For the first form, the stored Allocator value is obtained as specified in 24.2.2.2. For the second form, the stored Allocator value is constructed from a.

Postconditions: As specified in Table 144.

match_results(match_results&& m) noexcept;
match_results(match_results&& m, const Allocator& a);

Effects: For the first form, the stored Allocator value is move constructed from m.get_allocator(). For the second form, the stored Allocator value is constructed from a.

Postconditions: As specified in Table 144.

Throws: The second form throws nothing if a == m.get_allocator() is true.
match_results& operator=(const match_results& m);

Postconditions: As specified in Table 144.

match_results& operator=(match_results&& m);

Postconditions: As specified in Table 144.

Table 144 — match_results copy/move operation postconditions

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ready()</td>
<td>m.ready()</td>
</tr>
<tr>
<td>size()</td>
<td>m.size()</td>
</tr>
<tr>
<td>str(n)</td>
<td>m.str(n) for all non-negative integers n &lt; m.size()</td>
</tr>
<tr>
<td>prefix()</td>
<td>m.prefix()</td>
</tr>
<tr>
<td>suffix()</td>
<td>m.suffix()</td>
</tr>
<tr>
<td>(*this)[n]</td>
<td>m[n] for all non-negative integers n &lt; m.size()</td>
</tr>
<tr>
<td>length(n)</td>
<td>m.length(n) for all non-negative integers n &lt; m.size()</td>
</tr>
<tr>
<td>position(n)</td>
<td>m.position(n) for all non-negative integers n &lt; m.size()</td>
</tr>
</tbody>
</table>

32.9.3 State

bool ready() const;

Returns: true if *this has a fully established result state, otherwise false.

32.9.4 Size

size_type size() const;

Returns: One plus the number of marked sub-expressions in the regular expression that was matched if *this represents the result of a successful match. Otherwise returns 0.

[Note 1: The state of a match_results object can be modified only by passing that object to regex_match or regex_search. Subclauses 32.10.2 and 32.10.3 specify the effects of those algorithms on their match_results arguments. — end note]

size_type max_size() const;

Returns: The maximum number of sub_match elements that can be stored in *this.

[[nodiscard]] bool empty() const;

Returns: size() == 0.

32.9.5 Element access

difference_type length(size_type sub = 0) const;

Preconditions: ready() == true.

Returns: (*this)[sub].length().

difference_type position(size_type sub = 0) const;

Preconditions: ready() == true.

Returns: The distance from the start of the target sequence to (*this)[sub].first.

string_type str(size_type sub = 0) const;

Preconditions: ready() == true.

Returns: string_type((*this)[sub]).
const_reference operator[](size_type n) const;

Preconditions: ready() == true.

Returns: A reference to the sub_match object representing the character sequence that matched marked sub-expression n. If n == 0 then returns a reference to a sub_match object representing the character sequence that matched the whole regular expression. If n >= size() then returns a sub_match object representing an unmatched sub-expression.

const_reference prefix() const;

Preconditions: ready() == true.

Returns: A reference to the sub_match object representing the character sequence from the start of the string being matched/searched to the start of the match found.

const_reference suffix() const;

Preconditions: ready() == true.

Returns: A reference to the sub_match object representing the character sequence from the end of the match found to the end of the string being matched/searched.

const_iterator begin() const;
const_iterator cbegin() const;

Returns: A starting iterator that enumerates over all the sub-expressions stored in *this.

const_iterator end() const;
const_iterator cend() const;

Returns: A terminating iterator that enumerates over all the sub-expressions stored in *this.

32.9.6 Formatting

template<class OutputIter>
OutputIter format(
    OutputIter out,
    const char_type* fmt_first, const char_type* fmt_last,
    regex_constants::match_flag_type flags = regex_constants::format_default) const;

Preconditions: ready() == true and OutputIter meets the requirements for a Cpp17OutputIterator (25.3.5.4).

Effects: Copies the character sequence [fmt_first,fmt_last) to OutputIter out. Replaces each format specifier or escape sequence in the copied range with either the character(s) it represents or the sequence of characters within *this to which it refers. The bitmasks specified in flags determine which format specifiers and escape sequences are recognized.

Returns: out.

template<class OutputIter, class ST, class SA>
OutputIter format(
    OutputIter out,
    const basic_string<char_type, ST, SA>& fmt,
    regex_constants::match_flag_type flags = regex_constants::format_default) const;

Effects: Equivalent to:
    return format(out, fmt.data(), fmt.data() + fmt.size(), flags);

template<class ST, class SA>
basic_string<char_type, ST, SA> format(
    const basic_string<char_type, ST, SA>& fmt,
    regex_constants::match_flag_type flags = regex_constants::format_default) const;

Preconditions: ready() == true.

Effects: Constructs an empty string result of type basic_string<char_type, ST, SA> and calls:
    format(back_inserter(result), fmt, flags);

Returns: result.
string_type format(
    const char_type* fmt,
    regex_constants::match_flag_type flags = regex_constants::format_default) const;

Preconditions: ready() == true.
Effects: Constructs an empty string result of type string_type and calls:
    format(back_inserter(result), fmt, fmt + char_traits<char_type>::length(fmt), flags);
Returns: result.

32.9.7 Allocator

allocator_type get_allocator() const;
Returns: A copy of the Allocator that was passed to the object’s constructor or, if that allocator has
been replaced, a copy of the most recent replacement.

32.9.8 Swap

void swap(match_results& that);
Effects: Swaps the contents of the two sequences.
Postconditions: *this contains the sequence of matched sub-expressions that were in that, that
contains the sequence of matched sub-expressions that were in *this.
Complexity: Constant time.

template<class BidirectionalIterator, class Allocator>
void swap(match_results<BidirectionalIterator, Allocator>& m1,
          match_results<BidirectionalIterator, Allocator>& m2);
Effects: As if by m1.swap(m2).

32.9.9 Non-member functions

template<class BidirectionalIterator, class Allocator>
bool operator==(const match_results<BidirectionalIterator, Allocator>& m1,
                const match_results<BidirectionalIterator, Allocator>& m2);
Returns: true if neither match result is ready, false if one match result is ready and the other is not.
If both match results are ready, returns true only if

(1.1) — m1.empty() && m2.empty(), or
(1.2) — !m1.empty() && !m2.empty(), and the following conditions are satisfied:
(1.2.1) — m1.prefix() == m2.prefix(),
(1.2.2) — m1.size() == m2.size() && equal(m1.begin(), m1.end(), m2.begin()), and
(1.2.3) — m1.suffix() == m2.suffix().

[Note 1: The algorithm equal is defined in Clause 27. — end note]

32.10 Regular expression algorithms

32.10.1 Exceptions

The algorithms described in subclause 32.10 may throw an exception of type regex_error. If such an
exception e is thrown, e.code() shall return either regex_constants::error_complexity or regex_constants::error_stack.

32.10.2 regex_match

template<class BidirectionalIterator, class Allocator, class charT, class traits>
bool regex_match(BidirectionalIterator first, BidirectionalIterator last,
                 match_results<BidirectionalIterator, Allocator>& m,
                 const basic_regex<charT, traits>& e,
                 regex_constants::match_flag_type flags = regex_constants::match_default);
Preconditions: BidirectionalIterator models bidirectional_iterator (25.3.4.12).
Effects: Determines whether there is a match between the regular expression e, and all of the character sequence [first, last). The parameter flags is used to control how the expression is matched against the character sequence. When determining if there is a match, only potential matches that match the entire character sequence are considered. Returns true if such a match exists, false otherwise.

Example 1:
```c++
std::regex re("Get|GetValue");
std::cmatch m;
regex_search("GetValue", m, re); // returns true, and m[0] contains "Get"
regex_match ("GetValue", m, re); // returns true, and m[0] contains "GetValue"
regex_search("GetValues", m, re); // returns true, and m[0] contains "Get"
regex_match ("GetValues", m, re); // returns false
```

Postconditions: m.ready() == true in all cases. If the function returns false, then the effect on parameter m is unspecified except that m.size() returns 0 and m.empty() returns true. Otherwise the effects on parameter m are given in Table 145.

Table 145 — Effects of regex_match algorithm

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>m.size()</td>
<td>1 + e.mark_count()</td>
</tr>
<tr>
<td>m.empty()</td>
<td>false</td>
</tr>
<tr>
<td>m.prefix().first</td>
<td>first</td>
</tr>
<tr>
<td>m.prefix().second</td>
<td>first</td>
</tr>
<tr>
<td>m.prefix().matched</td>
<td>false</td>
</tr>
<tr>
<td>m.suffix().first</td>
<td>last</td>
</tr>
<tr>
<td>m.suffix().second</td>
<td>last</td>
</tr>
<tr>
<td>m.suffix().matched</td>
<td>false</td>
</tr>
<tr>
<td>m[0].first</td>
<td>first</td>
</tr>
<tr>
<td>m[0].second</td>
<td>last</td>
</tr>
<tr>
<td>m[0].matched</td>
<td>true</td>
</tr>
<tr>
<td>m[n].first</td>
<td>For all integers 0 &lt; n &lt; m.size(), the start of the sequence that matched sub-expression n. Alternatively, if sub-expression n did not participate in the match, then last.</td>
</tr>
<tr>
<td>m[n].second</td>
<td>For all integers 0 &lt; n &lt; m.size(), the end of the sequence that matched sub-expression n. Alternatively, if sub-expression n did not participate in the match, then last.</td>
</tr>
<tr>
<td>m[n].matched</td>
<td>For all integers 0 &lt; n &lt; m.size(), true if sub-expression n participated in the match, false otherwise.</td>
</tr>
</tbody>
</table>

Effects: Behaves “as if” by constructing an instance of match_results<BidirectionalIterator> what, and then returning the result of regex_match(first, last, what, e, flags).

Returns: regex_match(str, str + char_traits<charT>::length(str), m, e, flags).
template<class ST, class SA, class Allocator, class charT, class traits>
bool regex_match(const basic_string<charT, ST, SA>& s,
match_results<typename basic_string<charT, ST, SA>::const_iterator,
Allocator>& m,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

Returns: regex_match(s.begin(), s.end(), m, e, flags).

template<class charT, class traits>
bool regex_match(const charT* str,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

Returns: regex_match(str, str + char_traits<charT>::length(str), e, flags)

template<class ST, class SA, class charT, class traits>
bool regex_match(const basic_string<charT, ST, SA>& s,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

Returns: regex_match(s.begin(), s.end(), e, flags).

32.10.3 regex_search

template<class BidirectionalIterator, class Allocator, class charT, class traits>
bool regex_search(BidirectionalIterator first, BidirectionalIterator last,
match_results<BidirectionalIterator, Allocator>& m,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

Preconditions: BidirectionalIterator models bidirectional_iterator (25.3.4.12).

Effects: Determines whether there is some sub-sequence within [first, last) that matches the regular
expression e. The parameter flags is used to control how the expression is matched against the
character sequence. Returns true if such a sequence exists, false otherwise.

Postconditions: m.ready() == true in all cases. If the function returns false, then the effect on
parameter m is unspecified except that m.size() returns 0 and m.empty() returns true. Otherwise
the effects on parameter m are given in Table 146.

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>m.size()</td>
<td>1 + e.mark_count()</td>
</tr>
<tr>
<td>m.empty()</td>
<td>false</td>
</tr>
<tr>
<td>m.prefix().first</td>
<td>first</td>
</tr>
<tr>
<td>m.prefix().second</td>
<td>m[0].first</td>
</tr>
<tr>
<td>m.prefix().matched</td>
<td>m.prefix().first != m.prefix().second</td>
</tr>
<tr>
<td>m.suffix().first</td>
<td>m[0].second</td>
</tr>
<tr>
<td>m.suffix().second</td>
<td>last</td>
</tr>
<tr>
<td>m.suffix().matched</td>
<td>m.suffix().first != m.suffix().second</td>
</tr>
<tr>
<td>m[0].first</td>
<td>The start of the sequence of characters that matched the regular expression</td>
</tr>
<tr>
<td>m[0].second</td>
<td>The end of the sequence of characters that matched the regular expression</td>
</tr>
<tr>
<td>m[0].matched</td>
<td>true</td>
</tr>
<tr>
<td>m[n].first</td>
<td>For all integers 0 &lt; n &lt; m.size(), the start of the sequence that matched sub-expression n. Alternatively, if sub-expression n did not participate in the match, then last.</td>
</tr>
<tr>
<td>m[n].second</td>
<td>For all integers 0 &lt; n &lt; m.size(), the end of the sequence that matched sub-expression n. Alternatively, if sub-expression n did not participate in the match, then last.</td>
</tr>
</tbody>
</table>
Table 146 — Effects of regex_search algorithm (continued)

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>m[n].matched</code></td>
<td>For all integers <code>0 &lt; n &lt; m.size()</code>, <code>true</code> if sub-expression <code>n</code> participated in the match, <code>false</code> otherwise.</td>
</tr>
</tbody>
</table>

```
template<class charT, class Allocator, class traits>
bool regex_search(const charT* str, match_results<const charT*, Allocator>& m,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);
```

**Returns:** `regex_search(str, str + char_traits<charT>::length(str), m, e, flags)`.

```
template<class ST, class SA, class Allocator, class charT, class traits>
bool regex_search(const basic_string<charT, ST, SA>& s,
match_results<typename basic_string<charT, ST, SA>::const_iterator,
Allocator>& m,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);
```

**Returns:** `regex_search(s.begin(), s.end(), m, e, flags)`.

```
template<class BidirectionalIterator, class charT, class traits>
bool regex_search(BidirectionalIterator first, BidirectionalIterator last,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);
```

**Effects:** Behaves “as if” by constructing an object `what` of type `match_results<BidirectionalIterator>` and returning `regex_search(first, last, what, e, flags)`.

```
template<class charT, class traits>
bool regex_search(const charT* str,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);
```

**Returns:** `regex_search(str, str + char_traits<charT>::length(str), e, flags)`.

```
template<class ST, class SA, class charT, class traits>
bool regex_search(const basic_string<charT, ST, SA>& s,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);
```

**Returns:** `regex_search(s.begin(), s.end(), e, flags)`.

### 32.10.4 regex_replace

```
template<class OutputIterator, class BidirectionalIterator, 
class traits, class charT, class ST, class SA>
OutputIterator
regex_replace(OutputIterator out,
BidirectionalIterator first, BidirectionalIterator last,
const basic_regex<charT, traits>& e,
const basic_string<charT, ST, SA>& fmt,
regex_constants::match_flag_type flags = regex_constants::match_default);
```

**Effects:** Constructs a `regex_iterator` object `i` as if by

```
regex_iterator<BidirectionalIterator, charT, traits> i(first, last, e, flags)
```
and uses i to enumerate through all of the matches m of type match_results<BidirectionalIterator> that occur within the sequence (first, last). If no such matches are found and !(flags & regex_constants::format_no_copy), then calls

out = copy(first, last, out)

If any matches are found then, for each such match:

(1.1) — If !(flags & regex_constants::format_no_copy), calls

out = copy(m.prefix().first, m.prefix().second, out)

(1.2) — Then calls

out = m.format(out, fmt, flags)

for the first form of the function and

out = m.format(out, fmt, fmt + char_traits<charT>::length(fmt), flags)

for the second.

Finally, if such a match is found and !(flags & regex_constants::format_no_copy), calls

out = copy(last_m.suffix().first, last_m.suffix().second, out)

where last_m is a copy of the last match found. If flags & regex_constants::format_first_only is nonzero, then only the first match found is replaced.

Returns: out.

template<class traits, class charT, class ST, class SA, class FST, class FSA>

basic_string<charT, ST, SA>
regex_replace(const basic_string<charT, ST, SA>& s,
    const basic_regex<charT, traits>& e,
    const basic_string<charT, FST, FSA>& fmt,
    regex_constants::match_flag_type flags = regex_constants::match_default);

template<class traits, class charT, class ST, class SA>

basic_string<charT, ST, SA>
regex_replace(const basic_string<charT, ST, SA>& s,
    const basic_regex<charT, traits>& e,
    const charT* fmt,
    regex_constants::match_flag_type flags = regex_constants::match_default);

Effects: Constructs an empty string result of type basic_string<charT, ST, SA> and calls:

regex_replace(back_inserter(result), s.begin(), s.end(), e, fmt, flags);

Returns: result.

template<class traits, class charT, class ST, class SA>

basic_string<charT>
regex_replace(const charT* s,
    const basic_regex<charT, traits>& e,
    const basic_string<charT, ST, SA>& fmt,
    regex_constants::match_flag_type flags = regex_constants::match_default);

template<class traits, class charT>

basic_string<charT>
regex_replace(const charT* s,
    const basic_regex<charT, traits>& e,
    const charT* fmt,
    regex_constants::match_flag_type flags = regex_constants::match_default);

Effects: Constructs an empty string result of type basic_string<charT> and calls:

regex_replace(back_inserter(result), s, s + char_traits<charT>::length(s), e, fmt, flags);

Returns: result.
The class template `regex_iterator` is an iterator adaptor. It represents a new view of an existing iterator sequence, by enumerating all the occurrences of a regular expression within that sequence. A `regex_iterator` uses `regex_search` to find successive regular expression matches within the sequence from which it was constructed. After the iterator is constructed, and every time `operator++` is used, the iterator finds and stores a value of `match_results<BidirectionalIterator>`. If the end of the sequence is reached (`regex_search` returns `false`), the iterator becomes equal to the end-of-sequence iterator value. The default constructor constructs an end-of-sequence iterator object, which is the only legitimate iterator to be used for the end condition. The result of `operator*` on an end-of-sequence iterator is not defined. For any other iterator value a `const match_results<BidirectionalIterator>&` is returned. The result of `operator->` on an end-of-sequence iterator is not defined. For any other iterator value a `const match_results<BidirectionalIterator>*, const match_results<BidirectionalIterator>&` is returned. It is impossible to store things into `regex_iterators`. Two end-of-sequence iterators are always equal. An end-of-sequence iterator is not equal to a non-end-of-sequence iterator. Two non-end-of-sequence iterators are equal when they are constructed from the same arguments.

namespace std {
  template<class BidirectionalIterator,
    class charT = typename iterator_traits<BidirectionalIterator>::value_type,
    class traits = regex_traits<charT>>
  class regex_iterator {
    public:
      using regex_type = basic_regex<charT, traits>;
      using iterator_category = forward_iterator_tag;
      using iterator_concept = input_iterator_tag;
      using value_type = match_results<BidirectionalIterator>;
      using difference_type = ptrdiff_t;
      using pointer = const value_type*;
      using reference = const value_type&;
      regex_iterator();
      regex_iterator(BidirectionalIterator a, BidirectionalIterator b,
        const regex_type& re,
        regex_constants::match_flag_type m = regex_constants::match_default);
      regex_iterator(BidirectionalIterator, BidirectionalIterator,
        const regex_type&&,
        regex_constants::match_flag_type = regex_constants::match_default) = delete;
      regex_iterator(const regex_iterator&);
      regex_iterator& operator=(const regex_iterator&);
      bool operator==(const regex_iterator&) const;
      bool operator==(default_sentinel_t) const { return this == regex_iterator(); } const
      value_type& operator*() const;
      const value_type* operator->() const;
      regex_iterator& operator++();
      regex_iterator operator++(int);
  }
  private:
    BidirectionalIterator begin; // exposition only
    BidirectionalIterator end; // exposition only
    const regex_type* pregex; // exposition only
    regex_constants::match_flag_type flags; // exposition only
    match_results<BidirectionalIterator> match; // exposition only
  }
}

An object of type `regex_iterator` that is not an end-of-sequence iterator holds a zero-length match if `match[0].matched == true` and `match[0].first == match[0].second`.

[Note 1: For example, this can occur when the part of the regular expression that matched consists only of an assertion (such as `^`", `'$', `\b'`, `'\B'`). — end note]
32.11.1.2 Constructors

regex_iterator();

Effects: Constructs an end-of-sequence iterator.

regex_iterator(BidirectionalIterator a, BidirectionalIterator b,
const regex_type& re,
regex_constants::match_flag_type m = regex_constants::match_default);

Effects: Initializes begin and end to a and b, respectively, sets regex to addressof(re), sets flags to m, then calls regex_search(begin, end, match, *regex, flags). If this call returns false the constructor sets *this to the end-of-sequence iterator.

32.11.1.3 Comparisons

bool operator==(const regex_iterator& right) const;

Returns: true if *this and right are both end-of-sequence iterators or if the following conditions all hold:

(1.1) begin == right.begin,
(1.2) end == right.end,
(1.3) regex == right.regex,
(1.4) flags == right.flags, and
(1.5) match[0] == right.match[0];
otherwise false.

32.11.1.4 Indirection

const value_type& operator*() const;

Returns: match.

const value_type* operator->() const;

Returns: addressof(match).

32.11.1.5 Increment

regex_iterator& operator++();

Effects: Constructs a local variable start of type BidirectionalIterator and initializes it with the value of match[0].second.

If the iterator holds a zero-length match and start == end the operator sets *this to the end-of-sequence iterator and returns *this.

Otherwise, if the iterator holds a zero-length match, the operator calls:

regex_search(start, end, match, *regex,
flags | regex_constants::match_not_null | regex_constants::match_continuous)

If the call returns true the operator returns *this. Otherwise the operator increments start and continues as if the most recent match was not a zero-length match.

If the most recent match was not a zero-length match, the operator sets flags to flags | regex_constants::match_prev_avail and calls regex_search(start, end, match, *regex, flags). If the call returns false the iterator sets *this to the end-of-sequence iterator. The iterator then returns *this.

In all cases in which the call to regex_search returns true, match.prefix().first shall be equal to the previous value of match[0].second, and for each index i in the half-open range [0, match.size()) for which match[i].matched is true, match.position(i) shall return distance(begin, match[i].first).

[Note 1: This means that match.position(i) gives the offset from the beginning of the target sequence, which is often not the same as the offset from the sequence passed in the call to regex_search. — end note]

It is unspecified how the implementation makes these adjustments.
regex_iterator operator++(int);

Effects: As if by:

regex_iterator tmp = *this;
++(*this);
return tmp;

32.11.2 Class template regex_token_iterator

32.11.2.1 General

The class template regex_token_iterator is an iterator adaptor; that is to say it represents a new view of an existing iterator sequence, by enumerating all the occurrences of a regular expression within that sequence, and presenting one or more sub-expressions for each match found. Each position enumerated by the iterator is a sub_match class template instance that represents what matched a particular sub-expression within the regular expression.

When class regex_token_iterator is used to enumerate a single sub-expression with index −1 the iterator performs field splitting: that is to say it enumerates one sub-expression for each section of the character container sequence that does not match the regular expression specified.

After it is constructed, the iterator finds and stores a value regex_iteratorBidirectionalIterator position and sets the internal count N to zero. It also maintains a sequence subs which contains a list of the sub-expressions which will be enumerated. Every time operator++ is used the count N is incremented; if N exceeds or equals subs.size(), then the iterator increments member position and sets count N to zero.

If the end of sequence is reached (position is equal to the end of sequence iterator), the iterator becomes equal to the end-of-sequence iterator value, unless the sub-expression being enumerated has index −1, in which case the iterator enumerates one last sub-expression that contains all the characters from the end of the last regular expression match to the end of the input sequence being enumerated, provided that this would not be an empty sub-expression.

The default constructor constructs an end-of-sequence iterator object, which is the only legitimate iterator to be used for the end condition. The result of operator* on an end-of-sequence iterator is not defined. For any other iterator value a const sub_matchBidirectionalIterator& is returned. The result of operator-> on an end-of-sequence iterator is not defined. For any other iterator value a const sub_matchBidirectionalIterator* is returned.

It is impossible to store things into regex_token_iterators. Two end-of-sequence iterators are always equal. An end-of-sequence iterator is not equal to a non-end-of-sequence iterator. Two non-end-of-sequence iterators are equal when they are constructed from the same arguments.
	namespace std {
    template<class BidirectionalIterator,,
             class charT = typename iterator_traits<BidirectionalIterator>::value_type,
             class traits = regex_traits<charT>>
    class regex_token_iterator {
      public:
        using regex_type = basic_regex<charT, traits>;
        using iterator_category = forward_iterator_tag;
        using iterator_concept = input_iterator_tag;
        using value_type = sub_match<BidirectionalIterator>;
        using difference_type = ptrdiff_t;
        using pointer = const value_type*;
        using reference = const value_type&;

        regex_token_iterator();
        regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
                             const regex_type& re,
                             int submatch = 0,
                             regex_constants::match_flag_type m =
                             regex_constants::match_default);

§ 32.11.2.1 ©ISO/IEC 1925
regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type& re,
    const vector<int>& submatches,
    regex_constants::match_flag_type m =
    regex_constants::match_default);

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type& re,
    initializer_list<int> submatches,
    regex_constants::match_flag_type m =
    regex_constants::match_default);

template<size_t N>
regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type& re,
    const int (&submatches)[N],
    regex_constants::match_flag_type m =
    regex_constants::match_default) = delete;

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type&& re,
    int submatch = 0,
    regex_constants::match_flag_type m =
    regex_constants::match_default) = delete;

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type&& re,
    const vector<int>& submatches,
    regex_constants::match_flag_type m =
    regex_constants::match_default) = delete;

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type&& re,
    initializer_list<int> submatches,
    regex_constants::match_flag_type m =
    regex_constants::match_default) = delete;

template<size_t N>
regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b,
    const regex_type&& re,
    const int (&submatches)[N],
    regex_constants::match_flag_type m =
    regex_constants::match_default) = delete;

regex_token_iterator(const regex_token_iterator&);
regex_token_iterator& operator=(const regex_token_iterator&);

bool operator==(const regex_token_iterator&) const;
bool operator==(default_sentinel_t) const { return *this == regex_token_iterator(); }
const value_type& operator*() const;
const value_type* operator->() const;
regex_token_iterator& operator++();
regex_token_iterator operator++(int);

private:
    using position_iterator =
        regex_iterator<BidirectionalIterator, charT, traits>;  // exposition only
    position_iterator position;  // exposition only
    const value_type* result;  // exposition only
    value_type suffix;  // exposition only
    size_t N;
    vector<int> subs;  // exposition only
};

A suffix iterator is a regex_token_iterator object that points to a final sequence of characters at the end of the target sequence. In a suffix iterator the member result holds a pointer to the data member suffix, the value of the member suffix.match is true, suffix.first points to the beginning of the final sequence, and suffix.second points to the end of the final sequence.

[Note 1: For a suffix iterator, data member suffix.first is the same as the end of the last match found, and suffix.second is the same as the end of the target sequence. — end note]
The current match is (*position).prefix() if subs[N] == -1, or (*position)[subs[N]] for any other value of subs[N].

32.11.2.2 Constructors

regex_token_iterator();

Effects: Constructs the end-of-sequence iterator.

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b, const regex_type& re, int submatch = 0,
        regex_constants::match_flag_type m = regex_constants::match_default);

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b, const regex_type& re,
        const vector<int>& submatches,
        regex_constants::match_flag_type m = regex_constants::match_default);

regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b, const regex_type& re,
        initializer_list<int> submatches,
        regex_constants::match_flag_type m = regex_constants::match_default);

template<size_t N>
regex_token_iterator(BidirectionalIterator a, BidirectionalIterator b, const regex_type& re,
        const int (&submatches)[N],
        regex_constants::match_flag_type m = regex_constants::match_default);

Preconditions: Each of the initialization values of submatches is >= -1.

Effects: The first constructor initializes the member subs to hold the single value submatch. The second, third, and fourth constructors initialize the member subs to hold a copy of the sequence of integer values pointed to by the iterator range [begin(submatches), end(submatches)].

Each constructor then sets N to 0, and position to position_iterator(a, b, re, m). If position is not an end-of-sequence iterator the constructor sets result to the address of the current match. Otherwise if any of the values stored in subs is equal to -1 the constructor sets *this to a suffix iterator that points to the range [a, b), otherwise the constructor sets *this to an end-of-sequence iterator.

32.11.2.3 Comparisons

bool operator==(const regex_token_iterator& right) const;

Returns: true if *this and right are both end-of-sequence iterators, or if *this and right are both suffix iterators and suffix == right.suffix; otherwise returns false if *this or right is an end-of-sequence iterator or a suffix iterator. Otherwise returns true if position == right.position, N == right.N, and subs == right.subs. Otherwise returns false.

32.11.2.4 Indirection

const value_type& operator*() const;

Returns: *result.

const value_type* operator->() const;

Returns: result.

32.11.2.5 Increment

regex_token_iterator& operator++();

Effects: Constructs a local variable prev of type position_iterator, initialized with the value of position.

If *this is a suffix iterator, sets *this to an end-of-sequence iterator.
Otherwise, if \( N + 1 < \text{subs.size()} \), increments \( N \) and sets \( \text{result} \) to the address of the current match.

Otherwise, sets \( N \) to 0 and increments \( \text{position} \). If \( \text{position} \) is not an end-of-sequence iterator the operator sets \( *\text{this} \) to the address of the current match.

Otherwise, if any of the values stored in \( \text{subs} \) is equal to \(-1\) and \( \text{prev->suffix().length()} \) is not 0 the operator sets \( *\text{this} \) to a suffix iterator that points to the range [\( \text{prev->suffix().first} \), \( \text{prev->suffix().second} \)).

Otherwise, sets \( *\text{this} \) to an end-of-sequence iterator.

Returns: \( *\text{this} \)

\[
\text{regex_token_iterator& operator++(int);} \\
\text{Effects: Constructs a copy \( \text{tmp} \) of \( *\text{this} \), then calls ++(*\text{this}).} \\
\text{Returns: \( \text{tmp} \).}
\]

32.12 Modified ECMAScript regular expression grammar

The regular expression grammar recognized by \( \text{basic_regex} \) objects constructed with the ECMAScript flag is that specified by ECMA-262, except as specified below.

Objects of type specialization of \( \text{basic_regex} \) store within themselves a default-constructed instance of their \text{traits} template parameter, henceforth referred to as \( \text{traits\_inst} \). This \( \text{traits\_inst} \) object is used to support localization of the regular expression; \( \text{basic_regex} \) member functions shall not call any locale dependent C or C++ API, including the formatted string input functions. Instead they shall call the appropriate traits member function to achieve the required effect.

The following productions within the ECMAScript grammar are modified as follows:

\[
\text{ClassAtom} :: \\
\quad \text{ClassAtomNoDash} \\
\quad \text{ClassAtomExClass} \\
\quad \text{ClassAtomCollatingElement} \\
\quad \text{ClassAtomEquivalence} \\
\]

\[
\text{IdentityEscape} :: \\
\quad \text{SourceCharacter but not } c
\]

The following new productions are then added:

\[
\text{ClassAtomExClass} :: \\
\quad [ : \text{ClassName} : ] \\
\text{ClassAtomCollatingElement} :: \\
\quad [ . \text{ClassName} . ] \\
\text{ClassAtomEquivalence} :: \\
\quad [= \text{ClassName} =] \\
\text{ClassName} :: \\
\quad \text{ClassNameCharacter} \\
\quad \text{ClassNameCharacter ClassName} \\
\text{ClassNameCharacter} :: \\
\quad \text{SourceCharacter but not one of } . \text{ or } = \text{ or } : \\
\]

The productions \( \text{ClassAtomExClass} \), \( \text{ClassAtomCollatingElement} \) and \( \text{ClassAtomEquivalence} \) provide functionality equivalent to that of the same features in regular expressions in POSIX.

The regular expression grammar may be modified by any \text{regex\_constants::syntax\_option\_type} flags specified when constructing an object of type specialization of \( \text{basic_regex} \) according to the rules in Table 140.

A \( \text{ClassName} \) production, when used in \( \text{ClassAtomExClass} \), is not valid if \( \text{traits\_inst.lookup_classname} \) returns zero for that name. The names recognized as valid \( \text{ClassNames} \) are determined by the type of the traits class, but at least the following names shall be recognized: \text{alnum}, \text{alpha}, \text{blank}, \text{cntrl}, \text{digit}, \text{graph}, \text{lower}, \text{print}, \text{punct}, \text{space}, \text{upper}, \text{xdigit}, d, s, w. In addition the following expressions shall be equivalent:

\[
\backslash d \text{ and } [[:digit:]]
\]
A `ClassName` production when used in a `ClassAtomCollatingElement` production is not valid if the value returned by `traits_inst.lookup_collatename` for that name is an empty string.

The results from multiple calls to `traits_inst.lookup_classname` can be bitwise OR’ed together and subsequently passed to `traits_inst.isctype`.

A `ClassName` production when used in a `ClassAtomEquivalence` production is not valid if the value returned by `traits_inst.lookup_collatename` for that name is an empty string or if the value returned by `traits_inst.transform_primary` for the result of the call to `traits_inst.lookup_collatename` is an empty string.

When the sequence of characters being transformed to a finite state machine contains an invalid class name the translator shall throw an exception object of type `regex_error`.

If the CV of a `UnicodeEscapeSequence` is greater than the largest value that can be held in an object of type `charT` the translator shall throw an exception object of type `regex_error`.

Where the regular expression grammar requires the conversion of a sequence of characters to an integral value, this is accomplished by calling `traits_inst.value`.

The behavior of the internal finite state machine representation when used to match a sequence of characters is as described in ECMA-262. The behavior is modified according to any `match_flag_type` flags (32.4.3) specified when using the regular expression object in one of the regular expression algorithms (32.10). The behavior is also localized by interaction with the traits class template parameter as follows:

14.1 — During matching of a regular expression finite state machine against a sequence of characters, two characters c and d are compared using the following rules:

14.1.1 — if `(flags() & regex_constants::icase)` the two characters are equal if `traits_inst.translate_nocase(c) == traits_inst.translate_nocase(d);`

14.1.2 — otherwise, if `flags() & regex_constants::collate` the two characters are equal if `traits_inst.translate(c) == traits_inst.translate(d);`

14.1.3 — otherwise, the two characters are equal if `c == d`.

14.2 — During matching of a regular expression finite state machine against a sequence of characters, comparison of a collating element range c1-c2 against a character c is conducted as follows: if `flags() & regex_constants::collate` is false then the character c is matched if `c1 <= c && c <= c2`, otherwise character c is matched in accordance with the following algorithm:

```
string_type str1 = string_type(1, 
  flags() & icase ? 
    traits_inst.translate_nocase(c1) : traits_inst.translate(c1));
string_type str2 = string_type(1, 
  flags() & icase ? 
    traits_inst.translate_nocase(c2) : traits_inst.translate(c2));
string_type str = string_type(1, 
  flags() & icase ? 
    traits_inst.translate_nocase(c) : traits_inst.translate(c));
return traits_inst.transform(str1.begin(), str1.end()) <= traits_inst.transform(str.begin(), str.end()) 
  && traits_inst.transform(str.begin(), str.end()) 
  <= traits_inst.transform(str2.begin(), str2.end());
```

14.3 — During matching of a regular expression finite state machine against a sequence of characters, testing whether a collating element is a member of a primary equivalence class is conducted by first converting
the collating element and the equivalence class to sort keys using \texttt{traits::transform\_primary}, and then comparing the sort keys for equality.

(14.4) During matching of a regular expression finite state machine against a sequence of characters, a character $c$ is a member of a character class designated by an iterator range $[\text{first}, \text{last})$ if $\text{traits\_inst.isctype}(c, \text{traits\_inst.lookup\_classname(first, last, flags() & icase))}$ is true.

\textbf{See also:} ECMA-262 15.10
33 Concurrency support library  

33.1 General  

The following subclauses describe components to create and manage threads (6.9.2), perform mutual exclusion, and communicate conditions and values between threads, as summarized in Table 147.

Table 147 — Concurrency support library summary

<table>
<thead>
<tr>
<th>Subclause Header</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.2 Requirements</td>
<td></td>
</tr>
<tr>
<td>33.3 Stop tokens</td>
<td>&lt;stop_token&gt;</td>
</tr>
<tr>
<td>33.4 Threads</td>
<td>&lt;thread&gt;</td>
</tr>
<tr>
<td>33.5 Atomic operations</td>
<td>&lt;atomic&gt;, &lt;stdatomic.h&gt;</td>
</tr>
<tr>
<td>33.6 Mutual exclusion</td>
<td>&lt;mutex&gt;, &lt;shared_mutex&gt;</td>
</tr>
<tr>
<td>33.7 Condition variables</td>
<td>&lt;condition_variable&gt;</td>
</tr>
<tr>
<td>33.8 Semaphores</td>
<td>&lt;semaphore&gt;</td>
</tr>
<tr>
<td>33.9 Coordination types</td>
<td>&lt;latch&gt;, &lt;barrier&gt;</td>
</tr>
<tr>
<td>33.10 Futures</td>
<td>&lt;future&gt;</td>
</tr>
<tr>
<td>33.11 Safe reclamation</td>
<td>&lt;rcu&gt;, &lt;hazard_pointer&gt;</td>
</tr>
</tbody>
</table>

33.2 Requirements

33.2.1 Template parameter names

Throughout this Clause, the names of template parameters are used to express type requirements. Predicate is a function object type (22.10). Let pred denote an lvalue of type Predicate. Then the expression pred() shall be well-formed and the type decltype(pred()) shall model boolean-testable (18.5.2). The return value of pred(), converted to bool, yields true if the corresponding test condition is satisfied, and false otherwise. If a template parameter is named Clock, the corresponding template argument shall be a type C that meets the Cpp17Clock requirements (29.3); the program is ill-formed if is_clock_v<C> is false.

33.2.2 Exceptions

Some functions described in this Clause are specified to throw exceptions of type system_error (19.5.8). Such exceptions are thrown if any of the function’s error conditions is detected or a call to an operating system or other underlying API results in an error that prevents the library function from meeting its specifications. Failure to allocate storage is reported as described in 16.4.6.13.

[Example 1: Consider a function in this Clause that is specified to throw exceptions of type system_error and specifies error conditions that include operation_not_permitted for a thread that does not have the privilege to perform the operation. Assume that, during the execution of this function, an errno of EPERM is reported by a POSIX API call used by the implementation. Since POSIX specifies an errno of EPERM when “the caller does not have the privilege to perform the operation”, the implementation maps EPERM to an error_condition of operation_not_permitted (19.5) and an exception of type system_error is thrown. — end example]

The error_code reported by such an exception’s code() member function compares equal to one of the conditions specified in the function’s error condition element.

33.2.3 Native handles

Several classes described in this Clause have members native_handle_type and native_handle. The presence of these members and their semantics is implementation-defined.

[Note 1: These members allow implementations to provide access to implementation details. Their names are specified to facilitate portable compile-time detection. Actual use of these members is inherently non-portable. — end note]
33.2.4 Timing specifications

Several functions described in this Clause take an argument to specify a timeout. These timeouts are specified as either a duration or a time_point type as specified in Clause 29.

Implementations necessarily have some delay in returning from a timeout. Any overhead in interrupt response, function return, and scheduling induces a “quality of implementation” delay, expressed as duration \( D_i \). Ideally, this delay would be zero. Further, any contention for processor and memory resources induces a “quality of management” delay, expressed as duration \( D_m \). The delay durations may vary from timeout to timeout, but in all cases shorter is better.

The functions whose names end in _for take an argument that specifies a duration. These functions produce relative timeouts. Implementations should use a steady clock to measure time for these functions.

Given a duration argument \( D_t \), the real-time duration of the timeout is \( D_t + D_i + D_m \).

The functions whose names end in _until take an argument that specifies a time point. These functions produce absolute timeouts. Implementations should use the clock specified in the time point to measure time for these functions. Given a clock time point argument \( C_t \), the clock time point of the return from timeout should be \( C_t + D_i + D_m \) when the clock is not adjusted during the timeout. If the clock is adjusted to the time \( C_a \) during the timeout, the behavior should be as follows:

1. If \( C_a > C_t \), the waiting function should wake as soon as possible, i.e., \( C_a + D_i + D_m \), since the timeout is already satisfied. This specification may result in the total duration of the wait decreasing when measured against a steady clock.

2. If \( C_a \leq C_t \), the waiting function should not time out until \( \text{Clock::now()} \) returns a time \( C_n \geq C_t \), i.e., waking at \( C_t + D_i + D_m \).

   [Note 1: When the clock is adjusted backwards, this specification can result in the total duration of the wait increasing when measured against a steady clock. When the clock is adjusted forwards, this specification can result in the total duration of the wait decreasing when measured against a steady clock. —end note]

An implementation returns from such a timeout at any point from the time specified above to the time it would return from a steady-clock relative timeout on the difference between \( C_t \) and the time point of the call to the _until function.

Recommended practice: Implementations should decrease the duration of the wait when the clock is adjusted forwards.

[Note 2: If the clock is not synchronized with a steady clock, e.g., a CPU time clock, these timeouts can fail to provide useful functionality. —end note]

The resolution of timing provided by an implementation depends on both operating system and hardware. The finest resolution provided by an implementation is called the native resolution.

Implementation-provided clocks that are used for these functions meet the Cpp17TrivialClock requirements (29.3).

A function that takes an argument which specifies a timeout will throw if, during its execution, a clock, time point, or time duration throws an exception. Such exceptions are referred to as timeout-related exceptions.

[Note 3: Instantiations of clock, time point and duration types supplied by the implementation as specified in 29.7 do not throw exceptions. —end note]

33.2.5 Requirements for Cpp17Lockable types

33.2.5.1 General

An execution agent is an entity such as a thread that may perform work in parallel with other execution agents.

[Note 1: Implementations or users can introduce other kinds of agents such as processes or thread-pool tasks. —end note]

The calling agent is determined by context, e.g., the calling thread that contains the call, and so on.

[Note 2: Some lockable objects are “agent oblivious” in that they work for any execution agent model because they do not determine or store the agent’s ID (e.g., an ordinary spin lock). —end note]
The standard library templates `unique_lock (33.6.5.4), shared_lock (33.6.5.5), scoped_lock (33.6.5.3), lock_guard (33.6.5.2), lock, try_lock (33.6.6), and condition_variable_any (33.7.5) all operate on user-supplied lockable objects. The Cpp17BasicLockable requirements, the Cpp17Lockable requirements, the Cpp17TimedLockable requirements, the Cpp17SharedLockable requirements, and the Cpp17SharedTimedLockable requirements list the requirements imposed by these library types in order to acquire or release ownership of a lock by a given execution agent.

[Note 3: The nature of any lock ownership and any synchronization it entails are not part of these requirements. —end note]

A lock on an object \( m \) is said to be

\[(4.1)\] a non-shared lock if it is acquired by a call to `lock, try_lock, try_lock_for, or try_lock_until` on \( m \), or

\[(4.2)\] a shared lock if it is acquired by a call to `lock_shared, try_lock_shared, try_lock_shared_for, or try_lock_shared_until` on \( m \).

[Note 4: Only the method of lock acquisition is considered; the nature of any lock ownership is not part of these definitions. —end note]

### 33.2.5.2 Cpp17BasicLockable requirements

A type \( L \) meets the Cpp17BasicLockable requirements if the following expressions are well-formed and have the specified semantics (\( m \) denotes a value of type \( L \)).

\[
\begin{align*}
m\.lock() & : \text{Blocks until a lock can be acquired for the current execution agent. If an exception is thrown then a lock shall not have been acquired for the current execution agent.} \\
m\.unlock() & : \text{Preconditions: The current execution agent holds a non-shared lock on } m. \\
& \text{Effects: Releases a non-shared lock on } m \text{ held by the current execution agent.} \\
& \text{Throws: Nothing.}
\end{align*}
\]

### 33.2.5.3 Cpp17Lockable requirements

A type \( L \) meets the Cpp17Lockable requirements if it meets the Cpp17BasicLockable requirements and the following expressions are well-formed and have the specified semantics (\( m \) denotes a value of type \( L \)).

\[
\begin{align*}
m\.try_lock() & : \text{Attempts to acquire a lock for the current execution agent without blocking. If an exception is thrown then a lock shall not have been acquired for the current execution agent.} \\
& \text{Return type: } \text{bool}. \\
& \text{Returns: true if the lock was acquired, otherwise false.}
\end{align*}
\]

### 33.2.5.4 Cpp17TimedLockable requirements

A type \( L \) meets the Cpp17TimedLockable requirements if it meets the Cpp17Lockable requirements and the following expressions are well-formed and have the specified semantics (\( m \) denotes a value of type \( L \), \( \text{rel_time} \) denotes a value of an instantiation of \( \text{duration} (29.5) \), and \( \text{abs_time} \) denotes a value of an instantiation of \( \text{time_point} (29.6) \)).

\[
\begin{align*}
m\.try_lock_for(\text{rel_time}) & : \text{Attempts to acquire a lock for the current execution agent within the relative timeout (33.2.4) specified by } \text{rel_time}. \text{ The function will not return within the timeout specified by } \text{rel_time} \text{ unless it has obtained a lock on } m \text{ for the current execution agent. If an exception is thrown then a lock has not been acquired for the current execution agent.} \\
& \text{Return type: } \text{bool}. \\
& \text{Returns: true if the lock was acquired, otherwise false.}
\end{align*}
\]
m.try_lock_until(abs_time)

Effects: Attempts to acquire a lock for the current execution agent before the absolute timeout (33.2.4) specified by abs_time. The function will not return before the timeout specified by abs_time unless it has obtained a lock on m for the current execution agent. If an exception is thrown then a lock has not been acquired for the current execution agent.

Return type: bool.

Returns: true if the lock was acquired, otherwise false.

33.2.5.5 Cpp17SharedLockable requirements [thread.req.lockable.shared]

A type L meets the Cpp17SharedLockable requirements if the following expressions are well-formed, have the specified semantics, and the expression m.try_lock_shared() has type bool (m denotes a value of type L):

m.lock_shared()

Effects: Blocks until a lock can be acquired for the current execution agent. If an exception is thrown then a lock shall not have been acquired for the current execution agent.

m.try_lock_shared()

Effects: Attempts to acquire a lock for the current execution agent without blocking. If an exception is thrown then a lock shall not have been acquired for the current execution agent.

Returns: true if the lock was acquired, false otherwise.

m.unlock_shared()

Preconditions: The current execution agent holds a shared lock on m.

Effects: Releases a shared lock on m held by the current execution agent.

Throws: Nothing.

33.2.5.6 Cpp17SharedTimedLockable requirements [thread.req.lockable.shared.timed]

A type L meets the Cpp17SharedTimedLockable requirements if it meets the Cpp17SharedLockable requirements, and the following expressions are well-formed, have type bool, and have the specified semantics (m denotes a value of type L, rel_time denotes a value of a specialization of chrono::duration, and abs_time denotes a value of a specialization of chrono::time_point).

m.try_lock_shared_for(rel_time)

Effects: Attempts to acquire a lock for the current execution agent within the relative timeout (33.2.4) specified by rel_time. The function will not return within the timeout specified by rel_time unless it has obtained a lock on m for the current execution agent. If an exception is thrown then a lock has not been acquired for the current execution agent.

Returns: true if the lock was acquired, false otherwise.

m.try_lock_shared_until(abs_time)

Effects: Attempts to acquire a lock for the current execution agent before the absolute timeout (33.2.4) specified by abs_time. The function will not return before the timeout specified by abs_time unless it has obtained a lock on m for the current execution agent. If an exception is thrown then a lock has not been acquired for the current execution agent.

Returns: true if the lock was acquired, false otherwise.

33.3 Stop tokens [thread.stoptoken]

33.3.1 Introduction [thread.stoptoken.intro]

Subclause 33.3 describes components that can be used to asynchronously request that an operation stops execution in a timely manner, typically because the result is no longer required. Such a request is called a stop request.

stop_source, stop_token, and stop_callback implement semantics of shared ownership of a stop state. Any stop_source, stop_token, or stop_callback that shares ownership of the same stop state is an associated stop_source, stop_token, or stop_callback, respectively. The last remaining owner of the stop state automatically releases the resources associated with the stop state.
A `stop_token` can be passed to an operation which can either

(3.1) — actively poll the token to check if there has been a stop request, or

(3.2) — register a callback using the `stop_callback` class template which will be called in the event that a stop request is made.

A stop request made via a `stop_source` will be visible to all associated `stop_token` and `stop_source` objects. Once a stop request has been made it cannot be withdrawn (a subsequent stop request has no effect).

Callbacks registered via a `stop_callback` object are called when a stop request is first made by any associated `stop_source` object.

Calls to the functions `request_stop`, `stop_requested`, and `stop_possible` do not introduce data races. A call to `request_stop` that returns `true` synchronizes with a call to `stop_requested` on an associated `stop_token` or `stop_source` object that returns `true`. Registration of a callback synchronizes with the invocation of that callback.

### 33.3.2 Header `<stop_token>` synopsis

```cpp
namespace std {
    // 33.3.3, class stop_token
    class stop_token;

    // 33.3.4, class stop_source
    class stop_source;

    // no-shared-stop-state indicator
    struct nostopstate_t {
        explicit nostopstate_t() = default;
        inline constexpr nostopstate_t nostopstate{};
    };

    // 33.3.5, class template stop_callback
    template<class Callback>
    class stop_callback;
}
```

### 33.3.3 Class stop_token

#### 33.3.3.1 General

The class `stop_token` provides an interface for querying whether a stop request has been made (`stop_requested`) or can ever be made (`stop_possible`) using an associated `stop_source` object (33.3.4). A `stop_token` can also be passed to a `stop_callback` (33.3.5) constructor to register a callback to be called when a stop request has been made from an associated `stop_source`.

```cpp
namespace std {
    class stop_token {
    public:
        // 33.3.3.2, constructors, copy, and assignment
        stop_token() noexcept;
        stop_token(const stop_token&) noexcept;
        stop_token(stop_token&&) noexcept;
        stop_token& operator=(const stop_token&) noexcept;
        stop_token& operator=(stop_token&&) noexcept;
        ~stop_token();
        void swap(stop_token&) noexcept;

        // 33.3.3.3, stop handling
        [[nodiscard]] bool stop_requested() const noexcept;
        [[nodiscard]] bool stop_possible() const noexcept;

        [[nodiscard]] friend bool operator==(const stop_token& lhs, const stop_token& rhs) noexcept;
        friend void swap(stop_token& lhs, stop_token& rhs) noexcept;
    };
}
```
33.3.3.2 Constructors, copy, and assignment

```cpp
stop_token() noexcept;
```

*Postconditions*: `stop_possible()` is `false` and `stop_requested()` is `false`.

[Note 1: Because the created `stop_token` object can never receive a stop request, no resources are allocated for a stop state. — end note]

```cpp
stop_token(const stop_token& rhs) noexcept;
```

*Postconditions*: `*this` == `rhs` is `true`.

[Note 2: `*this` and `rhs` share the ownership of the same stop state, if any. — end note]

```cpp
stop_token(stop_token&& rhs) noexcept;
```

*Postconditions*: `*this` contains the value of `rhs` prior to the start of construction and `rhs.stop_possible()` is `false`.

```cpp
~stop_token();
```

*Effects*: Releases ownership of the stop state, if any.

```cpp
stop_token& operator=(const stop_token& rhs) noexcept;
```

*Effects*: Equivalent to: `stop_token(rhs).swap(*this)`.

```cpp
returns: *this.
```

```cpp
stop_token& operator=(stop_token&& rhs) noexcept;
```

*Effects*: Equivalent to: `stop_token(std::move(rhs)).swap(*this)`.

```cpp
Returns: *this.
```

```cpp
void swap(stop_token& rhs) noexcept;
```

*Effects*: Exchanges the values of `*this` and `rhs`.

33.3.3.3 Members

```cpp
[[nodiscard]] bool stop_requested() const noexcept;
```

*Returns*: `true` if `*this` has ownership of a stop state that has received a stop request; otherwise, `false`.

```cpp
[[nodiscard]] bool stop_possible() const noexcept;
```

*Returns*: `false` if

(2.1) `*this` does not have ownership of a stop state, or

(2.2) a stop request was not made and there are no associated `stop_source` objects; otherwise, `true`.

33.3.3.4 Non-member functions

```cpp
[[nodiscard]] bool operator==(const stop_token& lhs, const stop_token& rhs) noexcept;
```

*Returns*: `true` if `lhs` and `rhs` have ownership of the same stop state or if both `lhs` and `rhs` do not have ownership of a stop state; otherwise `false`.

```cpp
friend void swap(stop_token& x, stop_token& y) noexcept;
```

*Effects*: Equivalent to: `x.swap(y)`.

33.3.4 Class `stop_source`

33.3.4.1 General

The class `stop_source` implements the semantics of making a stop request. A stop request made on a `stop_source` object is visible to all associated `stop_source` and `stop_token` (33.3.3) objects. Once a stop request has been made it cannot be withdrawn (a subsequent stop request has no effect).
namespace std {
    // no-shared-stop-state indicator
    struct nostopstate_t {
        explicit nostopstate_t() = default;
    };
    inline constexpr nostopstate_t nostopstate{};

    class stop_source {
public:
    // 33.3.4.2, constructors, copy, and assignment
    explicit stop_source(nostopstate_t) noexcept;
    stop_source(const stop_source&) noexcept;
    stop_source(stop_source&&) noexcept;
    stop_source& operator=(const stop_source&) noexcept;
    stop_source& operator=(stop_source&&) noexcept;
    ~stop_source();
    void swap(stop_source&) noexcept;

    // 33.3.4.3, stop handling
    [[nodiscard]] stop_token get_token() const noexcept;
    [[nodiscard]] bool stop_possible() const noexcept;
    [[nodiscard]] bool stop_requested() const noexcept;
    bool request_stop() noexcept;

    [[nodiscard]] friend bool operator==(const stop_source& lhs, const stop_source& rhs) noexcept;
    friend void swap(stop_source& lhs, stop_source& rhs) noexcept;
};
}

33.3.4.2 Constructors, copy, and assignment

stop_source();

Effects: Initialises *this to have ownership of a new stop state.

Postconditions: stop_possible() is true and stop_requested() is false.

Throws: bad_alloc if memory cannot be allocated for the stop state.

explicit stop_source(nostopstate_t) noexcept;

Postconditions: stop_possible() is false and stop_requested() is false.

[Note 1: No resources are allocated for the state. — end note]

stop_source(const stop_source& rhs) noexcept;

Postconditions: *this == rhs is true.

[Note 2: *this and rhs share the ownership of the same stop state, if any. — end note]

stop_source(stop_source&& rhs) noexcept;

Postconditions: *this contains the value of rhs prior to the start of construction and rhs.stop_possible() is false.

~stop_source();

Effects: Releases ownership of the stop state, if any.

stop_source& operator=(const stop_source& rhs) noexcept;

Effects: Equivalent to: stop_source(rhs).swap(*this).

Returns: *this.

stop_source& operator=(stop_source&& rhs) noexcept;

Effects: Equivalent to: stop_source(std::move(rhs)).swap(*this).
void swap(stop_source& rhs) noexcept;

Effects: Exchanges the values of *this and rhs.

33.3.4.3 Members

[[nodiscard]] stop_token get_token() const noexcept;

Returns: stop_token() if stop_possible() is false; otherwise a new associated stop_token object.

[[nodiscard]] bool stop_possible() const noexcept;

Returns: true if *this has ownership of a stop state; otherwise, false.

[[nodiscard]] bool stop_requested() const noexcept;

Returns: true if *this has ownership of a stop state that has received a stop request; otherwise, false.

bool request_stop() noexcept;

Effects: If *this does not have ownership of a stop state, returns false. Otherwise, atomically determines whether the owned stop state has received a stop request, and if not, makes a stop request. The determination and making of the stop request are an atomic read-modify-write operation (6.9.2.2). If the request was made, the callbacks registered by associated stop_callback objects are synchronously called. If an invocation of a callback exits via an exception then terminate is invoked (14.6.2).

[Note 1: A stop request includes notifying all condition variables of type condition_variable_any temporarily registered during an interruptible wait (33.7.5.3). —end note]

Postconditions: stop_possible() is false or stop_requested() is true.

Returns: true if this call made a stop request; otherwise false.

33.3.4.4 Non-member functions

[[nodiscard]] friend bool operator==(const stop_source& lhs, const stop_source& rhs) noexcept;

Returns: true if lhs and rhs have ownership of the same stop state or if both lhs and rhs do not have ownership of a stop state; otherwise false.

friend void swap(stop_source& x, stop_source& y) noexcept;

Effects: Equivalent to: x.swap(y).

33.3.5 Class template stop_callback

33.3.5.1 General

namespace std {

    template<class Callback>
    class stop_callback {
        public:
            using callback_type = Callback;

            // 33.3.5.2, constructors and destructor
            template<class C>
            explicit stop_callback(const stop_token& st, C&& cb) noexcept(is_nothrow_constructible_v<Callback, C>);
            template<class C>
            explicit stop_callback(stop_token&& st, C&& cb) noexcept(is_nothrow_constructible_v<Callback, C>);
            -stop_callback();

            stop_callback(const stop_callback&) = delete;
            stop_callback(stop_callback&&) = delete;
            stop_callback& operator=(const stop_callback&) = delete;
            stop_callback& operator=(stop_callback&&) = delete;

    };

} // namespace std

§ 33.3.5.1 ©ISO/IEC 1938
private:
    Callback callback;  // exposition only
};

template<class Callback>
    stop_callback(stop_token, Callback) -> stop_callback<Callback>;

2 Mandates: stop_callback is instantiated with an argument for the template parameter Callback that
satisfies both invocable and destructible.

3 Preconditions: stop_callback is instantiated with an argument for the template parameter Callback that
models both invocable and destructible.

33.3.5.2 Constructors and destructor

[stopcallback.cons]
template<class C>
    explicit stop_callback(const stop_token& st, C&& cb)
    noexcept(is_nothrow_constructible_v<Callback, C>);
template<class C>
    explicit stop_callback(stop_token&& st, C&& cb)
    noexcept(is_nothrow_constructible_v<Callback, C>);

1 Constraints: Callback and C satisfy constructible_from<Callback, C>.

2 Preconditions: Callback and C model constructible_from<Callback, C>.

3 Effects: Initializes callback with std::forward<C>(cb). If st.stop_requested() is true, then
std::forward<Callback>(callback)() is evaluated in the current thread before the constructor
returns. Otherwise, if st has ownership of a stop state, acquires shared ownership of that stop state
and registers the callback with that stop state such that std::forward<Callback>(callback)() is
evaluated by the first call to request_stop() on an associated stop_source.

4 Throws: Any exception thrown by the initialization of callback.

5 Remarks: If evaluating std::forward<Callback>(callback)() exits via an exception, then terminate
is invoked (14.6.2).

~stop_callback();

6 Effects: Unregisters the callback from the owned stop state, if any. The destructor does not block
waiting for the execution of another callback registered by an associated stop_callback. If callback
is concurrently executing on another thread, then the return from the invocation of callback strongly
happens before (6.9.2.2) callback is destroyed. If callback is executing on the current thread, then
the destructor does not block (3.6) waiting for the return from the invocation of callback. Releases
ownership of the stop state, if any.

33.4 Threads

[thread.threads]
33.4.1 General

[thread.threads.general]

33.4 describes components that can be used to create and manage threads.

[Note 1: These threads are intended to map one-to-one with operating system threads. — end note]

33.4.2 Header <thread> synopsis

[thread.syn]

#include <compare>  // see 17.11.1

namespace std {
    // 33.4.3, class thread
class thread;

    void swap(thread& x, thread& y) noexcept;

    // 33.4.4, class jthread
class jthread;

§ 33.4.2 ©ISO/IEC 1939
namespace std {
    class thread {
public:
    // 33.4.3.2, class thread::id
    class id;
    using native_handle_type = implementation-defined;  // see 33.2.3

    // construct/copy/destroy
    thread() noexcept;
    template<class F, class... Args> explicit thread(F&& f, Args&&... args);
    ~thread();
    thread(const thread&) = delete;
    thread(thread&&) noexcept;
    thread& operator=(const thread&) = delete;
    thread& operator=(thread&&) noexcept;

    // 33.4.3.6, members
    void swap(thread&) noexcept;
    bool joinable() const noexcept;
    void join();
    void detach();
    id get_id() const noexcept;
    native_handle_type native_handle();  // see 33.2.3

    // static members
    static unsigned int hardware_concurrency() noexcept;
    }

    static unsigned int hardware_concurrency() noexcept;
};

namespace std {
    class thread::id {
public:
    id() noexcept;

    bool operator==(thread::id x, thread::id y) noexcept;
    strong_ordering operator<=>(thread::id x, thread::id y) noexcept;
    }
An object of type `thread::id` provides a unique identifier for each thread of execution and a single distinct value for all `thread` objects that do not represent a thread of execution (33.4.3). Each thread of execution has an associated `thread::id` object that is not equal to the `thread::id` object of any other thread of execution and that is not equal to the `thread::id` object of any `thread` object that does not represent threads of execution.

The text representation for the character type `charT` of an object of type `thread::id` is an unspecified sequence of `charT` such that, for two objects of type `thread::id` `x` and `y`, if `x == y` is `true`, the `thread::id` objects have the same text representation, and if `x != y` is `true`, the `thread::id` objects have distinct text representations.

`thread::id` is a trivially copyable class (11.2). The library may reuse the value of a `thread::id` of a terminated thread that can no longer be joined.

Postconditions: The constructed object does not represent a thread of execution.

Returns: `true` only if `x` and `y` represent the same thread of execution or neither `x` nor `y` represents a thread of execution.

Let `P(x,y)` be an unspecified total ordering over `thread::id` as described in 27.8.

Returns: `strong_ordering::less` if `P(x,y)` is `true`. Otherwise, `strong_ordering::greater` if `P(y,x)` is `true`. Otherwise, `strong_ordering::equal`.

Effects: Inserts the text representation for `charT` of `id` into `out`.

Returns: `out`.

`thread::id` is a trivially copyable class (11.2). The library may reuse the value of a `thread::id` of a terminated thread that can no longer be joined.

Postconditions: The constructed object does not represent a thread of execution.

Returns: `true` only if `x` and `y` represent the same thread of execution or neither `x` nor `y` represents a thread of execution.

Let `P(x,y)` be an unspecified total ordering over `thread::id` as described in 27.8.

Returns: `strong_ordering::less` if `P(x,y)` is `true`. Otherwise, `strong_ordering::greater` if `P(y,x)` is `true`. Otherwise, `strong_ordering::equal`.

Effects: Inserts the text representation for `charT` of `id` into `out`.

Returns: `out`.

`thread::id` is a trivially copyable class (11.2). The library may reuse the value of a `thread::id` of a terminated thread that can no longer be joined.

Postconditions: The constructed object does not represent a thread of execution.

Returns: `true` only if `x` and `y` represent the same thread of execution or neither `x` nor `y` represents a thread of execution.

Let `P(x,y)` be an unspecified total ordering over `thread::id` as described in 27.8.

Returns: `strong_ordering::less` if `P(x,y)` is `true`. Otherwise, `strong_ordering::greater` if `P(y,x)` is `true`. Otherwise, `strong_ordering::equal`.

Effects: Inserts the text representation for `charT` of `id` into `out`.

Returns: `out`.

`thread::id` is a trivially copyable class (11.2). The library may reuse the value of a `thread::id` of a terminated thread that can no longer be joined.

Postconditions: The constructed object does not represent a thread of execution.

Returns: `true` only if `x` and `y` represent the same thread of execution or neither `x` nor `y` represents a thread of execution.

Let `P(x,y)` be an unspecified total ordering over `thread::id` as described in 27.8.

Returns: `strong_ordering::less` if `P(x,y)` is `true`. Otherwise, `strong_ordering::greater` if `P(y,x)` is `true`. Otherwise, `strong_ordering::equal`.

Effects: Inserts the text representation for `charT` of `id` into `out`.

Returns: `out`.

The specialization is enabled (22.10.19).
thread() noexcept;

Effects: The object does not represent a thread of execution.
Postconditions: get_id() == id().

template<class F, class... Args> explicit thread(F&& f, Args&&... args);

Constraints: remove_cvref_t<F> is not the same type as thread.

Mandates: The following are all true:

1. is_constructible_v<decay_t<F>, F>.
2. (is_constructible_v<decay_t<Args>, Args> && ...), and
3. is_invocable_v<decay_t<F>, decay_t<Args>...>.

Effects: The new thread of execution executes

invoke(auto(std::forward<F>(f)),
       auto(std::forward<Args>(args))...) // for invoke, see 22.10.5

with the values produced by auto being materialized (7.3.5) in the constructing thread. Any return value from this invocation is ignored.

[Note 1: This implies that any exceptions not thrown from the invocation of the copy of f will be thrown in the constructing thread, not the new thread. —end note]

If the invocation of invoke terminates with an uncaught exception, terminate is invoked (14.6.2).

Synchronization: The completion of the invocation of the constructor synchronizes with the beginning of the invocation of the copy of f.

Postconditions: get_id() != id(). *this represents the newly started thread.

Throws: system_error if unable to start the new thread.

Error conditions:

1. resource_unavailable_try_again — the system lacked the necessary resources to create another thread, or the system-imposed limit on the number of threads in a process would be exceeded.

thread(thread&& x) noexcept;

Postconditions: x.get_id() == id() and get_id() returns the value of x.get_id() prior to the start of construction.

33.4.3.4 Destructor

~thread();

Effects: If joinable(), invokes terminate (14.6.2). Otherwise, has no effects.

[Note 1: Either implicitly detaching or joining a joinable() thread in its destructor can result in difficult to debug correctness (for detach) or performance (for join) bugs encountered only when an exception is thrown. These bugs can be avoided by ensuring that the destructor is never executed while the thread is still joinable. —end note]

33.4.3.5 Assignment

thread& operator=(thread&& x) noexcept;

Effects: If joinable(), invokes terminate (14.6.2). Otherwise, assigns the state of x to *this and sets x to a default constructed state.

Postconditions: x.get_id() == id() and get_id() returns the value of x.get_id() prior to the assignment.

Returns: *this.

33.4.3.6 Members

void swap(thread& x) noexcept;

Effects: Swaps the state of *this and x.
bool joinable() const noexcept;

void join();

Returns: \texttt{get\_id() \neq id()}. 

Effects: Blocks until the thread represented by \texttt{*this} has completed.

Synchronization: The completion of the thread represented by \texttt{*this} synchronizes with (6.9.2) the corresponding successful \texttt{join()} return.

[Note 1: Operations on \texttt{*this} are not synchronized. — end note]

Postconditions: The thread represented by \texttt{*this} has completed. \texttt{get\_id() \neq id()}. 

Throws: \texttt{system\_error} when an exception is required (33.2.2).

Error conditions:

- \texttt{resource\_deadlock\_would\_occur} — if deadlock is detected or \texttt{get\_id() \neq this\_thread::get\_id()}. 

- \texttt{no\_such\_process} — if the thread is not valid. 

- \texttt{invalid\_argument} — if the thread is not joinable. 

void detach();

Effects: The thread represented by \texttt{*this} continues execution without the calling thread blocking. When \texttt{detach()} returns, \texttt{*this} no longer represents the possibly continuing thread of execution. When the thread previously represented by \texttt{*this} ends execution, the implementation releases any owned resources.

Postconditions: \texttt{get\_id() \neq id()}. 

Throws: \texttt{system\_error} when an exception is required (33.2.2).

Error conditions:

- \texttt{no\_such\_process} — if the thread is not valid. 

- \texttt{invalid\_argument} — if the thread is not joinable. 

id get_id() const noexcept;

Returns: A default constructed \texttt{id} object if \texttt{*this} does not represent a thread, otherwise \texttt{this\_thread::get\_id()} for the thread of execution represented by \texttt{*this}. 

33.4.3.7 Static members 

unsigned hardware_concurrency() noexcept;

Returns: The number of hardware thread contexts.

[Note 1: This value should only be considered to be a hint. — end note]

If this value is not computable or well-defined, an implementation should return 0.

33.4.3.8 Specialized algorithms 

void swap(thread& x, thread& y) noexcept;

Effects: As if by \texttt{x.swap(y)}. 

33.4.4 Class \texttt{jthread} 

33.4.4.1 General 

The class \texttt{jthread} provides a mechanism to create a new thread of execution. The functionality is the same as for class \texttt{thread} (33.4.3) with the additional abilities to provide a \texttt{stop\_token} (33.3) to the new thread of execution, make stop requests, and automatically join.

namespace std {
    class jthread {
    public:
        // types
        using id = thread::id;
        using native_handle_type = thread::native_handle_type;
Constructors, move, and assignment

```cpp
// 33.4.4.2, constructors, move, and assignment
jthread() noexcept;
template<class F, class... Args> explicit jthread(F&& f, Args&&... args);
~jthread();
jthread(const jthread&) = delete;
jthread(jthread&&) noexcept;
jthread& operator=(const jthread&) = delete;
jthread& operator=(jthread&&) noexcept;
```

### Effects:
Constructs a `jthread` object that does not represent a thread of execution.

### Postconditions:
- `get_id() == id()` is true and `ssource.stop_possible()` is false.

```cpp
// 33.4.4.3, members
void swap(jthread&) noexcept;
[[nodiscard]] bool joinable() const noexcept;
void join();
void detach();
[[nodiscard]] id get_id() const noexcept;
[[nodiscard]] native_handle_type native_handle(); // see 33.2.3
```

### Constraints:
- `remove_cvref_t<F>` is not the same type as `jthread`.

### Mandates:
The following are all true:
1. `is_constructible_v<decay_t<F>, F>`,
2. `is_constructible_v<decay_t<Args>, Args && ...>`, and
3. `is_invocable_v<decay_t<F>, decay_t<Args>..., stop_token, decay_t<Args>...>`.

### Effects:
Initializes `ssource`. The new thread of execution executes `invoke(auto(std::forward<F>(f)), get_stop_token(), // for invoke, see 22.10.5 auto(std::forward<Args>(args))...)` if that expression is well-formed, otherwise `invoke(auto(std::forward<F>(f)), auto(std::forward<Args>(args))...)` with the values produced by `auto` being materialized (7.3.5) in the constructing thread. Any return value from this invocation is ignored.

### Note 1:
This implies that any exceptions not thrown from the invocation of the copy of `f` will be thrown in the constructing thread, not the new thread. —end note

If the `invoke` expression exits via an exception, `terminate` is called.
Synchronization: The completion of the invocation of the constructor synchronizes with the beginning of the invocation of the copy of \( f \).

Postconditions: get_id() != id() is true and ssoure.stop_possible() is true and *this represents the newly started thread.

[Note 2: The calling thread can make a stop request only once, because it cannot replace this stop token. — end note]

Throws: system_error if unable to start the new thread.

Error conditions:

(9.1) resource_unavailable_try_again — the system lacked the necessary resources to create another thread, or the system-imposed limit on the number of threads in a process would be exceeded.

void swap(jthread& x) noexcept;

Effects: Exchanges the values of *this and x.

[[nodiscard]] bool joinable() const noexcept;

Returns: get_id() != id().

void join();

Effects: Blocks until the thread represented by *this has completed.

Synchronization: The completion of the thread represented by *this synchronizes with (6.9.2) the corresponding successful join() return.

[Note 1: Operations on *this are not synchronized. — end note]

Postconditions: The thread represented by *this has completed. get_id() == id().

Throws: system_error when an exception is required (33.2.2).

Error conditions:

(7.1) resource_deadlock_would_occur — if deadlock is detected or get_id() == this_thread::get_id().

(7.2) no_such_process — if the thread is not valid.

(7.3) invalid_argument — if the thread is not joinable.

void detach();

Effects: The thread represented by *this continues execution without the calling thread blocking. When detach() returns, *this no longer represents the possibly continuing thread of execution. When the thread previously represented by *this ends execution, the implementation releases any owned resources.

§ 33.4.4.3
Postconditions: get_id() == id().

Throws: system_error when an exception is required (33.2.2).

Error conditions:

1. no_such_process — if the thread is not valid.
2. invalid_argument — if the thread is not joinable.

id get_id() const noexcept;

Returns: A default constructed id object if *this does not represent a thread, otherwise this_thread::get_id() for the thread of execution represented by *this.

33.4.4.4 Stop token handling

[[nodiscard]] stop_source get_stop_source() noexcept;

Effects: Equivalent to: return ssourse;

[[nodiscard]] stop_token get_stop_token() const noexcept;

Effects: Equivalent to: return ssourse.get_token();

bool request_stop() noexcept;

Effects: Equivalent to: return ssourse.request_stop();

33.4.4.5 Specialized algorithms

friend void swap(jthread& x, jthread& y) noexcept;

Effects: Equivalent to: x.swap(y).

33.4.4.6 Static members

[[nodiscard]] static unsigned int hardware_concurrency() noexcept;

Returns: thread::hardware_concurrency().

33.4.5 Namespace this_thread

namespace std::this_thread {
    thread::id get_id() noexcept;

    void yield() noexcept;

    template<class Clock, class Duration>
    void sleep_until(const chrono::time_point<Clock, Duration>& abs_time);

    template<class Rep, class Period>
    void sleep_for(const chrono::duration<Rep, Period>& rel_time);
}

thread::id this_thread::get_id() noexcept;

Returns: An object of type thread::id that uniquely identifies the current thread of execution. Every invocation from this thread of execution returns the same value. The object returned does not compare equal to a default-constructed thread::id.

void this_thread::yield() noexcept;

Effects: Offers the implementation the opportunity to reschedule.

Synchronization: None.

template<class Clock, class Duration>
void sleep_until(const chrono::time_point<Clock, Duration>& abs_time);

Effects: Blocks the calling thread for the absolute timeout (33.2.4) specified by abs_time.

Synchronization: None.

Throws: Timeout-related exceptions (33.2.4).
template<class Rep, class Period>  
void sleep_for(const chrono::duration<Rep, Period>& rel_time);

Effects: Blocks the calling thread for the relative timeout (33.2.4) specified by rel_time.

Synchronization: None.

Throws: Timeout-related exceptions (33.2.4).

33.5 Atomic operations

33.5.1 General

Subclause 33.5 describes components for fine-grained atomic access. This access is provided via operations on atomic objects.

33.5.2 Header <atomic> synopsis

namespace std {

// 33.5.4, order and consistency
enum class memory_order : unspecified;  // freestanding
inline constexpr memory_order memory_order_relaxed = memory_order::relaxed;  // freestanding
inline constexpr memory_order memory_order_consume = memory_order::consume;  // freestanding
inline constexpr memory_order memory_order_acquire = memory_order::acquire;  // freestanding
inline constexpr memory_order memory_order_release = memory_order::release;  // freestanding
inline constexpr memory_order memory_order_acq_rel = memory_order::acq_rel;  // freestanding
inline constexpr memory_order memory_order_seq_cst = memory_order::seq_cst;  // freestanding

template<class T>
T kill_dependency(T y) noexcept;  // freestanding

// 33.5.5, lock-free property
#define ATOMIC_BOOL_LOCK_FREE unspecified  // freestanding
#define ATOMIC_CHAR_LOCK_FREE unspecified  // freestanding
#define ATOMIC_CHAR8_T_LOCK_FREE unspecified  // freestanding
#define ATOMIC_CHAR16_T_LOCK_FREE unspecified  // freestanding
#define ATOMIC_CHAR32_T_LOCK_FREE unspecified  // freestanding
#define ATOMIC_WCHAR_T_LOCK_FREE unspecified  // freestanding
#define ATOMIC_SHORT_LOCK_FREE unspecified  // freestanding
#define ATOMIC_INT_LOCK_FREE unspecified  // freestanding
#define ATOMIC_LONG_LOCK_FREE unspecified  // freestanding
#define ATOMIC_LLONG_LOCK_FREE unspecified  // freestanding
#define ATOMIC_POINTER_LOCK_FREE unspecified  // freestanding

namespace std {

// 33.5.7, class template atomic_ref
template<class T> struct atomic_ref;  // freestanding
// 33.5.7.5, partial specialization for pointers
template<class T> struct atomic_ref<T*>;  // freestanding

// 33.5.8, class template atomic
template<class T> struct atomic;  // freestanding
// 33.5.8.5, partial specialization for pointers
template<class T> struct atomic<T*>;  // freestanding

// 33.5.9, non-member functions
template<class T>
bool atomic_is_lock_free(const volatile atomic<T>**) noexcept;  // freestanding

template<class T>
bool atomic_is_lock_free(const atomic<T>**) noexcept;  // freestanding

template<class T>
void atomic_store(volatile atomic<T>*);

template<class T>
void atomic_store(volatile atomic<T>*, typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
void atomic_store(atomic<T>*, typename atomic<T>::value_type) noexcept;  // freestanding

} // 33.5.2
template<class T>
void atomic_store_explicit(volatile atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept;  // freestanding

template<class T>
void atomic_store_explicit(atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept;  // freestanding

template<class T>
T atomic_load(const volatile atomic<T>*) noexcept;  // freestanding

template<class T>
T atomic_load(const atomic<T>*) noexcept;  // freestanding

template<class T>
T atomic_load_explicit(const volatile atomic<T>*,
    memory_order) noexcept;  // freestanding

template<class T>
T atomic_load_explicit(const atomic<T>*,
    memory_order) noexcept;  // freestanding

template<class T>
T atomic_exchange(const volatile atomic<T>*,
    typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
T atomic_exchange(const atomic<T>*,
    typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
T atomic_exchange_explicit(const volatile atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept;  // freestanding

template<class T>
T atomic_exchange_explicit(const atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_weak(const volatile atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_weak(const atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_strong(const volatile atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_strong(const atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_weak_explicit(const volatile atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type,
    memory_order, memory_order) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_weak_explicit(const atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type,
    memory_order, memory_order) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_strong_explicit(const volatile atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type,
    memory_order, memory_order) noexcept;  // freestanding

template<class T>
bool atomic_compare_exchange_strong_explicit(const atomic<T>*,
    typename atomic<T>::value_type*,
    typename atomic<T>::value_type,
    memory_order, memory_order) noexcept;  // freestanding
template<class T>
T atomic_fetch_add(volatile atomic<T>*,
        typename atomic<T>::difference_type) noexcept; // freestanding

// freestanding

// freestanding

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§ 33.5.2
template<class T>
T atomic_fetch_max(atomic<T>*,
    typename atomic<T>::value_type) noexcept; // freestanding

template<class T>
T atomic_fetch_max_explicit(volatile atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept; // freestanding

template<class T>
T atomic_fetch_max_explicit(atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept; // freestanding

template<class T>
T atomic_fetch_min(volatile atomic<T>*,
    typename atomic<T>::value_type) noexcept;

template<class T>
T atomic_fetch_min(atomic<T>*,
    typename atomic<T>::value_type) noexcept; // freestanding

template<class T>
T atomic_fetch_min_explicit(volatile atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept; // freestanding

template<class T>
T atomic_fetch_min_explicit(atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept; // freestanding

template<class T>
void atomic_wait(const volatile atomic<T>*,
    typename atomic<T>::value_type) noexcept; // freestanding

template<class T>
void atomic_wait(const atomic<T>*,
    typename atomic<T>::value_type) noexcept; // freestanding

template<class T>
void atomic_wait_explicit(const volatile atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept; // freestanding

template<class T>
void atomic_wait_explicit(const atomic<T>*,
    typename atomic<T>::value_type,
    memory_order) noexcept; // freestanding

template<class T>
void atomic_notify_one(volatile atomic<T>*) noexcept; // freestanding

template<class T>
void atomic_notify_one(atomic<T>*) noexcept; // freestanding

template<class T>
void atomic_notify_all(volatile atomic<T>*) noexcept; // freestanding

template<class T>
void atomic_notify_all(atomic<T>*) noexcept; // freestanding

using atomic_bool = atomic<bool>; // freestanding
using atomic_char = atomic<char>; // freestanding
using atomic_schar = atomic<signed char>; // freestanding
using atomic_uchar = atomic<unsigned char>; // freestanding
using atomic_short = atomic<short>; // freestanding
using atomic_ushort = atomic<unsigned short>; // freestanding
using atomic_int = atomic<int>; // freestanding
using atomic_uint = atomic<unsigned int>; // freestanding
using atomic_long = atomic<long>; // freestanding
using atomic_ulong = atomic<unsigned long>; // freestanding
using atomic_llong = atomic<long long>; // freestanding
using atomic_ullong = atomic<unsigned long long>; // freestanding
using atomic_char8_t = atomic<char8_t>; // freestanding
using atomic_char16_t = atomic<char16_t>; // freestanding
using atomic_char32_t = atomic<char32_t>; // freestanding
using atomic_wchar_t = atomic<wchar_t>; // freestanding
using atomic_int8_t = atomic<int8_t>;  // freestanding
using atomic_uint8_t = atomic<uint8_t>;  // freestanding
using atomic_int16_t = atomic<int16_t>;  // freestanding
using atomic_uint16_t = atomic<uint16_t>;  // freestanding
using atomic_int32_t = atomic<int32_t>;  // freestanding
using atomic_uint32_t = atomic<uint32_t>;  // freestanding
using atomic_int64_t = atomic<int64_t>;  // freestanding
using atomic_uint64_t = atomic<uint64_t>;  // freestanding
using atomic_int_least8_t = atomic<int_least8_t>;  // freestanding
using atomic_uint_least8_t = atomic<uint_least8_t>;  // freestanding
using atomic_int_least16_t = atomic<int_least16_t>;  // freestanding
using atomic_uint_least16_t = atomic<uint_least16_t>;  // freestanding
using atomic_int_least32_t = atomic<int_least32_t>;  // freestanding
using atomic_uint_least32_t = atomic<uint_least32_t>;  // freestanding
using atomic_int_least64_t = atomic<int_least64_t>;  // freestanding
using atomic_uint_least64_t = atomic<uint_least64_t>;  // freestanding
using atomic_int_fast8_t = atomic<int_fast8_t>;  // freestanding
using atomic_uint_fast8_t = atomic<uint_fast8_t>;  // freestanding
using atomic_int_fast16_t = atomic<int_fast16_t>;  // freestanding
using atomic_uint_fast16_t = atomic<uint_fast16_t>;  // freestanding
using atomic_int_fast32_t = atomic<int_fast32_t>;  // freestanding
using atomic_uint_fast32_t = atomic<uint_fast32_t>;  // freestanding
using atomic_int_fast64_t = atomic<int_fast64_t>;  // freestanding
using atomic_uint_fast64_t = atomic<uint_fast64_t>;  // freestanding
using atomicintptr_t = atomic<intptr_t>;  // freestanding
using atomicuintptr_t = atomic<uintptr_t>;  // freestanding
using atomic_size_t = atomic<size_t>;  // freestanding
using atomic_ptrdiff_t = atomic<ptrdiff_t>;  // freestanding
using atomic_intmax_t = atomic<intmax_t>;  // freestanding
using atomic_uintmax_t = atomic<uintmax_t>;  // freestanding
using atomic_signed_lock_free = see below;  // freestanding
using atomic_unsigned_lock_free = see below;  // freestanding

// 33.5.10, flag type and operations
struct atomic_flag;  // freestanding

bool atomic_flag_test(const volatile atomic_flag*) noexcept;  // freestanding
bool atomic_flag_test(const atomic_flag*) noexcept;  // freestanding
bool atomic_flag_test_explicit(const volatile atomic_flag*, memory_order) noexcept;  // freestanding
bool atomic_flag_test_explicit(const atomic_flag*, memory_order) noexcept;  // freestanding
bool atomic_flag_test_and_set(volatile atomic_flag*) noexcept;  // freestanding
bool atomic_flag_test_and_set(atomic_flag*) noexcept;  // freestanding
bool atomic_flag_test_and_set_explicit(volatile atomic_flag*, memory_order) noexcept;  // freestanding
bool atomic_flag_test_and_set_explicit(atomic_flag*, memory_order) noexcept;  // freestanding
void atomic_flag_clear(volatile atomic_flag*) noexcept;  // freestanding
void atomic_flag_clear(atomic_flag*) noexcept;  // freestanding
void atomic_flag_clear_explicit(volatile atomic_flag*, memory_order) noexcept;  // freestanding
void atomic_flag_clear_explicit(atomic_flag*, memory_order) noexcept;  // freestanding
void atomic_flag_wait(const volatile atomic_flag*, bool) noexcept;  // freestanding
void atomic_flag_wait(const atomic_flag*, bool) noexcept;  // freestanding
void atomic_flag_wait_explicit(const volatile atomic_flag*, bool, memory_order) noexcept;  // freestanding
void atomic_flag_wait_explicit(const atomic_flag*, bool, memory_order) noexcept;  // freestanding
void atomic_flag_notify_one(volatile atomic_flag*) noexcept;  // freestanding
void atomic_flag_notify_one(atomic_flag*) noexcept;  // freestanding
void atomic_flag_notify_all(volatile atomic_flag*) noexcept;  // freestanding

§ 33.5.2
void atomic_flag_notify_all(atomic_flag*) noexcept;  // freestanding
#define ATOMIC_FLAG_INIT see below  // freestanding

// 33.5.11, fences
extern "C" void atomic_thread_fence(memory_order) noexcept;  // freestanding
extern "C" void atomic_signal_fence(memory_order) noexcept;  // freestanding

33.5.3 Type aliases [atomics.alias]
1 The type aliases atomic_intN_t, atomic_uintN_t, atomic_intptr_t, and atomic_uintptr_t are defined if and only if intN_t, uintN_t, intptr_t, and uintptr_t are defined, respectively.
2 The type aliases atomic_signed_lock_free and atomic_unsigned_lock_free name specializations of atomic whose template arguments are integral types, respectively signed and unsigned, and whose is_always_lock_free property is true.
[Note 1: These aliases are optional in freestanding implementations (16.4.2.5). — end note]
Implementations should choose for these aliases the integral specializations of atomic for which the atomic waiting and notifying operations (33.5.6) are most efficient.

33.5.4 Order and consistency [atomics.order]

namespace std {
enum class memory_order : unspecified {
  relaxed, consume, acquire, release, acq_rel, seq_cst
};
}
1 The enumeration memory_order specifies the detailed regular (non-atomic) memory synchronization order as defined in 6.9.2 and may provide for operation ordering. Its enumerated values and their meanings are as follows:

(1.1) memory_order::relaxed: no operation orders memory.
(1.2) memory_order::release, memory_order::acq_rel, and memory_order::seq_cst: a store operation performs a release operation on the affected memory location.
(1.3) memory_order::consume: a load operation performs a consume operation on the affected memory location.
[Note 1: Prefer memory_order::acquire, which provides stronger guarantees than memory_order::consume. Implementations have found it infeasible to provide performance better than that of memory_order::acquire. Specification revisions are under consideration. — end note]
(1.4) memory_order::acquire, memory_order::acq_rel, and memory_order::seq_cst: a load operation performs an acquire operation on the affected memory location.
[Note 2: Atomic operations specifying memory_order::relaxed are relaxed with respect to memory ordering. Implementations must still guarantee that any given atomic access to a particular atomic object be indivisible with respect to all other atomic accesses to that object. — end note]
2 An atomic operation A that performs a release operation on an atomic object M synchronizes with an atomic operation B that performs an acquire operation on M and takes its value from any side effect in the release sequence headed by A.
3 An atomic operation A on some atomic object M is coherence-ordered before another atomic operation B on M if

(3.1) A is a modification, and B reads the value stored by A, or
(3.2) A precedes B in the modification order of M, or
(3.3) A and B are not the same atomic read-modify-write operation, and there exists an atomic modification X of M such that A reads the value stored by X and X precedes B in the modification order of M, or
(3.4) there exists an atomic modification X of M such that A is coherence-ordered before X and X is coherence-ordered before B.
4 There is a single total order S on all memory_order::seq_cst operations, including fences, that satisfies the following constraints. First, if A and B are memory_order::seq_cst operations and A strongly happens
before \(B\), then \(A\) precedes \(B\) in \(S\). Second, for every pair of atomic operations \(A\) and \(B\) on an object \(M\), where \(A\) is coherence-ordered before \(B\), the following four conditions are required to be satisfied by \(S\):

1. If \(A\) and \(B\) are both \texttt{memory\_order::seq\_cst} operations, then \(A\) precedes \(B\) in \(S\); and
2. If \(A\) is a \texttt{memory\_order::seq\_cst} operation and \(B\) happens before a \texttt{memory\_order::seq\_cst} fence \(Y\), then \(A\) precedes \(Y\) in \(S\); and
3. If a \texttt{memory\_order::seq\_cst} fence \(X\) happens before \(A\) and \(B\) is a \texttt{memory\_order::seq\_cst} operation, then \(X\) precedes \(B\) in \(S\); and
4. If a \texttt{memory\_order::seq\_cst} fence \(X\) happens before \(A\) and \(B\) happens before a \texttt{memory\_order::seq\_cst} fence \(Y\), then \(X\) precedes \(Y\) in \(S\).

\[\text{Note 3:}\] This definition ensures that \(S\) is consistent with the modification order of any atomic object \(M\). It also ensures that a \texttt{memory\_order::seq\_cst} load \(A\) of \(M\) gets its value either from the last modification of \(M\) that precedes \(A\) in \(S\) or from some non-\texttt{memory\_order::seq\_cst} modification of \(M\) that does not happen before any modification of \(M\) that precedes \(A\) in \(S\). —end note\]

\[\text{Note 4:}\] We do not require that \(S\) be consistent with “happens before” (6.9.2.2). This allows more efficient implementation of \texttt{memory\_order::acquire} and \texttt{memory\_order::release} on some machine architectures. It can produce surprising results when these are mixed with \texttt{memory\_order::seq\_cst} accesses. —end note\]

\[\text{Note 5:}\] \texttt{memory\_order::seq\_cst} ensures sequential consistency only for a program that is free of data races and uses exclusively \texttt{memory\_order::seq\_cst} atomic operations. Any use of weaker ordering will invalidate this guarantee unless extreme care is used. In many cases, \texttt{memory\_order::seq\_cst} atomic operations are reorderable with respect to other atomic operations performed by the same thread. —end note\]

Implementations should ensure that no “out-of-thin-air” values are computed that circularly depend on their own computation.

\[\text{Note 6:}\] For example, with \(x\) and \(y\) initially zero,

// Thread 1:
\(r1 = y.load(memory\_order::relaxed);\)
\(x.store(r1, memory\_order::relaxed);\)

// Thread 2:
\(r2 = x.load(memory\_order::relaxed);\)
\(y.store(r2, memory\_order::relaxed);\)

this recommendation discourages producing \(r1 == r2 == 42\), since the store of 42 to \(y\) is only possible if the store to \(x\) stores 42, which circularly depends on the store to \(y\) storing 42. Note that without this restriction, such an execution is possible. —end note\]

\[\text{Note 7:}\] The recommendation similarly disallows \(r1 == r2 == 42\) in the following example, with \(x\) and \(y\) again initially zero:

// Thread 1:
\(r1 = x.load(memory\_order::relaxed);\)
if (\(r1 == 42\)) \(y.store(42, memory\_order::relaxed);\)

// Thread 2:
\(r2 = y.load(memory\_order::relaxed);\)
if (\(r2 == 42\)) \(x.store(42, memory\_order::relaxed);\)

—end note\]

Atomic read-modify-write operations shall always read the last value (in the modification order) written before the write associated with the read-modify-write operation.

\textit{Recommended practice:} The implementation should make atomic stores visible to atomic loads, and atomic loads should observe atomic stores, within a reasonable amount of time.

\[\text{template<class T>}\]
\(T\) \texttt{kill\_dependency(T y) noexcept;}\]

\textit{Effects:} The argument does not carry a dependency to the return value (6.9.2).

\textit{Returns:} \(y\).

33.5.5 Lock-free property [atomics.lockfree]
#define ATOMIC_BOOL_LOCK_FREE unspecified
#define ATOMIC_CHAR_LOCK_FREE unspecified
#define ATOMIC_CHAR8_T_LOCK_FREE unspecified
#define ATOMIC_CHAR16_T_LOCK_FREE unspecified
#define ATOMIC_CHAR32_T_LOCK_FREE unspecified
#define ATOMIC_WCHAR_T_LOCK_FREE unspecified
#define ATOMIC_SHORT_LOCK_FREE unspecified
#define ATOMIC_INT_LOCK_FREE unspecified
#define ATOMIC_LONG_LOCK_FREE unspecified
#define ATOMIC_LLONG_LOCK_FREE unspecified
#define ATOMIC_POINTER_LOCK_FREE unspecified

1 The ATOMIC_..._LOCK_FREE macros indicate the lock-free property of the corresponding atomic types, with the signed and unsigned variants grouped together. The properties also apply to the corresponding (partial) specializations of the atomic template. A value of 0 indicates that the types are never lock-free. A value of 1 indicates that the types are sometimes lock-free. A value of 2 indicates that the types are always lock-free.

2 On a hosted implementation (16.4.2.5), at least one signed integral specialization of the atomic template, along with the specialization for the corresponding unsigned type (6.8.2), is always lock-free.

3 The functions atomic<T>::is_lock_free and atomic_is_lock_free (33.5.8.2) indicate whether the object is lock-free. In any given program execution, the result of the lock-free query is the same for all atomic objects of the same type.

4 Atomic operations that are not lock-free are considered to potentially block (6.9.2.3).

5 Recommended practice: Operations that are lock-free should also be address-free.300 The implementation of these operations should not depend on any per-process state.

[Note 1: This restriction enables communication by memory that is mapped into a process more than once and by memory that is shared between two processes. — end note]

33.5.6 Waiting and notifying [atomics.wait]

Atomic waiting operations and atomic notifying operations provide a mechanism to wait for the value of an atomic object to change more efficiently than can be achieved with polling. An atomic waiting operation may block until it is unblocked by an atomic notifying operation, according to each function’s effects.

[Note 1: Programs are not guaranteed to observe transient atomic values, an issue known as the A-B-A problem, resulting in continued blocking if a condition is only temporarily met. — end note]

2 [Note 2: The following functions are atomic waiting operations:

(2.1) — atomic<T>::wait,
(2.2) — atomic_flag::wait,
(2.3) — atomic_wait and atomic_wait_explicit,
(2.4) — atomic_flag_wait and atomic_flag_wait_explicit, and
(2.5) — atomic_ref<T>::wait.
— end note]

3 [Note 3: The following functions are atomic notifying operations:

(3.1) — atomic<T>::notify_one and atomic<T>::notify_all,
(3.2) — atomic_flag::notify_one and atomic_flag::notify_all,
(3.3) — atomic_notify_one and atomic_notify_all,
(3.4) — atomic_flag_notify_one and atomic_flag_notify_all, and
(3.5) — atomic_ref<T>::notify_one and atomic_ref<T>::notify_all.
— end note]

4 A call to an atomic waiting operation on an atomic object M is eligible to be unblocked by a call to an atomic notifying operation on M if there exist side effects X and Y on M such that:

(4.1) — the atomic waiting operation has blocked after observing the result of X,
(4.2) — X precedes Y in the modification order of M, and

300 That is, atomic operations on the same memory location via two different addresses will communicate atomically.
(4.3) — Y happens before the call to the atomic notifying operation.

33.5.7 Class template atomic_ref

33.5.7.1 General

namespace std {
    template<class T> struct atomic_ref {
        private:
            T* ptr; // exposition only

        public:
            using value_type = T;
            static constexpr size_t required_alignment = implementation-defined;
            static constexpr bool is_always_lock_free = implementation-defined;
            bool is_lock_free() const noexcept;
            explicit atomic_ref(T&);
            atomic_ref(const atomic_ref&) noexcept;
            atomic_ref& operator=(const atomic_ref&) = delete;
            void store(T, memory_order = memory_order::seq_cst) const noexcept;
            T operator=(T) const noexcept;
            T load(memory_order = memory_order::seq_cst) const noexcept;
            operator T() const noexcept;
            T exchange(T, memory_order = memory_order::seq_cst) const noexcept;
            bool compare_exchange_weak(T&, T, memory_order, memory_order) const noexcept;
            bool compare_exchange_strong(T&, T, memory_order, memory_order) const noexcept;
            void wait(T, memory_order = memory_order::seq_cst) const noexcept;
            void notify_one() const noexcept;
            void notify_all() const noexcept;
    };
}

1 An atomic_ref object applies atomic operations (33.5.1) to the object referenced by *ptr such that, for the lifetime (6.7.3) of the atomic_ref object, the object referenced by *ptr is an atomic object (6.9.2.2).

2 The program is ill-formed if is_trivially_copyable_v<T> is false.

3 The lifetime (6.7.3) of an object referenced by *ptr shall exceed the lifetime of all atomicRefs that reference the object. While any atomic_ref instances exist that reference the *ptr object, all accesses to that object shall exclusively occur through those atomic_ref instances. No subobject of the object referenced by atomic_ref shall be concurrently referenced by any other atomic_ref object.

4 Atomic operations applied to an object through a referencing atomic_ref are atomic with respect to atomic operations applied through any other atomic_ref referencing the same object.

[Note 1: Atomic operations or the atomic_ref constructor can acquire a shared resource, such as a lock associated with the referenced object, to enable atomic operations to be applied to the referenced object. — end note]

33.5.7.2 Operations

static constexpr size_t required_alignment;

1 The alignment required for an object to be referenced by an atomic reference, which is at least alignof(T).

2 [Note 1: Hardware could require an object referenced by an atomic_ref to have stricter alignment (6.7.6) than other objects of type T. Further, whether operations on an atomic_ref are lock-free could depend on
the alignment of the referenced object. For example, lock-free operations on `std::complex<double>` could be supported only if aligned to `2*alignof(double)`.

--- end note

```cpp
static constexpr bool is_always_lock_free;
3
The static data member `is_always_lock_free` is true if the `atomic_ref` type's operations are always lock-free, and false otherwise.

bool is_lock_free() const noexcept;
4
Returns: true if operations on all objects of the type `atomic_ref<T>` are lock-free, false otherwise.

atomic_ref(T& obj);
5
Preconditions: The referenced object is aligned to `required_alignment`.

Postconditions: `*this` references `obj`.

Throws: Nothing.

atomic_ref(const atomic_ref& ref) noexcept;
6
Postconditions: `*this` references the object referenced by `ref`.

void store(T desired, memory_order order = memory_order::seq_cst) const noexcept;
7
Preconditions: order is `memory_order::relaxed`, `memory_order::release`, or `memory_order::seq_cst`.

Effects: Atomically replaces the value referenced by `*ptr` with the value of `desired`. Memory is affected according to the value of `order`.

T operator=(T desired) const noexcept;
8
Effects: Equivalent to:

```
store(desired);
return desired;
```

T load(memory_order order = memory_order::seq_cst) const noexcept;
9
Preconditions: order is `memory_order::relaxed`, `memory_order::consume`, `memory_order::acquire`, or `memory_order::seq_cst`.

Effects: Memory is affected according to the value of `order`.

Returns: Atomically returns the value referenced by `*ptr`.

operator T() const noexcept;
10
Effects: Equivalent to: return `load()`;

T exchange(T desired, memory_order order = memory_order::seq_cst) const noexcept;
11
Effects: Atomically replaces the value referenced by `*ptr` with `desired`. Memory is affected according to the value of `order`. This operation is an atomic read-modify-write operation (6.9.2).

Returns: Atomically returns the value referenced by `*ptr` immediately before the effects.

bool compare_exchange_weak(T& expected, T desired,
12
memory_order success, memory_order failure) const noexcept;

bool compare_exchange_strong(T& expected, T desired,
13
memory_order success, memory_order failure) const noexcept;

bool compare_exchange_weak(T& expected, T desired,
14
memory_order order = memory_order::seq_cst) const noexcept;

bool compare_exchange_strong(T& expected, T desired,
15
memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: failure is `memory_order::relaxed`, `memory_order::consume`, `memory_order::acquire`, or `memory_order::seq_cst`.

§ 33.5.7.2
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Effects: Retrieves the value in expected. It then atomically compares the value represented by *ptr with that in desired. If and only if the comparison is true, memory is affected according to the value of success, and if the comparison is false, memory is affected according to the value of failure. When only one memory_order argument is supplied, the value of success is order, and the value of failure is order except that a value of memory_order::acq_rel shall be replaced by the value memory_order::acquire and a value of memory_order::release shall be replaced by the value memory_order::relaxed. If and only if the comparison is false then, after the atomic operation, the value in expected is replaced by the value read from the value referenced by *ptr during the atomic comparison. If the operation returns true, these operations are atomic read-modify-write operations (6.9.2.2) on the value referenced by *ptr. Otherwise, these operations are atomic load operations on that memory.

Returns: The result of the comparison.

Remarks: A weak compare-and-exchange operation may fail spuriously. That is, even when the contents of memory referred to by expected and ptr are equal, it may return false and store back to expected the same memory contents that were originally there.

[Note 2: This spurious failure enables implementation of compare-and-exchange on a broader class of machines, e.g., load-locked store-conditional machines. A consequence of spurious failure is that nearly all uses of weak compare-and-exchange will be in a loop. When a compare-and-exchange is in a loop, the weak version will yield better performance on some platforms. When a weak compare-and-exchange would require a loop and a strong one would not, the strong one is preferable. — end note]

void wait(T old, memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: order is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: Repeatedly performs the following steps, in order:

(23.1) — Evaluates load(order) and compares its value representation for equality against that of old.
(23.2) — If they compare unequal, returns.
(23.3) — Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

Remarks: This function is an atomic waiting operation (33.5.6) on atomic object *ptr.

void notify_one() const noexcept;

Effects: Unblocks the execution of at least one atomic waiting operation on *ptr that is eligible to be unblocked (33.5.6) by this call, if any such atomic waiting operations exist.

Remarks: This function is an atomic notifying operation (33.5.6) on atomic object *ptr.

void notify_all() const noexcept;

Effects: Unblocks the execution of all atomic waiting operations on *ptr that are eligible to be unblocked (33.5.6) by this call.

Remarks: This function is an atomic notifying operation (33.5.6) on atomic object *ptr.

33.5.7.3 Specializations for integral types

There are specializations of the atomic_ref class template for the integral types char, signed char, unsigned char, short, unsigned short, int, unsigned int, long, unsigned long, long long, char8_t, char16_t, char32_t, wchar_t, and any other types needed by the typedefs in the header <cstdint> (17.4.1). For each such type integral-type, the specialization atomic_ref<integral-type> provides additional atomic operations appropriate to integral types.

[Note 1: The specialization atomic_ref<bool> uses the primary template (33.5.7). — end note]
using difference_type = value_type;
static constexpr size_t required_alignment = implementation-defined;

static constexpr bool is_always_lock_free = implementation-defined;
bool is_lock_free() const noexcept;

explicit atomic_ref(integral-type&);
atomic_ref(const atomic_ref&) noexcept;
atomic_ref& operator=(const atomic_ref&) = delete;

void store(integral-type, memory_order = memory_order::seq_cst) const noexcept;
integral-type operator=(integral-type) const noexcept;
integral-type load(memory_order = memory_order::seq_cst) const noexcept;
operator integral-type() const noexcept;

integral-type exchange(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
bool compare_exchange_weak(integral-type&,
integral-type,
memory_order, memory_order) const noexcept;
bool compare_exchange_strong(integral-type&,
integral-type,
memory_order, memory_order) const noexcept;
bool compare_exchange_weak(integral-type&,
integral-type,
memory_order = memory_order::seq_cst) const noexcept;
bool compare_exchange_strong(integral-type&,
integral-type,
memory_order = memory_order::seq_cst) const noexcept;

integral-type fetch_add(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
integral-type fetch_sub(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
integral-type fetch_and(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
integral-type fetch_or(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
integral-type fetch_xor(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
integral-type fetch_max(integral-type,
memory_order = memory_order::seq_cst) const noexcept;
integral-type fetch_min(integral-type,
memory_order = memory_order::seq_cst) const noexcept;

integral-type operator++(int) const noexcept;
integral-type operator--(int) const noexcept;
integral-type operator++() const noexcept;
integral-type operator--() const noexcept;
integral-type operator+=(integral-type) const noexcept;
integral-type operator-=(integral-type) const noexcept;
integral-type operator&=(integral-type) const noexcept;
integral-type operator|=(integral-type) const noexcept;
integral-type operator^=(integral-type) const noexcept;

void wait(integral-type, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() const noexcept;
void notify_all() const noexcept;
};

2 Descriptions are provided below only for members that differ from the primary template.
3 The following operations perform arithmetic computations. The correspondence among key, operator, and computation is specified in Table 148.

§ 33.5.7.3
integral-type fetch_key(integral-type operand,
    memory_order order = memory_order::seq_cst) const noexcept;

Effects: Atomically replaces the value referenced by *ptr with the result of the computation applied to the value referenced by *ptr and the given operand. Memory is affected according to the value of order. These operations are atomic read-modify-write operations (6.9.2.2).

Returns: Atomically, the value referenced by *ptr immediately before the effects.

Remarks: Except for fetch_max and fetch_min, for signed integer types the result is as if the object value and parameters were converted to their corresponding unsigned types, the computation performed on those types, and the result converted back to the signed type.

[Note 2: There are no undefined results arising from the computation. — end note]

For fetch_max and fetch_min, the maximum and minimum computation is performed as if by max and min algorithms (27.8.9), respectively, with the object value and the first parameter as the arguments.

integral-type operator op=(integral-type operand) const noexcept;

Effects: Equivalent to: return fetch_key(operand) op operand;

33.5.7.4 Specializations for floating-point types [atomics.ref.float]

There are specializations of the atomic_ref class template for all cv-unqualified floating-point types. For each such type floating-point-type, the specialization atomic_ref<floating-point-type> provides additional atomic operations appropriate to floating-point types.

namespace std {
    template<> struct atomic_ref<floating-point-type> {
        private:
            floating-point-type* ptr; // exposition only

        public:
            using value_type = floating-point-type;
            using difference_type = value_type;
            static constexpr size_t required_alignment = implementation-defined;
            static constexpr bool is_always_lock_free = implementation-defined;

            bool is_lock_free() const noexcept;
            explicit atomic_ref(floating-point-type&);
            atomic_ref(const atomic_ref&) noexcept;
            atomic_ref& operator=(const atomic_ref&) = delete;

            void store(floating-point-type, memory_order = memory_order::seq_cst) const noexcept;
            floating-point-type operator=(floating-point-type) const noexcept;
            floating-point-type load(memory_order = memory_order::seq_cst) const noexcept;
            operator floating-point-type() const noexcept;

            floating-point-type exchange(floating-point-type,
                memory_order = memory_order::seq_cst) const noexcept;
            bool compare_exchange_weak(floating-point-type&, floating-point-type,
                memory_order, memory_order) const noexcept;

            bool compare_exchange_strong(floating-point-type&, floating-point-type,
                memory_order, memory_order) const noexcept;

            bool compare_exchange_weak(floating-point-type&, floating-point-type,
                memory_order = memory_order::seq_cst) const noexcept;

            bool compare_exchange_strong(floating-point-type&, floating-point-type,
                memory_order = memory_order::seq_cst) const noexcept;

            floating-point-type fetch_add(floating-point-type,
                memory_order = memory_order::seq_cst) const noexcept;

            floating-point-type fetch_sub(floating-point-type,
                memory_order = memory_order::seq_cst) const noexcept;

            floating-point-type operator+=(floating-point-type) const noexcept;
            floating-point-type operator-=(floating-point-type) const noexcept;

    };

§ 33.5.7.4 © ISO/IEC 1959
void wait(floating-point-type, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() const noexcept;
void notify_all() const noexcept;
};
}

Descriptions are provided below only for members that differ from the primary template.
The following operations perform arithmetic computations. The correspondence among key, operator, and computation is specified in Table 148.

floating-point-type fetch_key(floating-point-type operand,
   memory_order order = memory_order::seq_cst) const noexcept;

**Effects**: Atomically replaces the value referenced by *ptr with the result of the computation applied to the value referenced by *ptr and the given operand. Memory is affected according to the value of order. These operations are atomic read-modify-write operations (6.9.2.2).

**Returns**: Atomically, the value referenced by *ptr immediately before the effects.

**Remarks**: If the result is not a representable value for its type (7.1), the result is unspecified, but the operations otherwise have no undefined behavior. Atomic arithmetic operations on floating-point-type should conform to the std::numeric_limits-floating-point-type> traits associated with the floating-point type (17.3.3). The floating-point environment (28.3) for atomic arithmetic operations on floating-point-type may be different than the calling thread’s floating-point environment.

floating-point-type operator op=(floating-point-type operand) const noexcept;

**Effects**: Equivalent to: return fetch_key(operand) op operand;

### 33.5.7.5 Partial specialization for pointers

namespace std {
    template<class T> struct atomic_ref<T*> {
        private:
            T** ptr; // exposition only

        public:
            using value_type = T*;
            using difference_type = ptrdiff_t;
            static constexpr size_t required_alignment = implementation-defined;
            static constexpr bool is_always_lock_free = implementation-defined;
            bool is_lock_free() const noexcept;
            atomic_ref(T*&) noexcept;
            atomic_ref(const atomic_ref&) noexcept;
            atomic_ref& operator=(const atomic_ref&) = delete;
            void store(T*, memory_order = memory_order::seq_cst) const noexcept;
            T* operator=(T*) const noexcept;
            T* load(memory_order = memory_order::seq_cst) const noexcept;
            operator T*() const noexcept;
            T* exchange(T*, memory_order = memory_order::seq_cst) const noexcept;
            bool compare_exchange_weak(T*& t,
                memory_order, memory_order) const noexcept;
            bool compare_exchange_strong(T*& t,
                memory_order, memory_order) const noexcept;
            bool compare_exchange_weak(T*& t,
                memory_order = memory_order::seq_cst) const noexcept;
            bool compare_exchange_strong(T*& t,
                memory_order = memory_order::seq_cst) const noexcept;
            T* fetch_add(difference_type, memory_order = memory_order::seq_cst) const noexcept;
            T* fetch_sub(difference_type, memory_order = memory_order::seq_cst) const noexcept;
            T* fetch_max(T*, memory_order = memory_order::seq_cst) const noexcept;
            T* fetch_min(T*, memory_order = memory_order::seq_cst) const noexcept;
    };
}
T* operator++(int) const noexcept;
T* operator--(int) const noexcept;
T* operator++() const noexcept;
T* operator--() const noexcept;
T* operator+=(difference_type) const noexcept;
T* operator-=(difference_type) const noexcept;

void wait(T*, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() const noexcept;
void notify_all() const noexcept;

1 Descriptions are provided below only for members that differ from the primary template.

2 The following operations perform arithmetic computations. The correspondence among key, operator, and
computation is specified in Table 149.

T* fetch_key(difference_type operand, memory_order order = memory_order::seq_cst) const noexcept;

Mandates: T is a complete object type.

Effects: Atomically replaces the value referenced by *ptr with the result of the computation applied
to the value referenced by *ptr and the given operand. Memory is affected according to the value of
order. These operations are atomic read-modify-write operations (6.9.2.2).

Returns: Atomically, the value referenced by *ptr immediately before the effects.

Remarks: The result may be an undefined address, but the operations otherwise have no undefined
behavior.

7 For fetch_max and fetch_min, the maximum and minimum computation is performed as if by max and
min algorithms (27.8.9), respectively, with the object value and the first parameter as the arguments.

[Note 1: If the pointers point to different complete objects (or subobjects thereof), the < operator does not
establish a strict weak ordering (Table 29, 7.6.9). — end note]

T* operator op=(difference_type operand) const noexcept;

Effects: Equivalent to: return fetch_key(operand) op operand;

33.5.7.6 Member operators common to integers and pointers to objects [atomics.ref.memop]

value_type operator++(int) const noexcept;

Effects: Equivalent to: return fetch_add(1);

value_type operator--(int) const noexcept;

Effects: Equivalent to: return fetch_sub(1);

value_type operator++() const noexcept;

Effects: Equivalent to: return fetch_add(1) + 1;

value_type operator--() const noexcept;

Effects: Equivalent to: return fetch_sub(1) - 1;

33.5.8 Class template atomic [atomics.types.generic]

33.5.8.1 General [atomics.types.generic.general]

namespace std {

 template<
class T>
struct atomic {

using value_type = T;

static constexpr bool is_always_lock_free = implementation-defined;

bool is_lock_free() const volatile noexcept;

bool is_lock_free() const noexcept;

};
33.5.8.2, operations on atomic types

constexpr atomic() noexcept(is_nothrow_default_constructible_v<T>);
constexpr atomic(T) noexcept;
 atomic(const atomic&) = delete;
 atomic& operator=(const atomic&) = delete;
 atomic& operator=(const atomic&) volatile = delete;

T load(memory_order = memory_order::seq_cst) const volatile noexcept;
T load(memory_order = memory_order::seq_cst) const noexcept;
 operator T() const volatile noexcept;
 operator T() const noexcept;
void store(T, memory_order = memory_order::seq_cst) volatile noexcept;
void store(T, memory_order = memory_order::seq_cst) noexcept;
T operator=(T) volatile noexcept;
T operator=(T) noexcept;
T exchange(T, memory_order = memory_order::seq_cst) volatile noexcept;
T exchange(T, memory_order = memory_order::seq_cst) noexcept;
bool compare_exchange_weak(T&, T, memory_order, memory_order) volatile noexcept;
bool compare_exchange_weak(T&, T, memory_order, memory_order) noexcept;
bool compare_exchange_strong(T&, T, memory_order, memory_order) volatile noexcept;
bool compare_exchange_strong(T&, T, memory_order, memory_order) noexcept;
bool compare_exchange_weak(T&, T, memory_order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_weak(T&, T, memory_order = memory_order::seq_cst) noexcept;
bool compare_exchange_strong(T&, T, memory_order = memory_order::seq_cst) noexcept;
bool compare_exchange_strong(T&, T, memory_order = memory_order::seq_cst) noexcept;
void wait(T, memory_order = memory_order::seq_cst) const volatile noexcept;
void wait(T, memory_order = memory_order::seq_cst) const noexcept;
 void notify_one() volatile noexcept;
 void notify_one() noexcept;
 void notify_all() volatile noexcept;
 void notify_all() noexcept;

1 The template argument for $T$ shall meet the `Cpp17CopyConstructible` and `Cpp17CopyAssignable` requirements. The program is ill-formed if any of

1. `is_trivially_copyable_v<T>`
2. `is_copy_constructible_v<T>`
3. `is_move_constructible_v<T>`
4. `is_copy_assignable_v<T>`
5. `is_move_assignable_v<T>`

is false.

[Note 1: Type arguments that are not also statically initializable can be difficult to use. — end note]

2 The specialization `atomic<bool>` is a standard-layout struct. It has a trivial destructor.

[Note 2: The representation of an atomic specialization need not have the same size and alignment requirement as its corresponding argument type. — end note]

33.5.8.2 Operations on atomic types

constexpr atomic() noexcept(is_nothrow_default_constructible_v<T>);

Mandates: `is_default_constructible_v<T>` is true.

Effects: Initializes the atomic object with the value of $T()$. Initialization is not an atomic operation (6.9.2).

constexpr atomic(T desired) noexcept;

Effects: Initializes the object with the value `desired`. Initialization is not an atomic operation (6.9.2).
[Note 1: It is possible to have an access to an atomic object A race with its construction, for example by communicating the address of the just-constructed object A to another thread via memory_order::relaxed operations on a suitable atomic pointer variable, and then immediately accessing A in the receiving thread. This results in undefined behavior. — end note]

static constexpr bool is_always_lock_free = implementation-defined;

The static data member is_always_lock_free is true if the atomic type’s operations are always lock-free, and false otherwise.

[Note 2: The value of is_always_lock_free is consistent with the value of the corresponding ATOMIC_..._LOCK_FREE macro, if defined. — end note]

bool is_lock_free() const volatile noexcept;
bool is_lock_free() const noexcept;

Returns: true if the object’s operations are lock-free, false otherwise.

[Note 3: The return value of the is_lock_free member function is consistent with the value of is_always_lock_free for the same type. — end note]

void store(T desired, memory_order order = memory_order::seq_cst) volatile noexcept;
void store(T desired, memory_order order = memory_order::seq_cst) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Preconditions: order is memory_order::relaxed, memory_order::release, or memory_order::seq_cst.

Effects: Atomically replaces the value pointed to by this with the value of desired. Memory is affected according to the value of order.

T operator=(T desired) volatile noexcept;
T operator=(T desired) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to store(desired).

Returns: desired.

T load(memory_order order = memory_order::seq_cst) const volatile noexcept;
T load(memory_order order = memory_order::seq_cst) const noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Preconditions: order is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: Memory is affected according to the value of order.

Returns: Atomically returns the value pointed to by this.

operator T() const volatile noexcept;
operator T() const noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to: return load();

T exchange(T desired, memory_order order = memory_order::seq_cst) volatile noexcept;
T exchange(T desired, memory_order order = memory_order::seq_cst) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Atomically replaces the value pointed to by this with desired. Memory is affected according to the value of order. These operations are atomic read-modify-write operations (6.9.2).

Returns: Atomically returns the value pointed to by this immediately before the effects.

bool compare_exchange_weak(T& expected, T desired,
memory_order success, memory_order failure) volatile noexcept;
bool compare_exchange_weak(T& expected, T desired,
memory_order success, memory_order failure) noexcept;
bool compare_exchange_strong(T& expected, T desired, memory_order success, memory_order failure) volatile noexcept;
bool compare_exchange_strong(T& expected, T desired, memory_order success, memory_order failure) noexcept;
bool compare_exchange_weak(T& expected, T desired, memory_order order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_weak(T& expected, T desired, memory_order order = memory_order::seq_cst) noexcept;
bool compare_exchange_strong(T& expected, T desired, memory_order order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_strong(T& expected, T desired, memory_order order = memory_order::seq_cst) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Preconditions: failure is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: Retrieves the value in expected. It then atomically compares the value representation of the value pointed to by this for equality with that previously retrieved from expected, and if true, replaces the value pointed to by this with that in desired. If and only if the comparison is true, memory is affected according to the value of success, and if the comparison is false, memory is affected according to the value of failure. When only one memory_order argument is supplied, the value of success is order, and the value of failure is order except that a value of memory_order::acq_rel shall be replaced by the value memory_order::acquire and a value of memory_order::release shall be replaced by the value memory_order::relaxed. If and only if the comparison is false then, after the atomic operation, the value in expected is replaced by the value pointed to by this during the atomic comparison. If the operation returns true, these operations are atomic read-modify-write operations (6.9.2) on the memory pointed to by this. Otherwise, these operations are atomic load operations on that memory.

Returns: The result of the comparison.

[Note 4: For example, the effect of compare_exchange_strong on objects without padding bits (6.8.1) is]

if (memcmp(this, &expected, sizeof(*this)) == 0)
    memcpy(this, &desired, sizeof(*this));
else
    memcpy(&expected, this, sizeof(*this));
—end note]

[Example 1: The expected use of the compare-and-exchange operations is as follows. The compare-and-exchange operations will update expected when another iteration of the loop is needed.]

expected = current.load();
do {
    desired = function(expected);
} while (!current.compare_exchange_weak(expected, desired));
—end example]

[Example 2: Because the expected value is updated only on failure, code releasing the memory containing the expected value on success will work. For example, list head insertion will act atomically and would not introduce a data race in the following code:]

do {
    p->next = head;                         // make new list node point to the current head
} while (!head.compare_exchange_weak(p->next, p));  // try to insert
—end example]

Implementations should ensure that weak compare-and-exchange operations do not consistently return false unless either the atomic object has value different from expected or there are concurrent modifications to the atomic object.

Remarks: A weak compare-and-exchange operation may fail spuriously. That is, even when the contents of memory referred to by expected and this are equal, it may return false and store back to expected the same memory contents that were originally there.

[Note 5: This spurious failure enables implementation of compare-and-exchange on a broader class of machines, e.g., load-locked store-conditional machines. A consequence of spurious failure is that nearly all uses of weak
compare-and-exchange will be in a loop. When a compare-and-exchange is in a loop, the weak version will yield better performance on some platforms. When a weak compare-and-exchange would require a loop and a strong one would not, the strong one is preferable. —end note

[Note 6: Under cases where the memcpy and memcmp semantics of the compare-and-exchange operations apply, the comparisons can fail for values that compare equal with operator== if the value representation has trap bits or alternate representations of the same value. Notably, on implementations conforming to ISO/IEC 60559, floating-point -0.0 and +0.0 will not compare equal with memcpy but will compare equal with operator==, and NaNs with the same payload will compare equal with memcpy but will not compare equal with operator==. —end note]

[Note 7: Because compare-and-exchange acts on an object’s value representation, padding bits that never participate in the object’s value representation are ignored. As a consequence, the following code is guaranteed to avoid spurious failure:

```c
struct padded {
    char clank = 0x42;
    // Padding here.
    unsigned biff = 0xC0DEFEFE;
};
atomic<padded> pad = {};

bool zap() {
    padded expected, desired{0, 0};
    return pad.compare_exchange_strong(expected, desired);
}
—end note]

[Note 8: For a union with bits that participate in the value representation of some members but not others, compare-and-exchange might always fail. This is because such padding bits have an indeterminate value when they do not participate in the value representation of the active member. As a consequence, the following code is not guaranteed to ever succeed:

```c
union pony {
    double celestia = 0.;
    short luna; // padded
};
atomic<pony> princesses = {};

bool party(pony desired) {
    pony expected;
    return princesses.compare_exchange_strong(expected, desired);
}
—end note]

§ 33.5.8.2

The function wait() evaluates load(order) and compares its value representation for equality against that of old.

Effects: Repeatedly performs the following steps, in order:

- If they compare unequal, returns.
- Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

Remarks: This function is an atomic waiting operation (33.5.6).

The function notify_one() unblocks the execution of at least one atomic waiting operation that is eligible to be unblocked (33.5.6) by this call, if any such atomic waiting operations exist.

Remarks: This function is an atomic notifying operation (33.5.6).
```cpp
void notify_all() noexcept;

Effects: Unblocks the execution of all atomic waiting operations that are eligible to be unblocked (33.5.6) by this call.

Remarks: This function is an atomic notifying operation (33.5.6).

33.5.8.3 Specializations for integers [atomics.types.int]

There are specializations of the `atomic` class template for the integral types `char`, `signed char`, `unsigned char`, `short`, `unsigned short`, `int`, `unsigned int`, `long`, `unsigned long`, `long long`, `unsigned long long`, `char8_t`, `char16_t`, `char32_t`, `wchar_t`, and any other types needed by the typedefs in the header `<cstdint>` (17.4.1). For each such type `integral-type`, the specialization `atomic<integral-type>` provides additional atomic operations appropriate to integral types.

[Note 1: The specialization `atomic<bool>` uses the primary template (33.5.8). — end note]

namespace std {
    template<> struct atomic<integral-type> {
        using value_type = integral-type;
        using difference_type = value_type;

        static constexpr bool is_always_lock_free = implementation-defined;
        bool is_lock_free() const volatile noexcept;
        bool is_lock_free() const noexcept;

        constexpr atomic() noexcept;
        constexpr atomic(integral-type) noexcept;
        atomic(const atomic&) = delete;
        atomic& operator=(const atomic&) = delete;
        atomic& operator=(const atomic&) volatile = delete;
        void store(integral-type, memory_order = memory_order::seq_cst) volatile noexcept;
        void store(integral-type, memory_order = memory_order::seq_cst) noexcept;
        integral-type operator=(integral-type) volatile noexcept;
        integral-type operator=(integral-type) noexcept;
        integral-type load(memory_order = memory_order::seq_cst) const volatile noexcept;
        integral-type load(memory_order = memory_order::seq_cst) const noexcept;
        operator integral-type() const volatile noexcept;
        operator integral-type() const noexcept;
        integral-type exchange(integral-type,
            memory_order = memory_order::seq_cst) volatile noexcept;
        integral-type exchange(integral-type,
            memory_order = memory_order::seq_cst) noexcept;
        bool compare_exchange_weak(integral-type&, integral-type,
            memory_order, memory_order) volatile noexcept;
        bool compare_exchange_weak(integral-type&, integral-type,
            memory_order, memory_order) noexcept;
        bool compare_exchange_strong(integral-type&, integral-type,
            memory_order, memory_order) volatile noexcept;
        bool compare_exchange_strong(integral-type&, integral-type,
            memory_order, memory_order) noexcept;
        bool compare_exchange_weak(integral-type&, integral-type,
            memory_order = memory_order::seq_cst) volatile noexcept;
        bool compare_exchange_weak(integral-type&, integral-type,
            memory_order = memory_order::seq_cst) noexcept;
        bool compare_exchange_strong(integral-type&, integral-type,
            memory_order = memory_order::seq_cst) volatile noexcept;
        bool compare_exchange_strong(integral-type&, integral-type,
            memory_order = memory_order::seq_cst) noexcept;
        integral-type fetch_add(integral-type,
            memory_order = memory_order::seq_cst) volatile noexcept;
        integral-type fetch_add(integral-type,
            memory_order = memory_order::seq_cst) noexcept;
```
integral-type fetch_sub(integral-type,
    memory_order = memory_order::seq_cst) volatile noexcept;
integral-type fetch_sub(integral-type,
    memory_order = memory_order::seq_cst) noexcept;
integral-type fetch_and(integral-type,
    memory_order = memory_order::seq_cst) volatile noexcept;
integral-type fetch_and(integral-type,
    memory_order = memory_order::seq_cst) noexcept;
integral-type fetch_or(integral-type,
    memory_order = memory_order::seq_cst) volatile noexcept;
integral-type fetch_or(integral-type,
    memory_order = memory_order::seq_cst) noexcept;
integral-type fetch_xor(integral-type,
    memory_order = memory_order::seq_cst) volatile noexcept;
integral-type fetch_xor(integral-type,
    memory_order = memory_order::seq_cst) noexcept;
integral-type fetch_max(integral-type,
    memory_order = memory_order::seq_cst) volatile noexcept;
integral-type fetch_max(integral-type,
    memory_order = memory_order::seq_cst) noexcept;
integral-type fetch_min(integral-type,
    memory_order = memory_order::seq_cst) volatile noexcept;
integral-type fetch_min(integral-type,
    memory_order = memory_order::seq_cst) noexcept;
integral-type operator++(int) volatile noexcept;
integral-type operator++(int) noexcept;
integral-type operator--(int) volatile noexcept;
integral-type operator--(int) noexcept;
integral-type operator++() volatile noexcept;
integral-type operator++() noexcept;
integral-type operator--() volatile noexcept;
integral-type operator--() noexcept;
integral-type operator+=(integral-type) volatile noexcept;
integral-type operator+=(integral-type) noexcept;
integral-type operator-=(integral-type) volatile noexcept;
integral-type operator-=(integral-type) noexcept;
integral-type operator&=(integral-type) volatile noexcept;
integral-type operator&=(integral-type) noexcept;
integral-type operator|=(integral-type) volatile noexcept;
integral-type operator|=(integral-type) noexcept;
integral-type operator^=(integral-type) volatile noexcept;
integral-type operator^=(integral-type) noexcept;

void wait(integral-type, memory_order = memory_order::seq_cst) const volatile noexcept;
void wait(integral-type, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() volatile noexcept;
void notify_one() noexcept;
void notify_all() volatile noexcept;
void notify_all() noexcept;
}

2 The atomic integral specializations are standard-layout structs. They each have a trivial destructor.
3 Descriptions are provided below only for members that differ from the primary template.
4 The following operations perform arithmetic computations. The correspondence among key, operator, and
computation is specified in Table 148.

T fetch_key(T operand, memory_order order = memory_order::seq_cst) volatile noexcept;
T fetch_key(T operand, memory_order order = memory_order::seq_cst) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.
Table 148 — Atomic arithmetic computations

<table>
<thead>
<tr>
<th>key</th>
<th>Op</th>
<th>Computation</th>
<th>key</th>
<th>Op</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>add</td>
<td>+</td>
<td>addition</td>
<td>and</td>
<td>&amp;</td>
<td>bitwise and</td>
</tr>
<tr>
<td>sub</td>
<td>-</td>
<td>subtraction</td>
<td>or</td>
<td></td>
<td>bitwise inclusive or</td>
</tr>
<tr>
<td>max</td>
<td></td>
<td>maximum</td>
<td>xor</td>
<td>^</td>
<td>bitwise exclusive or</td>
</tr>
<tr>
<td>min</td>
<td></td>
<td>minimum</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effects: Atomically replaces the value pointed to by this with the result of the computation applied to the value pointed to by this and the given operand. Memory is affected according to the value of order. These operations are atomic read-modify-write operations (6.9.2).

Returns: Atomically, the value pointed to by this immediately before the effects.

Remarks: Except for `fetch_max` and `fetch_min`, for signed integer types the result is as if the object value and parameters were converted to their corresponding unsigned types, the computation performed on those types, and the result converted back to the signed type.

[Note 2: There are no undefined results arising from the computation. — end note]

For `fetch_max` and `fetch_min`, the maximum and minimum computation is performed as if by `max` and `min` algorithms (27.8.9), respectively, with the object value and the first parameter as the arguments.

```cpp
T operator op=(T operand) volatile noexcept;
T operator op=(T operand) noexcept;
```

Constraints: For the volatile overload of this function, `is_always_lock_free` is true.

Effects: Equivalent to: `return fetch_key(operand) op operand;`

33.5.8.4 Specializations for floating-point types

There are specializations of the `atomic` class template for all cv-unqualified floating-point types. For each such type `floating-point-type`, the specialization `atomic<floating-point-type>` provides additional atomic operations appropriate to floating-point types.

```cpp
namespace std {
    template<> struct atomic<floating-point-type> {
        using value_type = floating-point-type;
        using difference_type = value_type;

        static constexpr bool is_always_lock_free = implementation-defined;
        bool is_lock_free() const volatile noexcept;
        bool is_lock_free() const noexcept;

        constexpr atomic() noexcept;
        constexpr atomic(floating-point-type) noexcept;
        atomic(const atomic) = delete;
        atomic& operator=(const atomic) = delete;
        atomic& operator=(const atomic) volatile = delete;

        void store(floating-point-type, memory_order = memory_order::seq_cst) volatile noexcept;
        void store(floating-point-type, memory_order = memory_order::seq_cst) noexcept;
        floating-point-type operator=(floating-point-type) volatile noexcept;
        floating-point-type operator=(floating-point-type) noexcept;
        floating-point-type load(memory_order = memory_order::seq_cst) volatile noexcept;
        floating-point-type load(memory_order = memory_order::seq_cst) noexcept;
        operator floating-point-type() volatile noexcept;
        operator floating-point-type() noexcept;

        floating-point-type exchange(floating-point-type,
                                     memory_order = memory_order::seq_cst) volatile noexcept;
        floating-point-type exchange(floating-point-type,
                                     memory_order = memory_order::seq_cst) noexcept;
    }
}
```
bool compare_exchange_weak(floating-point-type&, floating-point-type, memory_order, memory_order) volatile noexcept;
bool compare_exchange_weak(floating-point-type&, floating-point-type, memory_order, memory_order) noexcept;
bool compare_exchange_strong(floating-point-type&, floating-point-type, memory_order, memory_order) volatile noexcept;
bool compare_exchange_strong(floating-point-type&, floating-point-type, memory_order, memory_order) noexcept;
bool compare_exchange_weak(floating-point-type&, floating-point-type, memory_order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_weak(floating-point-type&, floating-point-type, memory_order = memory_order::seq_cst) noexcept;
bool compare_exchange_strong(floating-point-type&, floating-point-type, memory_order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_strong(floating-point-type&, floating-point-type, memory_order = memory_order::seq_cst) noexcept;

floating-point-type fetch_add(floating-point-type, memory_order = memory_order::seq_cst) volatile noexcept;
floating-point-type fetch_add(floating-point-type, memory_order = memory_order::seq_cst) noexcept;
floating-point-type fetch_sub(floating-point-type, memory_order = memory_order::seq_cst) volatile noexcept;
floating-point-type fetch_sub(floating-point-type, memory_order = memory_order::seq_cst) noexcept;

floating-point-type operator+=(floating-point-type) volatile noexcept;
floating-point-type operator+=(floating-point-type) noexcept;
floating-point-type operator-=(floating-point-type) volatile noexcept;
floating-point-type operator-=(floating-point-type) noexcept;

void wait(floating-point-type, memory_order = memory_order::seq_cst) const volatile noexcept;
void wait(floating-point-type, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() volatile noexcept;
void notify_one() noexcept;
void notify_all() volatile noexcept;
void notify_all() noexcept;
};

2 The atomic floating-point specializations are standard-layout structs. They each have a trivial destructor.
3 Descriptions are provided below only for members that differ from the primary template.
4 The following operations perform arithmetic addition and subtraction computations. The correspondence
   among key, operator, and computation is specified in Table 148.
T fetch_key(T operand, memory_order order = memory_order::seq_cst) volatile noexcept;
T fetch_key(T operand, memory_order order = memory_order::seq_cst) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.
Effects: Atomically replaces the value pointed to by this with the result of the computation applied
   to the value pointed to by this and the given operand. Memory is affected according to the value of
   order. These operations are atomic read-modify-write operations (6.9.2).
Returns: Atomically, the value pointed to by this immediately before the effects.
Remarks: If the result is not a representable value for its type (7.1) the result is unspecified, but the operations
   otherwise have no undefined behavior. Atomic arithmetic operations on floating-point-type should conform to the
   std::numeric_limits<floating-point-type> traits associated with the floating-point type (17.3.3). The floating-point environment (28.3) for atomic arithmetic operations on
   floating-point-type may be different than the calling thread’s floating-point environment.

T operator op=(T operand) volatile noexcept;
T operator op=(T operand) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.
Effects: Equivalent to: \[\text{return fetch\_key(operand)} \op \text{operand};\]

Remarks: If the result is not a representable value for its type (7.1) the result is unspecified, but the operations otherwise have no undefined behavior. Atomic arithmetic operations on \text{floating-point-type} should conform to the \text{std::numeric\_limits<\text{floating-point-type}>} traits associated with the floating-point type (17.3.3). The floating-point environment (28.3) for atomic arithmetic operations on \text{floating-point-type} may be different than the calling thread’s floating-point environment.

33.5.8.5 Partial specialization for pointers

namespace std {
    template<class T> struct atomic<T*> {
        using value_type = T*;
        using difference_type = ptrdiff_t;

        static constexpr bool is_always_lock_free = implementation-defined;
        bool is_lock_free() const volatile noexcept;
        bool is_lock_free() const noexcept;

        constexpr atomic() noexcept;
        constexpr atomic(T*) noexcept;
        atomic(const atomic&) = delete;
        atomic& operator=(const atomic&) = delete;
        atomic& operator=(const atomic&) volatile = delete;

        void store(T*, memory_order = memory_order::seq_cst) volatile noexcept;
        void store(T*, memory_order = memory_order::seq_cst) noexcept;
        T* operator=(T*) volatile noexcept;
        T* operator=(T*) noexcept;
        T* load(memory_order = memory_order::seq_cst) const volatile noexcept;
        T* load(memory_order = memory_order::seq_cst) const noexcept;
        operator T*() const volatile noexcept;
        operator T*() const noexcept;
        T* exchange(T*, memory_order = memory_order::seq_cst) volatile noexcept;
        T* exchange(T*, memory_order = memory_order::seq_cst) noexcept;
        bool compare_exchange_weak(T*&, T*, memory_order, memory_order) volatile noexcept;
        bool compare_exchange_weak(T*&, T*, memory_order, memory_order) noexcept;
        bool compare_exchange_strong(T*&, T*, memory_order, memory_order) volatile noexcept;
        bool compare_exchange_strong(T*&, T*, memory_order, memory_order) noexcept;
        bool compare_exchange_weak(T*&, T*, memory_order = memory_order::seq_cst) volatile noexcept;
        bool compare_exchange_weak(T*&, T*, memory_order = memory_order::seq_cst) noexcept;
        bool compare_exchange_strong(T*&, T*, memory_order = memory_order::seq_cst) volatile noexcept;
        bool compare_exchange_strong(T*&, T*, memory_order = memory_order::seq_cst) noexcept;
        T* fetch_add(ptrdiff_t, memory_order = memory_order::seq_cst) volatile noexcept;
        T* fetch_add(ptrdiff_t, memory_order = memory_order::seq_cst) noexcept;
        T* fetch_sub(ptrdiff_t, memory_order = memory_order::seq_cst) volatile noexcept;
        T* fetch_sub(ptrdiff_t, memory_order = memory_order::seq_cst) noexcept;
        T* fetch_max(T*, memory_order = memory_order::seq_cst) volatile noexcept;
        T* fetch_max(T*, memory_order = memory_order::seq_cst) noexcept;
        T* fetch_min(T*, memory_order = memory_order::seq_cst) volatile noexcept;
        T* fetch_min(T*, memory_order = memory_order::seq_cst) noexcept;
        T* operator++(int) volatile noexcept;
        T* operator++(int) noexcept;
        T* operator--(int) volatile noexcept;
        T* operator--(int) noexcept;
        T* operator++() volatile noexcept;
        T* operator++() noexcept;
        T* operator--() volatile noexcept;
    }
}
T* operator--() noexcept;
T* operator+=(ptrdiff_t) volatile noexcept;
T* operator+=(ptrdiff_t) noexcept;
T* operator-=(ptrdiff_t) volatile noexcept;
T* operator-=(ptrdiff_t) noexcept;

void wait(T*, memory_order = memory_order::seq_cst) const volatile noexcept;
void wait(T*, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() volatile noexcept;
void notify_one() noexcept;
void notify_all() volatile noexcept;
void notify_all() noexcept;
}

There is a partial specialization of the atomic class template for pointers. Specializations of this partial specialization are standard-layout structs. They each have a trivial destructor.

Descriptions are provided below only for members that differ from the primary template.

The following operations perform pointer arithmetic. The correspondence among key, operator, and computation is specified in Table 149.

Table 149 — Atomic pointer computations  [tab:atomic.types.pointer.comp]

<table>
<thead>
<tr>
<th>key</th>
<th>Op</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>add</td>
<td>+</td>
<td>addition</td>
</tr>
<tr>
<td>max</td>
<td>maximum</td>
<td></td>
</tr>
<tr>
<td>sub</td>
<td>-</td>
<td>subtraction</td>
</tr>
<tr>
<td>min</td>
<td>minimum</td>
<td></td>
</tr>
</tbody>
</table>

T* fetch_key(ptrdiff_t operand, memory_order order = memory_order::seq_cst) volatile noexcept;
T* fetch_key(ptrdiff_t operand, memory_order order = memory_order::seq_cst) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Mandates: T is a complete object type.

[Note 1: Pointer arithmetic on void* or function pointers is ill-formed. — end note]

Effects: Atomically replaces the value pointed to by this with the result of the computation applied to the value pointed to by this and the given operand. Memory is affected according to the value of order. These operations are atomic read-modify-write operations (6.9.2).

Returns: Atomically, the value pointed to by this immediately before the effects.

Remarks: The result may be an undefined address, but the operations otherwise have no undefined behavior.

For fetch_max and fetch_min, the maximum and minimum computation is performed as if by max and min algorithms (27.8.9), respectively, with the object value and the first parameter as the arguments.

[Note 2: If the pointers point to different complete objects (or subobjects thereof), the < operator does not establish a strict weak ordering (Table 29, 7.6.9). — end note]

T* operator op=(ptrdiff_t operand) volatile noexcept;
T* operator op=(ptrdiff_t operand) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to: return fetch_key(operand) op operand;

33.5.8.6 Member operators common to integers and pointers to objects[atomics.types.memop]

value_type operator++(int) volatile noexcept;
value_type operator++(int) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to: return fetch_add(1);
value_type operator--(int) volatile noexcept;
value_type operator--(int) noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to: return fetch_sub(1);

value_type operator++() volatile noexcept;
value_type operator++() noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to: return fetch_add(1) + 1;

value_type operator--() volatile noexcept;
value_type operator--() noexcept;

Constraints: For the volatile overload of this function, is_always_lock_free is true.

Effects: Equivalent to: return fetch_sub(1) - 1;

33.5.8.7 Partial specializations for smart pointers

The library provides partial specializations of the atomic template for shared-ownership smart pointers (20.3.2).

[Note 1: The partial specializations are declared in header <memory> (20.2.2). — end note]

The behavior of all operations is as specified in 33.5.8, unless specified otherwise. The template parameter T of these partial specializations may be an incomplete type.

All changes to an atomic smart pointer in 33.5.8.7, and all associated use_count increments, are guaranteed to be performed atomically. Associated use_count decrements are sequenced after the atomic operation, but are not required to be part of it. Any associated deletion and deallocation are sequenced after the atomic update step and are not part of the atomic operation.

[Note 2: If the atomic operation uses locks, locks acquired by the implementation will be held when any use_count adjustments are performed, and will not be held when any destruction or deallocation resulting from this is performed. — end note]

[Example 1:]

```cpp
template<typename T> class atomic_list {
    struct node {
        T t;
        shared_ptr<node> next;
    };
    atomic<shared_ptr<node>> head;

    public:
    shared_ptr<node> find(T t) const {
        auto p = head.load();
        while (p && p->t != t)
            p = p->next;

        return p;
    }

    void push_front(T t) {
        auto p = make_shared<node>();
        p->t = t;
        p->next = head;
        while (!head.compare_exchange_weak(p->next, p)) {}
    }
};
```

—end example

33.5.8.7.2 Partial specialization for shared_ptr
namespace std {
  template<class T> struct atomic<shared_ptr<T>> {
    using value_type = shared_ptr<T>;
    static constexpr bool is_always_lock_free = implementation-defined;
    bool is_lock_free() const noexcept;
    atomic() noexcept;
    atomic(nullptr_t) noexcept : atomic() { }
    atomic(const atomic&) = delete;
    void operator=(const atomic&) = delete;
    shared_ptr<T> load(memory_order order = memory_order::seq_cst) const noexcept;
    operator shared_ptr<T>() const noexcept;
    void store(shared_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;
    void operator=(shared_ptr<T> desired) noexcept;
    void operator=(nullptr_t) noexcept;
    shared_ptr<T> exchange(shared_ptr<T> desired,
                           memory_order order = memory_order::seq_cst) noexcept;
    bool compare_exchange_weak(shared_ptr<T>& expected, shared_ptr<T> desired,
                                 memory_order order = memory_order::seq_cst) noexcept;
    bool compare_exchange_strong(shared_ptr<T>& expected, shared_ptr<T> desired,
                                  memory_order order = memory_order::seq_cst) noexcept;
    void wait(shared_ptr<T> old, memory_order order = memory_order::seq_cst) const noexcept;
    void notify_one() noexcept;
    void notify_all() noexcept;
    
    private:
      shared_ptr<T> p;    // exposition only
  };
}

constexpr atomic() noexcept;
Effects: Initializes p().

atomic(shared_ptr<T> desired) noexcept;
Effects: Initializes the object with the value desired. Initialization is not an atomic operation (6.9.2).

[Note 1: It is possible to have an access to an atomic object A race with its construction, for example, by communicating the address of the just-constructed object A to another thread via memory_order::relaxed operations on a suitable atomic pointer variable, and then immediately accessing A in the receiving thread. This results in undefined behavior. — end note]

void store(shared_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;
Preconditions: order is memory_order::relaxed, memory_order::release, or memory_order::seq_cst.
Effects: Atomically replaces the value pointed to by this with the value of desired as if by p.swap(desired). Memory is affected according to the value of order.

void operator=(shared_ptr<T> desired) noexcept;
Effects: Equivalent to store(desired).

void operator=(nullptr_t) noexcept;
Effects: Equivalent to store(nullptr).
shared_ptr<T> load(memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: order is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: Memory is affected according to the value of order.

Returns: Atomically returns p.

operator shared_ptr<T>() const noexcept;

Effects: Equivalent to: return load();

shared_ptr<T> exchange(shared_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;

Effects: Atomically replaces p with desired as if by p.swap(desired). Memory is affected according to the value of order. This is an atomic read-modify-write operation (6.9.2.2).

Returns: Atomically returns the value of p immediately before the effects.

bool compare_exchange_weak(shared_ptr<T>& expected, shared_ptr<T> desired, memory_order success, memory_order failure) noexcept;

bool compare_exchange_strong(shared_ptr<T>& expected, shared_ptr<T> desired, memory_order success, memory_order failure) noexcept;

Preconditions: failure is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: If p is equivalent to expected, assigns desired to p and has synchronization semantics corresponding to the value of success, otherwise assigns p to expected and has synchronization semantics corresponding to the value of failure.

Returns: true if p was equivalent to expected, false otherwise.

Remarks: Two shared_ptr objects are equivalent if they store the same pointer value and either share ownership or are both empty. The weak form may fail spuriously. See 33.5.8.2.

If the operation returns true, expected is not accessed after the atomic update and the operation is an atomic read-modify-write operation (6.9.2) on the memory pointed to by this. Otherwise, the operation is an atomic load operation on that memory, and expected is updated with the existing value read from the atomic object in the attempted atomic update. The use_count update corresponding to the write to expected is part of the atomic operation. The write to expected itself is not required to be part of the atomic operation.

bool compare_exchange_weak(shared_ptr<T>& expected, shared_ptr<T> desired,

memory_order order = memory_order::seq_cst) noexcept;

Effects: Equivalent to:

return compare_exchange_weak(expected, desired, order, fail_order);

where fail_order is the same as order except that a value of memory_order::acq_rel shall be replaced by the value memory_order::acquire and a value of memory_order::release shall be replaced by the value memory_order::relaxed.

bool compare_exchange_strong(shared_ptr<T>& expected, shared_ptr<T> desired,

memory_order order = memory_order::seq_cst) noexcept;

Effects: Equivalent to:

return compare_exchange_strong(expected, desired, order, fail_order);

where fail_order is the same as order except that a value of memory_order::acq_rel shall be replaced by the value memory_order::acquire and a value of memory_order::release shall be replaced by the value memory_order::relaxed.

void wait(shared_ptr<T> old, memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: order is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: Repeatedly performs the following steps, in order:

— Evaluates load(order) and compares it to old.
If the two are not equivalent, returns.

Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

Remarks: Two `shared_ptr` objects are equivalent if they store the same pointer and either share ownership or are both empty. This function is an atomic waiting operation (33.5.6).

```cpp
template<class T> struct atomic<weak_ptr<T>> {
    using value_type = weak_ptr<T>
    static constexpr bool is_always_lock_free = implementation-defined;
    constexpr bool is_lock_free() const noexcept;
    atomic() noexcept;
    atomic(weak_ptr<T> desired) noexcept;
    atomic(const atomic&) = delete;
    void operator=(const atomic&) = delete;
    weak_ptr<T> load(memory_order order = memory_order::seq_cst) const noexcept;
    operator weak_ptr<T>() const noexcept;
    void store(weak_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;
    void operator=(weak_ptr<T> desired) noexcept;
    weak_ptr<T> exchange(weak_ptr<T> desired,
        memory_order order = memory_order::seq_cst) noexcept;
    bool compare_exchange_weak(weak_ptr<T>& expected, weak_ptr<T> desired,
        memory_order success, memory_order failure) noexcept;
    bool compare_exchange_strong(weak_ptr<T>& expected, weak_ptr<T> desired,
        memory_order success, memory_order failure) noexcept;
    void wait(weak_ptr<T> old, memory_order order = memory_order::seq_cst) const noexcept;
    void notify_one() noexcept;
    void notify_all() noexcept;
private:
    weak_ptr<T> p;
};
```

```cpp
constexpr atomic() noexcept;
```

```cpp
atomic(weak_ptr<T> desired) noexcept;
```

Remarks: This function is an atomic notifying operation (33.5.6).

Effects: Unblocks the execution of at least one atomic waiting operation that is eligible to be unblocked (33.5.6) by this call, if any such atomic waiting operations exist.

Remarks: This function is an atomic notifying operation (33.5.6).

Effects: Unblocks the execution of all atomic waiting operations that are eligible to be unblocked (33.5.6) by this call.

Remarks: This function is an atomic notifying operation (33.5.6).

### 33.5.8.7.3 Partial specialization for `weak_ptr`

```cpp
namespace std {
    template<class T> struct atomic<weak_ptr<T>> {
        using value_type = weak_ptr<T>
        static constexpr bool is_always_lock_free = implementation-defined;
        bool is_lock_free() const noexcept;
        atomic() noexcept;
        atomic(weak_ptr<T> desired) noexcept;
        atomic(const atomic&) = delete;
        void operator=(const atomic&) = delete;
        weak_ptr<T> load(memory_order order = memory_order::seq_cst) const noexcept;
        operator weak_ptr<T>() const noexcept;
        void store(weak_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;
        void operator=(weak_ptr<T> desired) noexcept;
        weak_ptr<T> exchange(weak_ptr<T> desired,
            memory_order order = memory_order::seq_cst) noexcept;
        bool compare_exchange_weak(weak_ptr<T>& expected, weak_ptr<T> desired,
            memory_order success, memory_order failure) noexcept;
        bool compare_exchange_strong(weak_ptr<T>& expected, weak_ptr<T> desired,
            memory_order success, memory_order failure) noexcept;
        void wait(weak_ptr<T> old, memory_order order = memory_order::seq_cst) const noexcept;
        void notify_one() noexcept;
        void notify_all() noexcept;
private:
    weak_ptr<T> p;
    // exposition only
    }
}
```

Effects: Initializes `p{}`.

Effects: Initializes the object with the value `desired`. Initialization is not an atomic operation (6.9.2).
operations on a suitable atomic pointer variable, and then immediately accessing \( A \) in the receiving thread. This results in undefined behavior. — end note]

```cpp
void store(weak_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;
```

3  **Preconditions**: order is memory_order::relaxed, memory_order::release, or memory_order::seq_cst.

4  **Effects**: Atomically replaces the value pointed to by this with the value of desired as if by p.swap(desired). Memory is affected according to the value of order.

```cpp
void operator=(weak_ptr<T> desired) noexcept;
```

5  **Effects**: Equivalent to store(desired).

```cpp
weak_ptr<T> load(memory_order order = memory_order::seq_cst) const noexcept;
```

6  **Preconditions**: order is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

7  **Effects**: Memory is affected according to the value of order.

8  **Returns**: Atomically returns p.

```cpp
operator weak_ptr<T>() const noexcept;
```

9  **Effects**: Equivalent to: return load();

```cpp
weak_ptr<T> exchange(weak_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;
```

10  **Effects**: Atomically replaces p with desired as if by p.swap(desired). Memory is affected according to the value of order. This is an atomic read-modify-write operation (6.9.2.2).

11  **Returns**: Atomically returns the value of p immediately before the effects.

```cpp
bool compare_exchange_weak(weak_ptr<T>& expected, weak_ptr<T> desired,
                           memory_order success, memory_order failure) noexcept;
```

12  **Preconditions**: failure is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

13  **Effects**: If p is equivalent to expected, assigns desired to p and has synchronization semantics corresponding to the value of success, otherwise assigns p to expected and has synchronization semantics corresponding to the value of failure.

14  **Returns**: true if p was equivalent to expected, false otherwise.

15  **Remarks**: Two weak_ptr objects are equivalent if they store the same pointer value and either share ownership or are both empty. The weak form may fail spuriously. See 33.5.8.2.

16  If the operation returns true, expected is not accessed after the atomic update and the operation is an atomic read-modify-write operation (6.9.2) on the memory pointed to by this. Otherwise, the operation is an atomic load operation on that memory, and expected is updated with the existing value read from the atomic object in the attempted atomic update. The use_count update corresponding to the write to expected is part of the atomic operation. The write to expected itself is not required to be part of the atomic operation.

```cpp
bool compare_exchange_strong(weak_ptr<T>& expected, weak_ptr<T> desired,
                             memory_order success, memory_order order, fail_order) noexcept;
```

17  **Effects**: Equivalent to:

```
return compare_exchange_weak(expected, desired, order, fail_order);
```

where fail_order is the same as order except that a value of memory_order::acq_rel shall be replaced by the value memory_order::acquire and a value of memory_order::relaxed shall be replaced by the value memory_order::acquire.

```cpp
bool compare_exchange_strong(weak_ptr<T>& expected, weak_ptr<T> desired,
                             memory_order order = memory_order::seq_cst) noexcept;
```

18  **Effects**: Equivalent to:

§ 33.5.8.7.3
return compare_exchange_strong(expected, desired, order, fail_order);

where fail_order is the same as order except that a value of memory_order::acq_rel shall be replaced by the value memory_order::acquire and a value of memory_order::release shall be replaced by the value memory_order::relaxed.

void wait(weak_ptr<T> old, memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: order is memory_order::relaxed, memory_order::consume, memory_order::acquire, or memory_order::seq_cst.

Effects: Repeatedly performs the following steps, in order:

— Evaluates load(order) and compares it to old.
— If the two are not equivalent, returns.
— Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

Remarks: Two weak_ptr objects are equivalent if they store the same pointer and either share ownership or are both empty. This function is an atomic waiting operation (33.5.6).

void notify_one() noexcept;

Effects: Unblocks the execution of at least one atomic waiting operation that is eligible to be unblocked (33.5.6) by this call, if any such atomic waiting operations exist.

Remarks: This function is an atomic notifying operation (33.5.6).

void notify_all() noexcept;

Effects: Unblocks the execution of all atomic waiting operations that are eligible to be unblocked (33.5.6) by this call.

Remarks: This function is an atomic notifying operation (33.5.6).

33.5.9 Non-member functions

A non-member function template whose name matches the pattern atomic_f or the pattern atomic_f_-explicit invokes the member function f, with the value of the first parameter as the object expression and the values of the remaining parameters (if any) as the arguments of the member function call, in order. An argument for a parameter of type atomic<T>::value_type* is dereferenced when passed to the member function call. If no such member function exists, the program is ill-formed.

[Note 1: The non-member functions enable programmers to write code that can be compiled as either C or C++, for example in a shared header file. — end note]

33.5.10 Flag type and operations

namespace std {
  struct atomic_flag {
    constexpr atomic_flag() noexcept;
    atomic_flag(const atomic_flag&) = delete;
    atomic_flag& operator=(const atomic_flag&) = delete;
    atomic_flag& operator=(const atomic_flag& volatile) = delete;

    bool test(memory_order = memory_order::seq_cst) const volatile noexcept;
    bool test(memory_order = memory_order::seq_cst) const noexcept;
    bool test_and_set(memory_order = memory_order::seq_cst) volatile noexcept;
    bool test_and_set(memory_order = memory_order::seq_cst) noexcept;
    void clear(memory_order = memory_order::seq_cst) volatile noexcept;
    void clear(memory_order = memory_order::seq_cst) noexcept;

    void wait(bool, memory_order = memory_order::seq_cst) const volatile noexcept;
    void wait(bool, memory_order = memory_order::seq_cst) const noexcept;
    void notify_one() volatile noexcept;
    void notify_one() noexcept;
    void notify_all() volatile noexcept;
    void notify_all() noexcept;
  };
}
The `atomic_flag` type provides the classic test-and-set functionality. It has two states, set and clear.

Operations on an object of type `atomic_flag` shall be lock-free. The operations should also be address-free.

The `atomic_flag` type is a standard-layout struct. It has a trivial destructor.

```cpp
constexpr atomic_flag::atomic_flag() noexcept;
```

---

**Effects:** Initializes `*this` to the clear state.

```cpp
bool atomic_flag_test(const volatile atomic_flag* object) noexcept;
bool atomic_flag_test(const atomic_flag* object) noexcept;
bool atomic_flag_test_explicit(const volatile atomic_flag* object,
                               memory_order order) noexcept;
bool atomic_flag_test_explicit(const atomic_flag* object,
                               memory_order order) noexcept;
bool atomic_flag::test(memory_order order = memory_order::seq_cst) volatile noexcept;
bool atomic_flag::test(memory_order order = memory_order::seq_cst) noexcept;
```

---

For `atomic_flag_test`, let `order` be `memory_order::seq_cst`.

**Preconditions:** `order` is `memory_order::relaxed`, `memory_order::consume`, `memory_order::acquire`, or `memory_order::seq_cst`.

**Effects:** Memory is affected according to the value of `order`.

**Returns:** Atomically returns the value pointed to by `object` or this.

```cpp
bool atomic_flag_test_and_set(volatile atomic_flag* object) noexcept;
bool atomic_flag_test_and_set(atomic_flag* object) noexcept;
bool atomic_flag_test_and_set_explicit(volatile atomic_flag* object, memory_order order) noexcept;
bool atomic_flag_test_and_set_explicit(atomic_flag* object, memory_order order) noexcept;
bool atomic_flag::test_and_set(memory_order order = memory_order::seq_cst) volatile noexcept;
bool atomic_flag::test_and_set(memory_order order = memory_order::seq_cst) noexcept;
```

---

**Effects:** Atomically sets the value pointed to by `object` or by `this` to `true`. Memory is affected according to the value of `order`. These operations are atomic read-modify-write operations (6.9.2).

**Returns:** Atomically, the value of the object immediately before the effects.

```cpp
void atomic_flag_clear(volatile atomic_flag* object) noexcept;
void atomic_flag_clear(atomic_flag* object) noexcept;
void atomic_flag_clear_explicit(volatile atomic_flag* object, memory_order order) noexcept;
void atomic_flag_clear_explicit(atomic_flag* object, memory_order order) noexcept;
void atomic_flag::clear(memory_order order = memory_order::seq_cst) volatile noexcept;
void atomic_flag::clear(memory_order order = memory_order::seq_cst) noexcept;
```

---

**Preconditions:** `order` is `memory_order::relaxed`, `memory_order::release`, or `memory_order::seq_cst`.

**Effects:** Atomically sets the value pointed to by `object` or by `this` to `false`. Memory is affected according to the value of `order`.

```cpp
void atomic_flag_wait(const volatile atomic_flag* object, bool old) noexcept;
void atomic_flag_wait(const atomic_flag* object, bool old) noexcept;
void atomic_flag_wait_explicit(const volatile atomic_flag* object,
                               bool old, memory_order order) noexcept;
void atomic_flag_wait_explicit(const atomic_flag* object,
                               bool old, memory_order order) noexcept;
void atomic_flag::wait(bool old, memory_order order = memory_order::seq_cst) const volatile noexcept;
void atomic_flag::wait(bool old, memory_order order = memory_order::seq_cst) const noexcept;
```

---

For `atomic_flag_wait`, let `order` be `memory_order::seq_cst`. Let `flag` be `object` for the non-member functions and this for the member functions.

**Preconditions:** `order` is `memory_order::relaxed`, `memory_order::consume`, `memory_order::acquire`, or `memory_order::seq_cst`.

**Effects:** Repeatedly performs the following steps, in order:
— Evaluates flag->test(order) != old.
— If the result of that evaluation is true, returns.
— Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

Remarks: This function is an atomic waiting operation (33.5.6).

void atomic_flag_notify_one(volatile atomic_flag* object) noexcept;
void atomic_flag_notify_one(atomic_flag* object) noexcept;
void atomic_flag::notify_one() volatile noexcept;
void atomic_flag::notify_one() noexcept;

Effects: Unblocks the execution of at least one atomic waiting operation that is eligible to be unblocked (33.5.6) by this call, if any such atomic waiting operations exist.

Remarks: This function is an atomic notifying operation (33.5.6).

void atomic_flag_notify_all(volatile atomic_flag* object) noexcept;
void atomic_flag_notify_all(atomic_flag* object) noexcept;
void atomic_flag::notify_all() volatile noexcept;
void atomic_flag::notify_all() noexcept;

Effects: Unblocks the execution of all atomic waiting operations that are eligible to be unblocked (33.5.6) by this call.

Remarks: This function is an atomic notifying operation (33.5.6).

#define ATOMIC_FLAG_INIT see below

Remarks: The macro ATOMIC_FLAG_INIT is defined in such a way that it can be used to initialize an object of type atomic_flag to the clear state. The macro can be used in the form:

atomic_flag guard = ATOMIC_FLAG_INIT;

It is unspecified whether the macro can be used in other initialization contexts. For a complete static-duration object, that initialization shall be static.

33.5.11 Fences

This subclause introduces synchronization primitives called fences. Fences can have acquire semantics, release semantics, or both. A fence with acquire semantics is called an acquire fence. A fence with release semantics is called a release fence.

A release fence \(A\) synchronizes with an acquire fence \(B\) if there exist atomic operations \(X\) and \(Y\), both operating on some atomic object \(M\), such that \(A\) is sequenced before \(X\), \(X\) modifies \(M\), \(Y\) is sequenced before \(B\), and \(Y\) reads the value written by \(X\) or a value written by any side effect in the hypothetical release sequence \(X\) would head if it were a release operation.

A release fence \(A\) synchronizes with an atomic operation \(B\) that performs an acquire operation on an atomic object \(M\) if there exists an atomic operation \(X\) such that \(A\) is sequenced before \(X\), \(X\) modifies \(M\), and \(B\) reads the value written by \(X\) or a value written by any side effect in the hypothetical release sequence \(X\) would head if it were a release operation.

An atomic operation \(A\) that is a release operation on an atomic object \(M\) synchronizes with an acquire fence \(B\) if there exists some atomic operation \(X\) on \(M\) such that \(X\) is sequenced before \(B\) and reads the value written by \(A\) or a value written by any side effect in the release sequence headed by \(A\).

extern "C" void atomic_thread_fence(memory_order order) noexcept;

Effects: Depending on the value of order, this operation:

— has no effects, if order == memory_order::relaxed;
— is an acquire fence, if order == memory_order::acquire or order == memory_order::consume;
— is a release fence, if order == memory_order::release;
— is both an acquire fence and a release fence, if order == memory_order::acq_rel;
— is a sequentially consistent acquire and release fence, if order == memory_order::seq_cst.
extern "C" void atomic_signal_fence(memory_order order) noexcept;

Effects: Equivalent to atomic_thread_fence(order), except that the resulting ordering constraints are established only between a thread and a signal handler executed in the same thread.

[Note 1: atomic_signal_fence can be used to specify the order in which actions performed by the thread become visible to the signal handler. Compiler optimizations and reorderings of loads and stores are inhibited in the same way as with atomic_thread_fence, but the hardware fence instructions that atomic_thread_fence would have inserted are not emitted. — end note]

33.5.12 C compatibility

The header <stdatomic.h> provides the following definitions:

template<class T>
using std::atomic = std::atomic<T>;   // exposition only

#define _Atomic(T) std-atomic<T>
#define ATOMIC_BOOL_LOCK_FREE see below
#define ATOMIC_CHAR_LOCK_FREE see below
#define ATOMIC_CHAR16_T_LOCK_FREE see below
#define ATOMIC_CHAR32_T_LOCK_FREE see below
#define ATOMIC_WCHAR_T_LOCK_FREE see below
#define ATOMIC_SHORT_LOCK_FREE see below
#define ATOMIC_INT_LOCK_FREE see below
#define ATOMIC_LONG_LOCK_FREE see below
#define ATOMIC_LLONG_LOCK_FREE see below
#define ATOMIC_POINTER_LOCK_FREE see below

using std::memory_order;   // see below
using std::memory_order_relaxed; // see below
using std::memory_order_consume; // see below
using std::memory_order_acquire; // see below
using std::memory_order_release; // see below
using std::memory_order_acq_rel; // see below
using std::memory_order_seq_cst; // see below

using std::atomic_flag;   // see below
using std::atomic_bool;   // see below
using std::atomic_char;   // see below
using std::atomic_schar;  // see below
using std::atomic_uchar;  // see below
using std::atomic_short;  // see below
using std::atomic_ushort; // see below
using std::atomic_int;    // see below
using std::atomic_uint;   // see below
using std::atomic_long;   // see below
using std::atomic_ulong;  // see below
using std::atomic_int8_t; // see below
using std::atomic_uint8_t; // see below
using std::atomic_int16_t; // see below
using std::atomic_uint16_t; // see below
using std::atomic_int32_t; // see below
using std::atomic_uint32_t; // see below
using std::atomic_int64_t; // see below
using std::atomic_uint64_t; // see below
using std::atomic_int_least8_t; // see below
using std::atomic_uint_least8_t; // see below
using std::atomic_int_least16_t; // see below
using std::atomic_uint_least16_t; // see below
using std::atomic_int_least32_t; // see below
using std::atomic_uint_least32_t; // see below
using std::atomic_int_least64_t; // see below
using std::atomic_uint_least64_t; // see below
using std::atomic_int_least8_t; // see below
using std::atomic_uint_least8_t; // see below
using std::atomic_int_least16_t; // see below
using std::atomic_uint_least16_t; // see below
using std::atomic_int_least32_t; // see below
using std::atomic_uint_least32_t; // see below
using std::atomic_int_least64_t; // see below
using std::atomic_uint_least64_t; // see below
using std::atomic_int_least8_t; // see below
using std::atomic_uint_least8_t; // see below
using std::atomic_int_least16_t; // see below
using std::atomic_uint_least16_t; // see below
using std::atomic_int_least32_t; // see below
using std::atomic_uint_least32_t; // see below
using std::atomic_int_least64_t; // see below
using std::atomic_uint_least64_t; // see below
using std::atomic_thread_fence; // see below
using std::atomic_signal_fence; // see below

1 Each using-declaration for some name A in the synopsis above makes available the same entity as std::A declared in <atomic> (33.5.2). Each macro listed above other than _Atomic(T) is defined as in <atomic>. It is unspecified whether <stdatomic.h> makes available any declarations in namespace std.

2 Each of the using-declarations for intN_t, uintN_t, intptr_t, and uintptr_t listed above is defined if and only if the implementation defines the corresponding typedef-name in 33.5.2.

3 Neither the _Atomic macro, nor any of the non-macro global namespace declarations, are provided by any C++ standard library header other than <stdatomic.h>.

4 Recommended practice: Implementations should ensure that C and C++ representations of atomic objects are compatible, so that the same object can be accessed as both an _Atomic(T) from C code and an atomic<T> from C++ code. The representations should be the same, and the mechanisms used to ensure atomicity and memory ordering should be compatible.
33.6  Mutual exclusion

33.6.1  General

Subclause 33.6 provides mechanisms for mutual exclusion: mutexes, locks, and call once. These mechanisms ease the production of race-free programs (6.9.2).

33.6.2  Header <mutex> synopsis

```cpp
namespace std {
    // 33.6.4.2.2, class mutex
    class mutex;
    // 33.6.4.2.3, class recursive_mutex
    class recursive_mutex;
    // 33.6.4.3.2 class timed_mutex
    class timed_mutex;
    // 33.6.4.3.3, class recursive_timed_mutex
    class recursive_timed_mutex;

    struct defer_lock_t { explicit defer_lock_t() = default; };
    struct try_to_lock_t { explicit try_to_lock_t() = default; };
    struct adopt_lock_t { explicit adopt_lock_t() = default; };

    inline constexpr defer_lock_t defer_lock { };
    inline constexpr try_to_lock_t try_to_lock { };
    inline constexpr adopt_lock_t adopt_lock { };

    // 33.6.5, locks
    template<class Mutex> class lock_guard;
    template<class... MutexTypes> class scoped_lock;
    template<class Mutex> class unique_lock;

    template<class Mutex>
    void swap(unique_lock<Mutex>& x, unique_lock<Mutex>& y) noexcept;

    // 33.6.6, generic locking algorithms
    template<class L1, class L2, class... L3> int try_lock(L1&, L2&, L3&...);
    template<class L1, class L2, class... L3> void lock(L1&, L2&, L3&...);

    struct once_flag;

    template<class Callable, class... Args>
    void call_once(once_flag& flag, Callable&& func, Args&&... args);
}
```

33.6.3  Header <shared_mutex> synopsis

```cpp
namespace std {
    // 33.6.4.4.2, class shared_mutex
    class shared_mutex;
    // 33.6.4.5.2, class shared_timed_mutex
    class shared_timed_mutex;
    // 33.6.5.5, class template shared_lock
    template<class Mutex> class shared_lock;

    template<class Mutex>
    void swap(shared_lock<Mutex>& x, shared_lock<Mutex>& y) noexcept;
}
```

33.6.4  Mutex requirements

33.6.4.1  General

A mutex object facilitates protection against data races and allows safe synchronization of data between execution agents (33.2.5). An execution agent owns a mutex from the time it successfully calls one of the lock functions until it calls unlock. Mutexes can be either recursive or non-recursive, and can grant simultaneous ownership to one or many execution agents. Both recursive and non-recursive mutexes are supplied.
33.6.4.2 Mutex types

33.6.4.2.1 General

The mutex types are the standard library types `mutex`, `recursive_mutex`, `timed_mutex`, `recursive_timed_mutex`, `shared_mutex`, and `shared_timed_mutex`. They meet the requirements set out in 33.6.4.2. In this description, m denotes an object of a mutex type.

[Note 1: The mutex types meet the `Cpp17Lockable` requirements (33.2.5.3). — end note]

The mutex types meet `Cpp17DefaultConstructible` and `Cpp17Destructible`. If initialization of an object of a mutex type fails, an exception of type `system_error` is thrown. The mutex types are neither copyable nor movable.

The error conditions for error codes, if any, reported by member functions of the mutex types are as follows:

- (3.1) `resource_unavailable_try_again` — if any native handle type manipulated is not available.
- (3.2) `operation_not_permitted` — if the thread does not have the privilege to perform the operation.
- (3.3) `invalid_argument` — if any native handle type manipulated as part of mutex construction is incorrect.

The implementation provides lock and unlock operations, as described below. For purposes of determining the existence of a data race, these behave as atomic operations (6.9.2). The lock and unlock operations on a single mutex appears to occur in a single total order.

[Note 2: This can be viewed as the modification order (6.9.2) of the mutex. — end note]

[Note 3: Construction and destruction of an object of a mutex type need not be thread-safe; other synchronization can be used to ensure that mutex objects are initialized and visible to other threads. — end note]

The expression `m.lock()` is well-formed and has the following semantics:

- **Preconditions:** If `m` is of type `mutex`, `timed_mutex`, `shared_mutex`, or `shared_timed_mutex`, the calling thread does not own the mutex.
- **Effects:** Blocks the calling thread until ownership of the mutex can be obtained for the calling thread.
- **Synchronization:** Prior `unlock()` operations on the same object synchronize with (6.9.2) this operation.
- **Postconditions:** The calling thread owns the mutex.
- **Return type:** `void`.
- **Throws:** `system_error` when an exception is required (33.2.2).
- **Error conditions:**
  - (12.1) `operation_not_permitted` — if the thread does not have the privilege to perform the operation.
  - (12.2) `resource_deadlock_would_occur` — if the implementation detects that a deadlock would occur.

The expression `m.try_lock()` is well-formed and has the following semantics:

- **Preconditions:** If `m` is of type `mutex`, `timed_mutex`, `shared_mutex`, or `shared_timed_mutex`, the calling thread does not own the mutex.
- **Effects:** Attempts to obtain ownership of the mutex for the calling thread without blocking. If ownership is not obtained, there is no effect and `try_lock()` immediately returns. An implementation may fail to obtain the lock even if it is not held by any other thread.
  
  [Note 4: This spurious failure is normally uncommon, but allows interesting implementations based on a simple compare and exchange (33.5). — end note]
  
  An implementation should ensure that `try_lock()` does not consistently return `false` in the absence of contending mutex acquisitions.

- **Synchronization:** If `try_lock()` returns `true`, prior `unlock()` operations on the same object synchronize with (6.9.2) this operation.
  
  [Note 5: Since `lock()` does not synchronize with a failed subsequent `try_lock()`, the visibility rules are weak enough that little would be known about the state after a failure, even in the absence of spurious failures. — end note]

- **Return type:** `bool`.
- **Returns:** `true` if ownership was obtained, otherwise `false`.
- **Throws:** Nothing.
The expression `m.unlock()` is well-formed and has the following semantics:

**Preconditions:** The calling thread owns the mutex.

**Effects:** Releases the calling thread’s ownership of the mutex.

**Return type:** `void`.

**Synchronization:** This operation synchronizes with (6.9.2) subsequent lock operations that obtain ownership on the same object.

**Throws:** Nothing.

### 33.6.4.2.2 Class `mutex`

```cpp
namespace std {

class mutex {

public:
    constexpr mutex() noexcept;  // see 33.2.3
    ~mutex();
    mutex(const mutex&) = delete;
    mutex& operator=(const mutex&) = delete;

    void lock();
    bool try_lock();
    void unlock();

    using native_handle_type = implementation-defined;  // see 33.2.3
    native_handle_type native_handle();  // see 33.2.3

};
}
```

The class `mutex` provides a non-recursive mutex with exclusive ownership semantics. If one thread owns a mutex object, attempts by another thread to acquire ownership of that object will fail (for `try_lock()`) or block (for `lock()`) until the owning thread has released ownership with a call to `unlock()`.

[Note 1: After a thread A has called `unlock()`, releasing a mutex, it is possible for another thread B to lock the same mutex, observe that it is no longer in use, unlock it, and destroy it, before thread A appears to have returned from its unlock call. Conforming implementations handle such scenarios correctly, as long as thread A does not access the mutex after the unlock call returns. These cases typically occur when a reference-counted object contains a mutex that is used to protect the reference count. —end note]

The class `mutex` meets all of the mutex requirements (33.6.4). It is a standard-layout class (11.2).

[Note 2: A program can deadlock if the thread that owns a `mutex` object calls `lock()` on that object. If the implementation can detect the deadlock, a `resource_deadlock_would_occur` error condition might be observed. —end note]

The behavior of a program is undefined if it destroys a `mutex` object owned by any thread or a thread terminates while owning a `mutex` object.

### 33.6.4.2.3 Class `recursive_mutex`

```cpp
namespace std {

class recursive_mutex {

public:
    recursive_mutex();  // see 33.2.3
    ~recursive_mutex();
    recursive_mutex(const recursive_mutex&) = delete;
    recursive_mutex& operator=(const recursive_mutex&) = delete;

    void lock();
    bool try_lock() noexcept;
    void unlock();

    using native_handle_type = implementation-defined; // see 33.2.3
    native_handle_type native_handle(); // see 33.2.3

};
}
```

The behavior of a program is undefined if it destroys a `mutex` object owned by any thread or a thread terminates while owning a `mutex` object.
The class `recursive_mutex` provides a recursive mutex with exclusive ownership semantics. If one thread owns a `recursive_mutex` object, attempts by another thread to acquire ownership of that object will fail (for `try_lock()`) or block (for `lock()`) until the first thread has completely released ownership.

The class `recursive_mutex` meets all of the mutex requirements (33.6.4). It is a standard-layout class (11.2).

A thread that owns a `recursive_mutex` object may acquire additional levels of ownership by calling `lock()` or `try_lock()` on that object. It is unspecified how many levels of ownership may be acquired by a single thread. If a thread has already acquired the maximum level of ownership for a `recursive_mutex` object, additional calls to `try_lock()` fail, and additional calls to `lock()` throw an exception of type `system_error`. A thread shall call `unlock()` once for each level of ownership acquired by calls to `lock()` and `try_lock()`. Only when all levels of ownership have been released may ownership be acquired by another thread.

The behavior of a program is undefined if

1. it destroys a `recursive_mutex` object owned by any thread or
2. a thread terminates while owning a `recursive_mutex` object.

### 33.6.4.3 Timed mutex types

The timed mutex types are the standard library types `timed_mutex`, `recursive_timed_mutex`, and `shared_timed_mutex`. They meet the requirements set out below. In this description, `m` denotes an object of a mutex type, `rel_time` denotes an object of an instantiation of `duration` (29.5), and `abs_time` denotes an object of an instantiation of `time_point` (29.6).

1. **Preconditions**: If `m` is of type `timed_mutex` or `shared_timed_mutex`, the calling thread does not own the mutex.
2. **Effects**: The function attempts to obtain ownership of the mutex within the relative timeout (33.2.4) specified by `rel_time`. If the time specified by `rel_time` is less than or equal to `rel_time.zero()`, the function attempts to obtain ownership without blocking (as if by calling `try_lock()`). The function returns within the timeout specified by `rel_time` only if it has obtained ownership of the mutex object.
   
   - **Note 2**: As with `try_lock()`, there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note
   
3. **Synchronization**: If `try_lock_for()` returns `true`, prior `unlock()` operations on the same object synchronize with (6.9.2) this operation.
4. **Return type**: `bool`.
5. **Returns**: `true` if ownership was obtained, otherwise `false`.
6. **Throws**: Timeout-related exceptions (33.2.4).
7. The expression `m.try_lock_for(rel_time)` is well-formed and has the following semantics:
8. The expression `m.try_lock_until(abs_time)` is well-formed and has the following semantics:
9. **Preconditions**: If `m` is of type `timed_mutex` or `shared_timed_mutex`, the calling thread does not own the mutex.
10. **Effects**: The function attempts to obtain ownership of the mutex. If `abs_time` has already passed, the function attempts to obtain ownership without blocking (as if by calling `try_lock()`). The function returns before the absolute timeout (33.2.4) specified by `abs_time` only if it has obtained ownership of the mutex object.
11. **Synchronization**: If `try_lock_until()` returns `true`, prior `unlock()` operations on the same object synchronize with (6.9.2) this operation.
12. **Return type**: `bool`.
13. **Returns**: `true` if ownership was obtained, otherwise `false`.
14. **Throws**: Timeout-related exceptions (33.2.4).
33.6.4.3.2 Class `timed_mutex`  

namespace std {  
class timed_mutex {  
   public:  
      timed_mutex();  
      ~timed_mutex();  
      
      timed_mutex(const timed_mutex&) = delete;  
      timed_mutex& operator=(const timed_mutex&) = delete;  
      
      void lock();  // blocking  
      bool try_lock();  
      template<class Rep, class Period>  
         bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);  
      template<class Clock, class Duration>  
         bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);  
      void unlock();  
      
      using native_handle_type = implementation-defined;  // see 33.2.3  
      native_handle_type native_handle();  // see 33.2.3  
   };  
}  

The class `timed_mutex` provides a non-recursive mutex with exclusive ownership semantics. If one thread owns a `timed_mutex` object, attempts by another thread to acquire ownership of that object will fail (for `try_lock()`) or block (for `lock()`, `try_lock_for()`, and `try_lock_until()`) until the owning thread has released ownership with a call to `unlock()` or the call to `try_lock_for()` or `try_lock_until()` times out (having failed to obtain ownership).

The class `timed_mutex` meets all of the timed mutex requirements (33.6.4.3). It is a standard-layout class (11.2).

The behavior of a program is undefined if:

(3.1) it destroys a `timed_mutex` object owned by any thread,  
(3.2) a thread that owns a `timed_mutex` object calls `lock()`, `try_lock()`, `try_lock_for()`, or `try_lock_until()` on that object, or  
(3.3) a thread terminates while owning a `timed_mutex` object.

33.6.4.3.3 Class `recursive_timed_mutex`  

namespace std {  
class recursive_timed_mutex {  
   public:  
      recursive_timed_mutex();  
      ~recursive_timed_mutex();  
      
      recursive_timed_mutex(const recursive_timed_mutex&) = delete;  
      recursive_timed_mutex& operator=(const recursive_timed_mutex&) = delete;  
      
      void lock();  // blocking  
      bool try_lock() noexcept;  
      template<class Rep, class Period>  
         bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);  
      template<class Clock, class Duration>  
         bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);  
      void unlock();  
      
      using native_handle_type = implementation-defined;  // see 33.2.3  
      native_handle_type native_handle();  // see 33.2.3  
   };  
}  

The class `recursive_timed_mutex` provides a recursive mutex with exclusive ownership semantics. If one thread owns a `recursive_timed_mutex` object, attempts by another thread to acquire ownership of that
The class **recursive_timed_mutex** meets all of the timed mutex requirements (33.6.4.3). It is a standard-layout class (11.2).

A thread that owns a **recursive_timed_mutex** object may acquire additional levels of ownership by calling **lock()**, **try_lock()**, **try_lock_for()**, or **try_lock_until()** on that object. It is unspecified how many levels of ownership may be acquired by a single thread. If a thread has already acquired the maximum level of ownership for a **recursive_timed_mutex** object, additional calls to **try_lock()**, **try_lock_for()**, or **try_lock_until()** fail, and additional calls to **lock()** throw an exception of type **system_error**. A thread shall call **unlock()** once for each level of ownership acquired by calls to **lock()**, **try_lock()**, **try_lock_for()**, and **try_lock_until()**. Only when all levels of ownership have been released may ownership of the object be acquired by another thread.

The behavior of a program is undefined if

- it destroys a **recursive_timed_mutex** object owned by any thread, or
- a thread terminates while owning a **recursive_timed_mutex** object.

---

### § 33.6.4.4 Shared mutex types

33.6.4.4.1 General

The standard library types **shared_mutex** and **shared_timed_mutex** are shared mutex types. Shared mutex types meet the requirements of mutex types (33.6.4.2) and additionally meet the requirements set out below. In this description, \( m \) denotes an object of a shared mutex type.

[Note 1: The shared mutex types meet the **Cpp17SharedLockable** requirements (33.2.5.5). — end note]

In addition to the exclusive lock ownership mode specified in 33.6.4.2, shared mutex types provide a shared lock ownership mode. Multiple execution agents can simultaneously hold a shared lock ownership of a shared mutex type. But no execution agent holds a shared lock while another execution agent holds an exclusive lock on the same shared mutex type, and vice-versa. The maximum number of execution agents which can share a shared lock on a single shared mutex type is unspecified, but is at least 10000. If more than the maximum number of execution agents attempt to obtain a shared lock, the excess execution agents block until the number of shared locks are reduced below the maximum amount by other execution agents releasing their shared lock.

The expression \( m.\text{lock} \_\text{shared}() \) is well-formed and has the following semantics:

- **Preconditions**: The calling thread has no ownership of the mutex.
- **Effects**: Blocks the calling thread until shared ownership of the mutex can be obtained for the calling thread. If an exception is thrown then a shared lock has not been acquired for the current thread.
- **Synchronization**: Prior **unlock()** operations on the same object synchronize with (6.9.2) this operation.
- **Postconditions**: The calling thread has a shared lock on the mutex.
- **Return type**: void.
- **Throws**: **system_error** when an exception is required (33.2.2).
- **Error conditions**:
  - **operation_not_permitted** — if the thread does not have the privilege to perform the operation.
  - **resource_deadlock_would_occur** — if the implementation detects that a deadlock would occur.

The expression \( m.\text{unlock} \_\text{shared}() \) is well-formed and has the following semantics:

- **Preconditions**: The calling thread holds a shared lock on the mutex.
- **Effects**: Releases a shared lock on the mutex held by the calling thread.
- **Return type**: void.
- **Synchronization**: This operation synchronizes with (6.9.2) subsequent **lock()** operations that obtain ownership on the same object.
- **Throws**: Nothing.
The expression `m.try_lock_shared()` is well-formed and has the following semantics:

**Preconditions:** The calling thread has no ownership of the mutex.

**Effects:** Attempts to obtain shared ownership of the mutex for the calling thread without blocking. If shared ownership is not obtained, there is no effect and `try_lock_shared()` immediately returns. An implementation may fail to obtain the lock even if it is not held by any other thread.

**Synchronization:** If `try_lock_shared()` returns `true`, prior `unlock()` operations on the same object synchronize with (6.9.2) this operation.

**Return type:** `bool`.

**Returns:** `true` if the shared lock was acquired, otherwise `false`.

**Throws:** Nothing.

### 33.6.4.4.2 Class `shared_mutex`

```cpp
namespace std {
    class shared_mutex {
        public:
            shared_mutex();
            ~shared_mutex();

            shared_mutex(const shared_mutex&) = delete;
            shared_mutex& operator=(const shared_mutex&) = delete;

            // exclusive ownership
            void lock();  // blocking
            bool try_lock();
            void unlock();

            // shared ownership
            void lock_shared();  // blocking
            bool try_lock_shared();
            void unlock_shared();

            using native_handle_type = implementation-defined;  // see 33.2.3
            native_handle_type native_handle();  // see 33.2.3
    };
}
```

The class `shared_mutex` provides a non-recursive mutex with shared ownership semantics.

The class `shared_mutex` meets all of the shared mutex requirements (33.6.4.4). It is a standard-layout class (11.2).

The behavior of a program is undefined if

- (3.1) it destroys a `shared_mutex` object owned by any thread,
- (3.2) a thread attempts to recursively gain any ownership of a `shared_mutex`, or
- (3.3) a thread terminates while possessing any ownership of a `shared_mutex`.

`shared_mutex` may be a synonym for `shared_timed_mutex`.

### 33.6.4.5 Shared timed mutex types

The standard library type `shared_timed_mutex` is a `shared timed mutex type`. Shared timed mutex types meet the requirements of timed mutex types (33.6.4.3), shared mutex types (33.6.4.4), and additionally meet the requirements set out below. In this description, `m` denotes an object of a shared timed mutex type, `rel_time` denotes an object of an instantiation of `duration` (29.5), and `abs_time` denotes an object of an instantiation of `time_point` (29.6).

[Note 1: The shared timed mutex types meet the Cpp17SharedTimedLockable requirements (33.2.5.6). — end note]

The expression `m.try_lock_shared_for(rel_time)` is well-formed and has the following semantics:

**Preconditions:** The calling thread has no ownership of the mutex.
Effects: Attempts to obtain shared lock ownership for the calling thread within the relative timeout (33.2.4) specified by rel_time. If the time specified by rel_time is less than or equal to rel_time.zero(), the function attempts to obtain ownership without blocking (as if by calling try_lock_shared()). The function returns within the timeout specified by rel_time only if it has obtained shared ownership of the mutex object.

[Note 2: As with try_lock(), there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note]

If an exception is thrown then a shared lock has not been acquired for the current thread.

Synchronization: If try_lock_shared_for() returns true, prior unlock() operations on the same object synchronize with (6.9.2) this operation.

Return type: bool.

Returns: true if the shared lock was acquired, otherwise false.

Throws: Timeout-related exceptions (33.2.4).

The expression m.try_lock_shared_until(abs_time) is well-formed and has the following semantics:

Preconditions: The calling thread has no ownership of the mutex.

Effects: The function attempts to obtain shared ownership of the mutex. If abs_time has already passed, the function attempts to obtain shared ownership without blocking (as if by calling try_lock_shared()). The function returns before the absolute timeout (33.2.4) specified by abs_time only if it has obtained shared ownership of the mutex object.

[Note 3: As with try_lock(), there is no guarantee that ownership will be obtained if the lock is available, but implementations are expected to make a strong effort to do so. — end note]

If an exception is thrown then a shared lock has not been acquired for the current thread.

Synchronization: If try_lock_shared_until() returns true, prior unlock() operations on the same object synchronize with (6.9.2) this operation.

Return type: bool.

Returns: true if the shared lock was acquired, otherwise false.

Throws: Timeout-related exceptions (33.2.4).

33.6.4.5.2 Class shared_timed_mutex

```cpp
namespace std {
    class shared_timed_mutex {
    public:
        shared_timed_mutex();
        ~shared_timed_mutex();
        shared_timed_mutex(const shared_timed_mutex&) = delete;
        shared_timed_mutex& operator=(const shared_timed_mutex&) = delete;

        // exclusive ownership
        void lock();       // blocking
        bool try_lock();
        template<class Rep, class Period>
            bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
        template<class Clock, class Duration>
            bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
        void unlock();

        // shared ownership
        void lock_shared();    // blocking
        bool try_lock_shared();
        template<class Rep, class Period>
            bool try_lock_shared_for(const chrono::duration<Rep, Period>& rel_time);
        template<class Clock, class Duration>
            bool try_lock_shared_until(const chrono::time_point<Clock, Duration>& abs_time);
        void unlock_shared();
    }
}
```

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The class `shared_timed_mutex` provides a non-recursive mutex with shared ownership semantics.

The class `shared_timed_mutex` meets all of the shared timed mutex requirements (33.6.4.5). It is a standard-layout class (11.2).

The behavior of a program is undefined if
1. it destroys a `shared_timed_mutex` object owned by any thread,
2. a thread attempts to recursively gain any ownership of a `shared_timed_mutex`, or
3. a thread terminates while possessing any ownership of a `shared_timed_mutex`.

33.6.5 Locks

33.6.5.1 General

A lock is an object that holds a reference to a lockable object and may unlock the lockable object during the lock’s destruction (such as when leaving block scope). An execution agent may use a lock to aid in managing ownership of a lockable object in an exception safe manner. A lock is said to own a lockable object if it is currently managing the ownership of that lockable object for an execution agent. A lock does not manage the lifetime of the lockable object it references.

[Note 1: Locks are intended to ease the burden of unlocking the lockable object under both normal and exceptional circumstances. — end note]

Some lock constructors take tag types which describe what should be done with the lockable object during the lock’s construction.

```cpp
namespace std {
    struct defer_lock_t { }; // do not acquire ownership of the mutex
    struct try_to_lock_t { }; // try to acquire ownership of the mutex
        // without blocking
    struct adopt_lock_t { }; // assume the calling thread has already
        // obtained mutex ownership and manage it

    inline constexpr defer_lock_t defer_lock {}; // do not acquire ownership of the mutex
    inline constexpr try_to_lock_t try_to_lock {}; // try to acquire ownership of the mutex
        // without blocking
    inline constexpr adopt_lock_t adopt_lock {}; // assume the calling thread has already
        // obtained mutex ownership and manage it
}
```

33.6.5.2 Class template `lock_guard`

```cpp
namespace std {
    template<class Mutex>
    class lock_guard {
        using mutex_type = Mutex;

        explicit lock_guard(mutex_type& m);
        lock_guard(mutex_type& m, adopt_lock_t);
        ~lock_guard();
        lock_guard(const lock_guard&)=delete;
        lock_guard& operator=(const lock_guard&)=delete;

        private:
            mutex_type& pm; // exposition only
    };
}
```

An object of type `lock_guard` controls the ownership of a lockable object within a scope. A `lock_guard` object maintains ownership of a lockable object throughout the `lock_guard` object’s lifetime (6.7.3). The behavior of a program is undefined if the lockable object referenced by `pm` does not exist for the entire lifetime of the `lock_guard` object. The supplied `Mutex` type shall meet the `Cpp17BasicLockable` requirements (33.2.5.2).
33.6.5.3 Class template scoped_lock

namespace std {
    template<class... MutexTypes>
    class scoped_lock {
    public:
        using mutex_type = see below; // Only if sizeof...(MutexTypes) == 1 is true

        explicit scoped_lock(MutexTypes&... m);
        explicit scoped_lock(adopt_lock_t, MutexTypes&... m);
        ~scoped_lock();

        scoped_lock(const scoped_lock&) = delete;
        scoped_lock& operator=(const scoped_lock&) = delete;

    private:
        tuple<MutexTypes&...> pm; // exposition only
    }
}

1 An object of type scoped_lock controls the ownership of lockable objects within a scope. A scoped_lock object maintains ownership of lockable objects throughout the scoped_lock object’s lifetime (6.7.3). The behavior of a program is undefined if the lockable objects referenced by pm do not exist for the entire lifetime of the scoped_lock object.

(1.1) — If sizeof...(MutexTypes) is one, let Mutex denote the sole type constituting the pack MutexTypes. Mutex shall meet the Cpp17BasicLockable requirements (33.2.5.2). The member typedef-name mutex_type denotes the same type as Mutex.

(1.2) — Otherwise, all types in the template parameter pack MutexTypes shall meet the Cpp17Lockable requirements (33.2.5.3) and there is no member mutex_type.

2 explicit scoped_lock(MutexTypes&... m);

   Effects: Initializes pm with tie(m...). Then if sizeof...(MutexTypes) is 0, no effects. Otherwise if sizeof...(MutexTypes) is 1, then m.lock(). Otherwise, lock(m...).

3 explicit scoped_lock(adopt_lock_t, MutexTypes&... m);

   Preconditions: The calling thread holds a non-shared lock on each element of m.

   Effects: Initializes pm with tie(m...).

   Throws: Nothing.

4 ~scoped_lock();

   Effects: For all i in [0, sizeof...(MutexTypes)), get<i>(pm).unlock().

33.6.5.4 Class template unique_lock

33.6.5.4.1 General
namespace std {

    template<class Mutex>
    class unique_lock {
    public:
        using mutex_type = Mutex;

        // 33.6.5.4.2, construct/copy/destroy
        unique_lock() noexcept;
        explicit unique_lock(mutex_type& m);
        unique_lock(mutex_type& m, defer_lock_t) noexcept;
        unique_lock(mutex_type& m, try_to_lock_t);
        unique_lock(mutex_type& m, adopt_lock_t);
        template<class Clock, class Duration>
            unique_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);
        template<class Rep, class Period>
            unique_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);
        ~unique_lock();

        unique_lock(const unique_lock&) = delete;
        unique_lock& operator=(const unique_lock&);
        unique_lock(unique_lock&& u) noexcept;
        unique_lock& operator=(unique_lock&& u);

        // 33.6.5.4.3, locking
        void lock();
        bool try_lock();
        template<class Rep, class Period>
            bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
        template<class Clock, class Duration>
            bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
        void unlock();

        // 33.6.5.4.4, modifiers
        void swap(unique_lock& u) noexcept;
        mutex_type* release() noexcept;

        // 33.6.5.4.5, observers
        bool owns_lock() const noexcept;
        explicit operator bool () const noexcept;
        mutex_type* mutex() const noexcept;

    private:
        mutex_type* pm; // exposition only
        bool owns; // exposition only
    };
}

An object of type unique_lock controls the ownership of a lockable object within a scope. Ownership of
the lockable object may be acquired at construction or after construction, and may be transferred, after
acquisition, to another unique_lock object. Objects of type unique_lock are not copyable but are movable.
The behavior of a program is undefined if the contained pointer pm is not null and the lockable object pointed
to by pm does not exist for the entire remaining lifetime (6.7.3) of the unique_lock object. The supplied
Mutex type shall meet the Cpp17BasicLockable requirements (33.2.5.2).

[Note 1: unique_lock<Mutex> meets the Cpp17BasicLockable requirements. If Mutex meets the Cpp17Lockable
requirements (33.2.5.3), unique_lock<Mutex> also meets the Cpp17Lockable requirements; if Mutex meets the
Cpp17TimedLockable requirements (33.2.5.4), unique_lock<Mutex> also meets the Cpp17TimedLockable requirements.]

33.6.5.4.2 Constructors, destructor, and assignment
unique_lock() noexcept;
   Postconditions: pm == nullptr and owns == false.

explicit unique_lock(mutex_type& m);
   Effects: Calls m.lock().
   Postconditions: pm == addressof(m) and owns == true.

unique_lock(mutex_type& m, defer_lock_t) noexcept;
   Postconditions: pm == addressof(m) and owns == false.

unique_lock(mutex_type& m, try_to_lock_t);
   Preconditions: The supplied Mutex type meets the Cpp17Lockable requirements (33.2.5.3).
   Effects: Calls m.try_lock().
   Postconditions: pm == addressof(m) and owns == res, where res is the value returned by the call
to m.try_lock().

unique_lock(mutex_type& m, adopt_lock_t);
   Preconditions: The calling thread holds a non-shared lock on m.
   Postconditions: pm == addressof(m) and owns == true.
   Throws: Nothing.

template<class Clock, class Duration>
unique_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);
   Preconditions: The supplied Mutex type meets the Cpp17TimedLockable requirements (33.2.5.4).
   Effects: Calls m.try_lock_until(abs_time).
   Postconditions: pm == addressof(m) and owns == res, where res is the value returned by the call
to m.try_lock_until(abs_time).

template<class Rep, class Period>
unique_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);
   Preconditions: The supplied Mutex type meets the Cpp17TimedLockable requirements (33.2.5.4).
   Effects: Calls m.try_lock_for(rel_time).
   Postconditions: pm == addressof(m) and owns == res, where res is the value returned by the call
to m.try_lock_for(rel_time).

unique_lock(unique_lock&& u) noexcept;
   Postconditions: pm == u_p.pm and owns == u_p.owns (where u_p is the state of u just prior to this
construction), u.pm == 0 and u.owns == false.

unique_lock& operator=(unique_lock&& u);
   Effects: If owns calls pm->unlock().
   Postconditions: pm == u_p.pm and owns == u_p.owns (where u_p is the state of u just prior to this
construction), u.pm == 0 and u.owns == false.
   [Note 1: With a recursive mutex it is possible for both *this and u to own the same mutex before the assignment.
In this case, *this will own the mutex after the assignment and u will not. — end note]
   Throws: Nothing.

~unique_lock();
   Effects: If owns calls pm->unlock().

33.6.5.4.3 Locking [thread.lock.unique.locking]

void lock();
   Effects: As if by pm->lock().
**Postconditions**: owns == true.

**Throws**: Any exception thrown by pm->lock(). system_error when an exception is required (33.2.2).

**Error conditions**:
- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.

```cpp
bool try_lock();
```

**Preconditions**: The supplied Mutex meets the Cpp17Lockable requirements (33.2.5.3).

**Effects**: As if by pm->try_lock().

**Postconditions**: owns == res, where res is the value returned by pm->try_lock().

**Returns**: The value returned by pm->try_lock().

**Throws**: Any exception thrown by pm->try_lock(). system_error when an exception is required (33.2.2).

**Error conditions**:
- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.

```cpp
template<class Clock, class Duration>
bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
```

**Preconditions**: The supplied Mutex type meets the Cpp17TimedLockable requirements (33.2.5.4).

**Effects**: As if by pm->try_lock_until(abs_time).

**Postconditions**: owns == res, where res is the value returned by pm->try_lock_until(abs_time).

**Returns**: The value returned by pm->try_lock_until(abs_time).

**Throws**: Any exception thrown by pm->try_lock_until(abstime). system_error when an exception is required (33.2.2).

**Error conditions**:
- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occ
- resource_deadlock_would_occur — if on entry owns is true.

```cpp
template<class Rep, class Period>
bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
```

**Preconditions**: The supplied Mutex type meets the Cpp17TimedLockable requirements (33.2.5.4).

**Effects**: As if by pm->try_lock_for(rel_time).

**Postconditions**: owns == res, where res is the value returned by pm->try_lock_for(rel_time).

**Returns**: The value returned by pm->try_lock_for(rel_time).

**Throws**: Any exception thrown by pm->try_lock_for(rel_time). system_error when an exception is required (33.2.2).

**Error conditions**:
- operation_not_permitted — if pm is nullptr.
- resource_deadlock_would_occur — if on entry owns is true.

```cpp
void unlock();
```

**Effects**: As if by pm->unlock().

**Postconditions**: owns == false.

**Throws**: system_error when an exception is required (33.2.2).

**Error conditions**:
- operation_not_permitted — if on entry owns is false.
33.6.5.4.4 Modifiers

void swap(unique_lock& u) noexcept;

Effects: Swaps the data members of *this and u.

mutex_type* release() noexcept;

Postconditions: pm == 0 and owns == false.

Returns: The previous value of pm.

33.6.5.4.5 Observers

bool owns_lock() const noexcept;

Returns: owns.

explicit operator bool() const noexcept;

Returns: owns.

mutex_type *mutex() const noexcept;

Returns: pm.

33.6.5.5 Class template shared_lock

33.6.5.5.1 General

namespace std {

template<class Mutex>
class shared_lock {

public:
    using mutex_type = Mutex;

    // 33.6.5.5.2, construct/copy/destroy
    shared_lock() noexcept;
    explicit shared_lock(mutex_type& m); // blocking
    shared_lock(mutex_type& m, defer_lock_t) noexcept;
    shared_lock(mutex_type& m, try_to_lock_t);
    shared_lock(mutex_type& m, adopt_lock_t);
    template<class Clock, class Duration>
        shared_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);
    template<class Rep, class Period>
        shared_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);
    ~shared_lock();

    shared_lock(const shared_lock&) = delete;
    shared_lock& operator=(const shared_lock&) = delete;

    shared_lock(shared_lock& u) noexcept;
    shared_lock& operator=(shared_lock& u) noexcept;

    // 33.6.5.5.3, locking
    void lock(); // blocking
    bool try_lock();
    template<class Rep, class Period>
            bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);
    template<class Clock, class Duration>
            bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);
    void unlock();

    // 33.6.5.5.4, modifiers
    void swap(shared_lock& u) noexcept;
    mutex_type* release() noexcept;
}
An object of type `shared_lock` controls the shared ownership of a lockable object within a scope. Shared ownership of the lockable object may be acquired at construction or after construction, and may be transferred, after acquisition, to another `shared_lock` object. Objects of type `shared_lock` are not copyable but are movable. The behavior of a program is undefined if the contained pointer `pm` is not null and the lockable object pointed to by `pm` does not exist for the entire remaining lifetime (6.7.3) of the `shared_lock` object. The supplied `Mutex` type shall meet the `Cpp17SharedLockable` requirements (33.2.5.5).

[Note 1: `shared_lock<Mutex>` meets the `Cpp17Lockable` requirements (33.2.5.3). If `Mutex` meets the `Cpp17SharedTimedLockable` requirements (33.2.5.6), `shared_lock<Mutex>` also meets the `Cpp17TimedLockable` requirements (33.2.5.4). — end note]

### 33.6.5.5.2 Constructors, destructor, and assignment

**shared_lock()** noexcept;

Postconditions: `pm == nullptr` and `owns == false`.

**explicit shared_lock(mutex_type& m);**

Effects: Calls `m.lock_shared()`.

Postconditions: `pm == addressof(m)` and `owns == true`.

**shared_lock(mutex_type& m, defer_lock_t) noexcept;**

Postconditions: `pm == addressof(m)` and `owns == false`.

**shared_lock(mutex_type& m, try_to_lock_t);**

Effects: Calls `m.try_lock_shared()`.

Postconditions: `pm == addressof(m)` and `owns == res` where `res` is the value returned by the call to `m.try_lock_shared()`.

**shared_lock(mutex_type& m, adopt_lock_t);**

Preconditions: The calling thread holds a shared lock on `m`.

Postconditions: `pm == addressof(m)` and `owns == true`.

**template<class Clock, class Duration>**

**shared_lock(mutex_type& m, const chrono::time_point<Clock, Duration>& abs_time);**

Preconditions: `Mutex` meets the `Cpp17SharedTimedLockable` requirements (33.2.5.6).

Effects: Calls `m.try_lock_shared_until(abs_time)`.

Postconditions: `pm == addressof(m)` and `owns == res` where `res` is the value returned by the call to `m.try_lock_shared_until(abs_time)`.

**template<class Rep, class Period>**

**shared_lock(mutex_type& m, const chrono::duration<Rep, Period>& rel_time);**

Preconditions: `Mutex` meets the `Cpp17SharedTimedLockable` requirements (33.2.5.6).

Effects: Calls `m.try_lock_shared_for(rel_time)`.

Postconditions: `pm == addressof(m)` and `owns == res` where `res` is the value returned by the call to `m.try_lock_shared_for(rel_time)`.
-shared_lock();

    Effects: If owns calls pm->unlock_shared().

shared_lock(shared_lock&& sl) noexcept;

    Postconditions: pm == sl_p.pm and owns == sl_p.owns (where sl_p is the state of sl just prior to this construction), sl.pm == nullptr and sl.owns == false.

shared_lock& operator=(shared_lock&& sl) noexcept;

    Effects: If owns calls pm->unlock_shared().

    Postconditions: pm == sl_p.pm and owns == sl_p.owns (where sl_p is the state of sl just prior to this assignment), sl.pm == nullptr and sl.owns == false.

33.6.5.5.3 Locking

void lock();

    Effects: As if by pm->lock_shared().

    Postconditions: owns == true.

    Throws: Any exception thrown by pm->lock_shared(). system_error when an exception is required (33.2.2).

    Error conditions:

        — operation_not_permitted — if pm is nullptr.

        — resource_deadlock_would_occur — if on entry owns is true.

bool try_lock();

    Effects: As if by pm->try_lock_shared().

    Postconditions: owns == res, where res is the value returned by the call to pm->try_lock_shared().

    Returns: The value returned by the call to pm->try_lock_shared().

    Throws: Any exception thrown by pm->try_lock_shared(). system_error when an exception is required (33.2.2).

    Error conditions:

        — operation_not_permitted — if pm is nullptr.

        — resource_deadlock_would_occur — if on entry owns is true.

template<class Clock, class Duration>
bool try_lock_until(const chrono::time_point<Clock, Duration>& abs_time);

    Preconditions: Mutex meets the Cpp17SharedTimedLockable requirements (33.2.5.6).

    Effects: As if by pm->try_lock_shared_until(abs_time).

    Postconditions: owns == res, where res is the value returned by the call to pm->try_lock_shared_until(abs_time).

    Returns: The value returned by the call to pm->try_lock_shared_until(abs_time).

    Throws: Any exception thrown by pm->try_lock_shared_until(abs_time). system_error when an exception is required (33.2.2).

    Error conditions:

        — operation_not_permitted — if pm is nullptr.

        — resource_deadlock_would_occur — if on entry owns is true.

template<class Rep, class Period>
bool try_lock_for(const chrono::duration<Rep, Period>& rel_time);

    Preconditions: Mutex meets the Cpp17SharedTimedLockable requirements (33.2.5.6).

    Effects: As if by pm->try_lock_shared_for(rel_time).
Postconditions: owns == res, where res is the value returned by the call to pm->try_lock_shared_for(rel_time).

Returns: The value returned by the call to pm->try_lock_shared_for(rel_time).

Throws: Any exception thrown by pm->try_lock_shared_for(rel_time). system_error when an exception is required (33.2.2).

Error conditions:
(21.1) operation_not_permitted — if pm is nullptr.
(21.2) resource_deadlock_would_occur — if on entry owns is true.

void unlock();

Effects: As if by pm->unlock_shared().

Postconditions: owns == false.

Throws: system_error when an exception is required (33.2.2).

Error conditions:
(25.1) operation_not_permitted — if on entry owns is false.

### 33.6.5.5.4 Modifiers

```cpp
void swap(shared_lock& sl) noexcept;
```

Effects: Swaps the data members of *this and sl.

```cpp
mutex_type* release() noexcept;
```

Postconditions: pm == nullptr and owns == false.

Returns: The previous value of pm.

```cpp
template<class Mutex>
void swap(shared_lock<Mutex>& x, shared_lock<Mutex>& y) noexcept;
```

Effects: As if by x.swap(y).

### 33.6.5.5 Observers

```cpp
bool owns_lock() const noexcept;
```

Returns: owns.

```cpp
explicit operator bool() const noexcept;
```

Returns: owns.

```cpp
mutex_type* mutex() const noexcept;
```

Returns: pm.

### 33.6.6 Generic locking algorithms

```cpp
template<class L1, class L2, class... L3> int try_lock(L1&, L2&, L3&...);
```

Preconditions: Each template parameter type meets the Cpp17Lockable requirements.

[Note 1: The unique_lock class template meets these requirements when suitably instantiated. — end note]

Effects: Calls try_lock() for each argument in order beginning with the first until all arguments have been processed or a call to try_lock() fails, either by returning false or by throwing an exception. If a call to try_lock() fails, unlock() is called for all prior arguments with no further calls to try_lock().

Returns: -1 if all calls to try_lock() returned true, otherwise a zero-based index value that indicates the argument for which try_lock() returned false.

```cpp
template<class L1, class L2, class... L3> void lock(L1&, L2&, L3&...);
```

Preconditions: Each template parameter type meets the Cpp17Lockable requirements.

[Note 2: The unique_lock class template meets these requirements when suitably instantiated. — end note]

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Effects: All arguments are locked via a sequence of calls to `lock()`, `try_lock()`, or `unlock()` on each argument. The sequence of calls does not result in deadlock, but is otherwise unspecified.

[Note 3: A deadlock avoidance algorithm such as try-and-back-off can be used, but the specific algorithm is not specified to avoid over-constraining implementations. — end note]

If a call to `lock()` or `try_lock()` throws an exception, `unlock()` is called for any argument that had been locked by a call to `lock()` or `try_lock()`.

33.6.7 Call once

### 33.6.7.1 Struct `once_flag`

```cpp
namespace std {
    struct once_flag {
        constexpr once_flag() noexcept;
        once_flag(const once_flag&) = delete;
        once_flag& operator=(const once_flag&) = delete;
    };
}
```

1 The class `once_flag` is an opaque data structure that `call_once` uses to initialize data without causing a data race or deadlock.

```cpp
constexpr once_flag() noexcept;
```

2 **Synchronization:** The construction of a `once_flag` object is not synchronized.

3 **Postconditions:** The object’s internal state is set to indicate to an invocation of `call_once` with the object as its initial argument that no function has been called.

### 33.6.7.2 Function `call_once`

```cpp
template<class Callable, class... Args>
void call_once(once_flag& flag, Callable&& func, Args&&... args);
```

1 **Mandates:** `is_invocable_v<Callable, Args...>` is true.

2 **Effects:** An execution of `call_once` that does not call its `func` is a passive execution. An execution of `call_once` that calls its `func` is an active execution. An active execution evaluates `INVOKE(std::forward<Callable>(func), std::forward<Args>(args)...)` (22.10.4). If such a call to `func` throws an exception the execution is exceptional, otherwise it is returning. An exceptional execution propagates the exception to the caller of `call_once`. Among all executions of `call_once` for any given `once_flag`: at most one is a returning execution; if there is a returning execution, it is the last active execution; and there are passive executions only if there is a returning execution.

[Note 1: Passive executions allow other threads to reliably observe the results produced by the earlier returning execution. — end note]

3 **Synchronization:** For any given `once_flag`: all active executions occur in a total order; completion of an active execution synchronizes with (6.9.2) the start of the next one in this total order; and the returning execution synchronizes with the return from all passive executions.

4 **Throws:** `system_error` when an exception is required (33.2.2), or any exception thrown by `func`.

[Example 1:

```cpp
// global flag, regular function
void init();
std::once_flag flag;

void f() {
    std::call_once(flag, init);
}

// function static flag, function object
struct initializer {
    void operator()();
};
```
void g() {
    static std::once_flag flag2;
    std::call_once(flag2, initializer());
}

// object flag, member function
class information {
    std::once_flag verified;
    void verifier();
public:
    void verify() { std::call_once(verified, &information::verifier, *this); }
};
— end example

### 33.7 Condition variables

#### 33.7.1 General

1 Condition variables provide synchronization primitives used to block a thread until notified by some other thread that some condition is met or until a system time is reached. Class `condition_variable` provides a condition variable that can only wait on an object of type `unique_lock<mutex>`, allowing the implementation to be more efficient. Class `condition_variable_any` provides a general condition variable that can wait on objects of user-supplied lock types.

2 Condition variables permit concurrent invocation of the `wait`, `wait_for`, `wait_until`, `notify_one` and `notify_all` member functions.

3 The executions of `notify_one` and `notify_all` are atomic. The executions of `wait`, `wait_for`, and `wait_until` are performed in three atomic parts:
   1. the release of the mutex and entry into the waiting state;
   2. the unblocking of the wait; and
   3. the reacquisition of the lock.

4 The implementation behaves as if all executions of `notify_one`, `notify_all`, and each part of the `wait`, `wait_for`, and `wait_until` executions are executed in a single unspecified total order consistent with the “happens before” order.

5 Condition variable construction and destruction need not be synchronized.

#### 33.7.2 Header `<condition_variable>` synopsis

```cpp
namespace std {
    // 33.7.4, class condition_variable
    class condition_variable;
    // 33.7.5, class condition_variable_any
    class condition_variable_any;

    // 33.7.3, non-member functions
    void notify_all_at_thread_exit(condition_variable& cond, unique_lock<mutex> lk);

    enum class cv_status { no_timeout, timeout }
};
```

#### 33.7.3 Non-member functions

```cpp
void notify_all_at_thread_exit(condition_variable& cond, unique_lock<mutex> lk);
```

1 **Preconditions:** `lk` is locked by the calling thread and either

1.1 no other thread is waiting on `cond`, or

1.2 `lk.mutex()` returns the same value for each of the lock arguments supplied by all concurrently waiting (via `wait`, `wait_for`, or `wait_until`) threads.
Effects: Transfers ownership of the lock associated with \(lk\) into internal storage and schedules \(cond\) to be notified when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed. This notification is equivalent to:

\[
\begin{align*}
&lk.unlock(); \\
&cond.notify_all();
\end{align*}
\]

Synchronization: The implied \(lk.unlock()\) call is sequenced after the destruction of all objects with thread storage duration associated with the current thread.

[Note 1: The supplied lock is held until the thread-exits, which might cause deadlock due to lock ordering issues. — end note]

[Note 2: It is the user’s responsibility to ensure that waiting threads do not incorrectly assume that the thread has finished if they experience spurious wakeups. This typically requires that the condition being waited for is satisfied while holding the lock on \(lk\), and that this lock is not released and reacquired prior to calling \(notify_all_at_thread_exit\). — end note]

### 33.7.4 Class condition_variable

```cpp	namespace std {
    class condition_variable {
        public:
            condition_variable();
            ~condition_variable();
            condition_variable(const condition_variable&) = delete;
            condition_variable& operator=(const condition_variable&) = delete;

            void notify_one() noexcept;
            void notify_all() noexcept;
            void wait(unique_lock<mutex>& lock);
            template<class Predicate>
                void wait(unique_lock<mutex>& lock, Predicate pred);
            template<class Clock, class Duration>
                cv_status wait_until(unique_lock<mutex>& lock,
                    const chrono::time_point<Clock, Duration>& abs_time);
            template<class Clock, class Duration, class Predicate>
                bool wait_until(unique_lock<mutex>& lock,
                    const chrono::time_point<Clock, Duration>& abs_time,
                    Predicate pred);
            template<class Rep, class Period>
                cv_status wait_for(unique_lock<mutex>& lock,
                    const chrono::duration<Rep, Period>& rel_time);
            template<class Rep, class Period, class Predicate>
                bool wait_for(unique_lock<mutex>& lock,
                    const chrono::duration<Rep, Period>& rel_time,
                    Predicate pred);

            using native_handle_type = implementation-defined; // see 33.2.3
            native_handle_type native_handle(); // see 33.2.3
    };
}
```

The class `condition_variable` is a standard-layout class (11.2).

### 1

condition_variable();

### 2

**Throws:** `system_error` when an exception is required (33.2.2).

### 3

**Error conditions:**

- `resource_unavailable_try_again` — if some non-memory resource limitation prevents initialization.

### 4

**Preconditions:** There is no thread blocked on `*this`. 

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void notify_one() noexcept;

Effects: If any threads are blocked waiting for *this, unblocks one of those threads.

void notify_all() noexcept;

Effects: Unblocks all threads that are blocked waiting for *this.

void wait(unique_lock<mutex>& lock);

Preconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either
— no other thread is waiting on this condition_variable object or
— lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently
waiting (via wait, wait_for, or wait_until) threads.

Effects:
— Atomically calls lock.unlock() and blocks on *this.
— When unblocked, calls lock.lock() (possibly blocking on the lock), then returns.

Postconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Throws: Nothing.

Remarks: If the function fails to meet the postcondition, terminate() is invoked (14.6.2).

[Note 2: This can happen if the re-locking of the mutex throws an exception. — end note]

template<class Predicate>
void wait(unique_lock<mutex>& lock, Predicate pred);

Preconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either
— no other thread is waiting on this condition_variable object or
— lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently
waiting (via wait, wait_for, or wait_until) threads.

Effects: Equivalent to:
while (!pred())
    wait(lock);

Postconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Throws: Any exception thrown by pred.

Remarks: If the function fails to meet the postcondition, terminate() is invoked (14.6.2).

[Note 3: This can happen if the re-locking of the mutex throws an exception. — end note]

template<class Clock, class Duration>
cv_status wait_until(unique_lock<mutex>& lock, const chrono::time_point<Clock, Duration>& abs_time);

Preconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either
— no other thread is waiting on this condition_variable object or
— lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently
waiting (via wait, wait_for, or wait_until) threads.

Effects:
— Atomically calls lock.unlock() and blocks on *this.
— When unblocked, calls lock.lock() (possibly blocking on the lock), then returns.
The function will unblock when signaled by a call to notify_one(), a call to notify_all(), expiration of the absolute timeout (33.2.4) specified by abs_time, or spuriously.

Postconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Returns: cv_status::timeout if the absolute timeout (33.2.4) specified by abs_time expired, otherwise cv_status::no_timeout.

Throws: Timeout-related exceptions (33.2.4).

Remarks: If the function fails to meet the postcondition, terminate() is invoked (14.6.2).

[Note 4: This can happen if the re-locking of the mutex throws an exception. — end note]

```cpp
template<class Rep, class Period>
void wait_for(unique_lock<mutex>& lock,
              const chrono::duration<Rep, Period>& rel_time);
```

Preconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either

- no other thread is waiting on this condition_variable object or
- lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently waiting (via wait, wait_for, or wait_until) threads.

Effects: Equivalent to:

```cpp
return wait_until(lock, chrono::steady_clock::now() + rel_time);
```

Postconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

Returns: cv_status::timeout if the relative timeout (33.2.4) specified by rel_time expired, otherwise cv_status::no_timeout.

Throws: Timeout-related exceptions (33.2.4).

Remarks: If the function fails to meet the postcondition, terminate is invoked (14.6.2).

[Note 5: This can happen if the re-locking of the mutex throws an exception. — end note]

```cpp
template<class Clock, class Duration, class Predicate>
bool wait_until(unique_lock<mutex>& lock,
                const chrono::time_point<Clock, Duration>& abs_time,
                Predicate pred);
```

Preconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either

- no other thread is waiting on this condition_variable object or
- lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently waiting (via wait, wait_for, or wait_until) threads.

Effects: Equivalent to:

```cpp
while (!pred())
    if (wait_until(lock, abs_time) == cv_status::timeout)
        return pred();
return true;
```

Postconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

[Note 6: The returned value indicates whether the predicate evaluated to true regardless of whether the timeout was triggered. — end note]

Throws: Timeout-related exceptions (33.2.4) or any exception thrown by pred.

Remarks: If the function fails to meet the postcondition, terminate() is invoked (14.6.2).

[Note 7: This can happen if the re-locking of the mutex throws an exception. — end note]

```cpp
template<class Rep, class Period, class Predicate>
bool wait_for(unique_lock<mutex>& lock,
              const chrono::duration<Rep, Period>& rel_time,
              Predicate pred);
```

Preconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread, and either
— no other thread is waiting on this condition_variable object or
— lock.mutex() returns the same value for each of the lock arguments supplied by all concurrently
waiting (via wait, wait_for, or wait_until) threads.

Effects: Equivalent to:

```cpp
return wait_until(lock, chrono::steady_clock::now() + rel_time, std::move(pred));
```

[Note 8: There is no blocking if pred() is initially true, even if the timeout has already expired. — end note]

Postconditions: lock.owns_lock() is true and lock.mutex() is locked by the calling thread.

[Note 9: The returned value indicates whether the predicate evaluates to true regardless of whether the timeout
was triggered. — end note]

Throws: Timeout-related exceptions (33.2.4) or any exception thrown by pred.

Remarks: If the function fails to meet the postcondition, terminate() is invoked (14.6.2).

[Note 10: This can happen if the re-locking of the mutex throws an exception. — end note]

33.7.5 Class condition_variable_any

33.7.5.1 General

In 33.7.5, template arguments for template parameters named Lock shall meet the Cpp17BasicLockable
requirements (33.2.5.2).

[Note 1: All of the standard mutex types meet this requirement. If a type other than one of the standard mutex
types or a unique_lock wrapper for a standard mutex type is used with condition_variable_any, any necessary
synchronization is assumed to be in place with respect to the predicate associated with the condition_variable_any
instance. — end note]

```cpp
namespace std {
    class condition_variable_any {
    public:
        condition_variable_any();
        ~condition_variable_any();

        condition_variable_any(const condition_variable_any&) = delete;
        condition_variable_any& operator=(const condition_variable_any&) = delete;

        void notify_one() noexcept;
        void notify_all() noexcept;

        // 33.7.5.2, noninterruptible waits
        template<class Lock>
            void wait(Lock& lock);
        template<class Lock, class Predicate>
            void wait(Lock& lock, Predicate pred);

        template<class Lock, class Clock, class Duration>
            cv_status wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time);
        template<class Lock, class Clock, class Duration, class Predicate>
            bool wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time,
                            Predicate pred);

        template<class Lock, class Rep, class Period>
            cv_status wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time);
        template<class Lock, class Rep, class Period, class Predicate>
            bool wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time, Predicate pred);

        // 33.7.5.3, interruptible waits
        template<class Lock, class Predicate>
            bool wait(Lock& lock, stop_token stoken, Predicate pred);
        template<class Lock, class Clock, class Duration, class Predicate>
            bool wait_until(Lock& lock, stop_token stoken,
                            const chrono::time_point<Clock, Duration>& abs_time, Predicate pred);
        template<class Lock, class Rep, class Period, class Predicate>
            bool wait_for(Lock& lock, stop_token stoken,
                          const chrono::duration<Rep, Period>& rel_time, Predicate pred);
    }
}
```
};
}

condition_variable_any();

Throws: bad_alloc or system_error when an exception is required (33.2.2).

Error conditions:

(3.1) resource_unavailable_try_again — if some non-memory resource limitation prevents initialization.

(3.2) operation_not_permitted — if the thread does not have the privilege to perform the operation.

~condition_variable_any();

Preconditions: There is no thread blocked on *this.

[Note 2: That is, all threads have been notified; they can subsequently block on the lock specified in the wait. This relaxes the usual rules, which would have required all wait calls to happen before destruction. Only the notification to unblock the wait needs to happen before destruction. Undefined behavior ensues if a thread waits on *this once the destructor has been started, especially when the waiting threads are calling the wait functions in a loop or using the overloads of wait, wait_for, or wait_until that take a predicate. — end note]

void notify_one() noexcept;

Effects: If any threads are blocked waiting for *this, unblocks one of those threads.

void notify_all() noexcept;

Effects: Unblocks all threads that are blocked waiting for *this.

33.7.5.2 Noninterruptible waits [thread.condvarany.wait]

template<class Lock>
void wait(Lock& lock);

Effects:

(1.1) Atomically calls lock.unlock() and blocks on *this.

(1.2) When unblocked, calls lock.lock() (possibly blocking on the lock) and returns.

(1.3) The function will unblock when signaled by a call to notify_one(), a call to notify_all(), or spuriously.

Postconditions: lock is locked by the calling thread.

Throws: Nothing.

Remarks: If the function fails to meet the postcondition, terminate() is invoked (14.6.2).

[Note 1: This can happen if the re-locking of the mutex throws an exception. — end note]

template<class Lock, class Predicate>
void wait(Lock& lock, Predicate pred);

Effects: Equivalent to:

while (!pred())
    wait(lock);

template<class Lock, class Clock, class Duration>
cv_status wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time);

Effects:

(6.1) Atomically calls lock.unlock() and blocks on *this.

(6.2) When unblocked, calls lock.lock() (possibly blocking on the lock) and returns.

(6.3) The function will unblock when signaled by a call to notify_one(), a call to notify_all(), expiration of the absolute timeout (33.2.4) specified by abs_time, or spuriously.

(6.4) If the function exits via an exception, lock.lock() is called prior to exiting the function.
Postconditions: `lock` is locked by the calling thread.

Returns: `cv_status::timeout` if the absolute timeout (33.2.4) specified by `abs_time` expired, otherwise `cv_status::no_timeout`.

Throws: Timeout-related exceptions (33.2.4).

Remarks: If the function fails to meet the postcondition, `terminate()` is invoked (14.6.2).

[Note 2: This can happen if the re-locking of the mutex throws an exception. — end note]

```cpp
template<class Lock, class Rep, class Period>
cv_status wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time);
```

Effects: Equivalent to:

```
return wait_until(lock, chrono::steady_clock::now() + rel_time);
```

Postconditions: `lock` is locked by the calling thread.

Returns: `cv_status::timeout` if the relative timeout (33.2.4) specified by `rel_time` expired, otherwise `cv_status::no_timeout`.

Throws: Timeout-related exceptions (33.2.4).

Remarks: If the function fails to meet the postcondition, `terminate` is invoked (14.6.2).

[Note 3: This can happen if the re-locking of the mutex throws an exception. — end note]

```cpp
template<class Lock, class Clock, class Duration, class Predicate>
bool wait_until(Lock& lock, const chrono::time_point<Clock, Duration>& abs_time, Predicate pred);
```

Effects: Equivalent to:

```
while (!pred())
  if (wait_until(lock, abs_time) == cv_status::timeout)
    return pred();
  return true;
```

[Note 4: There is no blocking if `pred()` is initially `true`, or if the timeout has already expired. — end note]

[Note 5: The returned value indicates whether the predicate evaluates to `true` regardless of whether the timeout was triggered. — end note]

```cpp
template<class Lock, class Rep, class Period, class Predicate>
bool wait_for(Lock& lock, const chrono::duration<Rep, Period>& rel_time, Predicate pred);
```

Effects: Equivalent to:

```
return wait_until(lock, chrono::steady_clock::now() + rel_time, std::move(pred));
```

### 33.7.5.3 Interruptible waits

The following wait functions will be notified when there is a stop request on the passed `stop_token`. In that case the functions return immediately, returning `false` if the predicate evaluates to `false`.

```cpp
template<class Lock, class Predicate>
bool wait(Lock& lock, stop_token stoken, Predicate pred);
```

Effects: Registers for the duration of this call `*this` to get notified on a stop request on `stoken` during this call and then equivalent to:

```
while (!stoken.stop_requested()) {
  if (pred())
    return true;
  wait(lock);
}
return pred();
```

[Note 1: The returned value indicates whether the predicate evaluated to `true` regardless of whether there was a stop request. — end note]

Postconditions: `lock` is locked by the calling thread.

Throws: Any exception thrown by `pred`.

Remarks: If the function fails to meet the postcondition, `terminate` is called (14.6.2).
template<class Lock, class Clock, class Duration, class Predicate>
bool wait_until(Lock& lock, stop_token stoken,
const chrono::time_point<Clock, Duration>& abs_time, Predicate pred);

Effects: Registers for the duration of this call *this to get notified on a stop request on stoken during this call and then equivalent to:
while (!stoken.stop_requested()) {
  if (pred())
    return true;
  if (wait_until(lock, abs_time) == cv_status::timeout)
    return pred();
}
return pred();

[Note 3: There is no blocking if pred() is initially true, stoken.stop_requested() was already true or the timeout has already expired. — end note]

[Note 4: The returned value indicates whether the predicate evaluated to true regardless of whether the timeout was triggered or a stop request was made. — end note]

Postconditions: lock is locked by the calling thread.

Throws: Timeout-related exceptions (33.2.4), or any exception thrown by pred.

Remarks: If the function fails to meet the postcondition, terminate is called (14.6.2).

[Note 5: This can happen if the re-locking of the mutex throws an exception. — end note]

template<class Lock, class Rep, class Period, class Predicate>
bool wait_for(Lock& lock, stop_token stoken,
const chrono::duration<Rep, Period>& rel_time, Predicate pred);

Effects: Equivalent to:
return wait_until(lock, std::move(stoken), chrono::steady_clock::now() + rel_time,
std::move(pred));

33.8 Semaphore

33.8.1 General

Semaphores are lightweight synchronization primitives used to constrain concurrent access to a shared resource. They are widely used to implement other synchronization primitives and, whenever both are applicable, can be more efficient than condition variables.

A counting semaphore is a semaphore object that models a non-negative resource count. A binary semaphore is a semaphore object that has only two states. A binary semaphore should be more efficient than the default implementation of a counting semaphore with a unit resource count.

33.8.2 Header <semaphore> synopsis

namespace std {
  // 33.8.3, class template counting_semaphore
  template<ptrdiff_t least_max_value = implementation-defined>
  class counting_semaphore;

  using binary_semaphore = counting_semaphore<1>;
}

33.8.3 Class template counting_semaphore

namespace std {
  template<ptrdiff_t least_max_value = implementation-defined>
  class counting_semaphore {
  public:
    static constexpr ptrdiff_t max() noexcept;

    constexpr explicit counting_semaphore(ptrdiff_t desired);
    ~counting_semaphore();
  }
counting_semaphore(const counting_semaphore&) = delete;
counting_semaphore& operator=(const counting_semaphore&) = delete;

void release(ptrdiff_t update = 1);
void acquire();
bool try_acquire() noexcept;
template<class Rep, class Period>
  bool try_acquire_for(const chrono::duration<Rep, Period>& rel_time);
template<class Clock, class Duration>
  bool try_acquire_until(const chrono::time_point<Clock, Duration>& abs_time);

private:
  ptrdiff_t counter;   // exposition only

1 Class template counting_semaphore maintains an internal counter that is initialized when the semaphore is created. The counter is decremented when a thread acquires the semaphore, and is incremented when a thread releases the semaphore. If a thread tries to acquire the semaphore when the counter is zero, the thread will block until another thread increments the counter by releasing the semaphore.

2 least_max_value shall be non-negative; otherwise the program is ill-formed.

3 Concurrent invocations of the member functions of counting_semaphore, other than its destructor, do not introduce data races.

static constexpr ptrdiff_t max() noexcept;

4 Returns: The maximum value of counter. This value is greater than or equal to least_max_value.

countexpr explicit counting_semaphore(ptrdiff_t desired);

5 Preconditions: desired >= 0 is true, and desired <= max() is true.
6 Effects: Initializes counter with desired.
7 Throws: Nothing.

void release(ptrdiff_t update = 1);

8 Preconditions: update >= 0 is true, and update <= max() - counter is true.
9 Effects: Atomically execute counter += update. Then, unblocks any threads that are waiting for counter to be greater than zero.
10 Synchronization: Strongly happens before invocations of try_acquire that observe the result of the effects.
11 Throws: system_error when an exception is required (33.2.2).
12 Error conditions: Any of the error conditions allowed for mutex types (33.6.4.2).

bool try_acquire() noexcept;

13 Effects: Attempts to atomically decrement counter if it is positive, without blocking. If counter is not decremented, there is no effect and try_acquire immediately returns. An implementation may fail to decrement counter even if it is positive.

[Note 1: This spurious failure is normally uncommon, but allows interesting implementations based on a simple compare and exchange (33.5). — end note]

An implementation should ensure that try_acquire does not consistently return false in the absence of contending semaphore operations.

14 Returns: true if counter was decremented, otherwise false.

void acquire();

15 Effects: Repeatedly performs the following steps, in order:

(15.1) — Evaluates try_acquire(). If the result is true, returns.
(15.2) — Blocks on *this until counter is greater than zero.
**N4986**

16  *Throws:* `system_error` when an exception is required (33.2.2).

17  *Error conditions:* Any of the error conditions allowed for mutex types (33.6.4.2).

```cpp
template<class Rep, class Period>
bool try_acquire_for(const chrono::duration<Rep, Period>& rel_time);

template<class Clock, class Duration>
bool try_acquire_until(const chrono::time_point<Clock, Duration>& abs_time);
```

18  *Effects:* Repeatedly performs the following steps, in order:

18.1  — Evaluates `try_acquire()`. If the result is `true`, returns `true`.

18.2  — Blocks on `*this` until `counter` is greater than zero or until the timeout expires. If it is unblocked by the timeout expiring, returns `false`.

The timeout expires (33.2.4) when the current time is after `abs_time` (for `try_acquire_until`) or when at least `rel_time` has passed from the start of the function (for `try_acquire_for`).

19  *Throws:* Timeout-related exceptions (33.2.4), or `system_error` when a non-timeout-related exception is required (33.2.2).

20  *Error conditions:* Any of the error conditions allowed for mutex types (33.6.4.2).

### 33.9 Coordination types

#### 33.9.1 General

1 Subclause 33.9 describes various concepts related to thread coordination, and defines the coordination types `latch` and `barrier`. These types facilitate concurrent computation performed by a number of threads.

#### 33.9.2 Latches

#### 33.9.2.1 General

1 A latch is a thread coordination mechanism that allows any number of threads to block until an expected number of threads arrive at the latch (via the `count_down` function). The expected count is set when the latch is created. An individual latch is a single-use object; once the expected count has been reached, the latch cannot be reused.

#### 33.9.2.2 Header `<latch>` synopsis

```cpp
namespace std {
    class latch;
}
```

#### 33.9.2.3 Class `latch`

```cpp
namespace std {
    class latch {
        public:
            static constexpr ptrdiff_t max() noexcept;
            constexpr explicit latch(ptrdiff_t expected);
            -latch();

            latch(const latch&) = delete;
            latch& operator=(const latch&); = delete;

            void count_down(ptrdiff_t update = 1);
            bool try_wait() const noexcept;
            void wait() const;
            void arrive_and_wait(ptrdiff_t update = 1);

        private:
            ptrdiff_t counter;  // exposition only
        }
    }
```

1 A latch maintains an internal counter that is initialized when the latch is created. Threads can block on the latch object, waiting for counter to be decremented to zero.
Concurrent invocations of the member functions of `latch`, other than its destructor, do not introduce data races.

```cpp
static constexpr ptrdiff_t max() noexcept;
```

**Returns**: The maximum value of `counter` that the implementation supports.

```cpp
constexpr explicit latch(ptrdiff_t expected);
```

**Preconditions**: `expected >= 0` is true and `expected <= max()` is true.

**Effects**: Initializes `counter` with `expected`.

**Throws**: Nothing.

```cpp
void count_down(ptrdiff_t update = 1);
```

**Preconditions**: `update >= 0` is true, and `update <= counter` is true.

**Effects**: Atomically decrements `counter` by `update`. If `counter` is equal to zero, unblocks all threads blocked on `*this`.

**Synchronization**: Strongly happens before the returns from all calls that are unblocked.

**Throws**: `system_error` when an exception is required (33.2.2).

**Error conditions**: Any of the error conditions allowed for mutex types (33.6.4.2).

```cpp
bool try_wait() const noexcept;
```

**Returns**: With very low probability `false`. Otherwise `counter == 0`.

```cpp
void wait() const;
```

**Effects**: If `counter` equals zero, returns immediately. Otherwise, blocks on `*this` until a call to `count_down` that decrements `counter` to zero.

**Throws**: `system_error` when an exception is required (33.2.2).

**Error conditions**: Any of the error conditions allowed for mutex types (33.6.4.2).

```cpp
void arrive_and_wait(ptrdiff_t update = 1);
```

**Effects**: Equivalent to:

```cpp
  count_down(update);
  wait();
```

### 33.9.3 Barriers

#### 33.9.3.1 General

A barrier is a thread coordination mechanism whose lifetime consists of a sequence of barrier phases, where each phase allows at most an expected number of threads to block until the expected number of threads arrive at the barrier.

[Note 1: A barrier is useful for managing repeated tasks that are handled by multiple threads. — end note]

#### 33.9.3.2 Header `<barrier>` synopsis

```cpp
namespace std {
  template<class CompletionFunction = see below>
  class barrier;
}
```

#### 33.9.3.3 Class template barrier

```cpp
namespace std {
  template<class CompletionFunction = see below>
  class barrier {
    public:
      using arrival_token = see below;

      static constexpr ptrdiff_t max() noexcept;
  }
}
```
constexpr explicit barrier(ptrdiff_t expected,
  CompletionFunction f = CompletionFunction());

~barrier();
barrier(const barrier&) = delete;
barrier& operator=(const barrier&) = delete;

[[nodiscard]] arrival_token arrive(ptrdiff_t update = 1);
void wait(arrival_token&& arrival) const;
void arrive_and_wait();
void arrive_and_drop();

private:
  CompletionFunction completion; // exposition only
};

1 Each barrier phase consists of the following steps:
   (1.1) The expected count is decremented by each call to arrive or arrive_and_drop.
   (1.2) Exactly once after the expected count reaches zero, a thread executes the completion step during its call to arrive, arrive_and_drop, or wait, except that it is implementation-defined whether the step executes if no thread calls wait.
   (1.3) When the completion step finishes, the expected count is reset to what was specified by the expected argument to the constructor, possibly adjusted by calls to arrive_and_drop, and the next phase starts.

2 Each phase defines a phase synchronization point. Threads that arrive at the barrier during the phase can block on the phase synchronization point by calling wait, and will remain blocked until the phase completion step is run.

3 The phase completion step that is executed at the end of each phase has the following effects:
   (3.1) Invokes the completion function, equivalent to completion().
   (3.2) Unblocks all threads that are blocked on the phase synchronization point.

The end of the completion step strongly happens before the returns from all calls that were unblocked by the completion step. For specializations that do not have the default value of the CompletionFunction template parameter, the behavior is undefined if any of the barrier object’s member functions other than wait are called while the completion step is in progress.

4 Concurrent invocations of the member functions of barrier, other than its destructor, do not introduce data races. The member functions arrive and arrive_and_drop execute atomically.

5 CompletionFunction shall meet the Cpp17MoveConstructible (Table 31) and Cpp17Destructible (Table 35) requirements. is_nothrow_invocable_v<CompletionFunction&> shall be true.

6 The default value of the CompletionFunction template parameter is an unspecified type, such that, in addition to satisfying the requirements of CompletionFunction, it meets the Cpp17DefaultConstructible requirements (Table 30) and completion() has no effects.

7 barrier::arrival_token is an unspecified type, such that it meets the Cpp17MoveConstructible (Table 31), Cpp17MoveAssignable (Table 33), and Cpp17Destructible (Table 35) requirements.

static constexpr ptrdiff_t max() noexcept;

8 Returns: The maximum expected count that the implementation supports.

constexpr explicit barrier(ptrdiff_t expected,
  CompletionFunction f = CompletionFunction());

9 Preconditions: expected >= 0 is true and expected <= max() is true.

10 Effects: Sets both the initial expected count for each barrier phase and the current expected count for the first phase to expected. Initializes completion with std::move(f). Starts the first phase.

[Note 1: If expected is 0 this object can only be destroyed. — end note]

11 Throws: Any exception thrown by CompletionFunction’s move constructor.
arrival_token arrive(ptrdiff_t update = 1);

**Preconditions**: update > 0 is true, and update is less than or equal to the expected count for the current barrier phase.

**Effects**: Constructs an object of type arrival_token that is associated with the phase synchronization point for the current phase. Then, decrements the expected count by update.

**Synchronization**: The call to arrive strongly happens before the start of the phase completion step for the current phase.

**Returns**: The constructed arrival_token object.

**Throws**: system_error when an exception is required (33.2.2).

**Error conditions**: Any of the error conditions allowed for mutex types (33.6.4.2).

Note 2: This call can cause the completion step for the current phase to start. — end note

void wait(arrival_token&& arrival) const;

**Preconditions**: arrival is associated with the phase synchronization point for the current phase or the immediately preceding phase of the same barrier object.

**Effects**: Blocks at the synchronization point associated with std::move(arrival) until the phase completion step of the synchronization point’s phase is run.

Note 3: If arrival is associated with the synchronization point for a previous phase, the call returns immediately. — end note

**Throws**: system_error when an exception is required (33.2.2).

**Error conditions**: Any of the error conditions allowed for mutex types (33.6.4.2).

void arrive_and_wait();

**Effects**: Equivalent to: wait(arrive()).

void arrive_and_drop();

**Preconditions**: The expected count for the current barrier phase is greater than zero.

**Effects**: Decrement the initial expected count for all subsequent phases by one. Then decrements the expected count for the current phase by one.

**Synchronization**: The call to arrive_and_drop strongly happens before the start of the phase completion step for the current phase.

**Throws**: system_error when an exception is required (33.2.2).

**Error conditions**: Any of the error conditions allowed for mutex types (33.6.4.2).

Note 4: This call can cause the completion step for the current phase to start. — end note

### 33.10 Futures [futures]

#### 33.10.1 Overview [futures.overview]

33.10 describes components that a C++ program can use to retrieve in one thread the result (value or exception) from a function that has run in the same thread or another thread.

Note 1: These components are not restricted to multi-threaded programs but can be useful in single-threaded programs as well. — end note

#### 33.10.2 Header <future> synopsis [future.syn]

```cpp
namespace std {
    enum class future_errc {
        broken_promise = implementation-defined,
        future_already_retrieved = implementation-defined,
        promise_already_satisfied = implementation-defined,
        no_state = implementation-defined
    };
}
```
enum class launch : unspecified {
   async = unspecified,
   deferred = unspecified,
   implementation-defined
};

enum class future_status {
   ready,
   timeout,
   deferred
};

// 33.10.3, error handling
template<> struct is_error_code_enum<future_errc> : public true_type { };
error_code make_error_code(future_errc e) noexcept;
error_condition make_error_condition(future_errc e) noexcept;

const error_category& future_category() noexcept;

// 33.10.4, class future_error
class future_error;

// 33.10.6, class template promise
template<class R> class promise;
template<class R> class promise<R&>;
template<> class promise<void>;

template<class R>
void swap(promise<R>& x, promise<R>& y) noexcept;

template<class R, class Alloc>
struct uses_allocator<promise<R>, Alloc>;

// 33.10.7, class template future
template<class R> class future;
template<class R> class future<R&>;
template<> class future<void>;

// 33.10.8, class template shared_future
template<class R> class shared_future;
template<class R> class shared_future<R&>;
template<> class shared_future<void>;

// 33.10.10, class template packaged_task
template<class R> class packaged_task; // not defined

template<class R, class... ArgTypes>
class packaged_task<R(ArgTypes...)>;

template<class R, class... ArgTypes>
void swap(packaged_task<R(ArgTypes...>)&, packaged_task<R(ArgTypes...>)&) noexcept;

// 33.10.9, function template async
template<class F, class... Args>
[[nodiscard]] future<invoke_result_t<decay_t<F>, decay_t<Args>...>>
async(F&& f, Args&&... args);

template<class F, class... Args>
[[nodiscard]] future<invoke_result_t<decay_t<F>, decay_t<Args>...>>
async(launch policy, F&& f, Args&&... args);
}

The enum type launch is a bitmask type (16.3.3.3.3) with elements launch::async and launch::deferred. [Note 1: Implementations can provide bitmasks to specify restrictions on task interaction by functions launched by async() applicable to a corresponding subset of available launch policies. Implementations can extend the behavior of the first overload of async() by adding their extensions to the launch policy under the “as if” rule. — end note]
The enum values of future_errc are distinct and not zero.

33.10.3 Error handling

const error_category& future_category() noexcept;

Returns: A reference to an object of a type derived from class error_category.

The object’s default_error_condition and equivalent virtual functions shall behave as specified for the class error_category. The object’s name virtual function returns a pointer to the string "future".

error_code make_error_code(future_errc e) noexcept;

Returns: error_code(static_cast<int>(e), future_category()).

error_condition make_error_condition(future_errc e) noexcept;

Returns: error_condition(static_cast<int>(e), future_category()).

33.10.4 Class future_error

namespace std {
    class future_error : public logic_error {
        public:
            explicit future_error(future_errc e);
            
            const error_code& code() const noexcept;
            const char* what() const noexcept;
        
        private:
            error_code ec_;  // exposition only
        
    } explicit future_error(future_errc e);  

    Effects: Initializes ec_ with make_error_code(e).

    const error_code& code() const noexcept;

    Returns: ec_.

    const char* what() const noexcept;

    Returns: An ntrbs incorporating code().message().

33.10.5 Shared state

Many of the classes introduced in subclause 33.10 use some state to communicate results. This shared state consists of some state information and some (possibly not yet evaluated) result, which can be a (possibly void) value or an exception.

[Note 1: Futures, promises, and tasks defined in this Clause reference such shared state. — end note]

[Note 2: The result can be any kind of object including a function to compute that result, as used by async when policy is launch::deferred. — end note]

An asynchronous return object is an object that reads results from a shared state. A waiting function of an asynchronous return object is one that potentially blocks to wait for the shared state to be made ready. If a waiting function can return before the state is made ready because of a timeout (33.2.5), then it is a timed waiting function, otherwise it is a non-timed waiting function.

An asynchronous provider is an object that provides a result to a shared state. The result of a shared state is set by respective functions on the asynchronous provider.

[Example 1: Promises and tasks are examples of asynchronous providers. — end example]

The means of setting the result of a shared state is specified in the description of those classes and functions that create such a state object.

When an asynchronous return object or an asynchronous provider is said to release its shared state, it means:

— if the return object or provider holds the last reference to its shared state, the shared state is destroyed; and
— the return object or provider gives up its reference to its shared state; and

— these actions will not block for the shared state to become ready, except that it may block if all of the following are true: the shared state was created by a call to `std::async`, the shared state is not yet ready, and this was the last reference to the shared state.

When an asynchronous provider is said to make its shared state ready, it means:

— first, the provider marks its shared state as ready; and

— second, the provider unblocks any execution agents waiting for its shared state to become ready.

When an asynchronous provider is said to abandon its shared state, it means:

— first, if that state is not ready, the provider

— stores an exception object of type `future_error` with an error condition of `broken_promise` within its shared state; and then

— makes its shared state ready;

— second, the provider releases its shared state.

A shared state is ready only if it holds a value or an exception ready for retrieval. Waiting for a shared state to become ready may invoke code to compute the result on the waiting thread if so specified in the description of the class or function that creates the state object.

Calls to functions that successfully set the stored result of a shared state synchronize with (6.9.2) calls to functions successfully detecting the ready state resulting from that setting. The storage of the result (whether normal or exceptional) into the shared state synchronizes with (6.9.2) the successful return from a call to a waiting function on the shared state.

Some functions (e.g., `promise::set_value_at_thread_exit`) delay making the shared state ready until the calling thread exits. The destruction of each of that thread’s objects with thread storage duration (6.7.5.3) is sequenced before making that shared state ready.

Access to the result of the same shared state may conflict (6.9.2).

[Note 3: This explicitly specifies that the result of the shared state is visible in the objects that reference this state in the sense of data race avoidance (16.4.6.10). For example, concurrent accesses through references returned by `shared_future::get()` (33.10.8) must either use read-only operations or provide additional synchronization. — end note]

### 33.10.6 Class template promise

```cpp
namespace std {
    template<class R>
    class promise {
    public:
        promise();
        template<class Allocator>
        promise(allocation_arg_t, const Allocator& a);
        promise(promise&& rhs) noexcept;
        promise(const promise&) = delete;
        ~promise();

        // assignment
        promise& operator=(promise&& rhs) noexcept;
        promise& operator=(const promise&) = delete;
        void swap(promise& other) noexcept;

        // retrieving the result
        future<R> get_future();

        // setting the result
        void set_value(see below);
        void set_exception(exception_ptr p);

        // setting the result with deferred notification
        void set_value_at_thread_exit(see below);
        void set_exception_at_thread_exit(exception_ptr p);
    }
}
```
template<class R, class Alloc>
struct uses_allocator<promise<R>, Alloc>;

1 For the primary template, R shall be an object type that meets the Cpp17Destructible requirements.

2 The implementation provides the template promise and two specializations, promise<R&> and promise<void>. These differ only in the argument type of the member functions set_value and set_value_at_thread_exit, as set out in their descriptions, below.

3 The set_value, set_exception, set_value_at_thread_exit, and set_exception_at_thread_exit member functions behave as though they acquire a single mutex associated with the promise object while updating the promise object.

template<class R, class Alloc>
struct uses_allocator<promise<R>, Alloc>
: true_type { };  

4 Preconditions: Alloc meets the Cpp17Allocator requirements (16.4.4.6.1).

promise();
template<class Allocator>
    promise(allocator_arg_t, const Allocator& a);

5 Effects: Creates a shared state. The second constructor uses the allocator a to allocate memory for the shared state.

promise(promise&& rhs) noexcept;

6 Effects: Transfers ownership of the shared state of rhs (if any) to the newly-constructed object.

Postconditions: rhs has no shared state.

~promise();

8 Effects: Abandons any shared state (33.10.5).

promise& operator=(promise&& rhs) noexcept;

9 Effects: Abandons any shared state (33.10.5) and then as if promise(std::move(rhs)).swap(*this).

Returns: *this.

void swap(promise& other) noexcept;

10 Effects: Exchanges the shared state of *this and other.

11 Postconditions: *this has the shared state (if any) that other had prior to the call to swap. other has the shared state (if any) that *this had prior to the call to swap.

future<R> get_future();

13 Synchronization: Calls to this function do not introduce data races (6.9.2) with calls to set_value, set_exception, set_value_at_thread_exit, or set_exception_at_thread_exit.

[Note 1: Such calls need not synchronize with each other. — end note]

Returns: A future<R> object with the same shared state as *this.

Throws: future_error if *this has no shared state or if get_future has already been called on a promise with the same shared state as *this.

Error conditions:

(16.1) — future_already_retrieved if get_future has already been called on a promise with the same shared state as *this.

(16.2) — no_state if *this has no shared state.

void promise::set_value(const R& r);
void promise::set_value(R& r);
void promise<R&>::set_value(R& r);
void promise<void>::set_value();
17 Effects: Atomically stores the value \( r \) in the shared state and makes that state ready (33.10.5).
18 Throws:
(18.1) — future_error if its shared state already has a stored value or exception, or
(18.2) — for the first version, any exception thrown by the constructor selected to copy an object of \( R \), or
(18.3) — for the second version, any exception thrown by the constructor selected to move an object of \( R \).
19 Error conditions:
(19.1) — promise_already_satisfied if its shared state already has a stored value or exception.
(19.2) — no_state if \(*this\) has no shared state.

void set_exception(exception_ptr p);
20 Preconditions: \( p \) is not null.
21 Effects: Atomically stores the exception pointer \( p \) in the shared state and makes that state ready (33.10.5).
22 Throws: future_error if its shared state already has a stored value or exception.
23 Error conditions:
(23.1) — promise_already_satisfied if its shared state already has a stored value or exception.
(23.2) — no_state if \(*this\) has no shared state.

void promise::set_value_at_thread_exit(const R& r);
24 void promise::set_value_at_thread_exit(R&& r);
void promise<R&>::set_value_at_thread_exit(R& r);
void promise<void>::set_value_at_thread_exit();
25 Effects: Stores the value \( r \) in the shared state without making that state ready immediately. Schedules that state to be made ready when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed.
26 Throws:
(25.1) — future_error if its shared state already has a stored value or exception, or
(25.2) — for the first version, any exception thrown by the constructor selected to copy an object of \( R \), or
(25.3) — for the second version, any exception thrown by the constructor selected to move an object of \( R \).
27 Error conditions:
(26.1) — promise_already_satisfied if its shared state already has a stored value or exception.
(26.2) — no_state if \(*this\) has no shared state.

void set_exception_at_thread_exit(exception_ptr p);
27 Preconditions: \( p \) is not null.
28 Effects: Stores the exception pointer \( p \) in the shared state without making that state ready immediately. Schedules that state to be made ready when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed.
29 Throws: future_error if an error condition occurs.
30 Error conditions:
(30.1) — promise_already_satisfied if its shared state already has a stored value or exception.
(30.2) — no_state if \(*this\) has no shared state.

template<class R>
void swap(promise<R>& x, promise<R>& y) noexcept;
31 Effects: As if by \( x.\text{swap}(y) \).
### 33.10.7 Class template future

The class template `future` defines a type for asynchronous return objects which do not share their shared state with other asynchronous return objects. A default-constructed `future` object has no shared state. A `future` object with shared state can be created by functions on asynchronous providers (33.10.5) or by the move constructor and shares its shared state with the original asynchronous provider. The result (value or exception) of a `future` object can be set by calling a respective function on an object that shares the same shared state.

**Note 1:** Member functions of `future` do not synchronize with themselves or with member functions of `shared_future`. —end note

The effect of calling any member function other than the destructor, the move assignment operator, `share`, or `valid` on a `future` object for which `valid() == false` is undefined.

**Note 2:** It is valid to move from a future object for which `valid() == false`. —end note

**Recommended practice:** Implementations should detect this case and throw an object of type `future_error` with an error condition of `future_errc::no_state`.

```cpp
namespace std {
    template<class R>
    class future {
    public:
        future() noexcept;
        future(future&&) noexcept;
        future(const future&) = delete;
        ~future();
        future& operator=(const future&) = delete;
        future& operator=(future&&) noexcept;
        shared_future<R> share() noexcept;

        // retrieving the value
        see below get();

        // functions to check state
        bool valid() const noexcept;

        void wait() const;
        template<class Rep, class Period>
        future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;
        template<class Clock, class Duration>
        future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;
    }
}
```

For the primary template, `R` shall be an object type that meets the `Cpp17Destructible` requirements.

The implementation provides the template `future` and two specializations, `future<R&>` and `future<void>`. These differ only in the return type and return value of the member function `get`, as set out in its description, below.

- `future() noexcept;`

  **Effects:** The object does not refer to a shared state.

  **Postconditions:** `valid() == false`.

- `future(future&& rhs) noexcept;`

  **Effects:** Move constructs a `future` object that refers to the shared state that was originally referred to by `rhs` (if any).

  **Postconditions:**

  1. `valid()` returns the same value as `rhs.valid()` prior to the constructor invocation.
  2. `rhs.valid() == false`.

- `~future();`

**Effects:**
(10.1) — Releases any shared state (33.10.5);
(10.2) — destroys *this.

future& operator=(future&& rhs) noexcept;

11 Effects: If addressof(rhs) == this is true, there are no effects. Otherwise:
(11.1) — Releases any shared state (33.10.5).
(11.2) — move assigns the contents of rhs to *this.

12 Postconditions:
(12.1) — valid() returns the same value as rhs.valid() prior to the assignment.
(12.2) — If addressof(rhs) == this is false, rhs.valid() == false.

shared_future<R> share() noexcept;

13 Postconditions: valid() == false.

14 Returns: shared_future<R>(std::move(*this)).

R future::get();
R& future<R&>::get();
void future<void>::get();

15 [Note 3: As described above, the template and its two required specializations differ only in the return type and return value of the member function get. — end note]

16 Effects:
(16.1) — wait()s until the shared state is ready, then retrieves the value stored in the shared state;
(16.2) — releases any shared state (33.10.5).

17 Postconditions: valid() == false.

18 Returns:
(18.1) — future::get() returns the value v stored in the object’s shared state as std::move(v).
(18.2) — future<R&>::get() returns the reference stored as value in the object’s shared state.
(18.3) — future<void>::get() returns nothing.

19 Throws: The stored exception, if an exception was stored in the shared state.

bool valid() const noexcept;

20 Returns: true only if *this refers to a shared state.

void wait() const;

21 Effects: Blocks until the shared state is ready.

template<class Rep, class Period>
future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;

22 Effects: None if the shared state contains a deferred function (33.10.9), otherwise blocks until the shared state is ready or until the relative timeout (33.2.4) specified by rel_time has expired.

23 Returns:
(23.1) — future_status::deferred if the shared state contains a deferred function.
(23.2) — future_status::ready if the shared state is ready.
(23.3) — future_status::timeout if the function is returning because the relative timeout (33.2.4) specified by rel_time has expired.

24 Throws: timeout-related exceptions (33.2.4).

template<class Clock, class Duration>
future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;

25 Effects: None if the shared state contains a deferred function (33.10.9), otherwise blocks until the shared state is ready or until the absolute timeout (33.2.4) specified by abs_time has expired.
Returns:

- `future_status::deferred` if the shared state contains a deferred function.
- `future_status::ready` if the shared state is ready.
- `future_status::timeout` if the function is returning because the absolute timeout (33.2.4) specified by `abs_time` has expired.

Throws: timeout-related exceptions (33.2.4).

### 33.10.8 Class template `shared_future` [futures.shared.future]

1. The class template `shared_future` defines a type for asynchronous return objects which may share their shared state with other asynchronous return objects. A default-constructed `shared_future` object has no shared state. A `shared_future` object with shared state can be created by conversion from a `future` object and shares its shared state with the original asynchronous provider (33.10.5) of the shared state. The result (value or exception) of a `shared_future` object can be set by calling a respective function on an object that shares the same shared state.

   [Note 1: Member functions of `shared_future` do not synchronize with themselves, but they synchronize with the shared state. — end note]

2. The effect of calling any member function other than the destructor, the move assignment operator, the copy assignment operator, or `valid()` on a `shared_future` object for which `valid() == false` is undefined.

   [Note 2: It is valid to copy or move from a `shared_future` object for which `valid()` is false. — end note]

   **Recommended practice:** Implementations should detect this case and throw an object of type `future_error` with an error condition of `future_errc::no_state`.

   ```cpp
   namespace std {
   template<class R>
   class shared_future {
   public:
       shared_future() noexcept;
       shared_future(const shared_future& rhs) noexcept;
       shared_future(future<R>&&) noexcept;
       shared_future(shared_future&& rhs) noexcept;
       ~shared_future();
       shared_future& operator=(const shared_future& rhs) noexcept;
       shared_future& operator=(shared_future&& rhs) noexcept;

       // retrieving the value
       see below get() const;

       // functions to check state
       bool valid() const noexcept;

       void wait() const;
       template<class Rep, class Period>
       future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;
       template<class Clock, class Duration>
       future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;
   };
   }
   ```

4. For the primary template, `R` shall be an object type that meets the `Cpp17Destructible` requirements.

5. The implementation provides the template `shared_future` and two specializations, `shared_future<R&>` and `shared_future<void>`. These differ only in the return type and return value of the member function `get`, as set out in its description, below.

   ```cpp
   shared_future() noexcept;
   ```

   **Effects:** The object does not refer to a shared state.

   **Postconditions:** `valid() == false`.
shared_future(const shared_future& rhs) noexcept;

Effects: The object refers to the same shared state as rhs (if any).
Postconditions: valid() returns the same value as rhs.valid().

shared_future(future<R>&& rhs) noexcept;
shared_future(shared_future&& rhs) noexcept;

Effects: Move constructs a shared_future object that refers to the shared state that was originally referred to by rhs (if any).
Postconditions:
(11.1) valid() returns the same value as rhs.valid() returned prior to the constructor invocation.
(11.2) rhs.valid() == false.

~shared_future();

Effects:
(12.1) Releases any shared state (33.10.5);
(12.2) destroys *this.

shared_future& operator=(shared_future&& rhs) noexcept;

Effects: If addressof(rhs) == this is true, there are no effects. Otherwise:
(13.1) Releases any shared state (33.10.5);
(13.2) move assigns the contents of rhs to *this.
Postconditions:
(14.1) valid() returns the same value as rhs.valid() returned prior to the assignment.
(14.2) If addressof(rhs) == this is false, rhs.valid() == false.

shared_future& operator=(const shared_future& rhs) noexcept;

Effects: If addressof(rhs) == this is true, there are no effects. Otherwise:
(15.1) Releases any shared state (33.10.5);
(15.2) assigns the contents of rhs to *this.

[Note 3: As a result, *this refers to the same shared state as rhs (if any). — end note]

Postconditions: valid() == rhs.valid().

const R& shared_future::get() const;
R& shared_future<R&>::get() const;
void shared_future<void>::get() const;

[Note 4: As described above, the template and its two required specializations differ only in the return type and return value of the member function get. — end note]

[Note 5: Access to a value object stored in the shared state is unsynchronized, so operations on R might introduce a data race (6.9.2). — end note]

Effects: wait()s until the shared state is ready, then retrieves the value stored in the shared state.
Returns:
(20.1) shared_future::get() returns a const reference to the value stored in the object’s shared state.

[Note 6: Access through that reference after the shared state has been destroyed produces undefined behavior; this can be avoided by not storing the reference in any storage with a greater lifetime than the shared_future object that returned the reference. — end note]

(20.2) shared_future<R&>::get() returns the reference stored as value in the object’s shared state.
(20.3) shared_future<void>::get() returns nothing.

Throws: The stored exception, if an exception was stored in the shared state.

bool valid() const noexcept;

Returns: true only if *this refers to a shared state.
void wait() const;

Effects: Blocks until the shared state is ready.

Effects: None if the shared state contains a deferred function (33.10.9), otherwise blocks until the shared state is ready or until the relative timeout (33.2.4) specified by rel_time has expired.

Returns:

— future_status::deferred if the shared state contains a deferred function.

— future_status::ready if the shared state is ready.

— future_status::timeout if the function is returning because the relative timeout (33.2.4) specified by rel_time has expired.

Throws: timeout-related exceptions (33.2.4).

Effects: None if the shared state contains a deferred function (33.10.9), otherwise blocks until the shared state is ready or until the absolute timeout (33.2.4) specified by abs_time has expired.

Returns:

— future_status::deferred if the shared state contains a deferred function.

— future_status::ready if the shared state is ready.

— future_status::timeout if the function is returning because the absolute timeout (33.2.4) specified by abs_time has expired.

Throws: timeout-related exceptions (33.2.4).

33.10.9 Function template async

The function template async provides a mechanism to launch a function potentially in a new thread and provides the result of the function in a future object with which it shares a shared state.

Effects: The first function behaves the same as a call to the second function with a policy argument of launch::async | launch::deferred and the same arguments for F and Args. The second function creates a shared state that is associated with the returned future object. The further behavior of the second function depends on the policy argument as follows (if more than one of these conditions applies, the implementation may choose any of the corresponding policies):

— If launch::async is set in policy, calls invoke(auto(std::forward<F>(f)), auto(std::forward<Args>(args))...) (22.10.5, 33.4.3.3) as if in a new thread of execution represented by a thread object with the values produced by auto being materialized (7.3.5) in the thread that called async. Any return value is stored as the result in the shared state. Any exception propagated from the execution of invoke(auto(std::forward<F>(f)), auto(std::forward<Args>(args))...) is stored as the exceptional result in the shared state. The thread object is stored in the shared state and affects the behavior of any asynchronous return objects that reference that state.

— If launch::deferred is set in policy, stores auto(std::forward<F>(f)) and auto(std::forward<Args>(args))... in the shared state. These copies of f and args constitute a deferred
function. Invocation of the deferred function evaluates `invoke(std::move(g), std::move(xyz))` where `g` is the stored value of `auto(std::forward<F>(f))` and `xyz` is the stored copy of `auto(std::forward<Args>(args))`. Any return value is stored as the result in the shared state. Any exception propagated from the execution of the deferred function is stored as the exceptional result in the shared state. The shared state is not made ready until the function has completed. The first call to a non-timed waiting function (33.10.5) on an asynchronous return object referring to this shared state invokes the deferred function in the thread that called the waiting function. Once evaluation of `invoke(std::move(g), std::move(xyz))` begins, the function is no longer considered deferred.

**Recommended practice:** If this policy is specified together with other policies, such as when using a policy value of `launch::async | launch::deferred`, implementations should defer invocation or the selection of the policy when no more concurrency can be effectively exploited.

(3.3) If no value is set in the launch policy, or a value is set that is neither specified in this document nor by the implementation, the behavior is undefined.

4 **Synchronization:** The invocation of `async` synchronizes with the invocation of `f`. The completion of the function `f` is sequenced before the shared state is made ready.

[Note 1: These apply regardless of the provided policy argument, and even if the corresponding future object is moved to another thread. However, it is possible for `f` not to be called at all, in which case its completion never happens. — end note]

If the implementation chooses the `launch::async` policy,

(4.1) a call to a waiting function on an asynchronous return object that shares the shared state created by this `async` call shall block until the associated thread has completed, as if joined, or else time out (33.4.3.6);

(4.2) the associated thread completion synchronizes with (6.9.2) the return from the first function that successfully detects the ready status of the shared state or with the return from the last function that releases the shared state, whichever happens first.

5 **Returns:** An object of type `future<invoke_result_t<decay_t<F>, decay_t<Args>...>>` that refers to the shared state created by this call to `async`.

[Note 2: If a future obtained from `async` is moved outside the local scope, the future’s destructor can block for the shared state to become ready. — end note]

6 **Thros:** `system_error` if `policy == launch::async` and the implementation is unable to start a new thread, or `std::bad_alloc` if memory for the internal data structures cannot be allocated.

7 **Error conditions:**

(7.1) `resource_unavailable_try_again` — if `policy == launch::async` and the system is unable to start a new thread.

8 [Example 1:

```cpp
int work1(int value);
int work2(int value);
int work(int value) {
    auto handle = std::async([=]{ return work2(value); });
    int tmp = work1(value);
    return tmp + handle.get(); // #1
}
```

[Note 3: Line #1 might not result in concurrency because the `async` call uses the default policy, which might use `launch::deferred`, in which case the lambda might not be invoked until the `get()` call; in that case, `work1` and `work2` are called on the same thread and there is no concurrency. — end note]

— end example]

33.10.10 Class template `packaged_task` [futures.task]

33.10.1 General [futures.task.general]

The class template `packaged_task` defines a type for wrapping a function or callable object so that the return value of the function or callable object is stored in a future when it is invoked.
When the `packaged_task` object is invoked, its stored task is invoked and the result (whether normal or exceptional) stored in the shared state. Any futures that share the shared state will then be able to access the stored result.

```cpp
namespace std {
  template<class> class packaged_task; // not defined

  template<class R, class... ArgTypes>
  class packaged_task<R(ArgTypes...)> {
    public:
        // construction and destruction
      packaged_task() noexcept;
      template<class F>
      explicit packaged_task(F&& f);
      ~packaged_task();

        // no copy
      packaged_task(const packaged_task&) = delete;
      packaged_task& operator=(const packaged_task&) = delete;

        // move support
      packaged_task(packaged_task&& rhs) noexcept;
      packaged_task& operator=(packaged_task&& rhs) noexcept;
      void swap(packaged_task& other) noexcept;

      bool valid() const noexcept;

        // result retrieval
      future<R> get_future();

        // execution
      void operator()(ArgTypes...);
      void make_ready_at_thread_exit(ArgTypes...);
      void reset();
  };

  template<class R, class... ArgTypes>
  packaged_task(R (*)(ArgTypes...)) -> packaged_task<R(ArgTypes...)>

  template<class F> packaged_task(F) -> packaged_task<see below>

  }

33.10.10.2 Member functions

packaged_task() noexcept;

Effects: The object has no shared state and no stored task.

```
(7.1) — F::operator() is a non-static member function and decltype(&F::operator()) is either of the form R(G::*)(A...) cv k_opt noexcept opt or of the form R(*)(G, A...) noexcept opt for a type G, or

(7.2) — F::operator() is a static member function and decltype(&F::operator()) is of the form R(*)(A...) noexcept opt.

Remarks: The deduced type is packaged_task<R(A...)>

packaged_task(packaged_task&& rhs) noexcept;

Effects: Transfers ownership of rhs's shared state to *this, leaving rhs with no shared state. Moves
the stored task from rhs to *this.

Postconditions: rhs has no shared state.

packaged_task& operator=(packaged_task&& rhs) noexcept;

Effects:

(11.1) — Releases any shared state (33.10.5);
(11.2) — calls packaged_task(std::move(rhs)).swap(*this).

packaged_task();

Effects: Abandons any shared state (33.10.5).

void swap(packaged_task& other) noexcept;

Effects: Exchanges the shared states and stored tasks of *this and other.

Postconditions: *this has the same shared state and stored task (if any) as other prior to the call to
swap. other has the same shared state and stored task (if any) as *this prior to the call to swap.

bool valid() const noexcept;

Returns: true only if *this has a shared state.

future<R> get_future();

Synchronization: Calls to this function do not introduce data races (6.9.2) with calls to operator() or
make_ready_at_thread_exit.

[Note 1: Such calls need not synchronize with each other. — end note]

Returns: A future object that shares the same shared state as *this.

Throws: A future_error object if an error occurs.

Error conditions:

(19.1) — future_already_retrieved if get_future has already been called on a packaged_task object
with the same shared state as *this.
(19.2) — no_state if *this has no shared state.

void operator()(ArgTypes... args);

Effects: As if by INVOKE<R>(f, t_1, t_2, ..., t_N) (22.10.4), where f is the stored task of *this and
t_1, t_2, ..., t_N are the values in args... If the task returns normally, the return value is stored as
the asynchronous result in the shared state of *this, otherwise the exception thrown by the task is
stored. The shared state of *this is made ready, and any threads blocked in a function waiting for the
shared state of *this to become ready are unblocked.

Throws: A future_error exception object if there is no shared state or the stored task has already
been invoked.

Error conditions:

(22.1) — promise_already_satisfied if the stored task has already been invoked.
(22.2) — no_state if *this has no shared state.
void make_ready_at_thread_exit(ArgTypes... args);

Effects: As if by `INVOKE<R>(f, t_1, t_2, ..., t_N)` (22.10.4), where `f` is the stored task and `t_1, t_2, ..., t_N` are the values in `args`. If the task returns normally, the return value is stored as the asynchronous result in the shared state of `*this`, otherwise the exception thrown by the task is stored. In either case, this is done without making that state ready (33.10.5) immediately. Schedules the shared state to be made ready when the current thread exits, after all objects of thread storage duration associated with the current thread have been destroyed.

Throws: `future_error` if an error condition occurs.

Error conditions:
1. `promise_already_satisfied` if the stored task has already been invoked.
2. `no_state` if `*this` has no shared state.

void reset();

Effects: As if `*this = packaged_task(std::move(f))`, where `f` is the task stored in `*this`.

[Note 2: This constructs a new shared state for `*this`. The old state is abandoned (33.10.5). —end note]

Throws:
1. `bad_alloc` if memory for the new shared state cannot be allocated.
2. Any exception thrown by the move constructor of the task stored in the shared state.
3. `future_error` with an error condition of `no_state` if `*this` has no shared state.

33.10.10.3 Globals

```cpp
template<class R, class... ArgTypes>
void swap(packaged_task<R(ArgTypes...)>& x, packaged_task<R(ArgTypes...)>& y) noexcept;
```

Effects: As if by `x.swap(y)`.

33.11 Safe reclamation

33.11.1 General

Subclause 33.11 contains safe-reclamation techniques, which are most frequently used to straightforwardly resolve access-deletion races.

33.11.2 Read-copy update (RCU)

33.11.2.1 General

RCU is a synchronization mechanism that can be used for linked data structures that are frequently read, but seldom updated. RCU does not provide mutual exclusion, but instead allows the user to schedule specified actions such as deletion at some later time.

A class type `T` is rcu-protectable if it has exactly one base class of type `rcu_obj_base<T, D>` for some `D`, and that base is public and non-virtual, and it has no base classes of type `rcu_obj_base<X, Y>` for any other combination `X, Y`. An object is rcu-protectable if it is of rcu-protectable type.

An invocation of `unlock U` on an `rcu_domain dom` corresponds to an invocation of `lock L` on `dom` if `L` is sequenced before `U` and either

1. no other invocation of `lock L` on `dom` is sequenced after `L` and before `U`, or
2. every invocation of `unlock U2` on `dom` such that `L` is sequenced before `U2` and `U2` is sequenced before `U` corresponds to an invocation of `lock L2` on `dom` such that `L` is sequenced before `L2` and `L2` is sequenced before `U2`.

[Note 1: This pairs nested locks and unlocks on a given domain in each thread. —end note]

A region of RCU protection on a domain `dom` starts with a `lock L` on `dom` and ends with its corresponding `unlock U`.

A region of RCU protection `R` on a domain `dom` and given an evaluation `E` that scheduled another evaluation `F` in `dom`, if `E` does not strongly happen before the start of `R`, the end of `R` strongly happens before evaluating `F`.
The evaluation of a scheduled evaluation is potentially concurrent with any other scheduled evaluation. Each scheduled evaluation is evaluated at most once.

### 33.11.2.2 Header `<rcu>` synopsis

```
namespace std {
    // 33.11.2.3, class template rcu_obj_base
    template<class T, class D = default_delete<T>> class rcu_obj_base;

    // 33.11.2.4, class rcu_domain
    class rcu_domain;

    // 33.11.2.4.3 non-member functions
    rcu_domain& rcu_default_domain() noexcept;
    void rcu_synchronize(rcu_domain& dom = rcu_default_domain()) noexcept;
    void rcu_barrier(rcu_domain& dom = rcu_default_domain()) noexcept;
    template<class T, class D = default_delete<T>>
    void rcu_retire(T* p, D d = D(), rcu_domain& dom = rcu_default_domain());
}
```

### 33.11.2.3 Class template rcu_obj_base

1. Objects of type `T` to be protected by RCU inherit from a specialization `rcu_obj_base<T, D>` for some `D`.

   ```
   namespace std {
       template<class T, class D = default_delete<T>>
       class rcu_obj_base {
           public:
               void retire(D d = D(), rcu_domain& dom = rcu_default_domain()) noexcept;
               protected:
                   rcu_obj_base() = default;
                   rcu_obj_base(const rcu_obj_base&) = default;
                   rcu_obj_base(rcu_obj_base&) = default;
                   ~rcu_obj_base() = default;
           private:
               D deleter; // exposition only
           }
   }
   ```

2. The behavior of a program that adds specializations for `rcu_obj_base` is undefined.

3. `T` may be an incomplete type. It shall be complete before any member of the resulting specialization of `rcu_obj_base` is referenced.

4. `D` shall be a function object type (22.10) for which, given a value `d` of type `D` and a value `ptr` of type `T*`, the expression `d(ptr)` is valid.

5. `D` shall meet the requirements for `Cpp17DefaultConstructible` and `Cpp17MoveAssignable`.

6. If `D` is trivially copyable, all specializations of `rcu_obj_base<T, D>` are trivially copyable.

   ```
   void retire(D d = D(), rcu_domain& dom = rcu_default_domain()) noexcept;
   ```

7. **Mandates:** `T` is an rcu-protectable type.

8. **Preconditions:** `*this` is a base class subobject of an object `x` of type `T`. The member function `rcu_obj_base<T, D>::retire` was not invoked on `x` before. The assignment to `deleter` does not exit via an exception.

9. **Effects:** Evaluates `deleter = std::move(d)` and schedules the evaluation of the expression `deleter(addressof(x))` in the domain `dom`; the behavior is undefined if that evaluation exits via an exception. May invoke scheduled evaluations in `dom`.

   **[Note 1:]** If such evaluations acquire resources held across any invocation of `retire` on `dom`, deadlock can occur. **—end note**
33.11.2.4 Class rcu_domain

33.11.2.4.1 General

namespace std {
    class rcu_domain {
    public:
        rcu_domain(const rcu_domain&) = delete;
        rcu_domain& operator=(const rcu_domain&) = delete;
        void lock() noexcept;
        bool try_lock() noexcept;
        void unlock() noexcept;
    };
}

This class meets the requirements of Cpp17Lockable (33.2.5.3) and provides regions of RCU protection.

[Example 1:]
    std::scoped_lock<rcu_domain> rlock(rcu_default_domain());
    —end example]

1 The functions lock and unlock establish (possibly nested) regions of RCU protection.

33.11.2.4.2 Member functions

    void lock() noexcept;
1 Effects: Opens a region of RCU protection.
2 Remarks: Calls to lock do not introduce a data race (6.9.2.2) involving *this.

    bool try_lock() noexcept;
3 Effects: Equivalent to lock().
4 Returns: true.

    void unlock() noexcept;
5 Preconditions: A call to lock that opened an unclosed region of RCU protection is sequenced before the call to unlock.
6 Effects: Closes the unclosed region of RCU protection that was most recently opened. May invoke scheduled evaluations in *this.
7 [Note 1: If such evaluations acquire resources held across any invocation of unlock on *this, deadlock can occur. — end note]
8 Remarks: Calls to unlock do not introduce a data race involving *this.
[Note 2: Evaluation of scheduled evaluations can still cause a data race. — end note]

33.11.2.4.3 Non-member functions

    rcu_domain& rcu_default_domain() noexcept;
1 Returns: A reference to a static-duration object of type rcu_domain. A reference to the same object is returned every time this function is called.

    void rcu_synchronize(rcu_domain& dom = rcu_default_domain()) noexcept;
2 Effects: If the call to rcu_synchronize does not strongly happen before the lock opening an RCU protection region R on dom, blocks until the unlock closing R happens.
3 Synchronization: The unlock closing R strongly happens before the return from rcu_synchronize.

    void rcu_barrier(rcu_domain& dom = rcu_default_domain()) noexcept;
4 Effects: May evaluate any scheduled evaluations in dom. For any evaluation that happens before the call to rcu_barrier and that schedules an evaluation E in dom, blocks until E has been evaluated.
5 Synchronization: The evaluation of any such E strongly happens before the return from rcu_barrier.
[Note 1: A call to rcu_barrier does not imply a call to rcu_synchronize and vice versa. — end note]
template<class T, class D = default_delete<T>>
void rcu_retire(T* p, D d = D(), rcu_domain& dom = rcu_default_domain());

Mandates: is_move_constructible_v<D> is true and the expression d(p) is well-formed.

Preconditions: D meets the Cpp17MoveConstructible and Cpp17Destructible requirements.

Effects: May allocate memory. It is unspecified whether the memory allocation is performed by invoking
operator new. Initializes an object d1 of type D from std::move(d). Schedules the evaluation of
d1(p) in the domain dom; the behavior is undefined if that evaluation exits via an exception. May
invoke scheduled evaluations in dom.

[Note 2: If rcu_retire exits via an exception, no evaluation is scheduled. — end note]

Throws: bad_alloc or any exception thrown by the initialization of d1.

[Note 3: If scheduled evaluations acquire resources held across any invocation of rcu_retire on dom, deadlock
can occur. — end note]

33.11.3 Hazard pointers [safercl.hp]

33.11.3.1 General [safercl.hp.general]

A hazard pointer is a single-writer multi-reader pointer that can be owned by at most one thread at any
time. Only the owner of the hazard pointer can set its value, while any number of threads may read its value.
The owner thread sets the value of a hazard pointer to point to an object in order to indicate to concurrent
readers. The object of type

\[ x \]

is retired in an evaluation
dom

ifrcu_retire(p, d)

is invoked on
x

and for every protection epoch
E

happens before
h

in the domain dom; the behavior is undefined if that evaluation exits via an exception. May
invoke scheduled evaluations in dom.

[Note 2: If rcu_retire exits via an exception, no evaluation is scheduled. — end note]

Throws: bad_alloc or any exception thrown by the initialization of d1.

[Note 3: If scheduled evaluations acquire resources held across any invocation of rcu_retire on dom, deadlock
can occur. — end note]

33.11.3.1 General [safercl.hp.general]

1 A hazard pointer is a single-writer multi-reader pointer that can be owned by at most one thread at any
time. Only the owner of the hazard pointer can set its value, while any number of threads may read its value.
The owner thread sets the value of a hazard pointer to point to an object in order to indicate to concurrent
threads—which may delete such an object—that the object is not yet safe to delete.

2 A class type

T

is hazard-protectable if it has exactly one base class of type

hazard_pointer_obj_base<T, D>

for some D, that base is public and non-virtual, and it has no base classes of type

hazard_pointer_obj_base<T2, D2>

for any other combination

T2, D2.

An object is hazard-protectable if it is of hazard-protectable
type.

3 The time span between creation and destruction of a hazard pointer

h

is partitioned into a series of protection epochs; in each protection epoch, h either is associated with a hazard-protectable object, or is unassociated.

Upon creation, a hazard pointer is unassociated. Changing the association (possibly to the same object)
initiates a new protection epoch and ends the preceding one.

4 An object

x

of hazard-protectable type

T

is retired with a deleter of type

D

when the member function

hazard_pointer_obj_base<T, D>::retire

is invoked on
x.

Any given object

x

shall be retired at most

once.

5 A retired object

x

is reclaimed by invoking its deleter with a pointer to
x; the behavior is undefined if that
invocation exits via an exception.

6 A hazard-protectable object

x

is possibly-reclaimable with respect to an evaluation

A

if

(6.1) —

x

is not reclaimed; and

(6.2) —

x

is retired in an evaluation

R

and

A

does not happen before

R;

and

(6.3) —

for all hazard pointers

h

and for every protection epoch

E

of

h

during which

h

is associated with

x:

(6.3.1) —

if

the beginning of

E

happens before

R,

the end of

E

strongly happens before

A;

and

(6.3.2) —

if

E

begun by an evaluation of

try_protect

with argument

src,

label its atomic load operation

L.

If there exists an atomic modification

B

on

src

such that

L

observes a modification that is

modification-ordered before

B,

and

B

happens before

x

is retired, the end of

E

strongly happens before

A.

[Note 1: In typical use, a store to

src

sequenced before retiring

x

will be such an atomic operation

B. — end note]

[Note 2: The latter two conditions convey the informal notion that a protection epoch that began before retiring

x,

as implied either by the happens-before relation or the coherence order of some source, delays the reclamation of

x. — end note]

The number of possibly-reclaimable objects has an unspecified bound.

[Note 3: The bound can be a function of the number of hazard pointers, the number of threads that retire objects,
and the number of threads that use hazard pointers. — end note]

[Example 1: The following example shows how hazard pointers allow updates to be carried out in the presence of
concurrent readers. The object of type

hazard_pointer

in

print_name

protects the object

*ptr

from being reclaimed by

ptr->retire

until the end of the protection epoch.]
struct Name : public hazard_pointer_obj_base<Name> { /* details */ };
atomic<Name*> name;
// called often and in parallel!
void print_name() {
    hazard_pointer h = make_hazard_pointer();
    Name* ptr = h.protect(name);   // Protection epoch starts
    // ... safe to access *ptr
}   // Protection epoch ends.

// called rarely, but possibly concurrently with print_name
void update_name(Name* new_name) {
    Name* ptr = name.exchange(new_name);
    ptr->retire();
}
end example]

33.11.3.2 Header <hazard_pointer> synopsis [hazard.pointer.syn]
namespace std {
    // 33.11.3.3, class template hazard_pointer_obj_base
    template<class T, class D = default_delete<T>> class hazard_pointer_obj_base;
    // 33.11.3.4, class hazard_pointer
    class hazard_pointer;
    // 33.11.3.4.4, non-member functions
    hazard_pointer make_hazard_pointer();
    void swap(hazard_pointer&, hazard_pointer&) noexcept;
}

33.11.3.3 Class template hazard_pointer_obj_base [saferelc.hp.base]
namespace std {
    template<class T, class D = default_delete<T>>
    class hazard_pointer_obj_base {
    public:
        void retire(D d = D()) noexcept;
    protected:
        hazard_pointer_obj_base() = default;
        hazard_pointer_obj_base(const hazard_pointer_obj_base&) = default;
        hazard_pointer_obj_base(hazard_pointer_obj_base&) = default;
        hazard_pointer_obj_base& operator=(const hazard_pointer_obj_base&) = default;
        hazard_pointer_obj_base& operator=(hazard_pointer_obj_base&) = default;
        ~hazard_pointer_obj_base() = default;
    private:
        D deleter;       // exposition only
    };
}  

1 D shall be a function object type (22.10.4) for which, given a value d of type D and a value ptr of type T*,
the expression d(ptr) is valid.
2 The behavior of a program that adds specializations for hazard_pointer_obj_base is undefined.
3 D shall meet the requirements for Cpp17DefaultConstructible and Cpp17MoveAssignable.
4 T may be an incomplete type. It shall be complete before any member of the resulting specialization of
hazard_pointer_obj_base is referenced.

void retire(D d = D()) noexcept;

Mandates: T is a hazard-protectable type.

Preconditions: *this is a base class subobject of an object x of type T. x is not retired. Move-assigning
d to deleter does not exit via an exception.

Effects: Move-assigns d to deleter, thereby setting it as the deleter of x, then retires x. May reclaim
possibly-reclaimable objects.
33.11.3.4 Class hazard_pointer

33.11.3.4.1 General

```cpp
namespace std {
    class hazard_pointer {
        public:
            hazard_pointer() noexcept;
            hazard_pointer(hazard_pointer&&) noexcept;
            hazard_pointer& operator=(hazard_pointer&&) noexcept;
            ~hazard_pointer();
            [[nodiscard]] bool empty() const noexcept;
            template<class T> T* protect(const atomic<T*>& src) noexcept;
            template<class T> bool try_protect(T*& ptr, const atomic<T*>& src) noexcept;
            template<class T> void reset_protection(const T* ptr) noexcept;
            void reset_protection(nullptr_t = nullptr) noexcept;
            void swap(hazard_pointer&) noexcept;
    };
}

An object of type `hazard_pointer` is either empty or owns a hazard pointer. Each hazard pointer is owned by exactly one object of type `hazard_pointer`.

[Note 1: An empty `hazard_pointer` object is different from a `hazard_pointer` object that owns an unassociated hazard pointer. An empty `hazard_pointer` object does not own any hazard pointers. — end note]
(5.1) — Initializes a variable old of type T* with the value of ptr.
(5.2) — Evaluates reset_protection(old).
(5.3) — Assigns the value of src.load(memory_order::acquire) to ptr.
(5.4) — If old == ptr is false, evaluates reset_protection().

Returns: old == ptr.

template<class T> void reset_protection(const T* ptr) noexcept;

Mandates: T is a hazard-protectable type.

Preconditions: *this is not empty.

Effects: If ptr is a null pointer value, invokes reset_protection(). Otherwise, associates the hazard pointer owned by *this with *ptr, thereby ending the current protection epoch.

Complexity: Constant.

void reset_protection(nullptr_t = nullptr) noexcept;

Preconditions: *this is not empty.

Postconditions: The hazard pointer owned by *this is unassociated.

Complexity: Constant.

void swap(hazard_pointer& other) noexcept;

Effects: Swaps the hazard pointer ownership of this object with that of other.

[Note 1: The owned hazard pointers, if any, remain unchanged during the swap and continue to be associated with the respective objects that they were protecting before the swap, if any. No protection epochs are ended or initiated. — end note]

Complexity: Constant.

33.11.3.4.4 Non-member functions

hazard_pointer make_hazard_pointer();

Effects: Constructs a hazard pointer.

Returns: A hazard_pointer object that owns the newly-constructed hazard pointer.

Throws: May throw bad_alloc if memory for the hazard pointer could not be allocated.

void swap(hazard_pointer& a, hazard_pointer& b) noexcept;

Effects: Equivalent to a.swap(b).
Annex A
(informative)

Grammar summary

A.1 General

This summary of C++ grammar is intended to be an aid to comprehension. It is not an exact statement of the language. In particular, the grammar described here accepts a superset of valid C++ constructs. Disambiguation rules (8.9, 9.2, 6.5.2) are applied to distinguish expressions from declarations. Further, access control, ambiguity, and type rules are used to weed out syntactically valid but meaningless constructs.

A.2 Keywords

New context-dependent keywords are introduced into a program by typedef (9.2.4), namespace (9.8.2), class (Clause 11), enumeration (9.7.1), and template (Clause 13) declarations.

A.3 Lexical conventions

n-char: one of any member of the translation character set except the U+007D RIGHT CURLY BRACKET or new-line character

n-char-sequence: n-char n-char-sequence n-char

named-universal-character: \N{ n-char-sequence }

hex-quad: hexadecimal-digit hexadecimal-digit hexadecimal-digit hexadecimal-digit

simple-hexadecimal-digit-sequence: hexadecimal-digit hexadecimal-digit hexadecimal-digit hexadecimal-digit

universal-character-name: \u hex-quad \U hex-quad hex-quad \u{ simple-hexadecimal-digit-sequence }

named-universal-character
preprocessing-token:
  header-name
  import-keyword
  module-keyword
  export-keyword
  identifier
  pp-number
  character-literal
  user-defined-character-literal
  string-literal
  user-defined-string-literal
  preprocessing-op-or-punc
  each non-whitespace character that cannot be one of the above

token:
  identifier
  keyword
  literal
  operator-or-punctuator

header-name:
  < h-char-sequence >
  " q-char-sequence "

h-char-sequence:
  h-char
  h-char-sequence h-char

h-char:
  any member of the translation character set except new-line and U+003E GREATER-T..
keyword:
  any identifier listed in Table 5
import-keyword
module-keyword
export-keyword

preprocessing-op-or-punc:
  preprocessing-operator
operator-or-punctuator

preprocessing-operator: one of
  #   ##   %:   %:%:
operator-or-punctuator: one of
  {   }   [   ]   (   )
  <:   >:   <:%   %>   ;   :   ...
  ?:   ::   .*   ->   -*   ~
  !   +   -   *   /   %   ^   &   |
  ==   +=   -=   %=   /=   ^=   &=   ||=   <=   >=   ^=   &&   ||
  <<   >>   <<=   >>=   ++   --   ,
  and   or   xor   not   bitand   bitor   compl
  and_eq   or_eq   xor_eq   not_eq

literal:
  integer-literal
  character-literal
  floating-point-literal
  string-literal
  boolean-literal
  pointer-literal
  user-defined-literal

integer-literal:
  binary-literal integer-suffix_opt
  octal-literal integer-suffix_opt
  decimal-literal integer-suffix_opt
  hexadecimal-literal integer-suffix_opt

binary-literal:
  0b binary-digit
  0B binary-digit
  binary-literal [,opt] binary-digit

octal-literal:
  0
  octal-literal [,opt] octal-digit

decimal-literal:
  nonzero-digit
  decimal-literal [,opt] digit

hexadecimal-literal:
  hexadecimal-prefix hexadecimal-digit-sequence

binary-digit: one of
  0 1

octal-digit: one of
  0 1 2 3 4 5 6 7

nonzero-digit: one of
  1 2 3 4 5 6 7 8 9

hexadecimal-prefix: one of
  0x 0X

hexadecimal-digit-sequence:
  hexadecimal-digit
  hexadecimal-digit-sequence [,opt] hexadecimal-digit
hexadecimal-digit: one of
0 1 2 3 4 5 6 7 8 9
a b c d e f
A B C D E F

integer-suffix:
  unsigned-suffix long-suffix opt
  unsigned-suffix long-long-suffix opt
  unsigned-suffix size-suffix opt
  long-suffix unsigned-suffix opt
  long-long-suffix unsigned-suffix opt
  size-suffix unsigned-suffix opt

unsigned-suffix: one of
  u U

long-suffix: one of
  l L

long-long-suffix: one of
  ll LL

size-suffix: one of
  z Z

c-character-literal:
  encoding-prefix opt ' c-char-sequence '

encoding-prefix: one of
  u8 u U L

c-char-sequence:
  c-char
  c-char-sequence c-char

c-char:
  basic-c-char
  escape-sequence
  universal-character-name

basic-c-char:
  any member of the translation character set except the U+0027 APOSTROPHE,
  U+005C REVERSE SOLIDUS, or new-line character

escape-sequence:
  simple-escape-sequence
  numeric-escape-sequence
  conditional-escape-sequence

simple-escape-sequence:
  \ simple-escape-sequence-char

simple-escape-sequence-char: one of
  ' " ? \ a b f n r t v

numeric-escape-sequence:
  octal-escape-sequence
  hexadecimal-escape-sequence

simple-octal-digit-sequence:
  octal-digit
  simple-octal-digit-sequence octal-digit

octal-escape-sequence:
  \ octal-digit
  \ octal-digit octal-digit
  \ octal-digit octal-digit octal-digit
  \o{ simple-octal-digit-sequence }

hexadecimal-escape-sequence:
  \x simple-hexadecimal-digit-sequence
  \x{ simple-hexadecimal-digit-sequence }
conditional-escape-sequence:
\ conditional-escape-sequence-char

conditional-escape-sequence-char:
any member of the basic character set that is not an octal-digit, a simple-escape-sequence-char, or the characters \, o, u, U, or x

decimal-floating-point-literal:
decimal-floating-point-literal
hexadecimal-floating-point-literal
decimal-floating-point-literal:
fractional-constant exponent-part_opt floating-point-suffix_opt
digit-sequence exponent-part floating-point-suffix_opt
hexadecimal-floating-point-literal:
hexadecimal-prefix hexadecimal-fractional-constant binary-exponent-part floating-point-suffix_opt
decimal-fractional-constant: decimal-fractional-constant . digit-sequence
decimal-fractional-constant: hexadecimal-fractional-constant . hexadecimal-digit-sequence
decimal-fractional-constant: hexadecimal-fractional-constant . hexadecimal-digit-sequence

exponent-part:
e signopt digit-sequence
E signopt digit-sequence

binary-exponent-part:
p signopt digit-sequence
P signopt digit-sequence

sign: one of
+ -

digit-sequence:
digit
digit-sequence 'opt digit

floating-point-suffix: one of
f l f16 f32 f64 f128 bf16 F L F16 F32 F64 F128 BF16

string-literal:
encoding-prefix_opt " s-char-sequence_opt "
encoding-prefix_opt R raw-string
s-char-sequence:
s-char
s-char-sequence s-char

s-char:
basic-s-char
escape-sequence
universal-character-name

basic-s-char:
any member of the translation character set except the U+0022 QUOTATION MARK,
U+005C REVERSE SOLIDUS, or new-line character

raw-string:
" d-char-sequence_opt ( r-char-sequence_opt ) d-char-sequence_opt "

r-char-sequence:
r-char
r-char-sequence r-char

r-char:
any member of the translation character set, except a U+0029 RIGHT PARENTHESIS followed by
the initial d-char-sequence (which may be empty) followed by a U+0022 QUOTATION MARK

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d-char-sequence:
  d-char
  d-char-sequence d-char

d-char:
  any member of the basic character set except:
    U+0020 SPACE, U+0028 LEFT PARENTHESES, U+0029 RIGHT PARENTHESES, U+005C REVERSE SOLIDUS,
    U+0009 CHARACTER TABULATION, U+000B LINE TABULATION, U+000C FORM FEED, and new-line

unevaluated-string:
  string-literal

boolean-literal:
  false
  true

pointer-literal:
  nullptr

user-defined-literal:
  user-defined-integer-literal
  user-defined-floating-point-literal
  user-defined-string-literal
  user-defined-character-literal

user-defined-integer-literal:
  decimal-literal ud-suffix
  octal-literal ud-suffix
  hexadecimal-literal ud-suffix
  binary-literal ud-suffix

user-defined-floating-point-literal:
  fractional-constant exponent-part_opt ud-suffix
  digit-sequence exponent-part ud-suffix
  hexadecimal-prefix hexadecimal-fractional-constant binary-exponent-part ud-suffix
  hexadecimal-prefix hexadecimal-digit-sequence binary-exponent-part ud-suffix

user-defined-string-literal:
  string-literal ud-suffix

user-defined-character-literal:
  character-literal ud-suffix

ud-suffix:
  identifier

A.4 Basics

translation-unit:
  declaration-seq_opt
  global-module-fragment_opt module-declaration declaration-seq_opt private-module-fragment_opt

A.5 Expressions

primary-expression:
  literal
  this
  ( expression )
  id-expression
  lambda-expression
  fold-expression
  requires-expression

id-expression:
  unqualified-id
  qualified-id
  pack-index-expression

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unqualified-id:
identifier
operator-function-id
conversion-function-id
literal-operator-id
~ type-name
~ computed-type-specifier
template-id

qualified-id:
nested-name-specifier template_opt unqualified-id

nested-name-specifier:
::
type-name ::
namespace-name ::
computed-type-specifier ::
nested-name-specifier identifier ::
nested-name-specifier template_opt simple-template-id ::

pack-index-expression:
id-expression ... [ constant-expression ]

lambda-expression:
lambda-introducer attribute-specifier-seq_opt lambda-declarator compound-statement
lambda-introducer < template-parameter-list > requires-clause_opt attribute-specifier-seq_opt
lambda-declarator compound-statement

lambda-introducer:
[ lambda-capture_opt ]

lambda-declarator:
lambda-specifier-seq noexcept-specifier_opt attribute-specifier-seq_opt trailing-return-type_opt
noexcept-specifier attribute-specifier-seq_opt trailing-return-type_opt
trailing-return-type_opt
( parameter-declaration-clause ) lambda-specifier-seq_opt noexcept-specifier_opt attribute-specifier-seq_opt
trailing-return-type_opt requires-clause_opt

lambda-specifier:
consteval
constexpr
mutable
static

lambda-specifier-seq:
lambda-specifier
lambda-specifier lambda-specifier-seq

lambda-capture:
capture-default
capture-list
capture-default , capture-list

capture-default:
&
=
capture-list:
capture
capture-list , capture
capture:
simple-capture
init-capture

simple-capture:
identifier ... opt
& identifier ... opt
this
* this

§ A.5
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init-capture:
    ...opt identifier initializer
    & ...opt identifier initializer

fold-expression:
    ( cast-expression fold-operator ... )
    ( ... fold-operator cast-expression )
    ( cast-expression fold-operator ... fold-operator cast-expression )

fold-operator: one of
    + - * / % ^ & | << >>
    += -= *= /= %= ^= &= |= <<= >>= =
    != < > <= >= && || , .* ->*

requires-expression:
    requires requirement-parameter-listopt requirement-body

requirement-parameter-list:
    ( parameter-declaration-clause )

requirement-body:
    { requirement-seq }

requirement-seq:
    requirement
    requirement requirement-seq

requirement:
    simple-requirement
    type-requirement
    compound-requirement
    nested-requirement

simple-requirement:
    expression ;

type-requirement:
    typename nested-name-specifieropt type-name ;

compound-requirement:
    { expression } noexceptopt return-type-requirementopt ;

return-type-requirement:
    -> type-constraint

nested-requirement:
    requires constraint-expression ;

postfix-expression:
    primary-expression
    postfix-expression [ expression-listopt ]
    postfix-expression ( expression-listopt )
    simple-type-specifier ( expression-listopt )
    typename-specifier ( expression-listopt )
    simple-type-specifier braced-init-list
    typename-specifier braced-init-list
    postfix-expression . templateopt id-expression
    postfix-expression -> templateopt id-expression
    postfix-expression ++
    postfix-expression --
    dynamic_cast < type-id > ( expression )
    static_cast < type-id > ( expression )
    reinterpret_cast < type-id > ( expression )
    const_cast < type-id > ( expression )
    typeid ( expression )
    typeid ( type-id )

expression-list:
    initializer-list
unary-expression:
  postfix-expression
  unary-operator cast-expression
  ++ cast-expression
  -- cast-expression
  await-expression
  sizeof unary-expression
  sizeof ( type-id )
  sizeof ... ( identifier )
  alignof ( type-id )
  noexcept-expression
  new-expression
  delete-expression

unary-operator: one of
  * & + - ! ~

await-expression:
  co_await cast-expression

noexcept-expression:
  noexcept ( expression )

new-expression:
  :: opt new new-placement_opt new-type-id new-initializer_opt
  :: opt new new-placement_opt ( type-id ) new-initializer_opt

new-placement:
  ( expression-list )

new-type-id:
  type-specifier-seq new-declarator_opt

new-declarator:
  ptr-operator new-declarator_opt
  noptr-new-declarator

noptr-new-declarator:
  [ expression_opt ] attribute-specifier-seq_opt
  noptr-new-declarator [ constant-expression ] attribute-specifier-seq_opt

new-initializer:
  ( expression-list_opt )
  braced-init-list

delete-expression:
  :: opt delete cast-expression
  :: opt delete [ ] cast-expression

cast-expression:
  unary-expression
  ( type-id ) cast-expression

pm-expression:
  cast-expression
  pm-expression .* cast-expression
  pm-expression ->* cast-expression

multiplicative-expression:
  pm-expression
  multiplicative-expression * pm-expression
  multiplicative-expression / pm-expression
  multiplicative-expression % pm-expression

additive-expression:
  multiplicative-expression
  additive-expression + multiplicative-expression
  additive-expression - multiplicative-expression

shift-expression:
  additive-expression
  shift-expression << additive-expression
  shift-expression >> additive-expression
compare-expression:
    shift-expression
    compare-expression <=> shift-expression

relational-expression:
    compare-expression
    relational-expression < compare-expression
    relational-expression > compare-expression
    relational-expression <= compare-expression
    relational-expression >= compare-expression

equality-expression:
    relational-expression
    equality-expression == relational-expression
    equality-expression != relational-expression

and-expression:
    equality-expression
    and-expression & equality-expression

exclusive-or-expression:
    and-expression
    exclusive-or-expression ^ and-expression

inclusive-or-expression:
    exclusive-or-expression
    inclusive-or-expression | exclusive-or-expression

logical-and-expression:
    inclusive-or-expression
    logical-and-expression && inclusive-or-expression

logical-or-expression:
    logical-and-expression
    logical-or-expression || logical-and-expression

conditional-expression:
    logical-or-expression
    logical-or-expression ? expression : assignment-expression

yield-expression:
    co_yield assignment-expression
    co_yield braced-init-list

throw-expression:
    throw assignment-expression_opt

assignment-expression:
    conditional-expression
    yield-expression
    throw-expression
    logical-or-expression assignment-operator initializer-clause

assignment-operator: one of
    = <<= /= %= += -= >>= <<= &= ^= |=

expression:
    assignment-expression
    expression , assignment-expression

constant-expression:
    conditional-expression

A.6 Statements

[gram.stmt]
N4986

statement:
- labeled-statement
- attribute-specifier-seq<opt> expression-statement
- attribute-specifier-seq<opt> compound-statement
- attribute-specifier-seq<opt> selection-statement
- attribute-specifier-seq<opt> iteration-statement
- attribute-specifier-seq<opt> jump-statement
- declaration-statement
- attribute-specifier-seq<opt> try-block

init-statement:
- expression-statement
- simple-declaration
- alias-declaration

condition:
- expression
- attribute-specifier-seq<opt> decl-specifier-seq declarator brace-or-equal-Initializer
- structured-binding-declaration initializer

label:
- attribute-specifier-seq<opt> identifier :
- attribute-specifier-seq<opt> case constant-expression :
- attribute-specifier-seq<opt> default :

labeled-statement:
- label statement

expression-statement:
- expression<opt> ;

compound-statement:
- { statement-seq<opt> label-seq<opt> }

statement-seq:
- statement
- statement-seq statement

label-seq:
- label
- label-seq label

selection-statement:
- if constexpr<opt> ( init-statement<opt> condition ) statement
- if constexpr<opt> ( init-statement<opt> condition ) statement else statement
- if ! consteval compound-statement
- if ! consteval compound-statement else statement
- switch ( init-statement<opt> condition ) statement

iteration-statement:
- while ( condition ) statement
- do statement while ( expression ) ;
- for ( init-statement condition<opt> ; expression<opt> ) statement
- for ( init-statement<opt> for-range-declaration : for-range-initializer ) statement

for-range-declaration:
- attribute-specifier-seq<opt> decl-specifier-seq declarator
- structured-binding-declaration

for-range-initializer:
- expr-or-braced-init-list

jump-statement:
- break ;
- continue ;
- return expr-or-braced-init-list<opt> ;
- coroutine-return-statement
- goto identifier ;

coroutine-return-statement:
- co_return expr-or-braced-init-list<opt> ;
A.7 Declarations

declaration-statement:
  block-declaration

[gram.dcl]

```plaintext
A.7  Declarations

declaration-seq:
  declaration
  declaration-seq declaration

declaration:
  name-declaration
  special-declaration

name-declaration:
  block-declaration
  nodeclspec-function-declaration
  function-definition
  friend-type-declaration
  template-declaration
  deduction-guide
  linkage-specification
  namespace-definition
  empty-declaration
  attribute-declaration
  module-import-declaration

special-declaration:
  explicit-instantiation
  explicit-specialization
  export-declaration

block-declaration:
  simple-declaration
  asm-declaration
  namespace-alias-definition
  using-declaration
  using-enum-declaration
  using-directive
  static_assert-declaration
  alias-declaration
  opaque-enum-declaration

nodeclspec-function-declaration:
  attribute-specifier-seq_opt declarator ;

alias-declaration:
  using identifier attribute-specifier-seq_opt = defining-type-id ;

attributed-identifier:
  identifier attribute-specifier-seq_opt

attributed-identifier-list:
  attributed-identifier
  attributed-identifier-list , attributed-identifier

structured-binding-declaration:
  attribute-specifier-seq_opt decl-specifier-seq ref-qualifier_opt [ attributed-identifier-list ]

simple-declaration:
  decl-specifier-seq init-declarator-list_opt ;
  attribute-specifier-seq decl-specifier-seq init-declarator-list ;
  structured-binding-declaration initializer ;

static_assert-message:
  unevaluated-string
  constant-expression

static_assert-declaration:
  static_assert ( constant-expression )
  static_assert ( constant-expression , static_assert-message )
```
empty-declaration:  
  ;

attribute-declaration:  
  attribute-specifier-seq ;

decl-specifier:  
  storage-class-specifier  
  defining-type-specifier  
  function-specifier  
  friend  
  typedef  
  constexpr  
  consteval  
  constinit  
  inline

decl-specifier-seq:  
  decl-specifier attribute-specifier-seq opt  
  decl-specifier decl-specifier-seq

storage-class-specifier:  
  static  
  thread_local  
  extern  
  mutable

function-specifier:  
  virtual  
  explicit-specifier

explicit-specifier:  
  explicit ( constant-expression )  
  explicit

typedef-name:  
  identifier  
  simple-template-id

type-specifier:  
  simple-type-specifier  
  elaborated-type-specifier  
  typename-specifier  
  cv-qualifier

type-specifier-seq:  
  type-specifier attribute-specifier-seq opt  
  type-specifier type-specifier-seq

defining-type-specifier:  
  type-specifier  
  class-specifier  
  enum-specifier

defining-type-specifier-seq:  
  defining-type-specifier attribute-specifier-seq opt  
  defining-type-specifier defining-type-specifier-seq
simple-type-specifier:
  nested-name-specifier_opt type-name
  nested-name-specifier template simple-template-id
  computed-type-specifier
  placeholder-type-specifier
  nested-name-specifier_opt template-name
  char
  char8_t
  char16_t
  char32_t
  wchar_t
  bool
  short
  int
  long
  signed
  unsigned
  float
  double
  void

type-name:
  class-name
  enum-name
  typedef-name

computed-type-specifier:
  decltype-specifier
  pack-index-specifier

pack-index-specifier:
  typedef-name ... [ constant-expression ]

elaborated-type-specifier:
  class-key attribute-specifier-seq_opt nested-name-specifier_opt identifier
  class-key simple-template-id
  class-key nested-name-specifier template_opt simple-template-id
  enum nested-name-specifier_opt identifier

dcltype-specifier:
  decltype ( expression )

placeholder-type-specifier:
  type-constraint_opt auto
  type-constraint_opt decltype ( auto )

init-declarator-list:
  init-declarator
  init-declarator-list , init-declarator

init-declarator:
  declarator initialization_opt
  declarator requires-clause

declarator:
  ptr-declarator
  noptr-declarator parameters-and-qualifiers trailing-return-type

ptr-declarator:
  noptr-declarator
  ptr-operator ptr-declarator

noptr-declarator:
  declarator-id attribute-specifier-seq_opt
  noptr-declarator parameters-and-qualifiers
  noptr-declarator [ constant-expression_opt ] attribute-specifier-seq_opt
  ( ptr-declarator )

parameters-and-qualifiers:
  ( parameter-declaration-clause ) cv-qualification_opt
  ref-qualification_opt noexcept-qualification_opt attribute-specifier-seq_opt
trailing-return-type:
   -> type-id

ptr-operator:
   * attribute-specifier-seq\textsubscript{opt} cv-qualifier-seq\textsubscript{opt}
   & attribute-specifier-seq\textsubscript{opt}
   && attribute-specifier-seq\textsubscript{opt}
   nested-name-specifier * attribute-specifier-seq\textsubscript{opt} cv-qualifier-seq\textsubscript{opt}

cv-qualifier-seq:
   cv-qualifier cv-qualifier-seq\textsubscript{opt}

cv-qualifier:
   const
   volatile

ref-qualifier:
   &
   &&

declarator-id:
   \ldots\textsubscript{opt} id-expression

type-id:
   type-specifier-seq abstract-declarator\textsubscript{opt}

defining-type-id:
   defining-type-specifier-seq abstract-declarator\textsubscript{opt}

abstract-declarator:
   ptr-abstract-declarator
   noptr-abstract-declarator\textsubscript{opt} parameters-and-qualifiers trailing-return-type
   abstract-pack-declarator

ptr-abstract-declarator:
   noptr-abstract-declarator
   ptr-operator ptr-abstract-declarator\textsubscript{opt}

noptr-abstract-declarator:
   noptr-abstract-declarator\textsubscript{opt} parameters-and-qualifiers
   noptr-abstract-declarator\textsubscript{opt} [ constant-expression\textsubscript{opt} ] attribute-specifier-seq\textsubscript{opt}
   ( ptr-abstract-declarator )

abstract-pack-declarator:
   noptr-abstract-pack-declarator
   ptr-operator abstract-pack-declarator

noptr-abstract-pack-declarator:
   noptr-abstract-pack-declarator parameters-and-qualifiers
   \ldots

parameter-declaration-clause:
   parameter-declaration-list\textsubscript{opt} \ldots\textsubscript{opt}
   parameter-declaration-list, ...

parameter-declaration-list:
   parameter-declaration
   parameter-declaration-list, parameter-declaration

parameter-declaration:
   attribute-specifier-seq\textsubscript{opt} this\textsubscript{opt} decl-specifier-seq declarator
   attribute-specifier-seq\textsubscript{opt} decl-specifier-seq declarator = initializer-clause
   attribute-specifier-seq\textsubscript{opt} this\textsubscript{opt} decl-specifier-seq abstract-declarator\textsubscript{opt}
   attribute-specifier-seq\textsubscript{opt} decl-specifier-seq abstract-declarator\textsubscript{opt} = initializer-clause

initializer:
   brace-or-equal-initializer
   ( expression-list )

brace-or-equal-initializer:
   = initializer-clause
   braced-init-list
N4986

initializer-clause:
  assignment-expression
  braced-init-list

braced-init-list:
  \{ initializer-list \, opt \}
  \{ designated-initializer-list \, opt \}
  \{ \}

initializer-list:
  initializer-clause \, ... opt
  initializer-list \, initializer-clause \, ... opt
designated-initializer-list:
  designated-initializer-clause
designated-initializer-list:
  designated-initializer-clause
designated-initializer-clause:
  designator brace-or-equal-initializer
designator:
  . identifier

expr-or-braced-init-list:
  expression
  braced-init-list

function-definition:
  attribute-specifier-seq\, opt
dcl-specifier-seq\, opt
declarator virt-specifier-seq\, opt
definition-body
  attribute-specifier-seq\, opt
dcl-specifier-seq\, opt
declarator requires-clause definition-body

definition-body:
  ctor-initializer\, opt
  compound-statement
  function-try-block
  = default ;
definition-body
  deleted-function-body
  = delete ;
definition-body
  = delete ( unevaluated-string ) ;

enum-name:
  identifier
enum-specifier:
  enum-head { enumerator-list \, opt \}
  enum-head { enumerator-list , }

enum-head:
  enum-key attribute-specifier-seq\, opt
denom-head\, opt
denom-head\, opt
denom-head\, opt
  enum-key attribute-specifier-seq\, opt
denom-head\, opt
denom-head\, opt
  identifier

opaque-enum-declaration:
  enum-key attribute-specifier-seq\, opt
denom-head\, opt
denom-head\, opt
denom-head\, opt
denom-head\, opt
  enum-key attribute-specifier-seq\, opt
denom-head\, opt
denom-head\, opt
  identifier
enum-key:
  enum
denom-class
denom-struct

enum-base:
  : type-specifier-seq
enumerator-list:
  enumerator-definition
enumerator-list , enumerator-definition
enumerator-definition:
  enumerator
  enumerator = constant-expression
enumerator:
  identifier attribute-specifier-seq\, opt
using-enum-declaration:
   using enum using-enumerator ;
using-enumerator:
   nested-name-specifier\opt identifier
   nested-name-specifier\opt simple-template-id
namespace-name:
   identifier
   namespace-alias
namespace-definition:
   named-namespace-definition
   unnamed-namespace-definition
   nested-namespace-definition
named-namespace-definition:
   \inline namespace attribute-specifier-seq\opt identifier \{ namespace-body \}
unnamed-namespace-definition:
   \inline namespace attribute-specifier-seq\opt \{ namespace-body \}
nested-namespace-definition:
   namespace enclosing-namespace-specifier :: \inline identifier \{ namespace-body \}
enclosing-namespace-specifier:
   identifier
   enclosing-namespace-specifier :: \inline identifier
namespace-body:
   declaration-seq\opt
namespace-alias:
   identifier
namespace-alias-definition:
   namespace identifier = qualified-namespace-specifier ;
qualified-namespace-specifier:
   nested-name-specifier\opt namespace-name
using-directive:
   attribute-specifier-seq\opt using namespace nested-name-specifier\opt namespace-name ;
using-declaration:
   using using-declarator-list ;
using-declarator-list:
   using-declarator \ldots\opt
   using-declarator-list , using-declarator \ldots\opt
using-declarator:
   typename\opt nested-name-specifier unqualified-id
asm-declaration:
   attribute-specifier-seq\opt \asm \{ balanced-token-seq \} ;
linkage-specification:
   extern unevaluated-string \{ declaration-seq\opt \}
   extern unevaluated-string name-declaration
attribute-specifier-seq:
   attribute-specifier-seq\opt attribute-specifier
attribute-specifier:
   \[ \[ attribute-using-prefix\opt attribute-list \] \]
alignment-specifier:
   alignas \{ type-id \ldots\opt \}
   alignas \{ constant-expression \ldots\opt \}
attribute-using-prefix:
   using attribute-namespace ;
attribute-list:
  attribute_opt
  attribute-list , attribute_opt
  attribute ...
  attribute-list , attribute ...

attribute:
  attribute-token attribute-argument-clause_opt

attribute-token:
  identifier
  attribute-scoped-token

attribute-scoped-token:
  attribute-namespace :: identifier

attribute-namespace:
  identifier

attribute-argument-clause:
  ( balanced-token-seq_opt )

balanced-token-seq:
  balanced-token
  balanced-token-seq balanced-token

balanced-token:
  ( balanced-token-seq_opt )
  [ balanced-token-seq_opt ]
  { balanced-token-seq_opt }
  any token other than a parenthesis, a bracket, or a brace

A.8 Modules

[gram.module]

module-declaration:
  export-keyword_opt module-keyword module-name module-partition_opt attribute-specifier-seq_opt ;

module-name:
  module-name-qualifier_opt identifier

module-partition:
  : module-name-qualifier_opt identifier

module-name-qualifier:
  identifier . module-name-qualifier identifier .

export-declaration:
  export name-declaration
  export { declaration-seq_opt }
  export-keyword module-import-declaration

module-import-declaration:
  import-keyword module-name attribute-specifier-seq_opt ;
  import-keyword module-partition attribute-specifier-seq_opt ;
  import-keyword header-name attribute-specifier-seq_opt ;

global-module-fragment:
  module-keyword ; declaration-seq_opt

private-module-fragment:
  module-keyword : private ; declaration-seq_opt

A.9 Classes

[gram.class]

class-name:
  identifier
  simple-template-id

class-specifier:
  class-head { member-specification_opt }

class-head:
  class-key attribute-specifier-seq_opt class-head-name class-virt-specifier_opt base-clause_opt
  class-key attribute-specifier-seq_opt base-clause_opt
class-head-name:
  nested-name-specifier\textsubscript{opt} class-name

class-virt-specifier:
  final

class-key:
  class
  struct
  union

member-specification:
  member-declaration member-specification\textsubscript{opt}
  access-specifier : member-specification\textsubscript{opt}

member-declaration:
  attribute-specifier-seq\textsubscript{opt} declspecifier-seq\textsubscript{opt} member-declarator-list\textsubscript{opt} ;
  friend-type-declaration
  using-declaration
  using-enum-declaration
  static_assert-declaration
  template-declaration
  explicit-specialization
  deduction-guide
  alias-declaration
  opaque-enum-declaration
  empty-declaration

member-declarator-list:
  member-declarator
  member-declarator-list , member-declarator

member-declarator:
  declarator virt-specifier-seq\textsubscript{opt} pure-specifier\textsubscript{opt}
  declarator requires-clause
  declarator brace-or-equal-initializer
  identifier\textsubscript{opt} attribute-specifier-seq\textsubscript{opt} : constant-expression brace-or-equal-initializer\textsubscript{opt}

virt-specifier-seq:
  virt-specifier
  virt-specifier-seq virt-specifier

virt-specifier:
  override
  final

pure-specifier:
  = 0

friend-type-declaration:
  friend friend-type-specifier-list ;

friend-type-specifier-list:
  friend-type-specifier \ldots\textsubscript{opt}
  friend-type-specifier-list , friend-type-specifier \ldots\textsubscript{opt}

friend-type-specifier:
  simple-type-specifier
  elaborated-type-specifier
  typename-specifier

conversion-function-id:
  operator conversion-type-id

conversion-type-id:
  type-specifier-seq conversion-declarator\textsubscript{opt}

conversion-declarator:
  ptr-operator conversion-declarator\textsubscript{opt}

base-clause:
  : base-specifier-list
A.10 Overloading

operator-function-id:
operator operator

operator: one of
new delete new[] delete[] co_await () [] -> -*
| = += -= *= /= %= ^= &= |
| = == != < > <= >= <=> &&
| || << >> <<= >>= ++ -- ,

A.11 Templates

template-declaration:
template-head declaration
template-head concept-definition
template-head:
template < template-parameter-list > requires-clause

template-parameter-list:
template-parameter
template-parameter-list , template-parameter
template-parameter:
template-parameter-list requires-clause

requires-clause:
requires constraint-logical-or-expression
constraint-logical-or-expression:
constraint-logical-and-expression
constraint-logical-or-expression || constraint-logical-and-expression
constraint-logical-and-expression:
primary-expression
constraint-logical-and-expression && primary-expression
A.12 Exception handling

try-block:
  try compound-statement handler-seq

function-try-block:
  try_ctor-initializeropt compound-statement handler-seq

handler-seq:
  handler handler-seqopt
catch ( exception-declaration ) compound-statement

exception-declaration:
  attribute-specifier-seq_opt type-specifier-seq declarator
  attribute-specifier-seq_opt type-specifier-seq abstract-declarator_opt
  ...

noexcept-specifier:
  noexcept ( constant-expression )
  noexcept

A.13 Preprocessing directives

preprocessing-file:
  group_opt
  module-file

module-file:
  pp-global-module-fragment_opt pp-module group_opt pp-private-module-fragment_opt

pp-global-module-fragment:
  module ; new-line group_opt

pp-private-module-fragment:
  module : private ; new-line group_opt

group:
  group-part
  group group-part

group-part:
  control-line
  if-section
  text-line
  # conditionally-supported-directive

control-line:
  # include pp-tokens new-line
  pp-import
  # define identifier replacement-list new-line
  # define identifier (paren identifier-list_opt) replacement-list new-line
  # define identifier (paren . . . ) replacement-list new-line
  # define identifier (paren identifier-list , . . . ) replacement-list new-line
  # undef identifier new-line
  # line pp-tokens new-line
  # error pp-tokens new-line
  # warning pp-tokens new-line
  # pragma pp-tokens new-line
  # new-line

if-section:
  if-group elif-groups else-group_opt endif-line

if-group:
  # if constant-expression new-line group_opt
  # ifdef identifier new-line group_opt
  # ifndef identifier new-line group_opt

elif-groups:
  elif-group
  elif-groups elif-group

elif-group:
  # elif constant-expression new-line group_opt
  # elifdef identifier new-line group_opt
  # ifndefdef identifier new-line group_opt

else-group:
  # else new-line group_opt
endif-line:
    # endif

new-line:
    pp-tokens_opt new-line

cconditionally-supported-directive:
    pp-tokens new-line

lparen:
    a ( character not immediately preceded by whitespace

identifier-list:
    identifier
    identifier-list , identifier

replacement-list:
    pp-tokens_opt

pp-tokens:
    preprocessing-token
    pp-tokens preprocessing-token

text-line
    the new-line character

defined-macro-expression:
    defined identifier
    defined ( identifier )

text-line
    any preprocessing-token other than >

h-preprocessing-token:
    any preprocessing-token other than >

h-pp-tokens:
    h-preprocessing-token
    h-pp-tokens h-preprocessing-token

h-preprocessing-token:
    string-literal
    < h-pp-tokens >

has-include-expression:
    __has_include ( header-name )
    __has_include ( header-name-tokens )

has-attribute-expression:
    __has_cpp_attribute ( pp-tokens )

has-include-expression:
    __has_include ( header-name )
    __has_include ( header-name-tokens )

has-attribute-expression:
    __has_cpp_attribute ( pp-tokens )

h-preprocessing-token:
    string-literal
    < h-pp-tokens >

has-include-expression:
    __has_include ( header-name )
    __has_include ( header-name-tokens )

has-attribute-expression:
    __has_cpp_attribute ( pp-tokens )

pp-module:
    export_opt module pp-tokens_opt ; new-line

pp-import:
    export_opt import header-name pp-tokens_opt ; new-line
    export_opt import header-name-tokens pp-tokens_opt ; new-line
    export_opt import pp-tokens ; new-line

va-opt-replacement:
    __VA_OPT__ ( pp-tokens_opt )
Annex B
(informative)

Implementation quantities

Implementations can exhibit limitations for various quantities; some possibilities are presented in the following list. The bracketed number following each quantity is a potential minimum value for that quantity.

1. Nesting levels of compound statements (8.4), iteration control structures (8.6), and selection control structures (8.5) [256].
2. Nesting levels of conditional inclusion (15.2) [256].
3. Pointer (9.3.4.2), pointer-to-member (9.3.4.4), array (9.3.4.5), and function (9.3.4.6) declarators (in any combination) modifying a type in a declaration [256].
4. Nesting levels of parenthesized expressions (7.5.4) within a full-expression [256].
5. Number of characters in an internal identifier (5.10) or macro name (15.6) [1024].
6. Number of characters in an external identifier (5.10, 6.6) [1024].
7. External identifiers (6.6) in one translation unit [65536].
8. Identifiers with block scope declared in one block (6.4.3) [1024].
9. Structured bindings (9.6) introduced in one declaration [256].
10. Macro identifiers (15.6) simultaneously defined in one translation unit [65536].
11. Parameters in one function definition (9.5.1) [256].
12. Arguments in one function call (7.6.1.3) [256].
13. Parameters in one macro definition (15.6) [256].
14. Arguments in one macro invocation (15.6) [256].
15. Characters in one logical source line (5.2) [65536].
16. Characters in a string-literal (5.13.5) (after concatenation (5.2)) [65536].
17. Size of an object (6.7.2) [262144].
18. Nesting levels for #include files (15.3) [256].
19. Case labels for a switch statement (8.5.3) (excluding those for any nested switch statements) [16384].
20. Non-static data members (including inherited ones) in a single class (11.4) [16384].
21. Lambda-captures in one lambda-expression (7.5.6.3) [256].
22. Enumeration constants in a single enumeration (9.7.1) [4096].
23. Levels of nested class definitions (11.4.12) in a single member-specification [256].
24. Functions registered by atexit() (17.5) [32].
25. Functions registered by at_quick_exit() (17.5) [32].
26. Direct and indirect base classes (11.7) [16384].
27. Direct base classes for a single class (11.7) [1024].
28. Class members declared in a single member-specification (including member functions) (11.4) [4096].
29. Final overriding virtual functions in a class, accessible or not (11.7.3) [16384].
30. Direct and indirect virtual bases of a class (11.7.2) [1024].
31. Static data members of a class (11.4.9.3) [1024].
— Friend declarations in a class (11.8.4) [4096].
— Access control declarations in a class (11.8.2) [4096].
— Member initializers in a constructor definition (11.9.3) [6144].
— *initializer-clauses* in one *braced-init-list* (9.4) [16384].
— Scope qualifications of one identifier (7.5.5.3) [256].
— Nested *linkage-specifications* (9.11) [1024].
— Recursive constexpr function invocations (9.2.6) [512].
— Full-expressions evaluated within a core constant expression (7.7) [1048576].
— Template parameters in a template declaration (13.2) [1024].
— Recursively nested template instantiations (13.9.2), including substitution during template argument deduction (13.10.3) [1024].
— Handlers per try block (14.4) [256].
— Number of placeholders (22.10.15.5) [10].
— Number of hazard-protectable possibly-reclaimable objects (33.11.3.1) [256].
Annex C
(informative)

Compatibility

C.1 C++ and ISO C++ 2023
C.1.1 General

Subclause C.1 lists the differences between C++ and ISO C++ 2023, by the chapters of this document.

C.1.2 Clause 7: expressions

1 Affected subclause: 7.4
Change: Operations mixing a value of an enumeration type and a value of a different enumeration type or of a floating-point type are no longer valid.
Rationale: Reinforcing type safety.
Effect on original feature: A valid C++ 2023 program that performs operations mixing a value of an enumeration type and a value of a different enumeration type or of a floating-point type is ill-formed.

[Example 1]:
```cpp
enum E1 { e };  
enum E2 { f };  
bool b = e <= 3.7;  // ill-formed; previously well-formed  
int k = f - e;  // ill-formed; previously well-formed  
auto x = true ? e : f;  // ill-formed; previously well-formed  
```
—end example]

2 Affected subclause: 7.6.2.9
Change: Calling `delete` on a pointer to an incomplete class is ill-formed.
Rationale: Reduce undefined behavior.
Effect on original feature: A valid C++ 2023 program that that calls `delete` on an incomplete class type is ill-formed.

[Example 2]:
```cpp
struct S;  
void f(S *p) {  
delete p;  // ill-formed; previously well-formed  
}  
struct S {};  
```
—end example]

C.1.3 Clause 9: Declarations

1 Affected subclause: 9.4.5
Change: Pointer comparisons between `initializer_list` objects’ backing arrays are unspecified.
Rationale: Permit the implementation to store backing arrays in static read-only memory.
Effect on original feature: Valid C++ 2023 code that relies on the result of pointer comparison between backing arrays may change behavior.

[Example 1]:
```cpp
bool ne(std::initializer_list<int> a, std::initializer_list<int> b) {  
  return a.begin() != b.begin() + 1;  
}  
bool b = ne({2,3}, {1,2,3});  // unspecified result; previously false
```
Affected subclause: 9.3.4.5
Change: Previously, T...[n] would declare a pack of function parameters. T...[n] is now a pack-index-specifier.
Rationale: Improve the handling of packs.
Effect on original feature: Valid C++ 2023 code that declares a pack of parameters without specifying a declarator-id becomes ill-formed.

Example 2:
```cpp
template <typename... T>
void f(T... [1]);
```
```cpp
template <typename... T>
void g(T... ptr[1]);
```
```cpp
int main()
{
    f<int, double>(nullptr, nullptr); // ill-formed, previously void f<int, double>(int [1], double [1])
    g<int, double>(nullptr, nullptr); // ok
}
```

C.1.4 Clause 13: templates

Affected subclause: 13.5
Change: Some atomic constraints become fold expanded constraints.
Rationale: Permit the subsumption of fold expressions.
Effect on original feature: Valid C++ 2023 code may become ill-formed.

Example 1:
```cpp
template <typename ...V> struct A;
struct S {
    static constexpr int compare(const S&) { return 1; }
};
```
```cpp
template <typename ...T, typename ...U>
void f(A<T ...> *, A<U ...> *)
requires (T::compare(U{}) && ...);
```
```cpp
void g(A<S, S> *ap) {
    f(ap, ap);
}
```

C.1.5 Clause 16: library introduction

Affected subclause: 16.4.2.3
Change: New headers.
Rationale: New functionality.
Effect on original feature: The following C++ headers are new: <debugging> (22.16.2), <hazard_pointer> (33.11.3.2), <inplace_vector> (24.3.7), <linalg> (28.9.2), <rcu> (33.11.2.2), and <text_encoding> (30.6.1). Valid C++ 2023 code that #includes headers with these names may be invalid in this revision of C++.

C.1.6 Clause 23: strings library

Affected subclause: 23.4.5
Change: Output of floating-point overloads of to_string and to_wstring.
Rationale: Prevent loss of information and improve consistency with other formatting facilities.
Effect on original feature: to_string and to_wstring function calls that take floating-point arguments may produce a different output.

Example 1:
```cpp
auto s = std::to_string(1e-7); // 1e-07
```
C.1.7 Clause 24: containers library

**Affected subclause:** 24.7.2.2.1

**Change:** `span<const T>` is constructible from `initializer_list<T>`.

**Rationale:** Permit passing a braced initializer list to a function taking `span`.

**Effect on original feature:** Valid C++ 2023 code that relies on the lack of this constructor may refuse to compile, or change behavior in this revision of C++.

[Example 1]

```cpp
void one(pair<int, int>);  // #1
void one(span<const int>);  // #2
void t1() {.ye((1, 2)); }  // ambiguous between #1 and #2; previously called #1
void t2() { t2({{1, 2}}); }  // ill-formed; previously well-formed

void *a[10];
int x = span<void* const>{a, 0}.size();  // x is 2; previously 0
any b[10];
int y = span<const any>{b, b + 10}.size();  // y is 2; previously 10
```

C.1.8 Annex D: compatibility features

**Change:** Remove the type alias `allocator<T>::is_always_equal`.

**Rationale:** Non-empty allocator classes derived from `allocator` needed to explicitly define an `is_always_equal` member type so that `allocator_traits` would not use the one from the allocator base class.

**Effect on original feature:** It is simpler to correctly define an allocator class with an allocator base class.

[Example 1]

```cpp
template <class T>
struct MyAlloc : allocator<T> {
  int tag;
};

static_assert(!allocator_traits<MyAlloc<int>>::is_always_equal);  // Error in C++ 2023,
  // OK in C++ 2026
```

**Change:** Removal of atomic access API for `shared_ptr` objects.

**Rationale:** The old behavior was brittle. `shared_ptr` objects using the old API were not protected by the type system, and certain interactions with code not using this API would, in some cases, silently produce undefined behavior. A complete type-safe replacement is provided in the form of `atomic<shared_ptr<T>>`.

**Effect on original feature:** A valid C++ 2023 program that relies on the presence of the removed functions may fail to compile.

**Change:** Remove the overload of `reserve()` with no parameters.

**Rationale:** The overload of `reserve()` with no parameters is redundant. The `shrink_to_fit` member function can be used instead.

**Effect on original feature:** A valid C++ 2023 program that calls `reserve()` on a `basic_string` object may fail to compile. The old functionality can be achieved by calling `shrink_to_fit()` instead, or the function call can be safely eliminated with no side effects.

**Change:** Remove header `<codecvt>` and all its contents.

**Rationale:** The header has been deprecated for the previous three editions of this document and no longer implements the current Unicode standard, supporting only the obsolete UCS-2 encoding. Ongoing support is at implementer’s discretion, exercising freedoms granted by 16.4.5.3.2.

**Effect on original feature:** A valid C++ 2023 program #include-ing the header or importing the header unit may fail to compile. Code that uses any of the following names by importing the standard library modules may fail to compile:

(4.1) `codecvt_mode`
Change: Remove header `<sstream>` and all its contents.

**Rationale:** The header has been deprecated since the original C++ standard; the `<spanstream>` header provides an updated, safer facility. Ongoing support is at implementer’s discretion, exercising freedoms granted by 16.4.5.3.2.

**Effect on original feature:** A valid C++ 2023 program `#include`-ing the header or importing the header unit may become ill-formed. Code that uses any of the following classes by importing one of the standard library modules may become ill-formed:

- `istrstream`
- `ostrstream`
- `sstream`
- `sstreambuf`

Change: Remove convenience interfaces `wstring_convert` and `wbuffer_convert`.

**Rationale:** These features were underspecified with no clear error reporting mechanism and were deprecated for the last three editions of this document. Ongoing support is at implementer’s discretion, exercising freedoms granted by 16.4.5.3.2.

**Effect on original feature:** A valid C++ 2023 program using these interfaces may become ill-formed.
Affected subclause: 7.6.1.2
Change: Change the meaning of comma in subscript expressions.
Rationale: Enable repurposing a deprecated syntax to support multidimensional indexing.
Effect on original feature: Valid C++ 2020 code that uses a comma expression within a subscript expression may fail to compile.

[Example 2:
arr[1, 2] // was equivalent to arr[(1, 2)],
// now equivalent to arr.operator[](1, 2) or ill-formed
— end example]

C.2.4 Clause 8: statements

Affected subclause: 8.6.5
Change: The lifetime of temporary objects in the for-range-initializer is extended until the end of the loop (6.7.7).
Rationale: Improve usability of the range-based for statement.
Effect on original feature: Destructors of some temporary objects are invoked later.

[Example 1:
void f() {
    std::vector<int> v = { 42, 17, 13 };  
    std::mutex m;

    for (int x :
        static_cast<void>(std::lock_guard<std::mutex>(m)), v) {  // lock released in C++ 2020
        std::lock_guard<std::mutex> guard(m);  // OK in C++ 2020, now deadlocks
    }
}  
— end example]

C.2.5 Clause 9: declarations

Affected subclause: 9.4.3
Change: UTF-8 string literals may initialize arrays of char or unsigned char.
Rationale: Compatibility with previously written code that conformed to previous versions of this document.
Effect on original feature: Arrays of char or unsigned char may now be initialized with a UTF-8 string literal. This can affect initialization that includes arrays that are directly initialized within class types, typically aggregates.

[Example 1:
struct A {
    char8_t s[10];
};
struct B {
    char s[10];
};

void f(A);
void f(B);

int main() {
    f(u8"");  // ambiguous
}  
— end example]

C.2.6 Clause 13: templates

Affected subclause: 13.10.3.6
Change: Deducing template arguments from exception specifications.
Rationale: Facilitate generic handling of throwing and non-throwing functions.
Effect on original feature: Valid ISO C++ 2020 code may be ill-formed in this revision of C++. 

§ C.2.6  ©ISO/IEC 2062
Example 1:

```cpp
template<bool> struct A { }
template<bool B> void f(void (*)(A<B>) noexcept(B));
void g(A<false>) noexcept;
void h() {
  f(g);
  // ill-formed; previously well-formed
}

— end example
```

C.2.7 Clause 16: library introduction

Affected subclause: 16.4.2.3
Change: New headers.
Rationale: New functionality.
Effect on original feature: The following C++ headers are new: `<expected>` (22.8.2), `<flat_map>` (24.6.4), `<flat_set>` (24.6.5), `<generator>` (26.8.2), `<mdspan>` (24.7.3.2), `<print>` (31.7.4), `<spanstream>` (31.9.2), `<stacktrace>` (19.6.2), `<stdatomic.h>` (33.5.12), and `<stdfloat>` (17.4.2). Valid C++ 2020 code that includes headers with these names may be invalid in this revision of C++.

C.2.8 Clause 18: concepts library

Affected subclauses: 17.11.4, 18.5.4, and 18.5.5
Change: Replace `common_reference_with` in `three_way_comparable_with`, `equality_comparable_with`, and `totally_ordered_with` with an exposition-only concept.
Rationale: Allow uncopyable, but movable, types to model these concepts.
Effect on original feature: Valid C++ 2020 code relying on subsumption with `common_reference_with` may fail to compile in this revision of C++.

Example 1:

```cpp
template<class T, class U>
requires equality_comparable_with<T, U>
bool attempted_equals(const T& t, const U& u); // previously selected overload

template<class T, class U>
requires common_reference_with<const remove_reference_t<T>&, const remove_reference_t<U>&>
bool attempted_equals(const T& t, const U& u); // ambiguous overload; previously rejected by partial ordering

bool test(shared_ptr<int> p) {
  return attempted_equals(p, nullptr); // ill-formed; previously well-formed
}

— end example
```

C.2.9 Clause 20: memory management library

Affected subclause: 20.2.9.1
Change: Forbid partial and explicit program-defined specializations of `allocator_traits`.
Rationale: Allow addition of `allocate_at_least` to `allocator_traits`, and potentially other members in the future.
Effect on original feature: Valid C++ 2020 code that partially or explicitly specializes `allocator_traits` is ill-formed with no diagnostic required in this revision of C++.

C.2.10 Clause 22: general utilities library

Affected subclause: 22.14
Change: Signature changes: `format`, `format_to`, `vformat_to`, `format_to_n`, `formatted_size`. Removal of `format_args_t`.
Rationale: Improve safety via compile-time format string checks, avoid unnecessary template instantiations.
Effect on original feature: Valid C++ 2020 code that contained errors in format strings or relied on previous format string signatures or `format_args_t` may become ill-formed.

Example 1:

```cpp
auto s = std::format("{:d}", "I am not a number"); // ill-formed, previously threw format_error

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Affected subclause: 22.14
Change: Signature changes: `format`, `format_to`, `format_to_n`, `formatted_size`.
Rationale: Enable formatting of views that do not support iteration when const-qualified and that are not copyable.
Effect on original feature: Valid C++ 2020 code that passes bit-fields to formatting functions may become ill-formed.

Example 2:
```cpp
struct tiny {
    int bit: 1;
};

auto t = tiny();
std::format("{}, t.bit); // ill-formed, previously returned "0"
```

Affected subclause: 22.14.2.2
Change: Restrict types of formatting arguments used as width or precision in a `std-format-spec`.
Rationale: Disallow types that do not have useful or portable semantics as a formatting width or precision.
Effect on original feature: Valid C++ 2020 code that passes a boolean or character type as `arg-id` becomes invalid.

Example 3:
```cpp
std::format("{}^{*{}}", true); // ill-formed, previously returned "*
std::format("{}^{*{}}", '1'); // ill-formed, previously returned an implementation-defined number of '/* characters
```

Affected subclause: 22.14.6.4
Change: Removed the `formatter` specialization:
```cpp
template<size_t N> struct formatter<const charT[N], charT>;
```
Rationale: The specialization is inconsistent with the design of `formatter`, which is intended to be instantiated only with cv-unqualified object types.
Effect on original feature: Valid C++ 2020 code that instantiated the removed specialization can become ill-formed.

C.2.11 Clause 23: strings library

Affected subclause: 23.4
Change: Additional rvalue overload for the `substr` member function and the corresponding constructor.
Rationale: Improve efficiency of operations on rvalues.
Effect on original feature: Valid C++ 2020 code that created a substring by calling `substr` (or the corresponding constructor) on an xvalue expression with type `S` that is a specialization of `basic_string` may change meaning in this revision of C++.

Example 1:
```cpp
std::string s1 = "some long string that forces allocation", s2 = s1;
std::move(s1).substr(10, 5);
assert(s1 == s2); // unspecified, previously guaranteed to be true
std::string s3(std::move(s2), 10, 5);
assert(s1 == s2); // unspecified, previously guaranteed to be true
```

C.2.12 Clause 24: containers library

Affected subclauses: 24.2.7 and 24.2.8
Change: Heterogeneous `extract` and `erase` overloads for associative containers.
Rationale: Improve efficiency of erasing elements from associative containers.
Effect on original feature: Valid C++ 2020 code may fail to compile in this revision of C++.
Example 1:

```cpp
struct B {
    auto operator<=>(const B& b) const = default;
};

struct D : private B {
    void f(std::set<B, std::less<>>& s) {
        s.erase(*this);
    }
};
```

—end example]

C.2.13 Clause 33: concurrency support library

Affected subclause: 33.9.3

Change: In this revision of C++, it is implementation-defined whether a barrier's phase completion step runs if no thread calls `wait`. Previously the phase completion step was guaranteed to run on the last thread that calls `arrive` or `arrive_and_drop` during the phase. In this revision of C++, it can run on any of the threads that arrived or waited at the barrier during the phase.

Rationale: Correct contradictory wording and improve implementation flexibility for performance.

Effect on original feature: Valid C++ 2020 code using a barrier might have different semantics in this revision of C++ if it depends on a completion function’s side effects occurring exactly once, on a specific thread running the phase completion step, or on a completion function’s side effects occurring without `wait` having been called.

Example 1:

```cpp
auto b0 = std::barrier(1);
b0.arrive();
b0.arrive();  // implementation-defined; previously well-defined

int data = 0;
auto b1 = std::barrier(1, [&] { data++; });
b1.arrive();
assert(data == 1);  // implementation-defined; previously well-defined
b1.arrive();  // implementation-defined; previously well-defined
```

—end example]

C.3 C++ and ISO C++ 2017

C.3.1 General

Subclause C.3 lists the differences between C++ and ISO C++ 2017, in addition to those listed above, by the chapters of this document.

C.3.2 Clause 5: lexical conventions

Affected subclauses: 5.4, 10.1, 10.3, 15.1, 15.4, and 15.5

Change: New identifiers with special meaning.

Rationale: Required for new features.

Effect on original feature: Logical lines beginning with `module` or `import` may be interpreted differently in this revision of C++.

Example 1:

```cpp
class module {};
module m1;  // was variable declaration; now module-declaration
module *m2;  // variable declaration

class import {};
import j1;  // was variable declaration; now module-import-declaration
::import j2;  // variable declaration
```

—end example]
Affected subclause: 5.8
Change: header-name tokens are formed in more contexts.
Rationale: Required for new features.
Effect on original feature: When the identifier import is followed by a < character, a header-name token may be formed.

[Example 2:
```cpp
template<typename> class import {}
import<int> f(); // ill-formed; previously well-formed
::import<int> g(); // OK
end example]
```

Affected subclause: 5.11
Change: New keywords.
Rationale: Required for new features.

(3.1) — The char8_t keyword is added to differentiate the types of ordinary and UTF-8 literals (5.13.5).
(3.2) — The concept keyword is added to enable the definition of concepts (13.7.9).
(3.3) — The constexpr keyword is added to declare immediate functions (9.2.6).
(3.4) — The constinit keyword is added to prevent unintended dynamic initialization (9.2.7).
(3.5) — The co_await, co_yield, and co_return keywords are added to enable the definition of coroutines (9.5.4).
(3.6) — The requires keyword is added to introduce constraints through a requires-clause (13.1) or a requires-expression (7.5.8).

Effect on original feature: Valid C++ 2017 code using char8_t, concept, constexpr, constinit, co_await, co_yield, co_return, or requires as an identifier is not valid in this revision of C++.

Affected subclause: 5.12
Change: New operator <=>.
Rationale: Necessary for new functionality.
Effect on original feature: Valid C++ 2017 code that contains a <= token immediately followed by a > token may be ill-formed or have different semantics in this revision of C++.

[Example 3:
```cpp
namespace N {
  struct X {}
  bool operator<=(X, X);
  template<bool(X, X)> struct Y {};
  Y<operator<=> y; // ill-formed; previously well-formed
}
end example]
```

Affected subclause: 5.13
Change: Type of UTF-8 string and character literals.
Rationale: Required for new features. The changed types enable function overloading, template specialization, and type deduction to distinguish ordinary and UTF-8 string and character literals.
Effect on original feature: Valid C++ 2017 code that depends on UTF-8 string literals having type “array of const char” and UTF-8 character literals having type “char” is not valid in this revision of C++.

[Example 4:
```cpp
const auto *u8s = u8"text"; // u8s previously deduced as const char*; now deduced as const char8_t*
const char *ps = u8s; // ill-formed; previously well-formed
auto u8c = u8'c'; // u8c previously deduced as char; now deduced as char8_t
char *pc = &u8c; // ill-formed; previously well-formed
std::string s = u8"text"; // ill-formed; previously well-formed
void f(const char *s);
f(u8"text"); // ill-formed; previously well-formed
```
template<typename> struct ct;
template<> struct ct<char> {
    using type = char;
};
ct<decltype(u8'c')>::type x;  // ill-formed; previously well-formed.

— end example]

C.3.3 Clause 6: basics  [diff.cpp17.basic]

1 Affected subclause: 6.7.3

Change: A pseudo-destructor call ends the lifetime of the object to which it is applied.

Rationale: Increase consistency of the language model.

Effect on original feature: Valid ISO C++ 2017 code may be ill-formed or have undefined behavior in this revision of C++.

[Example 1:
    int f() {
        int a = 123;
        using T = int;
        a.-T();
        return a; // undefined behavior; previously returned 123
    }
— end example]

2 Affected subclause: 6.9.2.2

Change: Except for the initial release operation, a release sequence consists solely of atomic read-modify-write operations.

Rationale: Removal of rarely used and confusing feature.

Effect on original feature: If a memory_order_release atomic store is followed by a memory_order_-relaxed store to the same variable by the same thread, then reading the latter value with a memory_order_-_acquire load no longer provides any “happens before” guarantees, even in the absence of intervening stores by another thread.

C.3.4 Clause 7: expressions  [diff.cpp17.expr]

1 Affected subclause: 7.5.6.3

Change: Implicit lambda capture may capture additional entities.

Rationale: Rule simplification, necessary to resolve interactions with constexpr if.

Effect on original feature: Lambdas with a capture-default may capture local entities that were not captured in C++ 2017 if those entities are only referenced in contexts that do not result in an odr-use.

C.3.5 Clause 9: declarations  [diff.cpp17.dcl.dcl]

1 Affected sub clause: 9.2.4

Change: Unnamed classes with a typedef name for linkage purposes can contain only C-compatible constructs.

Rationale: Necessary for implementability.

Effect on original feature: Valid C++ 2017 code may be ill-formed in this revision of C++.

[Example 1:
    typedef struct {
        void f() {}
    } S;
— end example]

2 Affected subclause: 9.3.4.7

Change: A function cannot have different default arguments in different translation units.

Rationale: Required for modules support.

Effect on original feature: Valid C++ 2017 code may be ill-formed in this revision of C++, with no diagnostic required.

[Example 2:
    // Translation unit 1
    int f(int a = 42);
int g() { return f(); }

// Translation unit 2
int f(int a = 76) { return a; }       // ill-formed, no diagnostic required; previously well-formed
int g();
int main() { return g(); }          // used to return 42

—end example

3 Affected subclause: 9.4.2
Change: A class that has user-declared constructors is never an aggregate.
Rationale: Remove potentially error-prone aggregate initialization which may apply notwithstanding the declared constructors of a class.
Effect on original feature: Valid C++ 2017 code that aggregate-initializes a type with a user-declared constructor may be ill-formed or have different semantics in this revision of C++.

[Example 3:
  struct A {
    A() = delete;
  };

  struct B {
    B() = default;
    int i = 0;
  };

  struct C {
    C(C&&) = default;
    int a, b;
  };

  A a{};       // ill-formed; previously well-formed
  B b = {1};   // ill-formed; previously well-formed
  auto* c = new C{2, 3}; // ill-formed; previously well-formed

  struct Y;

  struct X {
    operator Y();
  };

  struct Y {
    Y(const Y&) = default;
    X x;
  };

  Y y{X{}};      // copy constructor call; previously aggregate-initialization
—end example]

4 Affected subclause: 9.4.5
Change: Boolean conversion from a pointer or pointer-to-member type is now a narrowing conversion.
Rationale: Catches bugs.
Effect on original feature: Valid C++ 2017 code may fail to compile in this revision of C++.

[Example 4:
  bool y[] = { "bc" };     // ill-formed; previously well-formed
—end example]

C.3.6 Clause 11: classes

1 Affected subclauses: 11.4.5 and 11.4.8.3
Change: The class name can no longer be used parenthesized immediately after an explicit decl-specifier in a constructor declaration. The conversion-function-id can no longer be used parenthesized immediately after an explicit decl-specifier in a conversion function declaration.
Rationale: Necessary for new functionality.

Effect on original feature: Valid C++ 2017 code may fail to compile in this revision of C++.

[Example 1:

```cpp
struct S {
    explicit (S)(const S&); // ill-formed; previously well-formed
    explicit (operator int)(); // ill-formed; previously well-formed
    explicit(true) (S)(int); // OK
};
—end example]
```

2 Affected subclauses: 11.4.5 and 11.4.7

Change: A `simple-template-id` is no longer valid as the `declarator-id` of a constructor or destructor.

Rationale: Remove potentially error-prone option for redundancy.

Effect on original feature: Valid C++ 2017 code may fail to compile in this revision of C++.

[Example 2:

```cpp
template<class T>
struct A {
    A(T()); // error: simple-template-id not allowed for constructor
    A(int); // OK, injected-class-name used
    ~A<T>(); // error: simple-template-id not allowed for destructor
};
—end example]
```

3 Affected subclause: 11.9.6

Change: A function returning an implicitly movable entity may invoke a constructor taking an rvalue reference to a type different from that of the returned expression. Function and catch-clause parameters can be thrown using move constructors.

Rationale: Side effect of making it easier to write more efficient code that takes advantage of moves.

Effect on original feature: Valid C++ 2017 code may fail to compile or have different semantics in this revision of C++.

[Example 3:

```cpp
struct base {
    base();
    base(base const &);
private:
    base(base &&);
};

struct derived : base {};

base f(base b) {
    throw b; // error: base(base &&) is private
    derived d;
    return d; // error: base(base &&) is private
}

struct S {
    S(const char *s) : m(s) { }
    S(const S&) = default;
    S(S&& other) : m(other.m) { other.m = nullptr; }
    const char * m;
};

S consume(S&& s) { return s; }

void g() {
    S s("text");
    consume(static_cast<S&&>(s));
    char c = *s.m; // undefined behavior; previously ok
}
```
C.3.7 Clause 12: overloading

Affected subclause: 12.2.2.3

Change: Equality and inequality expressions can now find reversed and rewritten candidates.

Rationale: Improve consistency of equality with three-way comparison and make it easier to write the full complement of equality operations.

Effect on original feature: For certain pairs of types where one is convertible to the other, equality or inequality expressions between an object of one type and an object of the other type invoke a different operator. Also, for certain types, equality or inequality expressions between two objects of that type become ambiguous.

[Example 1:]

```cpp
struct A {
    operator int() const;
};

bool operator==(A, int);   // #1
// #2 is built-in candidate: bool operator==(int, int);
// #3 is built-in candidate: bool operator!=(int, int);

int check(A x, A y) {
    return (x == y) +
           // ill-formed; previously well-formed
           (10 == x) +
           // calls #1, previously selected #2
           (10 != x);    // calls #1, previously selected #3
}

—end example—
```

Affected subclause: 12.2.2.3

Change: Overload resolution may change for equality operators (7.6.10).

Rationale: Support calling `operator==` with reversed order of arguments.

Effect on original feature: Valid C++ 2017 code that uses equality operators with conversion functions may be ill-formed or have different semantics in this revision of C++.

[Example 2:]

```cpp
struct A {
    operator int() const { return 10; }
};

bool operator==(A, int);   // #1
// #2 is built-in candidate: bool operator==(int, int);

bool b = 10 == A();        // calls #1 with reversed order of arguments; previously selected #2

struct B {
    bool operator==(const B&); // member function with no cv-qualifier
};
B b1;
bool eq = (b1 == b1);      // ambiguous; previously well-formed

—end example—
```

C.3.8 Clause 13: templates

Affected subclause: 13.3

Change: An `unqualified-id` that is followed by a `<` and for which name lookup finds nothing or finds a function will be treated as a `template-name` in order to potentially cause argument-dependent lookup to be performed.

Rationale: It was problematic to call a function template with an explicit template argument list via argument-dependent lookup because of the need to have a template with the same name visible via normal lookup.

Effect on original feature: Previously valid code that uses a function name as the left operand of a `<` operator would become ill-formed.
Example 1:

```cpp
struct A {
    bool operator<(void (*fp)(), A);
    void f() {}
    int main() {
        A a;
        f < a; // ill-formed; previously well-formed
        (f) < a; // still well-formed
    }
}
```

C.3.9 Clause 14: exception handling

Affected subclause: 14.5

Change: Remove `throw()` exception specification.

Rationale: Removal of obsolete feature that has been replaced by `noexcept`.

Effect on original feature: A valid C++ 2017 function declaration, member function declaration, function pointer declaration, or function reference declaration that uses `throw()` for its exception specification will be rejected as ill-formed in this revision of C++. It should simply be replaced with `noexcept` for no change of meaning since C++ 2017.

[Note 1: There is no way to write a function declaration that is non-throwing in this revision of C++ and is also non-throwing in C++ 2003 except by using the preprocessor to generate a different token sequence in each case. — end note]

C.3.10 Clause 16: library introduction

Affected subclause: 16.4.2.3

Change: New headers.

Rationale: New functionality.

Effect on original feature: The following C++ headers are new: `<barrier> (33.9.3.2), `<bit>` (22.15.2), `<charconv>` (22.13.1), `<compare>` (17.11.1), `<concepts>` (18.3), `<coroutine>` (17.12.2), `<format>` (22.14.1), `<latch>` (33.9.2.2), `<numbers>` (28.8.1), `<ranges>` (26.2), `<semaphore>` (33.8.2), `<source_location>` (17.8.1), `<span>` (24.7.2.1), `<stop_token>` (33.3.2), `<syncstream>` (31.11.1), and `<version>` (17.3.1). Valid C++ 2017 code that `#include` s headers with these names may be invalid in this revision of C++.

[2.1] a `#include` of `<ccomplex>` can be replaced by a `#include` of `<complex>` (28.4.2),

[2.2] a `#include` of `<ctgmath>` can be replaced by a `#include` of `<cmath>` (28.7.1) and a `#include` of `<complex>`, and

[2.3] a `#include` of `<ciso646>`, `<cstdlib>`, or `<cstddef>` can simply be removed.

C.3.11 Clause 24: containers library

Affected subclauses: 24.3.10 and 24.3.11

Change: Return types of `remove`, `remove_if`, and `unique` changed from `void` to `container::size_type`.

Rationale: Improve efficiency and convenience of finding number of removed elements.

Effect on original feature: Code that depends on the return types might have different semantics in this revision of C++. Translation units compiled against this version of C++ may be incompatible with translation units compiled against C++ 2017, either failing to link or having undefined behavior.

C.3.12 Clause 25: iterators library

Affected subclause: 25.3.2.3

Change: The specialization of `iterator_traits` for `void` and for function pointer types no longer contains any nested typedefs.

Rationale: Corrects an issue misidentifying pointer types that are not incrementable as iterator types.
Effect on original feature: A valid C++ 2017 program that relies on the presence of the typedefs may fail to compile, or have different behavior.

C.3.13 Clause 27: algorithms library

1 Affected subclause: 27.2
Change: The number and order of deducible template parameters for algorithm declarations is now unspecified, instead of being as-declared.
Rationale: Increase implementor freedom and allow some function templates to be implemented as function objects with templated call operators.
Effect on original feature: A valid C++ 2017 program that passes explicit template arguments to algorithms not explicitly specified to allow such in this version of C++ may fail to compile or have undefined behavior.

C.3.14 Clause 31: input/output library

1 Affected subclause: 31.7.5.3.3
Change: Character array extraction only takes array types.
Rationale: Increase safety via preventing buffer overflow at compile time.
Effect on original feature: Valid C++ 2017 code may fail to compile in this revision of C++.

[Example 1]:
```cpp
auto p = new char[100];
char q[100];
std::cin >> std::setw(20) >> p;  // ill-formed; previously well-formed
std::cin >> std::setw(20) >> q;  // OK
```
—end example]

2 Affected subclause: 31.7.6.3.4
Change: Overload resolution for ostream inserters used with UTF-8 literals.
Rationale: Required for new features.
Effect on original feature: Valid C++ 2017 code that passes UTF-8 literals to `basic_ostream<char, \ldots>::operator<<` or `basic_ostream<wchar_t, \ldots>::operator<<` is now ill-formed.

[Example 2]:
```cpp
std::cout << u8"text";  // previously called `operator<<(const char*)` and printed a string;
// now ill-formed
std::cout << u8'X';    // previously called `operator<<(char)` and printed a character;
// now ill-formed
```
—end example]

3 Affected subclause: 31.7.6.3.4
Change: Overload resolution for ostream inserters used with `wchar_t`, `char16_t`, or `char32_t` types.
Rationale: Removal of surprising behavior.
Effect on original feature: Valid C++ 2017 code that passes `wchar_t`, `char16_t`, or `char32_t` characters or strings to `basic_ostream<char, \ldots>::operator<<` or that passes `char16_t` or `char32_t` characters or strings to `basic_ostream<wchar_t, \ldots>::operator<<` is now ill-formed.

[Example 3]:
```cpp
std::cout << u"text";  // previously formatted the string as a pointer value;
// now ill-formed
std::cout << u'X';    // previously formatted the character as an integer value;
// now ill-formed
```
—end example]

4 Affected subclause: 31.12.6
Change: Return type of filesystem path format observer member functions.
Rationale: Required for new features.
Effect on original feature: Valid C++ 2017 code that depends on the `u8string()` and `generic_u8string()` member functions of `std::filesystem::path` returning `std::string` is not valid in this revision of C++.

[Example 4]:
```cpp
std::filesystem::path p;
std::string s1 = p.u8string();  // ill-formed; previously well-formed
std::string s2 = p.generic_u8string();  // ill-formed; previously well-formed
```
C.3.15 Annex D: compatibility features

1 Change: Remove uncaught_exception.
   Rationale: The function did not have a clear specification when multiple exceptions were active, and has been superseded by uncaught_exceptions.
   Effect on original feature: A valid C++ 2017 program that calls std::uncaught_exception may fail to compile. It can be revised to use std::uncaught_exceptions instead, for clear and portable semantics.

2 Change: Remove support for adaptable function API.
   Rationale: The deprecated support relied on a limited convention that could not be extended to support the general case or new language features. It has been superseded by direct language support with decltype, and by the std::bind and std::not_fn function templates.
   Effect on original feature: A valid C++ 2017 program that relies on the presence of result_type, argument_type, first_argument_type, or second_argument_type in a standard library class may fail to compile. A valid C++ 2017 program that calls not1 or not2, or uses the class templates unary_negate or binary_negate, may fail to compile.

3 Change: Remove redundant members from std::allocator.
   Rationale: std::allocator was overspecified, encouraging direct usage in user containers rather than relying on std::allocator_traits, leading to poor containers.
   Effect on original feature: A valid C++ 2017 program that uses this iterator class may fail to compile.

4 Change: Remove raw_storage_iterator.
   Rationale: The iterator encouraged use of potentially-throwing algorithms, but did not return the number of elements successfully constructed, as would be necessary to destroy them.
   Effect on original feature: A valid C++ 2017 program that uses this iterator class may fail to compile.

5 Change: Remove temporary buffers API.
   Rationale: The temporary buffer facility was intended to provide an efficient optimization for small memory requests, but there is little evidence that this was achieved in practice, while requiring the user to provide their own exception-safe wrappers to guard use of the facility in many cases.
   Effect on original feature: A valid C++ 2017 program that calls get_temporary_buffer or return_-temporary_buffer may fail to compile.

6 Change: Remove shared_ptr::unique.
   Rationale: The result of a call to this member function is not reliable in the presence of multiple threads and weak pointers. The member function use_count is similarly unreliable, but has a clearer contract in such cases, and remains available for well-defined use in single-threaded cases.
   Effect on original feature: A valid C++ 2017 program that calls unique on a shared_ptr object may fail to compile.

7 Affected subclause: D.14
   Change: Remove deprecated type traits.
   Rationale: The traits had unreliable or awkward interfaces. The is_literal_type trait provided no way to detect which subset of constructors and member functions of a type were declared constexpr. The result_of trait had a surprising syntax that did not directly support function types. It has been superseded by the invoke_result trait.
   Effect on original feature: A valid C++ 2017 program that relies on the is_literal_type or result_of type traits, on the is_literal_type_v variable template, or on the result_of_t alias template may fail to compile.

C.4 C++ and ISO C++ 2014

C.4.1 General

Subclause C.4 lists the differences between C++ and ISO C++ 2014, in addition to those listed above, by the chapters of this document.

C.4.2 Clause 5: lexical conventions

Affected subclause: 5.2
Change: Removal of trigraph support as a required feature.
Rationale: Prevents accidental uses of trigraphs in non-raw string literals and comments.
Effect on original feature: Valid C++ 2014 code that uses trigraphs may not be valid or may have different semantics in this revision of C++. Implementations may choose to translate trigraphs as specified in C++ 2014 if they appear outside of a raw string literal, as part of the implementation-defined mapping from input source file characters to the translation character set.

Affected subclause: 5.9
Change: pp-number can contain p sign and P sign.
Rationale: Necessary to enable hexadecimal-floating-point-literals.
Effect on original feature: Valid C++ 2014 code may fail to compile or produce different results in this revision of C++. Specifically, character sequences like 0p+0 and 0e1_p+0 are three separate tokens each in C++ 2014, but one single token in this revision of C++.

Example 1:
```cpp
#define F(a) b ## a
int b0p = F(0p+0); // ill-formed; equivalent to “int b0p = b0p + 0;” in C++ 2014
```
—end example

C.4.3 Clause 7: expressions

Affected subclauses: 7.6.1.6 and 7.6.2.3
Change: Remove increment operator with bool operand.
Rationale: Obsolete feature with occasionally surprising semantics.
Effect on original feature: A valid C++ 2014 expression utilizing the increment operator on a bool lvalue is ill-formed in this revision of C++.

Affected subclauses: 7.6.2.8 and 7.6.2.9
Change: Dynamic allocation mechanism for over-aligned types.
Rationale: Simplify use of over-aligned types.
Effect on original feature: In C++ 2014 code that uses a new-expression to allocate an object with an over-aligned class type, where that class has no allocation functions of its own, ::operator new(std::size_t) is used to allocate the memory. In this revision of C++, ::operator new(std::size_t, std::align_val_t) is used instead.

C.4.4 Clause 9: declarations

Affected subclause: 9.2.2
Change: Removal of register storage-class-specifier.
Rationale: Enable repurposing of deprecated keyword in future revisions of C++.
Effect on original feature: A valid C++ 2014 declaration utilizing the register storage-class-specifier is ill-formed in this revision of C++. The specifier can simply be removed to retain the original meaning.

Affected subclause: 9.2.9.7
Change: auto deduction from braced-init-list.
Rationale: More intuitive deduction behavior.
Effect on original feature: Valid C++ 2014 code may fail to compile or may change meaning in this revision of C++.

Example 1:
```cpp
auto x1{}; // was std::initializer_list<int>, now int
auto x2(1, 2); // was std::initializer_list<int>, now ill-formed
```
—end example

Affected subclause: 9.3.4.6
Change: Make exception specifications be part of the type system.
Rationale: Improve type-safety.
Effect on original feature: Valid C++ 2014 code may fail to compile or change meaning in this revision of C++.

Example 2:
```cpp
void g1() noexcept;
void g2();
template<class T> int f(T *, T *);
int x = f(g1, g2); // ill-formed; previously well-formed
```
Affected subclause: 9.4.2
Change: Definition of an aggregate is extended to apply to user-defined types with base classes.
Rationale: To increase convenience of aggregate initialization.
Effect on original feature: Valid C++ 2014 code may fail to compile or produce different results in this revision of C++; initialization from an empty initializer list will perform aggregate initialization instead of invoking a default constructor for the affected types.

[Example 3:
```cpp
struct derived;
struct base {
    friend struct derived;
private:
    base();
};
struct derived : base {};
```
d2(); // error; the code was well-formed in C++ 2014
d2; // still OK
— end example]

C.4.5 Clause 11: classes

Affected subclause: 11.9.4
Change: Inheriting a constructor no longer injects a constructor into the derived class.
Rationale: Better interaction with other language features.
Effect on original feature: Valid C++ 2014 code that uses inheriting constructors may not be valid or may have different semantics. A using-declaration that names a constructor now makes the corresponding base class constructors visible to initializations of the derived class rather than declaring additional derived class constructors.

[Example 1:
```cpp
struct A {
    template<typename T> A(T, typename T::type = 0);
    A(int);
};
struct B : A {
    using A::A;
    B(int);
};
B b(42L);
    // now calls B(int), used to call B<long>(long),
    // which called A(int) due to substitution failure
    // in A<long>(long).
```
— end example]

C.4.6 Clause 13: templates

Affected subclause: 13.10.3.6
Change: Allowance to deduce from the type of a non-type template argument.
Rationale: In combination with the ability to declare non-type template arguments with placeholder types, allows partial specializations to decompose from the type deduced for the non-type template argument.
Effect on original feature: Valid C++ 2014 code may fail to compile or produce different results in this revision of C++.

[Example 1:
```cpp
template <typename T, T N> int foo(A<N> *) = delete;
void foo(void *){
    foo(p);  // ill-formed; previously well-formed
}
```
— end example]
C.4.7 Clause 14: exception handling  
Affected subclause: 14.5
Change: Remove dynamic exception specifications.
Rationale: Dynamic exception specifications were a deprecated feature that was complex and brittle in use. They interacted badly with the type system, which became a more significant issue in this revision of C++ where (non-dynamic) exception specifications are part of the function type.
Effect on original feature: A valid C++ 2014 function declaration, member function declaration, function pointer declaration, or function reference declaration, if it has a potentially throwing dynamic exception specification, is rejected as ill-formed in this revision of C++. Violating a non-throwing dynamic exception specification calls terminate rather than unexpected, and it is unspecified whether stack unwinding is performed prior to such a call.

C.4.8 Clause 16: library introduction
Affected subclause: 16.4.2.3
Change: New headers.
Rationale: New functionality.
Effect on original feature: The following C++ headers are new: <any> (22.7.2), <charconv> (22.13.1), <execution> (22.12.2), <filesystem> (31.12.4), <memory_resource> (20.4.1), <optional> (22.5.2), <string_view> (23.3.2), and <variant> (22.6.2). Valid C++ 2014 code that #includes headers with these names may be invalid in this revision of C++.

C.4.9 Clause 22: general utilities library
Affected subclause: 22.10.17
Change: Constructors taking allocators removed.
Rationale: No implementation consensus.
Effect on original feature: Valid C++ 2014 code may fail to compile or may change meaning in this revision of C++. Specifically, constructing a std::function with an allocator is ill-formed and uses-allocator construction will not pass an allocator to std::function constructors in this revision of C++.

C.4.10 Clause 23: strings library
Affected subclause: 23.4.3
Change: Non-const .data() member added.
Rationale: The lack of a non-const .data() differed from the similar member of std::vector. This change regularizes behavior.
Effect on original feature: Overloaded functions which have differing code paths for char* and const char* arguments will execute differently when called with a non-const string’s .data() member in this revision of C++.
Example 1:

```c++
int f(char *) = delete;
int f(const char *);
string s;
int x = f(s.data()); // ill-formed; previously well-formed
```

— end example

C.4.11 Clause 24: containers library

Affected subclause: 24.2.7

Change: Requirements change.

Rationale: Increase portability, clarification of associative container requirements.

Effect on original feature: Valid C++ 2014 code that attempts to use associative containers having a
comparison object with non-const function call operator may fail to compile in this revision of C++.

Example 1:

```c++
#include <set>
struct compare
{
    bool operator()(int a, int b)
    {
        return a < b;
    }
};

int main()
{
    const std::set<int, compare> s;
    s.find(0);
}
```

— end example

C.4.12 Annex D: compatibility features

Change: The class templates `auto_ptr`, `unary_function`, and `binary_function`, the function templates
`random_shuffle`, and the function templates (and their return types) `ptr_fun`, `mem_fun`, `mem_fun_ref`,
`bind1st`, and `bind2nd` are not defined.

Rationale: Superseded by new features.

Effect on original feature: Valid C++ 2014 code that uses these class templates and function templates
may fail to compile in this revision of C++.

Change: Remove old iostreams members [depr.ios.members].

Rationale: Redundant feature for compatibility with pre-standard code has served its time.

Effect on original feature: A valid C++ 2014 program using these identifiers may be ill-formed in this
revision of C++.

C.5 C++ and ISO C++ 2011

C.5.1 General

Subclause C.5 lists the differences between C++ and ISO C++ 2011, in addition to those listed above, by the
chapters of this document.

C.5.2 Clause 5: lexical conventions

Affected subclause: 5.9

Change: `pp-number` can contain one or more single quotes.

Rationale: Necessary to enable single quotes as digit separators.

Effect on original feature: Valid C++ 2011 code may fail to compile or may change meaning in this
revision of C++. For example, the following code is valid both in C++ 2011 and in this revision of C++, but
the macro invocation produces different outcomes because the single quotes delimit a `character-literal` in C++
2011, whereas they are digit separators in this revision of C++.
Example 1:
```
#define M(x, ...) __VA_ARGS__
int x[2] = { M(1'2,3'4, 5) };  // int x[2] = { 1, 2, 3, 4, 5 }; — C++ 2011
```

C.5.3 Clause 6: basics

Affected subclause: 6.7.5.5.3

Change: New usual (non-placement) deallocator.

Rationale: Required for sized deallocation.

Effect on original feature: Valid C++ 2011 code can declare a global placement allocation function and deallocation function as follows:
```
void* operator new(std::size_t, std::size_t);
void operator delete(void*, std::size_t) noexcept;
```

In this revision of C++, however, the declaration of `operator delete` might match a predefined usual (non-placement) `operator delete` (6.7.5.5). If so, the program is ill-formed, as it was for class member allocation functions and deallocation functions (7.6.2.8).

C.5.4 Clause 7: expressions

Affected subclause: 7.6.16

Change: A conditional expression with a throw expression as its second or third operand keeps the type and value category of the other operand.

Rationale: Formerly mandated conversions (lvalue-to-rvalue (7.3.2), array-to-pointer (7.3.3), and function-to-pointer (7.3.4) standard conversions), especially the creation of the temporary due to lvalue-to-rvalue conversion, were considered gratuitous and surprising.

Effect on original feature: Valid C++ 2011 code that relies on the conversions may behave differently in this revision of C++.

Example 1:
```
struct S {
    int x = 1;
    void mf() { x = 2; }
};
int f(bool cond) {
    S s;
    (cond ? s : throw 0).mf();
    return s.x;
}
```

In C++ 2011, `f(true)` returns 1. In this revision of C++, it returns 2.

```
#include <cassert>
size_t * p = new char[10];
assert(p[0] == 0);
delete[] p;
```

In C++ 2011, the expression yields `sizeof(const char*)`. In this revision of C++, it yields `sizeof(const char[1])`. — end example

C.5.5 Clause 9: declarations

Affected subclause: 9.2.6

Change: `constexpr` non-static member functions are not implicitly `const` member functions.

Rationale: Necessary to allow `constexpr` member functions to mutate the object.

Effect on original feature: Valid C++ 2011 code may fail to compile in this revision of C++.

Example 1:
```
struct S {
    constexpr const int &f();
    const int &f();
};
```

This code is valid in C++ 2011 but invalid in this revision of C++ because it declares the same member function twice with different return types. — end example

§ C.5.5 © ISO/IEC 2078
Affected subclause: 9.4.2
Change: Classes with default member initializers can be aggregates.
Rationale: Necessary to allow default member initializers to be used by aggregate initialization.
Effect on original feature: Valid C++ 2011 code may fail to compile or may change meaning in this revision of C++.

[Example 2:
struct S {
    int m = 1;
};
struct X {
    operator int();
    operator S();
};
X a{};
S b(a);       // uses copy constructor in C++ 2011,
// performs aggregate initialization in this revision of C++
— end example]

C.5.6 Clause 16: library introduction

Affected subclause: 16.4.2.3
Change: New header.
Rationale: New functionality.
Effect on original feature: The C++ header <shared_mutex> (33.6.3) is new. Valid C++ 2011 code that #include s a header with that name may be invalid in this revision of C++.

C.5.7 Clause 31: input/output library

Affected subclause: 31.13
Change: gets is not defined.
Rationale: Use of gets is considered dangerous.
Effect on original feature: Valid C++ 2011 code that uses the gets function may fail to compile in this revision of C++.

C.6 C++ and ISO C++ 2003

C.6.1 General

Subclause C.6 lists the differences between C++ and ISO C++ 2003, in addition to those listed above, by the chapters of this document.

C.6.2 Clause 5: lexical conventions

Affected subclause: 5.4
Change: New kinds of string-literals.
Rationale: Required for new features.
Effect on original feature: Valid C++ 2003 code may fail to compile or produce different results in this revision of C++. Specifically, macros named R, u8, u8R, u, uR, U, UR, or LR will not be expanded when adjacent to a string-literal but will be interpreted as part of the string-literal.

[Example 1:
#define u8 "abc"
    const char* s = u8"def";      // Previously "abcdef", now "def"
— end example]

Affected subclause: 5.4
Change: User-defined literal string support.
Rationale: Required for new features.
Effect on original feature: Valid C++ 2003 code may fail to compile or produce different results in this revision of C++.

[Example 2:
#define _x "there"
"hello"_x     // #1

§ C.6.2 ©ISO/IEC 2079
Previously, #1 would have consisted of two separate preprocessing tokens and the macro \_x would have been expanded. In this revision of C++, #1 consists of a single preprocessing token, so the macro is not expanded. — end example]

3 Affected subclause: 5.11
Change: New keywords.
Rationale: Required for new features.
Effect on original feature: Added to Table 5, the following identifiers are new keywords: alignas, alignof, char16_t, char32_t, constexpr, decltype, noexcept, nullptr, static_assert, and thread_local. Valid C++ 2003 code using these identifiers is invalid in this revision of C++.

4 Affected subclause: 5.13.2
Change: Type of integer literals.
Rationale: C99 compatibility.
Effect on original feature: Certain integer literals larger than can be represented by long could change from an unsigned integer type to signed long long.

C.6.3 Clause 7: expressions

1 Affected subclause: 7.3.12
Change: Only literals are integer null pointer constants.
Rationale: Removing surprising interactions with templates and constant expressions.
Effect on original feature: Valid C++ 2003 code may fail to compile or produce different results in this revision of C++.

[Example 1:
  void f(void *); // #1
  void f(...); // #2
  template<int N> void g() {
    f(0*N); // calls #2; used to call #1
  }
  — end example]

2 Affected subclause: 7.6.1.8
Change: Evaluation of operands in typeid.
Rationale: Introduce additional expression value categories.
Effect on original feature: Valid C++ 2003 code that uses xvalues as operands for typeid may change behavior in this revision of C++.

[Example 2:
  void f() {
    struct B {
      B() {}
      virtual ~B() {} 
    };
    struct C { B b; };
    typeid(C().b); // unevaluated in C++ 2003, evaluated in C++ 2011
  }
  — end example]

3 Affected subclause: 7.6.5
Change: Specify rounding for results of integer / and \%
Rationale: Increase portability, C99 compatibility.
Effect on original feature: Valid C++ 2003 code that uses integer division rounds the result toward 0 or toward negative infinity, whereas this revision of C++ always rounds the result toward 0.

4 Affected subclause: 7.6.14
Change: && is valid in a type-name.
Rationale: Required for new features.
Effect on original feature: Valid C++ 2003 code may fail to compile or produce different results in this revision of C++.

[Example 3:
  bool b1 = new int && false; // previously false, now ill-formed
  struct S { operator int(); };]
bool b2 = &S::operator int && false; // previously false, now ill-formed
— end example]

5 Affected subclause: 7.6.16
Change: Fewer copies in the conditional operator.
Rationale: Introduce additional expression value categories.
Effect on original feature: Valid C++ 2003 code that uses xvalues as operands for the conditional operator may change behavior in this revision of C++.

[Example 4:
    void f() {
        struct B {
            B() {}
            B(const B&) {}
        };
        struct D : B {};
        struct BB { B b; };
        struct DD { D d; };
        true ? BB().b : DD().d;  // additional copy in C++ 2003, no copy or move in C++ 2011
    }
— end example]

C.6.4 Clause 9: declarations  [diff.cpp03.dcl.dcl]

1 Affected subclause: 9.2
Change: Remove auto as a storage class specifier.
Rationale: New feature.
Effect on original feature: Valid C++ 2003 code that uses the keyword auto as a storage class specifier may be invalid in this revision of C++. In this revision of C++, auto indicates that the type of a variable is to be deduced from its initializer expression.

2 Affected subclause: 9.4.5
Change: Narrowing restrictions in aggregate initializers.
Rationale: Catches bugs.
Effect on original feature: Valid C++ 2003 code may fail to compile in this revision of C++.

[Example 1:
    int x[] = { 2.0 };  
This code is valid in C++ 2003 but invalid in this revision of C++ because double to int is a narrowing conversion.  — end example]

3 Affected subclause: 9.11
Change: Names declared in an anonymous namespace changed from external linkage to internal linkage; language linkage applies to names with external linkage only.
Rationale: Alignment with user expectations.
Effect on original feature: Valid C++ 2003 code may violate the one-definition rule (6.3) in this revision of C++.

[Example 2:
    namespace { extern "C" { extern int x; } }  // #1, previously external linkage and C language linkage,
    namespace A { extern "C" int x = 42; }  // #2, external linkage and C language linkage
    int main(void) { return x; }  
This code is valid in C++ 2003, but #2 is not a definition for #1 in this revision of C++, violating the one-definition rule.  — end example]

C.6.5 Clause 11: classes  [diff.cpp03.class]

1 Affected subclauses: 11.4.5.2, 11.4.7, 11.4.5.3, and 11.4.6
Change: Implicitly-declared special member functions are defined as deleted when the implicit definition would have been ill-formed.
Rationale: Improves template argument deduction failure.
Effect on original feature: A valid C++ 2003 program that uses one of these special member functions in a context where the definition is not required (e.g., in an expression that is not potentially evaluated) becomes ill-formed.

2 Affected subclause: 11.4.7
Change: User-declared destructors have an implicit exception specification.
Rationale: Clarification of destructor requirements.
Effect on original feature: Valid C++ 2003 code may execute differently in this revision of C++. In particular, destructors that throw exceptions will call std::terminate (without calling std::unexpected) if their exception specification is non-throwing.

C.6.6 Clause 13: templates

1 Affected subclause: 13.2
Change: Repurpose export for modules (Clause 10, 15.4, 15.5).
Rationale: No implementation consensus for the C++ 2003 meaning of export.
Effect on original feature: A valid C++ 2003 program containing export is ill-formed in this revision of C++.

2 Affected subclause: 13.4
Change: Remove whitespace requirement for nested closing template right angle brackets.
Rationale: Considered a persistent but minor annoyance. Template aliases representing non-class types would exacerbate whitespace issues.
Effect on original feature: Change to semantics of well-defined expression. A valid C++ 2003 expression containing a right angle bracket (”>”) followed immediately by another right angle bracket may now be treated as closing two templates.

[Example 1:
    template <class T> struct X { };  
    template <int N> struct Y { };  
    X< Y< 1 >> 2 > > x;  
This code is valid in C++ 2003 because “>>” is a right-shift operator, but invalid in this revision of C++ because “>>” closes two templates. —end example]

3 Affected subclause: 13.8.4.2
Change: Allow dependent calls of functions with internal linkage.
Rationale: Overly constrained, simplify overload resolution rules.
Effect on original feature: A valid C++ 2003 program can get a different result in this revision of C++.

C.6.7 Clause 16: library introduction

1 Affected: Clause 16 – Clause 33
Change: New reserved identifiers.
Rationale: Required by new features.
Effect on original feature: Valid C++ 2003 code that uses any identifiers added to the C++ standard library by later revisions of C++ may fail to compile or produce different results in this revision of C++. A comprehensive list of identifiers used by the C++ standard library can be found in the Index of Library Names in this document.

2 Affected subclause: 16.4.2.3
Change: New headers.
Rationale: New functionality.
Effect on original feature: The following C++ headers are new: <array> (24.3.2), <atomic> (33.5.2), <chrono> (29.2), <condition_variable> (33.7.2), <forward_list> (24.3.4), <future> (33.10.2), <initializer_list> (17.10.2), <mutex> (33.6.2), <random> (28.5.2), <ratio> (21.4.2), <regex> (32.3), <scoped_allocator> (20.5.1), <system_error> (19.5.2), <thread> (33.4.2), <tuple> (22.4.2), <typeindex> (22.11.1), <type_traits> (21.3.3), <unordered_map> (24.5.2), and <unordered_set> (24.5.3). In addition the following C compatibility headers are new: <cfenv> (28.3.1), <cinttypes> (31.13.2), <cstdint> (17.4.1), and <cuchar> (23.5.5). Valid C++ 2003 code that #includes headers with these names may be invalid in this revision of C++.

3 Affected subclause: 16.4.4.3
Effect on original feature: Function swap moved to a different header
Rationale: Remove dependency on <algorithm> (27.4) for swap.
Effect on original feature: Valid C++ 2003 code that has been compiled expecting swap to be in `<algorithm>` (27.4) may have to instead include `<utility>` (22.2.1).

4 Affected subclause: 16.4.5.2.2
   Change: New reserved namespace.
   Rationale: New functionality.
Effect on original feature: The global namespace posix is now reserved for standardization. Valid C++ 2003 code that uses a top-level namespace posix may be invalid in this revision of C++.

5 Affected subclause: 16.4.6.3
   Change: Additional restrictions on macro names.
   Rationale: Avoid hard to diagnose or non-portable constructs.
Effect on original feature: Names of attribute identifiers may not be used as macro names. Valid C++ 2003 code that defines override, final, carries_dependency, or noreturn as macros is invalid in this revision of C++.

C.6.8 Clause 17: language support library [diff.cpp03.language.support]

1 Affected subclause: 17.6.3.2
   Change: operator new may throw exceptions other than std::bad_alloc.
   Rationale: Consistent application of noexcept.
Effect on original feature: Valid C++ 2003 code that assumes that global operator new only throws std::bad_alloc may execute differently in this revision of C++. Valid C++ 2003 code that replaces the global replaceable operator new is ill-formed in this revision of C++, because the exception specification of throw(std::bad_alloc) was removed.

C.6.9 Clause 19: diagnostics library [diff.cpp03.diagnostics]

1 Affected subclause: 19.4
   Change: Thread-local error numbers.
   Rationale: Support for new thread facilities.
Effect on original feature: Valid but implementation-specific C++ 2003 code that relies on errno being the same across threads may change behavior in this revision of C++.

C.6.10 Clause 22: general utilities library [diff.cpp03.utilities]

1 Affected subclauses: 22.10.6, 22.10.7, 22.10.8, 22.10.10, and 22.10.11
   Change: Standard function object types no longer derived from std::unary_function or std::binary_function.
   Rationale: Superseded by new feature; unary_function and binary_function are no longer defined.
Effect on original feature: Valid C++ 2003 code that depends on function object types being derived from unary_function or binary_function may fail to compile in this revision of C++.

C.6.11 Clause 23: strings library [diff.cpp03.strings]

1 Affected subclause: 23.4
   Change: basic_string requirements no longer allow reference-counted strings.
   Rationale: Invalidation is subtly different with reference-counted strings. This change regularizes behavior.
Effect on original feature: Valid C++ 2003 code may execute differently in this revision of C++.

2 Affected subclause: 23.4.3.2
   Change: Loosen basic_string invalidation rules.
   Rationale: Allow small-string optimization.
Effect on original feature: Valid C++ 2003 code may execute differently in this revision of C++. Some const member functions, such as data and c_str, no longer invalidate iterators.

C.6.12 Clause 24: containers library [diff.cpp03.containers]

1 Affected subclause: 24.2
   Change: Complexity of size() member functions now constant.
   Rationale: Lack of specification of complexity of size() resulted in divergent implementations with inconsistent performance characteristics.
Effect on original feature: Some container implementations that conform to C++ 2003 may not conform to the specified size() requirements in this revision of C++. Adjusting containers such as std::list to the stricter requirements may require incompatible changes.
Affected subclause: 24.2
Change: Requirements change: relaxation.
Rationale: Clarification.
Effect on original feature: Valid C++ 2003 code that attempts to meet the specified container requirements may now be over-specified. Code that attempted to be portable across containers may need to be adjusted as follows:

- not all containers provide \texttt{size()}; use \texttt{empty()} instead of \texttt{size() == 0};
- not all containers are empty after construction (array);
- not all containers have constant complexity for \texttt{swap()} (array).

Affected subclause: 24.2
Change: Requirements change: default constructible.
Rationale: Clarification of container requirements.
Effect on original feature: Valid C++ 2003 code that attempts to explicitly instantiate a container using a user-defined type with no default constructor may fail to compile.

Affected subclauses: 24.2.4 and 24.2.7
Change: Signature changes: from \texttt{void} return types.
Rationale: Old signature threw away useful information that may be expensive to recalculate.
Effect on original feature: The following member functions have changed:

- \texttt{erase(iter)} for \texttt{set}, \texttt{multiset}, \texttt{map}, \texttt{multimap}
- \texttt{erase(begin, end)} for \texttt{set}, \texttt{multiset}, \texttt{map}, \texttt{multimap}
- \texttt{insert(pos, num, val)} for \texttt{vector}, \texttt{deque}, \texttt{list}, \texttt{forward_list}
- \texttt{insert(pos, beg, end)} for \texttt{vector}, \texttt{deque}, \texttt{list}, \texttt{forward_list}

Valid C++ 2003 code that relies on these functions returning \texttt{void} (e.g., code that creates a pointer to member function that points to one of these functions) will fail to compile with this revision of C++.

Affected subclauses: 24.2.4 and 24.2.7
Change: Signature changes: from \texttt{iterator} to \texttt{const_iterator} parameters.
Rationale: Overspecification.
Effect on original feature: The signatures of the following member functions changed from taking an \texttt{iterator} to taking a \texttt{const_iterator}:

- \texttt{insert(iter, val)} for \texttt{vector}, \texttt{deque}, \texttt{list}, \texttt{set}, \texttt{multiset}, \texttt{map}, \texttt{multimap}
- \texttt{insert(pos, beg, end)} for \texttt{vector}, \texttt{deque}, \texttt{list}, \texttt{forward_list}
- \texttt{erase(begin, end)} for \texttt{set}, \texttt{multiset}, \texttt{map}, \texttt{multimap}
- \texttt{all forms of list::splice}
- \texttt{all forms of list::merge}

Valid C++ 2003 code that uses these functions may fail to compile with this revision of C++.

Affected subclauses: 24.2.4 and 24.2.7
Change: Signature changes: \texttt{resize}.
Rationale: Performance, compatibility with move semantics.
Effect on original feature: For \texttt{vector}, \texttt{deque}, and \texttt{list} the fill value passed to \texttt{resize} is now passed by reference instead of by value, and an additional overload of \texttt{resize} has been added. Valid C++ 2003 code that uses this function may fail to compile with this revision of C++.
C.6.14 Clause 28: numerics library

Affected subclause: 28.4
Change: Specified representation of complex numbers.
Rationale: Compatibility with C99.
Effect on original feature: Valid C++ 2003 code that uses implementation-specific knowledge about the binary representation of the required template specializations of std::complex may not be compatible with this revision of C++.

C.6.15 Clause 30: localization library

Affected subclause: 30.4.3.2.3
Change: The num_get facet recognizes hexadecimal floating point values.
Rationale: Required by new feature.
Effect on original feature: Valid C++ 2003 code may have different behavior in this revision of C++.

C.6.16 Clause 31: input/output library

Affected subclauses: 31.7.5.2.4, 31.7.6.2.4, and 31.5.4.4
Change: Specify use of explicit in existing boolean conversion functions.
Rationale: Clarify intentions, avoid workarounds.
Effect on original feature: Valid C++ 2003 code that relies on implicit boolean conversions will fail to compile with this revision of C++. Such conversions occur in the following conditions:

1. passing a value to a function that takes an argument of type bool;
2. using operator== to compare to false or true;
3. returning a value from a function with a return type of bool;
4. initializing members of type bool via aggregate initialization;
5. initializing a const bool& which would bind to a temporary object.

Affected subclause: 31.5.2.2.1
Change: Change base class of std::ios_base::failure.
Rationale: More detailed error messages.
Effect on original feature: std::ios_base::failure is no longer derived directly from std::exception, but is now derived from std::system_error, which in turn is derived from std::runtime_error. Valid C++ 2003 code that assumes that std::ios_base::failure is derived directly from std::exception may execute differently in this revision of C++.

Affected subclause: 31.5.2
Change: Flag types in std::ios_base are now bitmasks with values defined as constexpr static members.
Rationale: Required for new features.
Effect on original feature: Valid C++ 2003 code that relies on std::ios_base flag types being represented as std::bitset or as an integer type may fail to compile with this revision of C++.

Example 1:

```cpp
#include <iostream>

int main() {
    int flag = std::ios_base::hex;
    std::cout.setf(flag); // error: setf does not take argument of type int
}
```

— end example

C.7 C++ and C

C.7.1 General

Subclause C.7 lists the differences between C++ and C, in addition to those listed above, by the chapters of this document.

C.7.2 Clause 5: lexical conventions

Affected subclause: 5.11
Change: New Keywords
New keywords are added to C++; see 5.11.

**Rationale:** These keywords were added in order to implement the new semantics of C++.

**Effect on original feature:** Change to semantics of well-defined feature. Any C programs that used any of these keywords as identifiers are not valid C++ programs.

**Difficulty of converting:** Syntactic transformation. Converting one specific program is easy. Converting a large collection of related programs takes more work.

**How widely used:** Common.

2 **Affected subclause:** 5.13.3

**Change:** Type of character-literal is changed from int to char.

**Rationale:** This is needed for improved overloaded function argument type matching.

[Example 1:

```
int function( int i);
int function( char c);

function('x');
```

It is preferable that this call match the second version of function rather than the first. — end example]

**Effect on original feature:** Change to semantics of well-defined feature. C programs which depend on `sizeof('x') == sizeof(int)` will not work the same as C++ programs.

**Difficulty of converting:** Simple.

**How widely used:** Programs which depend upon `sizeof('x')` are probably rare.

3 **Affected subclause:** 5.13.5

**Change:** Concatenated string-literals can no longer have conflicting encoding-prefixes.

**Rationale:** Removal of non-portable feature.

**Effect on original feature:** Concatenation of string-literals with different encoding-prefixes is now ill-formed.

**Difficulty of converting:** Syntactic transformation.

**How widely used:** Seldom.

4 **Affected subclause:** 5.13.5

**Change:** String literals made const.

The type of a string-literal is changed from “array of char” to “array of const char”. The type of a UTF-8 string literal is changed from “array of char” to “array of const char8_t”. The type of a UTF-16 string literal is changed from “array of some-integer-type” to “array of const char16_t”. The type of a wide string literal is changed from “array of wchar_t” to “array of const wchar_t”.

**Rationale:** This avoids calling an inappropriate overloaded function, which might expect to be able to modify its argument.

**Effect on original feature:** Change to semantics of well-defined feature.

**Difficulty of converting:** Syntactic transformation. The fix is to add a cast:

```
char* p = "abc"; // valid in C, invalid in C++
void f(char*) {
  char* p = (char*)"abc"; // OK, cast added
  f(p);
  f((char*)"def"); // OK, cast added
}
```

**How widely used:** Programs that have a legitimate reason to treat string literal objects as potentially modifiable memory are probably rare.

C.7.3 **Clause 6:** basics

1 **Affected subclause:** 6.2

**Change:** C++ does not have “tentative definitions” as in C.

[Example 1: At file scope,

```
int i;
int i;
```

is valid in C, invalid in C++. — end example]
This makes it impossible to define mutually referential file-local objects with static storage duration, if initializers are restricted to the syntactic forms of C.

[Example 2:]

```c
struct X { int i; struct X* next; };

static struct X a;
static struct X b = { 0, &a };
static struct X a = { 1, &b };
—end example]
```

Rationale: This avoids having different initialization rules for fundamental types and user-defined types.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. In C++, the initializer for one of a set of mutually-referential file-local objects with static storage duration must invoke a function call to achieve the initialization.

How widely used: Seldom.

2 Affected subclause: 6.4

Change: A `struct` is a scope in C++, not in C.

[Example 3:]

```c
struct X {
    struct Y { int a; } b;
};
struct Y c;
```

is valid in C but not in C++, which would require `X::Y c;`. —end example]

Rationale: Class scope is crucial to C++, and a struct is a class.

Effect on original feature: Change to semantics of well-defined feature.

Difficulty of converting: Semantic transformation.

How widely used: C programs use `struct` extremely frequently, but the change is only noticeable when `struct`, enumeration, or enumerator names are referred to outside the `struct`. The latter is probably rare.

3 Affected subclause: 6.6 [also 9.2.9]

Change: A name of file scope that is explicitly declared `const`, and not explicitly declared `extern`, has internal linkage, while in C it would have external linkage.

Rationale: Because `const` objects may be used as values during translation in C++, this feature urges programmers to provide an explicit initializer for each `const` object. This feature allows the user to put `const` objects in source files that are included in more than one translation unit.

Effect on original feature: Change to semantics of well-defined feature.

Difficulty of converting: Semantic transformation.

How widely used: Seldom.

4 Affected subclause: 6.9.3.1

Change: The `main` function cannot be called recursively and cannot have its address taken.

Rationale: The `main` function may require special actions.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Trivial: create an intermediary function such as `mymain(argc, argv)`.

How widely used: Seldom.

5 Affected subclause: 6.8

Change: C allows “compatible types” in several places, C++ does not. For example, otherwise-identical `struct` types with different tag names are “compatible” in C but are distinctly different types in C++.

Rationale: Stricter type checking is essential for C++.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. The “typesafe linkage” mechanism will find many, but not all, of such problems. Those problems not found by typesafe linkage will continue to function properly, according to the “layout compatibility rules” of this document.

How widely used: Common.
C.7.4 Clause 7: expressions

Affected subclause: 7.3.12
Change: Converting void* to a pointer-to-object type requires casting.

Example 1:

```c
char a[10];
void* b = a;
void foo() {
    char* c = b;
}
```

C accepts this usage of pointer to void being assigned to a pointer to object type. C++ does not. — end example

Rationale: C++ tries harder than C to enforce compile-time type safety.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Can be automated. Violations will be diagnosed by the C++ translator. The fix is to add a cast.

Example 2:

```c
char* c = (char*) b;
```

—end example

How widely used: This is fairly widely used but it is good programming practice to add the cast when assigning pointer-to-void to pointer-to-object. Some C translators will give a warning if the cast is not used.

Affected subclause: 7.4
Change: Operations mixing a value of an enumeration type and a value of a different enumeration type or of a floating-point type are not valid.

Example 3:

```c
enum E1 { e };
enume E2 { f };
int b = e <= 3.7; // valid in C; ill-formed in C++
int k = f - e;  // valid in C; ill-formed in C++
int x = 1 ? e : f; // valid in C; ill-formed in C++
```

—end example

Rationale: Reinforcing type safety in C++.

Effect on original feature: Well-formed C code will not compile with this International Standard.

Difficulty of converting: Violations will be diagnosed by the C++ translator. The original behavior can be restored with a cast or integral promotion.

Example 4:

```c
enum E1 { e };
enume E2 { f };
int b = (int)e <= 3.7;
int k = +f - e;
```

—end example

How widely used: Uncommon.

Affected subclauses: 7.6.1.6 and 7.6.2.3
Change: Decrement operator is not allowed with bool operand.

Rationale: Feature with surprising semantics.

Effect on original feature: A valid C expression utilizing the decrement operator on a bool lvalue (for instance, via the C typedef in <stdbool.h> (17.14.5)) is ill-formed in C++.

Affected subclauses: 7.6.2.5 and 7.6.3
Change: In C++, types can only be defined in declarations, not in expressions.
In C, a sizeof expression or cast expression may define a new type.

Example 5:

```c
p = (void*)(struct x {int i;}) *0;
```

defines a new type, struct x. —end example
Rationale: This prohibition helps to clarify the location of definitions in the source code.
Effect on original feature: Deletion of semantically well-defined feature.
Difficulty of converting: Syntactic transformation.
How widely used: Seldom.

Affected subclauses: 7.6.16, 7.6.19, and 7.6.20
Change: The result of a conditional expression, an assignment expression, or a comma expression may be an lvalue.
Rationale: C++ is an object-oriented language, placing relatively more emphasis on lvalues. For example, function calls may yield lvalues.
Effect on original feature: Change to semantics of well-defined feature. Some C expressions that implicitly rely on value-to-rvalue conversions will yield different results.

[Example 6:]
char arr[100];
sizeof(0, arr)
yields 100 in C++ and sizeof(char*) in C. — end example]

Difficulty of converting: Programs must add explicit casts to the appropriate rvalue.
How widely used: Rare.

C.7.5 Clause 8: statements

Affected subclauses: 8.5.3 and 8.7.6
Change: It is now invalid to jump past a declaration with explicit or implicit initializer (except across entire block not entered).
Rationale: Constructors used in initializers may allocate resources which need to be de-allocated upon leaving the block. Allowing jump past initializers would require complicated runtime determination of allocation. Furthermore, many operations on such an uninitialized object have undefined behavior. With this simple compile-time rule, C++ assures that if an initialized variable is in scope, then it has assuredly been initialized.
Effect on original feature: Deletion of semantically well-defined feature.
Difficulty of converting: Semantic transformation.
How widely used: Seldom.

C.7.6 Clause 9: declarations

Affected subclause: 9.2.2
Change: In C++, the static or extern specifiers can only be applied to names of objects or functions. Using these specifiers with type declarations is illegal in C++. In C, these specifiers are ignored when used on type declarations.

[Example 1:]
static struct S {
    int i;
};
— end example]
Rationale: Storage class specifiers don’t have any meaning when associated with a type. In C++, class members can be declared with the static storage class specifier. Storage class specifiers on type declarations can be confusing for users.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Syntactic transformation.

How widely used: Seldom.

2 Affected subclause: 9.2.2

Change: In C++, register is not a storage class specifier.

Rationale: The storage class specifier had no effect in C++.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Syntactic transformation.

How widely used: Common.

3 Affected subclause: 9.2.4

Change: A C++ typedef-name must be different from any class type name declared in the same scope (except if the typedef is a synonym of the class name with the same name). In C, a typedef-name and a struct tag name declared in the same scope can have the same name (because they have different name spaces).

[Example 2:

typedef struct namel { /* ... */ } namel;  // valid C and C++
struct name { /* ... */ };  // valid C, invalid C++
—end example]

Rationale: For ease of use, C++ doesn’t require that a type name be prefixed with the keywords class, struct or union when used in object declarations or type casts.

[Example 3:

class name { /* ... */ };  
name i;  // i has type class name
—end example]

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. One of the 2 types has to be renamed.

How widely used: Seldom.

4 Affected subclause: 9.2.9 [see also 6.6]

Change: Const objects must be initialized in C++ but can be left uninitialized in C.

Rationale: A const object cannot be assigned to so it must be initialized to hold a useful value.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation.

How widely used: Seldom.

5 Affected subclause: 9.2.9.7

Change: The keyword auto cannot be used as a storage class specifier.

[Example 4:

void f() {
  auto int x;  // valid C, invalid C++
}
—end example]

Rationale: Allowing the use of auto to deduce the type of a variable from its initializer results in undesired interpretations of auto as a storage class specifier in certain contexts.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Syntactic transformation.

How widely used: Rare.

6 Affected subclause: 9.3.4.6

Change: In C++, a function declared with an empty parameter list takes no arguments. In C, an empty parameter list means that the number and type of the function arguments are unknown.

[Example 5:

int f();  // means int f(void) in C++

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\[ \text{// int } f( \text{ unknown }) \text{ in } C \]

—end example]

**Rationale:**  This is to avoid function calls with the wrong number or type of arguments.

**Effect on original feature:**  Change to semantics of well-defined feature. This feature was marked as “obsolete” in C.

**Difficulty of converting:**  Syntactic transformation. The function declarations using C incomplete declaration style must be completed to become full prototype declarations. A program may need to be updated further if different calls to the same (non-prototype) function have different numbers of arguments or if the type of corresponding arguments differed.

**How widely used:**  Common.

7 **Affected subclause:**  9.3.4.6 [see 7.6.2.5]

**Change:**  In C++, types may not be defined in return or parameter types. In C, these type definitions are allowed.

[Example 6:

```c
void f( struct S { int a; } arg ) {} // valid C, invalid C++
enum E { A, B, C } f() {} // valid C, invalid C++
```

—end example]

**Rationale:**  When comparing types in different translation units, C++ relies on name equivalence when C relies on structural equivalence. Regarding parameter types: since the type defined in a parameter list would be in the scope of the function, the only legal calls in C++ would be from within the function itself.

**Effect on original feature:**  Deletion of semantically well-defined feature.

**Difficulty of converting:**  Semantic transformation. The type definitions must be moved to file scope, or in header files.

**How widely used:**  Seldom. This style of type definition is seen as poor coding style.

8 **Affected subclause:**  9.5

**Change:**  In C++, the syntax for function definition excludes the “old-style” C function. In C, “old-style” syntax is allowed, but deprecated as “obsolete”.

**Rationale:**  Prototypes are essential to type safety.

**Effect on original feature:**  Deletion of semantically well-defined feature.

**Difficulty of converting:**  Syntactic transformation.

**How widely used:**  Common in old programs, but already known to be obsolescent.

9 **Affected subclause:**  9.4.2

**Change:**  In C++, designated initialization support is restricted compared to the corresponding functionality in C. In C++, designators for non-static data members must be specified in declaration order, designators for array elements and nested designators are not supported, and designated and non-designated initializers cannot be mixed in the same initializer list.

[Example 7:

```c
struct A { int x, y; };
struct B { struct A a; };
struct A a = { .y = 1, .x = 2 }; // valid C, invalid C++
struct B b = { .a.x = 0 }; // valid C, invalid C++
struct A c = { .x = 1, 2 }; // valid C, invalid C++
```

—end example]

**Rationale:**  In C++, members are destroyed in reverse construction order and the elements of an initializer list are evaluated in lexical order, so member initializers must be specified in order. Array designators conflict with lambda-expression syntax. Nested designators are seldom used.

**Effect on original feature:**  Deletion of feature that is incompatible with C++.

**Difficulty of converting:**  Syntactic transformation.

**How widely used:**  Out-of-order initializers are common. The other features are seldom used.

10 **Affected subclause:**  9.4.3

**Change:**  In C++, when initializing an array of character with a string, the number of characters in the string (including the terminating ‘\0’) must not exceed the number of elements in the array. In C, an array can be initialized with a string even if the array is not large enough to contain the string-terminating ‘\0’.
Example 8:

```c
char array[4] = "abcd";  // valid C, invalid C++
```

—end example

Rationale: When these non-terminated arrays are manipulated by standard string functions, there is potential for major catastrophe.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. The arrays must be declared one element bigger to contain the string terminating '\0'.

How widely used: Seldom. This style of array initialization is seen as poor coding style.

Affected subclause: 9.7.1

Change: C++ objects of enumeration type can only be assigned values of the same enumeration type. In C, objects of enumeration type can be assigned values of any integral type.

Example 9:

```c
enum color { red, blue, green };
enum color c = 1;  // valid C, invalid C++
```

—end example

Rationale: The type-safe nature of C++.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Syntactic transformation. (The type error produced by the assignment can be automatically corrected by applying an explicit cast.)

How widely used: Common.

Affected subclause: 9.7.1

Change: In C++, the type of an enumerator is its enumeration. In C, the type of an enumerator is `int`.

Example 10:

```c
enum e { A };
sizeof(A) == sizeof(int)  // in C
sizeof(A) == sizeof(e)   // in C++
/* and sizeof(int) is not necessarily equal to sizeof(e) */
```

—end example

Rationale: In C++, an enumeration is a distinct type.

Effect on original feature: Change to semantics of well-defined feature.

Difficulty of converting: Semantic transformation.

How widely used: Seldom. The only time this affects existing C code is when the size of an enumerator is taken. Taking the size of an enumerator is not a common C coding practice.

Affected subclause: 9.12.2

Change: In C++, an `alignment-specifier` is an `attribute-specifier`. In C, an `alignment-specifier` is a `declaration-specifier`.

Example 11:

```c
#include <stdalign.h>
unsigned alignas(8) int x;  // valid C, invalid C++
unsigned int y alignas(8);  // valid C++, invalid C
```

—end example

Rationale: C++ requires unambiguous placement of the `alignment-specifier`.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Syntactic transformation.

How widely used: Seldom.

C.7.7 Clause 11: classes
Example 1:
```c
int x[99];
void f() {
    struct x { int a; };
    sizeof(x); /* size of the array in C */
    /* size of the struct in C++ */
}
```
—end example

**Rationale:** This is one of the few incompatibilities between C and C++ that can be attributed to the new C++ name space definition where a name can be declared as a type and as a non-type in a single scope causing the non-type name to hide the type name and requiring that the keywords `class`, `struct`, `union` or `enum` be used to refer to the type name. This new name space definition provides important notational conveniences to C++ programmers and helps making the use of the user-defined types as similar as possible to the use of fundamental types. The advantages of the new name space definition were judged to outweigh by far the incompatibility with C described above.

**Effect on original feature:** Change to semantics of well-defined feature.

**Difficulty of converting:** Semantic transformation. If the hidden name that needs to be accessed is at global scope, the `::` C++ operator can be used. If the hidden name is at block scope, either the type or the struct tag has to be renamed.

**How widely used:** Seldom.

2 **Affected subclause:** 11.4.5.3

**Change:** Copying volatile objects.

The implicitly-declared copy constructor and implicitly-declared copy assignment operator cannot make a copy of a volatile lvalue.

Example 2: The following is valid in C:
```c
struct X { int i; }; volatile struct X x1 = {0};
struct X x2 = x1;    // invalid C++
struct X x3;
    x3 = x1;             // also invalid C++
```
—end example

**Rationale:** Several alternatives were debated at length. Changing the parameter to `volatile const X&` would greatly complicate the generation of efficient code for class objects. Discussion of providing two alternative signatures for these implicitly-defined operations raised unanswered concerns about creating ambiguities and complicating the rules that specify the formation of these operators according to the bases and members.

**Effect on original feature:** Deletion of semantically well-defined feature.

**Difficulty of converting:** Semantic transformation. If volatile semantics are required for the copy, a user-declared constructor or assignment must be provided. If non-volatile semantics are required, an explicit `const_cast` can be used.

**How widely used:** Seldom.

3 **Affected subclause:** 11.4.10

**Change:** Bit-fields of type plain `int` are signed.

**Rationale:** The signedness needs to be consistent among template specializations. For consistency, the implementation freedom was eliminated for non-dependent types, too.

**Effect on original feature:** The choice is implementation-defined in C, but not so in C++.

**Difficulty of converting:** Syntactic transformation.

**How widely used:** Seldom.

4 **Affected subclause:** 11.4.12

**Change:** In C++, the name of a nested class is local to its enclosing class. In C the name of the nested class belongs to the same scope as the name of the outermost enclosing class.

Example 3:
```c
struct X {
    struct Y { /* ... */ } y;
};
```
struct Y yy; // valid C, invalid C++
—end example]

Rationale: C++ classes have member functions which require that classes establish scopes. The C rule would leave classes as an incomplete scope mechanism which would prevent C++ programmers from maintaining locality within a class. A coherent set of scope rules for C++ based on the C rule would be very complicated and C++ programmers would be unable to predict reliably the meanings of nontrivial examples involving nested or local functions.

Effect on original feature: Change to semantics of well-defined feature.

Difficulty of converting: Semantic transformation. To make the struct type name visible in the scope of the enclosing struct, the struct tag can be declared in the scope of the enclosing struct, before the enclosing struct is defined.

[Example 4:

```c
struct Y;
// struct Y and struct X are at the same scope
struct X {
    struct Y { /* ... */ } y;
};
—end example]
```

All the definitions of C struct types enclosed in other struct definitions and accessed outside the scope of the enclosing struct can be exported to the scope of the enclosing struct. Note: this is a consequence of the difference in scope rules, which is documented in 6.4.

How widely used: Seldom.

5 Affected subclause: 6.5.2

Change: In C++, a typedef-name may not be redeclared in a class definition after being used in that definition.

[Example 5:

```c
typedef int I;
struct S {
    I i;
    int I;   // valid C, invalid C++
};
—end example]
```

Rationale: When classes become complicated, allowing such a redefinition after the type has been used can create confusion for C++ programmers as to what the meaning of I really is.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. Either the type or the struct member has to be renamed.

How widely used: Seldom.

C.7.8 Clause 15: preprocessing directives [diff.cpp]

1 Affected subclause: 15.11

Change: Whether __STDC__ is defined and if so, what its value is, are implementation-defined.

Rationale: C++ is not identical to C. Mandating that __STDC__ be defined would require that translators make an incorrect claim.

Effect on original feature: Change to semantics of well-defined feature.

Difficulty of converting: Semantic transformation.

How widely used: Programs and headers that reference __STDC__ are quite common.

C.8 C standard library [diff.library]

C.8.1 General [diff.library.general]

1 Subclause C.8 summarizes the explicit changes in headers, definitions, declarations, or behavior between the C standard library in the C standard and the parts of the C++ standard library that were included from the C standard library.
C.8.2 Modifications to headers

1 For compatibility with the C standard library, the C++ standard library provides the C headers enumerated in 17.14.
2 There are no C++ headers for the C standard library’s headers `<stdnoreturn.h>` and `<threads.h>`, nor are these headers from the C standard library headers themselves part of C++.
3 The C headers `<complex.h>` and `<tgmath.h>` do not contain any of the content from the C standard library and instead merely include other headers from the C++ standard library.

C.8.3 Modifications to definitions

C.8.3.1 Types char16_t and char32_t

1 The types `char16_t` and `char32_t` are distinct types rather than typedefs to existing integral types. The tokens `char16_t` and `char32_t` are keywords in C++ (5.11). They do not appear as macro or type names defined in `<cuchar>` (23.5.5).

C.8.3.2 Type wchar_t

1 The type `wchar_t` is a distinct type rather than a typedef to an existing integral type. The token `wchar_t` is a keyword in C++ (5.11). It does not appear as a macro or type name defined in any of `<cassert>` (19.3.2), `<cstdlib>` (17.2.2), or `<cwchar>` (23.5.4).

C.8.3.3 Header `<assert.h>`

1 The token `static_assert` is a keyword in C++. It does not appear as a macro name defined in `<assert>` (19.3.2).

C.8.3.4 Header `<iso646.h>`

1 The tokens `and`, `and_eq`, `bitand`, `bitor`, `compl`, `not`, `not_eq`, `or`, `or_eq`, `xor`, and `xor_eq` are keywords in C++ (5.11), and are not introduced as macros by `<iso646.h>` (17.14.3).

C.8.3.5 Header `<stdalign.h>`

1 The token `alignas` is a keyword in C++ (5.11), and is not introduced as a macro by `<stdalign.h>` (17.14.4).

C.8.3.6 Header `<stdbool.h>`

1 The tokens `bool`, `true`, and `false` are keywords in C++ (5.11), and are not introduced as macros by `<stdbool.h>` (17.14.5).

C.8.3.7 Macro NULL

1 The macro NULL, defined in any of `<locale>` (30.5.1), `<cstdlib>` (17.2.1), `<stdio>` (31.13.1), `<stdlib>` (17.2.2), `<cstring>` (23.5.3), `<ctime>` (29.15), or `<cwchar>` (23.5.4), is an implementation-defined null pointer constant in C++ (17.2).

C.8.4 Modifications to declarations

1 Header `<cstring>` (23.5.3): The following functions have different declarations:

   (1.1) — strchr
   (1.2) — strpbrk
   (1.3) — strrrchr
   (1.4) — strstr
   (1.5) — memchr

   Subclause 23.5.3 describes the changes.

2 Header `<cwchar>` (23.5.4): The following functions have different declarations:

   (2.1) — wcschr
   (2.2) — wcsapbrk
   (2.3) — wcsrchr
   (2.4) — wcsstr
   (2.5) — wmemchr
Subclause 23.5.4 describes the changes.

3 Header `<cstddef>` (17.2.1) declares the names `nullptr_t`, `byte`, and `to_integer`, and the operators and operator templates in (17.2.5), in addition to the names declared in `<stddef.h>` (17.14) in the C standard library.

C.8.5 Modifications to behavior [diff.mods.to.behavior]

C.8.5.1 General [diff.mods.to.behavior.general]

1 Header `<cstdlib>` (17.2.2): The following functions have different behavior:

(1.1) — `atexit`
(1.2) — `exit`
(1.3) — `abort`

Subclause 17.5 describes the changes.

2 Header `<csetjmp>` (17.13.3): The following functions have different behavior:

(2.1) — `longjmp`

Subclause 17.13.3 describes the changes.

C.8.5.2 Macro `offsetof(type, member-designator)` [diffoffsetof]

1 The macro `offsetof`, defined in `<cstddef>` (17.2.1), accepts a restricted set of `type` arguments in C++. Subclause 17.2.4 describes the change.

C.8.5.3 Memory allocation functions [diffmalloc]

1 The functions `aligned_alloc`, `calloc`, `malloc`, and `realloc` are restricted in C++. Subclause 20.2.12 describes the changes.
Annex D
(normative)

Compatibility features

D.1 General

1 This Annex describes features of this document that are specified for compatibility with existing implementations.

2 These are deprecated features, where deprecated is defined as: Normative for the current revision of C++, but having been identified as a candidate for removal from future revisions. An implementation may declare library names and entities described in this Clause with the deprecated attribute (9.12.5).

D.2 Implicit capture of *this by reference

1 For compatibility with prior revisions of C++, a lambda-expression with capture-default = (7.5.6.3) may implicitly capture *this by reference.

[Example 1:

```c++
struct X {
    int x;
    void foo(int n) {
        auto f = [=]() { x = n; }; // deprecated: x means this->x, not a copy thereof
        auto g = [=, this]() { x = n; }; // recommended replacement
    }
};
```
—end example]

D.3 Array comparisons

1 Equality and relational comparisons (7.6.10, 7.6.9) between two operands of array type are deprecated.

[Note 1: Three-way comparisons (7.6.8) between such operands are ill-formed. — end note]

[Example 1:

```c++
int arr1[5];
int arr2[5];
bool same = arr1 == arr2; // deprecated, same as &arr1[0] == &arr2[0],
// does not compare array contents
auto cmp = arr1 <=> arr2; // error
```
—end example]

D.4 Deprecated volatile types

1 Postfix ++ and -- expressions (7.6.1.6) and prefix ++ and -- expressions (7.6.2.3) of volatile-qualified arithmetic and pointer types are deprecated.

[Example 1:

```c++
volatile int velociraptor;
++velociraptor; // deprecated
```
—end example]

2 Certain assignments where the left operand is a volatile-qualified non-class type are deprecated; see 7.6.19.

[Example 2:

```c++
int neck, tail;
volatile int brachiosaur;
brachiosaur = neck; // OK
```
A function type (9.3.4.6) with a parameter with volatile-qualified type or with a volatile-qualified return type is deprecated.

[Example 3:

```c
volatile struct amber jurassic(); // deprecated
trex(volatile short left_arm, volatile short right_arm); // deprecated
fly(volatile struct pterosaur* pteranodon); // OK
```
—end example]

A structured binding (9.6) of a volatile-qualified type is deprecated.

[Example 4:

```c
struct linhenykus { short forelimb; }
void park(linhenykus alvarezsauroid) {
  volatile auto [what_is_this] = alvarezsauroid; // deprecated
  // ...
}
```
—end example]

D.5 Redeclaration of static constexpr data members

For compatibility with prior revisions of C++, a constexpr static data member may be redundantly redeclared outside the class with no initializer (6.2, 11.4.9.3). This usage is deprecated.

[Example 1:

```c
struct A {
  static constexpr int n = 5; // definition (declaration in C++ 2014)
};
constexpr int A::n; // redundant declaration (definition in C++ 2014)
```
—end example]

D.6 Non-local use of TU-local entities

A declaration of a non-TU-local entity that is an exposure (6.6) is deprecated.

[Note 1: Such a declaration in an importable module unit is ill-formed. — end note]

[Example 1:

```c
namespace {
  struct A {
    void f() {}
  }
}
A h(); // deprecated: not internal linkage
inline void g() {A().f();} // deprecated: inline and not internal linkage
```
—end example]

D.7 Implicit declaration of copy functions

The implicit definition of a copy constructor (11.4.5.3) as defaulted is deprecated if the class has a user-declared copy assignment operator or a user-declared destructor (11.4.7). The implicit definition of a copy assignment operator (11.4.6) as defaulted is deprecated if the class has a user-declared copy constructor or a user-declared destructor. It is possible that future versions of C++ will specify that these implicit definitions are deleted (9.5.3).

D.8 Literal operator function declarations using an identifier

A literal-operator-id (12.6) of the form

```c
operator string-literal identifier
```

is deprecated.
D.9 template keyword before qualified names

The use of the keyword `template` before the qualified name of a class or alias template without a template argument list is deprecated (13.3).

D.10 has_denorm members in numeric_limits

The following type is defined in addition to those specified in `<limits>` (17.3.3):
```cpp
namespace std {
    enum float_denorm_style {
        denorm_indeterminate = -1,
        denorm_absent = 0,
        denorm_present = 1
    }
}
```

The following members are defined in addition to those specified in 17.3.5.1:
```cpp
static constexpr float_denorm_style has_denorm = denorm_absent;
static constexpr bool has_denorm_loss = false;
```

The values of `has_denorm` and `has_denorm_loss` of specializations of `numeric_limits` are unspecified.

The following members of the specialization `numeric_limits<bool>` are defined in addition to those specified in 17.3.5.3:
```cpp
static constexpr float_denorm_style has_denorm = denorm_absent;
static constexpr bool has_denorm_loss = false;
```

D.11 Deprecated C macros

The header `<stdalign.h>` has the following macros:
```cpp
#define __alignas_is_defined 1
#define __alignof_is_defined 1
```

The header `<stdbool.h>` has the following macro:
```cpp
#define __bool_true_false_are_defined 1
```

D.12 Relational operators

The header `<utility>` (22.2.1) has the following additions:
```cpp
namespace std::rel_ops {
    template<class T> bool operator!=(const T&, const T&);
    template<class T> bool operator> (const T&, const T&);
    template<class T> bool operator<=(const T&, const T&);
    template<class T> bool operator>=(const T&, const T&);
}
```

To avoid redundant definitions of `operator!=` out of `operator==` and operators `>`, `<=`, and `>=` out of `operator<`, the library provides the following:
```cpp
template<class T> bool operator!=(const T& x, const T& y);
```

**Preconditions:** `T` meets the `Cpp17EqualityComparable` requirements (Table 28).

**Returns:** `!(x == y)`.

```cpp
template<class T> bool operator>(const T& x, const T& y);
```

**Preconditions:** `T` meets the `Cpp17LessThanComparable` requirements (Table 29).

**Returns:** `y < x`.

```cpp
template<class T> bool operator<=(const T& x, const T& y);
```

**Preconditions:** `T` meets the `Cpp17LessThanComparable` requirements (Table 29).

**Returns:** `!(y < x)`.
template<class T> bool operator>=(const T& x, const T& y);

Preconditions: T meets the Cpp17LessThanComparable requirements (Table 29).

Returns: !(x < y).

D.13 Deprecated error numbers

The following macros are defined in addition to those specified in 19.4.2:

```
#define ENODATA see below
#define ENOSR see below
#define ENOSTR see below
#define ETIME see below
```

The meaning of these macros is defined by the POSIX standard.

The following `enum errc` enumerators are defined in addition to those specified in 19.5.2:

```
no_message_available, // ENODATA
no_stream_resources, // ENOSR
not_a_stream, // ENOSTR
stream_timeout, // ETIME
```

The value of each `enum errc` enumerator above is the same as the value of the `<cerrno>` macro shown in the above synopsis.

D.14 Deprecated type traits

The header `<type_traits>` (21.3.3) has the following addition:

```
namespace std {
    template<class T> struct is_pod;
    template<class T> constexpr bool is_pod_v = is_pod<T>::value;
    template<size_t Len, size_t Align = default_alignment> // see below
        struct aligned_storage;
    template<size_t Len, size_t Align = default_alignment> // see below
        using aligned_storage_t = typename aligned_storage<Len, Align>::type;
    template<size_t Len, class... Types>
        using aligned_union_t = typename aligned_union<Len, Types...>::type;
}
```

The behavior of a program that adds specializations for any of the templates defined in this subclause is undefined, unless explicitly permitted by the specification of the corresponding template.

A **POD class** is a class that is both a trivial class and a standard-layout class, and has no non-static data members of type non-POD class (or array thereof). A **POD type** is a scalar type, a POD class, an array of such a type, or a cv-qualified version of one of these types.

```
template<class T> struct is_pod;
```

Preconditions: `remove_all_extents_t<T>` shall be a complete type or cv void.

Remarks: `is_pod<T>` is a Cpp17UnaryTypeTrait (21.3.2) with a base characteristic of true_type if T is a POD type, and false_type otherwise.

[Note 1: It is unspecified whether a closure type (7.5.6.2) is a POD type. — end note]

```
template<size_t Len, size_t Align = default_alignment>
    struct aligned_storage;
```

The value of `default_alignment` is the most stringent alignment requirement for any object type whose size is no greater than `Len` (6.8).

Mandates: `Len` is not zero. `Aligned<Align>` is equal to `alignof(T)` for some type T or to `default_alignment`.

The member typedef type denotes a trivial standard-layout type suitable for use as uninitialized storage for any object whose size is at most `Len` and whose alignment is a divisor of `Align`.

[Note 2: Uses of `aligned_storage<Len, Align>::type` can be replaced by an array `std::byte[Len]` declared with `alignas(Align)`. — end note]
[Note 3: A typical implementation would define \texttt{aligned_storage} as:

\begin{verbatim}
template<size_t Len, size_t Alignment>
struct aligned_storage {
  typedef struct {
    alignas(Alignment) unsigned char __data[Len];
  } type;
};
\end{verbatim}

— end note]

\begin{verbatim}
template<size_t Len, class... Types>
struct aligned_union;
\end{verbatim}

\textbf{Mandates:} At least one type is provided. Each type in the template parameter pack \texttt{Types} is a complete object type.

The member typedef \texttt{type} denotes a trivial standard-layout type suitable for use as uninitialized storage for any object whose type is listed in \texttt{Types}; its size shall be at least \texttt{Len}. The static member \texttt{alignment_value} is an integral constant of type \texttt{size_t} whose value is the strictest alignment of all types listed in \texttt{Types}.

### D.15 Tuple

The header \texttt{<tuple>} (22.4.2) has the following additions:

\begin{verbatim}
namespace std {
  template<class T> struct tuple_size<volatile T>;
  template<class T> struct tuple_size<const volatile T>;
  template<size_t I, class T> struct tuple_element<I, volatile T>;
  template<size_t I, class T> struct tuple_element<I, const volatile T>;
}
\end{verbatim}

\begin{verbatim}
template<class T> struct tuple_size<volatile T>;
\end{verbatim}

Let \texttt{TS} denote \texttt{tuple_size<T>} of the cv-unqualified type \texttt{T}. If the expression \texttt{TS::value} is well-formed when treated as an unevaluated operand (7.2.3), then specializations of each of the two templates meet the \texttt{Cpp17TransformationTrait} requirements with a base characteristic of \texttt{integral_constant<

Access checking is performed as if in a context unrelated to \texttt{TS} and \texttt{T}. Only the validity of the immediate context of the expression is considered.

In addition to being available via inclusion of the \texttt{<tuple>} (22.4.2) header, the two templates are available when any of the headers \texttt{<array>} (24.3.2), \texttt{<ranges>} (26.2), or \texttt{<utility>} (22.2.1) are included.

\begin{verbatim}
template<size_t I, class T> struct tuple_element<I, volatile T>;
\end{verbatim}

\begin{verbatim}
template<class T> struct tuple_size<const volatile T>;
\end{verbatim}

Let \texttt{TE} denote \texttt{tuple_element_t<I, T>} of the cv-unqualified type \texttt{T}. Then specializations of each of the two templates meet the \texttt{Cpp17TransformationTrait} requirements with a member typedef \texttt{type} that names the following type:

\begin{enumerate}
  \item for the first specialization, \texttt{add_volatile_t<TE>}, and
  \item for the second specialization, \texttt{add_cv_t<TE>}.
\end{enumerate}

In addition to being available via inclusion of the \texttt{<tuple>} (22.4.2) header, the two templates are available when any of the headers \texttt{<array>} (24.3.2), \texttt{<ranges>} (26.2), or \texttt{<utility>} (22.2.1) are included.

### D.16 Variant

The header \texttt{<variant>} (22.6.2) has the following additions:

\begin{verbatim}
namespace std {
  template<class T> struct variant_size<volatile T>;
  template<class T> struct variant_size<const volatile T>;
}
\end{verbatim}

\begin{verbatim}
template<class T> struct variant_size<volatile T>;
\end{verbatim}

\section*{\textsection D.16 © ISO/IEC 2101}
Let \( VS \) denote \( \text{variant\_size<T>} \) of the cv-unqualified type \( T \). Then specializations of each of the two templates meet the \( \text{Cpp17UnaryTypeTrait} \) requirements with a base characteristic of \( \text{integral\_constant<size_t, VS::value>} \).

Let \( VA \) denote \( \text{variant\_alternative<I, T>} \) of the cv-unqualified type \( T \). Then specializations of each of the two templates meet the \( \text{Cpp17TransformationTrait} \) requirements with a member typedef \( \text{type} \) that names the following type:

- for the first specialization, \( \text{add\_volatile\_t<VA::type>} \), and
- for the second specialization, \( \text{add\_cv\_t<VA::type>} \).

D.17 Deprecated iterator class template

The header \(<\text{iterator}>\) (25.2) has the following addition:

```cpp
namespace std {
  template<class Category, class T, class Distance = ptrdiff_t,
    class Pointer = T*, class Reference = T&>
  struct iterator {
    using iterator_category = Category;
    using value_type = T;
    using difference_type = Distance;
    using pointer = Pointer;
    using reference = Reference;
  };
}
```

The \( \text{iterator} \) template may be used as a base class to ease the definition of required types for new iterators.

[Note 1: If the new iterator type is a class template, then these aliases will not be visible from within the iterator class’s template definition, but only to callers of that class. —end note]

[Example 1: If a C++ program wants to define a bidirectional iterator for some data structure containing \( \text{double} \) and such that it works on a large memory model of the implementation, it can do so with:

```cpp
class MyIterator :
  public iterator<bidirectional_iterator_tag, double, long, T*, T&> {
    // code implementing ++, etc.
  };

- end example]

D.18 Deprecated move\_iterator access

The following member is declared in addition to those members specified in 25.5.4.6:

```cpp
namespace std {
  template<class Iterator>
  class move_iterator {
  public:
    constexpr pointer operator->() const;
  };
}
```

```cpp
constexpr pointer operator->() const;
```

Returns: current.
D.19 Deprecated formatting

D.19.1 Header <format> synopsis

The header <format> (22.14.1) has the following additions:

```cpp
namespace std {
    template<class Visitor, class Context>
    decltype(auto) visit_format_arg(Visitor&& vis, basic_format_arg<Context> arg);
}
```

D.19.2 Formatting arguments

```cpp
template<class Visitor, class Context>
dec_type(auto) visit_format_arg(Visitor&& vis, basic_format_arg<Context> arg);
```

Effects: Equivalent to: return visit(std::forward<Visitor>(vis), arg.value);

D.20 Deprecated locale category facets

1 The `ctype` locale category includes the following facets as if they were specified in table Table 107 of 30.3.1.2.1.
- `codecvt<char16_t, char, mbstate_t>`
- `codecvt<char32_t, char, mbstate_t>`
- `codecvt<char16_t, char8_t, mbstate_t>`
- `codecvt<char32_t, char8_t, mbstate_t>`

2 The `ctype` locale category includes the following facets as if they were specified in table Table 108 of 30.3.1.2.1.
- `codecvt_byname<char16_t, char, mbstate_t>`
- `codecvt_byname<char32_t, char, mbstate_t>`
- `codecvt_byname<char16_t, char8_t, mbstate_t>`
- `codecvt_byname<char32_t, char8_t, mbstate_t>`

3 The following class template specializations are required in addition to those specified in 30.4.2.5. The specializations `codecvt<char16_t, char, mbstate_t>` and `codecvt<char16_t, char8_t, mbstate_t>` convert between the UTF-16 and UTF-8 encoding forms, and the specializations `codecvt<char32_t, char, mbstate_t>` and `codecvt<char32_t, char8_t, mbstate_t>` convert between the UTF-32 and UTF-8 encoding forms.

D.21 Deprecated filesystem path factory functions

1 The header <filesystem> (31.12.4) has the following additions:

```cpp
template<class Source>
path u8path(const Source& source);

template<class InputIterator>
path u8path(InputIterator first, InputIterator last);
```

Mandates: The value type of `Source` and `InputIterator` is `char` or `char8_t`.

Preconditions: The `source` and `[first, last)` sequences are UTF-8 encoded. `Source` meets the requirements specified in 31.12.6.4.

Returns:

(4.1) — If `path::value_type` is `char` and the current native narrow encoding (31.12.6.3.2) is UTF-8, return `path(source)` or `path(first, last)`; otherwise,

(4.2) — if `path::value_type` is `wchar_t` and the native wide encoding is UTF-16, or if `path::value_type` is `char16_t` or `char32_t`, convert `source` or `[first, last)` to a temporary, `tmp`, of type `path::string_type` and return `path(tmp)`; otherwise,

(4.3) — convert `source` or `[first, last)` to a temporary, `tmp`, of type `u32string` and return `path(tmp)`.

Remarks: Argument format conversion (31.12.6.3.1) applies to the arguments for these functions. How Unicode encoding conversions are performed is unspecified.

[Example 1: A string is to be read from a database that is encoded in UTF-8, and used to create a directory using the native encoding for filenames:

```cpp
namespace fs = std::filesystem;
std::string utf8_string = read_utf8_data();
fs::create_directory(fs::u8path(utf8_string));
```]
For POSIX-based operating systems with the native narrow encoding set to UTF-8, no encoding or type conversion occurs.

For POSIX-based operating systems with the native narrow encoding not set to UTF-8, a conversion to UTF-32 occurs, followed by a conversion to the current native narrow encoding. Some Unicode characters may have no native character set representation.

For Windows-based operating systems a conversion from UTF-8 to UTF-16 occurs.

—end example

[Note 1: The example above is representative of a historical use of filesystem::u8path. To indicate a UTF-8 encoding, passing a std::u8string to path's constructor is preferred as it is consistent with path's handling of other encodings. — end note]

D.22 Deprecated atomic operations [depr.atomics]

D.22.1 General [depr.atomics.general]

1 The header <atomic> (33.5.2) has the following additions.

```cpp
namespace std {
    template<class T>
    void atomic_init(volatile atomic<T>* object, typename atomic<T>::value_type desired) noexcept;
    template<class T>
    void atomic_init(atomic<T>* object, typename atomic<T>::value_type desired) noexcept;

    #define ATOMIC_VAR_INIT(value) see below
}
```

D.22.2 Volatile access [depr.atomics.volatile]

1 If an atomic (33.5.8) specialization has one of the following overloads, then that overload participates in overload resolution even if atomic<T>::is_always_lock_free is false:

```cpp
void store(T desired, memory_order order = memory_order::seq_cst) volatile noexcept;
T operator=(T desired) volatile noexcept;
T load(memory_order order = memory_order::seq_cst) const volatile noexcept;
operator T() const volatile noexcept;
T exchange(T desired, memory_order order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_weak(T& expected, T desired,
    memory_order success, memory_order failure) volatile noexcept;
bool compare_exchange_strong(T& expected, T desired,
    memory_order success, memory_order failure) volatile noexcept;
bool compare_exchange_weak(T& expected, T desired,
    memory_order order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_strong(T& expected, T desired,
    memory_order order = memory_order::seq_cst) volatile noexcept;
T fetch_key(T operand, memory_order order = memory_order::seq_cst) volatile noexcept;
T operator op=(T operand) volatile noexcept;
T* fetch_key(ptrdiff_t operand, memory_order order = memory_order::seq_cst) volatile noexcept;
```

D.22.3 Non-member functions [depr.atomics.nonmembers]

```cpp
template<class T>
void atomic_init(volatile atomic<T>* object, typename atomic<T>::value_type desired) noexcept;
template<class T>
void atomic_init(atomic<T>* object, typename atomic<T>::value_type desired) noexcept;
```

1 Effects: Equivalent to: atomic_store_explicit(object, desired, memory_order::relaxed);

D.22.4 Operations on atomic types [depr.atomics.types.operations]

```cpp
#define ATOMIC_VAR_INIT(value) see below
```

1 The macro expands to a token sequence suitable for constant initialization of an atomic variable of static storage duration of a type that is initialization-compatible with value.

[Note 1: This operation possibly needs to initialize locks. — end note]

Concurrent access to the variable being initialized, even via an atomic operation, constitutes a data race.
Example 1:

    atomic<int> v = ATOMIC_VAR_INIT(5);

— end example]
Annex E
(informative)

Conformance with UAX #31 [uaxid]

E.1 General [uaxid.general]

This Annex describes the choices made in application of UAX #31 (“Unicode Identifier and Pattern Syntax”) to C++ in terms of the requirements from UAX #31 and how they do or do not apply to this document. In terms of UAX #31, this document conforms by meeting the requirements R1 “Default Identifiers” and R4 “Equivalent Normalized Identifiers” from UAX #31. The other requirements from UAX #31, also listed below, are either alternatives not taken or do not apply to this document.

E.2 R1 Default identifiers [uaxid.def]

E.2.1 General [uaxid.def.general]

1 UAX #31 specifies a default syntax for identifiers based on properties from the Unicode Character Database, UAX #44. The general syntax is

\[
\text{<Identifier>} := \text{<Start>} \text{<Continue>}^* (\text{<Medial>} \text{<Continue>}^+)\* \\
\text{where <Start>} has the XID\_Start property, \text{<Continue>} has the XID\_Continue property, and \text{<Medial>} is a list of characters permitted between continue characters. For C++ we add the character U+005F LOW LINE, or _, to the set of permitted \text{<Start>} characters, the \text{<Medial>} set is empty, and the \text{<Continue>} characters are unmodified. In the grammar used in UAX #31, this is
\]

\[
\text{<Identifier>} := \text{<Start>} \text{<Continue>}^* \\
\text{<Start>} := \text{XID\_Start} + \text{U+005F} \\
\text{<Continue>} := \text{<Start>} + \text{XID\_Continue}
\]

2 This is described in the C++ grammar in 5.10, where identifier is formed from identifier-start or identifier followed by identifier-continue.

E.2.2 R1a Restricted format characters [uaxid.def.rfmt]

1 If an implementation of UAX #31 wishes to allow format characters such as U+200D ZERO WIDTH JOINER or U+200C ZERO WIDTH NON-JOINER it must define a profile allowing them, or describe precisely which combinations are permitted.

2 C++ does not allow format characters in identifiers, so this does not apply.

E.2.3 R1b Stable identifiers [uaxid.def.stable]

1 An implementation of UAX #31 may choose to guarantee that identifiers are stable across versions of the Unicode Standard. Once a string qualifies as an identifier it does so in all future versions.

2 C++ does not make this guarantee, except to the extent that UAX #31 guarantees the stability of the XID\_Start and XID\_Continue properties.

E.3 R2 Immutable identifiers [uaxid.immutable]

1 An implementation may choose to guarantee that the set of identifiers will never change by fixing the set of code points allowed in identifiers forever.

2 C++ does not choose to make this guarantee. As scripts are added to Unicode, additional characters in those scripts may become available for use in identifiers.

E.4 R3 Pattern\_White\_Space and Pattern\_Syntax characters [uaxid.pattern]

1 UAX #31 describes how formal languages such as computer languages should describe and implement their use of whitespace and syntactically significant characters during the processes of lexing and parsing.
This document does not claim conformance with this requirement from UAX #31.

**E.5 R4 Equivalent normalized identifiers**

1 UAX #31 requires that implementations describe how identifiers are compared and considered equivalent.
2 This document requires that identifiers be in Normalization Form C and therefore identifiers that compare the same under NFC are equivalent. This is described in 5.10.

**E.6 R5 Equivalent case-insensitive identifiers**

1 This document considers case to be significant in identifier comparison, and does not do any case folding. This requirement from UAX #31 does not apply to this document.

**E.7 R6 Filtered normalized identifiers**

1 If any characters are excluded from normalization, UAX #31 requires a precise specification of those exclusions.
2 This document does not make any such exclusions.

**E.8 R7 Filtered case-insensitive identifiers**

1 C++ identifiers are case sensitive, and therefore this requirement from UAX #31 does not apply.

**E.9 R8 Hashtag identifiers**

1 There are no hashtags in C++, so this requirement from UAX #31 does not apply.
Bibliography

[1] ISO 4217:2015, Codes for the representation of currencies


Cross-references

Each clause and subclause label is listed below along with the corresponding clause or subclause number and page number, in alphabetical order by label.

accumulate (27.10.3) 1457
adjacent.difference (27.10.12) 1464
adjustfield.manip (31.5.5.2) 1768
alg.adjacent.find (27.6.10) 1400
alg.all.of (27.6.1) 1394
alg.binary.search (27.8.4) 1432
alg.binary.search.general (27.8.4.1) 1432
alg.c.library (27.13) 1474
alg.clamp (27.8.10) 1450
alg.contains (27.6.4) 1395
alg.copy (27.7.1) 1409
alg.count (27.6.11) 1401
alg.ends.with (27.6.17) 1407
alg.equal (27.6.13) 1403
alg.fill (27.7.6) 1417
alg.find (27.6.6) 1397
alg.find.end (27.6.8) 1399
alg.find.first.of (27.6.9) 1399
alg.find.last (27.6.7) 1398
alg.fold (27.6.18) 1408
alg.foreach (27.6.5) 1395
alg.generate (27.7.6) 1418
alg.heap.operations (27.8.8) 1444
alg.heap.operations.general (27.8.8.1) 1444
alg.is.permutation (27.6.14) 1404
alg.lex.comparison (27.8.11) 1450
alg.mismatch (27.6.12) 1402
alg.modifying.operations (27.7) 1409
alg.move (27.7.2) 1412
alg.none.of (27.6.3) 1395
alg.nonmodifying (27.6) 1394
alg.nth.element (27.8.3) 1431
alg.partitions (27.8.5) 1434
alg.permutation.generators (27.8.13) 1452
alg.rand (27.12) 1473
alg.rand.general (27.12.1) 1473
alg.rand.generate (27.12.2) 1473
alg.random.sample (27.7.12) 1424
alg.random.shuffle (27.7.13) 1425
alg.replace (27.7.8) 1418
alg.req (25.3.7) 1146
alg.req.general (25.3.7.1) 1146
alg.req.ind.cmp (25.3.7.5) 1147
alg.req.ind.copy (25.3.7.3) 1146
alg.req.ind.move (25.3.7.2) 1146
alg.req.ind.swap (25.3.7.4) 1147
alg.req.mergeable (25.3.7.7) 1147
alg.req.permutable (25.3.7.6) 1147
alg.req.sortable (25.3.7.8) 1148
alg.reverse (27.7.10) 1422
alg.rotate (27.7.11) 1423
alg.search (27.6.15) 1405
alg.set.operations (27.8.7) 1439
alg.set.operations.general (27.8.7.1) 1439
alg.shift (27.7.14) 1425
alg.sort (27.8.2) 1427
alg.sorting (27.8) 1426
alg.sorting.general (27.8.1) 1426
alg.starts.with (27.6.16) 1407
alg.swap (27.7.3) 1413
alg.three.way (27.8.12) 1451
alg.transform (27.7.4) 1413
alg.unique (27.7.9) 1420
algorithm.stable (16.4.6.8) 520
algorithm.syn (27.4) 1352
algorithms (Clause 27) 1347
algorithms.general (27.1) 1347
algorithms.parallel (27.3) 1349
algorithms.parallel.defns (27.3.1) 1349
algorithms.parallel.exceptions (27.3.4) 1351
algorithms.parallel.exec (27.3.3) 1350
algorithms.parallel.overloads (27.3.5) 1352
algorithms.parallel.user (27.3.2) 1350
algorithms.requirements (27.2) 1347
algorithms.results (27.5) 1391
alloc.errors (17.6.4) 546
allocator.adaptor (20.5) 662
allocator.adaptor.cnstr (20.5.3) 664
allocator.adaptor.members (20.5.4) 665
allocator.adaptor.syn (20.5.1) 662
allocator.adaptor.types (20.5.2) 664
allocator.globals (20.2.10.3) 624
allocator.members (20.2.10.2) 624
allocator.requirements (16.4.4.6) 508
allocator.requirements.completeness (16.4.4.6.2) 514
allocator.requirements.general (16.4.4.6.1) 508
allocator.tag (20.2.7) 618
allocator.trait (20.2.9) 621
allocator.trait.general (20.2.9.1) 621
allocator.trait.members (20.2.9.3) 623
allocator.trait.other (20.2.9.4) 623
allocator.trait.types (20.2.9.2) 622
allocator.uses (20.2.8) 618
allocator.uses.construction (20.2.8.2) 618
allocator.uses.trait (20.2.8.1) 618
basic.stc.dynamic.allocation (6.7.5.5.2) 71
basic.stc.dynamic.deallocation (6.7.5.5.3) 72
basic.stc.dynamic.general (6.7.5.5.1) 70
basic.stc.inherit (6.7.5.6) 72
basic.stc.static (6.7.5.2) 69
basic.stc.thread (6.7.5.3) 70
basic.string (23.4.3) 875
basic.string.general (23.4.3.1) 875
basic.string.hash (23.4.6) 900
basic.string.literals (23.4.7) 900
basic.type.qualifier (6.8.5) 83
basic.types (6.8) 76
basic.types.general (6.8.1) 76
bidirectional.iterators (25.3.5.6) 1143
binary.search (27.8.4.5) 1434
bit (22.15) 852
bit.byteswap (22.15.4) 854
bit.cast (22.15.3) 853
bit.count (22.15.7) 854
bit.endian (22.15.8) 855
bit.general (22.15.1) 852
bit.pow.two (22.15.5) 854
bit.rotate (22.15.6) 854
bitmask.types (22.15.3) 859
bitset (22.9) 777
bitset.cons (22.9.2.2) 779
bitset.hash (22.9.3) 782
bitset.members (22.9.2.3) 780
bitset.operators (22.9.4) 782
bitset.syn (22.9.1) 777
bitwise.operations (22.10.11) 798
bitwise.operations.and (22.10.11.2) 798
bitwise.operations.general (22.10.11.1) 798
bitwise.operations.nor (22.10.11.5) 799
bitwise.operations.or (22.10.11.3) 798
bitwise.operations.xor (22.10.11.4) 798
byte.strings (16.3.3.3.4.2) 497
c.files (31.13) 1892
clocales (30.5) 1740
c.malloc (20.2.12) 625
c.math (28.7) 1545
c.math.abs (28.7.2) 1552
c.math.fpclass (28.7.5) 1552
c.math.hypot3 (28.7.3) 1552
c.math.lerp (28.7.4) 1552
c.math.rand (28.5.10) 1526
c.mb.wcs (23.5.6) 903
c.strings (23.5) 900
cassert.syn (19.3.2) 590
category.collate (30.4.5) 1727
category.type (30.4.2) 1709
category.type.general (30.4.2.1) 1709
category.messages (30.4.8) 1739
category.messages.general (30.4.8.1) 1739
category.monetary (30.4.7) 1733
category.monetary.general (30.4.7.1) 1733
category.numeric (30.4.3) 1717
category.numeric.general (30.4.3.1) 1718
category.time (30.4.6) 1728
category.time.general (30.4.6.1) 1728
cctype.syn (23.5.1) 900
cerrno.syn (19.4.2) 591
cfenv (28.3) 1475
cfenv.syn (28.3.1) 1475
cfenv.thread (28.3.2) 1476
cfloat.syn (17.3.7) 537
class (Clause 11) 277
class.access (11.8) 313
class.access.base (11.8.3) 316
class.access.general (11.8.1) 314
class.access.nest (11.8.8) 323
class.access.spec (11.8.2) 315
class.access.virt (11.8.6) 322
class.base.init (11.9.3) 324
class.ctor (11.4.10) 300
class.editor (11.9.5) 330
class.compare (11.10) 336
class.compare.default (11.10.1) 336
class.compare.secondary (11.10.4) 338
class.conv (11.4.8) 295
class.conv.ctor (11.4.8.2) 296
class.conv.fct (11.4.8.3) 297
class.conv.general (11.4.8.1) 295
class.copy.assign (11.4.6) 290
class.copy.ctor (11.4.5.3) 288
class.copy.elision (11.9.6) 333
class.dtor (11.4.5) 286
class.dtor.general (11.4.5.1) 286
class.default.ctor (11.4.5.2) 287
class.derived (11.7) 306
class.derived.general (11.7.1) 306
class.dtor (11.4.7) 293
class.eq (11.10.2) 337
class.expl.init (11.9.2) 324
class.free (11.4.11) 300
class.friend (11.8.4) 318

Cross-references © ISO/IEC 2111
<table>
<thead>
<tr>
<th>Cross-references</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>const.iterators.iterator (25.5.3.3)</td>
<td>1159</td>
</tr>
<tr>
<td>const.iterators.ops (25.5.3.5)</td>
<td>1161</td>
</tr>
<tr>
<td>const.iterators.types (25.5.3.4)</td>
<td>1161</td>
</tr>
<tr>
<td>constexpr.functions (16.4.6.7)</td>
<td>519</td>
</tr>
<tr>
<td>constraints (16.4.5)</td>
<td>514</td>
</tr>
<tr>
<td>constraints.overview (16.4.5.1)</td>
<td>514</td>
</tr>
<tr>
<td>container.adaptors (24.6)</td>
<td>1024</td>
</tr>
<tr>
<td>container.adaptors.format (24.6.13)</td>
<td>1070</td>
</tr>
<tr>
<td>container.adaptors.general (24.6.1.1)</td>
<td>1024</td>
</tr>
<tr>
<td>container.alloc.reqmts (24.2.2.5)</td>
<td>911</td>
</tr>
<tr>
<td>container.insert.return (24.2.6)</td>
<td>921</td>
</tr>
<tr>
<td>container.into.reqmts (24.2.2.1)</td>
<td>906</td>
</tr>
<tr>
<td>container.node (24.2.5)</td>
<td>919</td>
</tr>
<tr>
<td>container.node.cons (24.2.5.2)</td>
<td>920</td>
</tr>
<tr>
<td>container.node.dtor (24.2.5.3)</td>
<td>920</td>
</tr>
<tr>
<td>container.node.modifiers (24.2.5.5)</td>
<td>921</td>
</tr>
<tr>
<td>container.node.observers (24.2.5.4)</td>
<td>920</td>
</tr>
<tr>
<td>container.node.overview (24.2.5.1)</td>
<td>919</td>
</tr>
<tr>
<td>container.opt.reqmts (24.2.2.4)</td>
<td>906</td>
</tr>
<tr>
<td>container.reqmts (24.2.2.2)</td>
<td>907</td>
</tr>
<tr>
<td>container.requirements (24.2)</td>
<td>906</td>
</tr>
<tr>
<td>container.requirements.dataraces (24.2.3)</td>
<td>913</td>
</tr>
<tr>
<td>container.requirements.general (24.2.2.2)</td>
<td>906</td>
</tr>
<tr>
<td>container.rev.reqmts (24.2.2.3)</td>
<td>910</td>
</tr>
<tr>
<td>containers (Clause 24)</td>
<td>906</td>
</tr>
<tr>
<td>contents (16.4.2.2)</td>
<td>500</td>
</tr>
<tr>
<td>conv (7.3)</td>
<td>100</td>
</tr>
<tr>
<td>conv.array (7.3.3)</td>
<td>102</td>
</tr>
<tr>
<td>conv.bool (7.3.15)</td>
<td>105</td>
</tr>
<tr>
<td>conv.double (7.3.10)</td>
<td>104</td>
</tr>
<tr>
<td>conv.fctptr (7.3.14)</td>
<td>105</td>
</tr>
<tr>
<td>conv.fpint (7.3.11)</td>
<td>104</td>
</tr>
<tr>
<td>conv.fpprom (7.3.8)</td>
<td>104</td>
</tr>
<tr>
<td>conv.func (7.3.4)</td>
<td>102</td>
</tr>
<tr>
<td>conv.general (7.3.1)</td>
<td>101</td>
</tr>
<tr>
<td>conv.integral (7.3.9)</td>
<td>104</td>
</tr>
<tr>
<td>conv.lval (7.3.2)</td>
<td>101</td>
</tr>
<tr>
<td>conv.mem (7.3.13)</td>
<td>105</td>
</tr>
<tr>
<td>conv.prom (7.3.7)</td>
<td>103</td>
</tr>
<tr>
<td>conv.ptr (7.3.12)</td>
<td>105</td>
</tr>
<tr>
<td>conv.qual (7.3.6)</td>
<td>102</td>
</tr>
<tr>
<td>conv.rank (6.8.6)</td>
<td>83</td>
</tr>
<tr>
<td>conv.rval (7.3.5)</td>
<td>102</td>
</tr>
<tr>
<td>conventions (16.3.3)</td>
<td>495</td>
</tr>
<tr>
<td>conventions.general (16.3.3.1)</td>
<td>495</td>
</tr>
<tr>
<td>conversions.character (30.3.3.2)</td>
<td>1708</td>
</tr>
<tr>
<td>coro.generator (26.8)</td>
<td>1340</td>
</tr>
<tr>
<td>coro.generator.class (26.8.3)</td>
<td>1341</td>
</tr>
<tr>
<td>coro.generator.iterator (26.8.6)</td>
<td>1345</td>
</tr>
<tr>
<td>coro.generator.members (26.8.4)</td>
<td>1342</td>
</tr>
<tr>
<td>coro.generator.promise (26.8.5)</td>
<td>1342</td>
</tr>
<tr>
<td>coroutine.generator.overview (26.8.1)</td>
<td>1340</td>
</tr>
<tr>
<td>coroutine.handle (17.12.4)</td>
<td>566</td>
</tr>
<tr>
<td>coroutine.handle.compare (17.12.4.8)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.handle.con (17.12.4.2)</td>
<td>567</td>
</tr>
<tr>
<td>coroutine.handle.conv (17.12.4.3)</td>
<td>567</td>
</tr>
<tr>
<td>coroutine.handle.export.import (17.12.4.4)</td>
<td>567</td>
</tr>
<tr>
<td>coroutine.handle.general (17.12.4.1)</td>
<td>566</td>
</tr>
<tr>
<td>coroutine.handle.hash (17.12.4.9)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.handle.noop (17.12.5.2)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.handle.noop.address (17.12.5.2.6)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.handle.noop.conv (17.12.5.2.2)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.handle.noop.general (17.12.5.2.1)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.handle.noop.observers (17.12.5.2.3)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.handle.noop.promise (17.12.5.2.5)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.handle.noop.resumption (17.12.5.2.4)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.handle.observers (17.12.4.5)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.handle.promise (17.12.4.7)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.handle.resumption (17.12.4.6)</td>
<td>567</td>
</tr>
<tr>
<td>coroutine.noop (17.12.5)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.noop.coroutine (17.12.5.3)</td>
<td>569</td>
</tr>
<tr>
<td>coroutine.promise.noop (17.12.5.1)</td>
<td>568</td>
</tr>
<tr>
<td>coroutine.syn (17.12.2)</td>
<td>565</td>
</tr>
<tr>
<td>coroutine.trait (17.12.3)</td>
<td>565</td>
</tr>
<tr>
<td>coroutine.trait.general (17.12.3.1)</td>
<td>565</td>
</tr>
<tr>
<td>coroutine.trait.primary (17.12.3.2)</td>
<td>565</td>
</tr>
<tr>
<td>coroutine.trivial.awaits (17.12.6)</td>
<td>569</td>
</tr>
<tr>
<td>counted.iter.access (25.5.7.3)</td>
<td>1175</td>
</tr>
<tr>
<td>counted.iter cigars (25.5.7.6)</td>
<td>1177</td>
</tr>
<tr>
<td>counted.iter.const (25.5.7.2)</td>
<td>1174</td>
</tr>
<tr>
<td>counted.iter.cust (25.5.7.7)</td>
<td>1177</td>
</tr>
<tr>
<td>counted.iter.elem (25.5.7.4)</td>
<td>1175</td>
</tr>
<tr>
<td>counted.iter.nav (25.5.7.5)</td>
<td>1175</td>
</tr>
<tr>
<td>counted.iterator (25.5.7.1)</td>
<td>1173</td>
</tr>
<tr>
<td>cpp (Clause 15)</td>
<td>473</td>
</tr>
<tr>
<td>cpp.concat (15.6.4)</td>
<td>484</td>
</tr>
<tr>
<td>cpp.cond (15.2)</td>
<td>475</td>
</tr>
<tr>
<td>cpp.error (15.8)</td>
<td>486</td>
</tr>
<tr>
<td>cpp.import (15.5)</td>
<td>479</td>
</tr>
<tr>
<td>cpp.include (15.3)</td>
<td>477</td>
</tr>
<tr>
<td>cpp.line (15.7)</td>
<td>486</td>
</tr>
<tr>
<td>cpp.module (15.4)</td>
<td>478</td>
</tr>
<tr>
<td>cpp.null (15.10)</td>
<td>486</td>
</tr>
<tr>
<td>cpp pragma (15.9)</td>
<td>486</td>
</tr>
<tr>
<td>cpp pragma.op (15.12)</td>
<td>489</td>
</tr>
<tr>
<td>cpp.pre (15.1)</td>
<td>473</td>
</tr>
<tr>
<td>cpp predefined (15.11)</td>
<td>487</td>
</tr>
<tr>
<td>cpp replace (15.6)</td>
<td>480</td>
</tr>
<tr>
<td>cpp.replace.general (15.6.1)</td>
<td>480</td>
</tr>
<tr>
<td>cpp rescan (15.6.5)</td>
<td>485</td>
</tr>
<tr>
<td>cpp scope (15.6.6)</td>
<td>486</td>
</tr>
<tr>
<td>cpp stringify (15.6.3)</td>
<td>483</td>
</tr>
<tr>
<td>cpp subst (15.6.2)</td>
<td>482</td>
</tr>
<tr>
<td>csetjmp.syn (17.13.3)</td>
<td>570</td>
</tr>
<tr>
<td>csignal.syn (17.13.4)</td>
<td>570</td>
</tr>
<tr>
<td>cstdarg.syn (17.13.2)</td>
<td>570</td>
</tr>
<tr>
<td>cstddef.syn (17.2.1)</td>
<td>522</td>
</tr>
<tr>
<td>cstdint.syn (17.4.1)</td>
<td>538</td>
</tr>
<tr>
<td>cstdio.syn (31.13.1)</td>
<td>1893</td>
</tr>
<tr>
<td>cstdlib.syn (17.2.2)</td>
<td>523</td>
</tr>
<tr>
<td>cstring.syn (23.5.3)</td>
<td>901</td>
</tr>
<tr>
<td>ctime.syn (29.15)</td>
<td>1699</td>
</tr>
<tr>
<td>cuchar.syn (23.5.4)</td>
<td>903</td>
</tr>
<tr>
<td>customization.point.object (16.3.3.3.5)</td>
<td>497</td>
</tr>
<tr>
<td>cwchar.syn (23.5.4)</td>
<td>902</td>
</tr>
</tbody>
</table>
expr.cast (7.6.3) 147
expr.comma (7.6.20) 157
expr.compound (7.6) 125
expr.cond (7.6.16) 154
expr.const (7.7) 158
expr.const.cast (7.6.1.11) 135
expr.context (7.2.3) 100
expr.delete (7.6.2.9) 145
expr.dynamic.cast (7.6.1.7) 130
expr.eq (7.6.10) 152
expr.log.and (7.6.14) 154
expr.log.or (7.6.15) 154
expr.mptr.oper (7.6.4) 148
expr.mul (7.6.5) 149
expr.new (7.6.2.8) 140
expr.or (7.6.13) 153
expr.post (7.6.1) 125
expr.post.general (7.6.1.1) 125
expr.pre (7.1) 97
expr.pre.incr (7.6.1.6) 130
expr.post (7.6.1) 125
expr.post.general (7.6.1.1) 125
expr.pre (7.6.1) 125
expr.pre.incr (7.6.2.3) 138
expr.prim (7.5) 106
expr.prim.fold (7.5.7) 122
expr.prim.grammar (7.5.1) 106
expr.prim.id (7.5.5) 107
expr.prim.id.dtor (7.5.5.5) 111
expr.prim.id.general (7.5.5.1) 107
expr.prim.id.qual (7.5.5.3) 110
expr.prim.id.unqual (7.5.5.2) 109
expr.prim.lambda (7.5.6) 111
expr.prim.lambda.capture (7.5.6.3) 117
expr.prim.lambda.closure (7.5.6.2) 112
expr.prim.lambda.general (7.5.6.1) 111
expr.prim.literal (7.5.2) 106
expr.prim.req (7.5.8) 122
expr.prim.req.compound (7.5.8.4) 124
expr.prim.req.general (7.5.8.1) 122
expr.prim.req.nested (7.5.8.5) 125
expr.prim.req.simple (7.5.8.2) 123
expr.prim.req.type (7.5.8.3) 124
expr.prim.this (7.5.3) 107
expr.prop (7.2) 97
expr.ref (7.6.1.5) 128
expr.reinterpret.cast (7.6.1.10) 134
expr.rel (7.6.9) 151
expr.shift (7.6.7) 150
expr.sizeof (7.6.2.5) 139
expr.spaceship (7.6.8) 150
expr.static.cast (7.6.1.9) 132
expr.sub (7.6.1.2) 125
expr.throw (7.6.18) 156
expr.type (7.2.2) 99
expr.type.conv (7.6.1.4) 128
expr.typeid (7.6.1.8) 131
expr.unary (7.6.2) 136
expr.unary.general (7.6.2.1) 136
expr.unary.noexcept (7.6.2.7) 140
expr.unary.op (7.6.2.2) 136
expr.xor (7.6.12) 153
expr.yield (7.6.17) 155
eext.manip (31.7.8) 1801
extern.names (16.4.5.3.4) 516
extern.types (16.4.5.3.5) 516
facet.ctype.char.dtor (30.4.2.4.2) 1713
facet.ctype.char.members (30.4.2.4.3) 1713
facet.ctype.char.natives (30.4.2.4.4) 1713
facet.ctype.char.virtuals (30.4.2.4.5) 1714
facet.ctype.special (30.4.2.4) 1712
facet.ctype.special.general (30.4.2.4.1) 1712
facet.num.get.simple (30.4.3.2.3) 1719
facet.num.get.virtuals (30.4.3.3.2) 1722
facet.num.get.virtuals (30.4.3.3.3) 1722
facet.mumpunct (30.4.4) 1725
facet.mumpunct.members (30.4.4.1.2) 1726
facet.mumpunct.virtuals (30.4.4.1.3) 1726
file.native (31.10.2) 1829
file.streams (31.10) 1828
filebuf (31.10.3) 1829
filebuf.assign (31.10.3.3) 1831
filebuf.cons (31.10.3.2) 1831
filebuf.general (31.10.3.1) 1829
filebuf.members (31.10.3.4) 1831
filebuf.virtuals (31.10.3.5) 1833
filesystems (31.12) 1846
flat.map (24.6.9) 1037
flat.map.access (24.6.9.6) 1045
flat.map.capacity (24.6.9.5) 1045
flat.map.cons (24.6.9.3) 1043
flat.map.cons.alloc (24.6.9.4) 1044
flat.map.dfn (24.6.9.2) 1038
flat.map.erase (24.6.9.8) 1049
flat.map.modifiers (24.6.9.7) 1045
flat.map.overview (24.6.9.1) 1037
flat.map.syn (24.6.4) 1026
flat.map (24.6.10) 1049
flat.map.virtuals (24.6.10.3) 1055
flat.map.virtuals (24.6.10.4) 1055
flat.map.dfn (24.6.10.2) 1050
flat.map.erase (24.6.10.5) 1056
flat.map.overview (24.6.10.1) 1049
flat.set (24.6.12) 1063
flat.set (24.6.12.3) 1068
flat.set.dfn (24.6.12.2) 1064
flat.set.erase (24.6.12.6) 1070
flat.set.modifiers (24.6.12.5) 1069
flat.set.overview (24.6.12.1) 1063
flat.set (24.6.11) 1056
flat.set.cons (24.6.11.3) 1061
flat.set.cons (24.6.11.4) 1061
flat.set.dfn (24.6.11.2) 1057
flat.set.erase (24.6.11.6) 1063
flat.set.modifiers (24.6.11.5) 1062
flat.set.overview (24.6.11.1) 1056
pointer.traits.optmem (20.2.3.4) 616
pointer.traits.types (20.2.3.2) 616
pop.heap (27.8.8.3) 1444
predef.iterators (25.5) 1151
print.fun (31.7.10) 1803
print.syn (31.7.4) 1779
priority.queue (24.6.7) 1030
priqueue.cons (24.6.7.2) 1032
priqueue.cons.alloc (24.6.7.3) 1033
priqueue.members (24.6.7.4) 1034
priqueue.overview (24.6.7.1) 1030
priqueue.special (24.6.7.5) 1034
projected (25.3.6.4) 1145
propagation (17.9.7) 554
ptr.align (20.2.5) 617
ptr.launder (17.6.5) 547
push.heap (27.8.8.2) 1444
rand (28.5) 1483
rand.adapt (28.5.5) 1498
rand.adapt.disc (28.5.5.2) 1498
rand.adapt.general (28.5.5.1) 1498
rand.adapt.ibits (28.5.5.3) 1499
rand.adapt.shuf (28.5.5.4) 1500
rand.device (28.5.7) 1502
rand.dist (28.5.9.1) 1505
rand.dist.bern (28.5.9.3) 1507
rand.dist.bern.bernoulli (28.5.9.3.1) 1508
rand.dist.bern.bin (28.5.9.3.2) 1508
rand.dist.bern.geo (28.5.9.3.3) 1509
rand.dist.bern.negbin (28.5.9.3.4) 1510
rand.dist.general (28.5.9.1) 1505
rand.dist.norm (28.5.9.5) 1516
rand.dist.norm.cauchy (28.5.9.5.4) 1519
rand.dist.norm.chisq (28.5.9.5.3) 1518
rand.dist.norm.f (28.5.9.5.5) 1520
rand.dist.norm.lognormal (28.5.9.5.2) 1517
rand.dist.norm.normal (28.5.9.5.1) 1516
rand.dist.norm.t (28.5.9.5.6) 1520
rand.dist.pois (28.5.9.4) 1511
rand.dist.pois.exp (28.5.9.4.2) 1512
rand.dist.pois.extreme (28.5.9.4.5) 1515
rand.dist.pois.gamma (28.5.9.4.3) 1513
rand.dist.pois.poisson (28.5.9.4.1) 1511
rand.dist.pois.weibull (28.5.9.4.4) 1514
rand.dist.samp (28.5.9.6) 1521
rand.dist.samp.discrete (28.5.9.6.1) 1521
rand.dist.samp.pconst (28.5.9.6.2) 1523
rand.dist.samp.plinear (28.5.9.6.3) 1525
rand.dist.uni (28.5.9.2) 1505
rand.dist.uni.int (28.5.9.2.1) 1506
rand.dist.uni.real (28.5.9.2.2) 1506
rand.eng (28.5.4) 1493
rand.eng.general (28.5.4.1) 1493
rand.eng.lcong (28.5.4.2) 1494
rand.eng.mers (28.5.4.3) 1495
rand.eng.sub (28.5.4.4) 1496
rand.general (28.5.1) 1483
rand.predef (28.5.6) 1501
rand.req (28.5.3) 1486
rand.req.adapt (28.5.3.5) 1490
rand.req.dist (28.5.3.6) 1491
rand.req.eng (28.5.3.4) 1488
rand.req.genl (28.5.3.1) 1486
rand.req.seedseq (28.5.3.2) 1487
rand.req.unrg (28.5.3.3) 1488
rand.synopsis (28.5.2) 1484
rand.util (28.5.8) 1503
rand.util.canonical (28.5.8.2) 1505
rand.util.seedseq (28.5.8.1) 1503
random.access.iterators (25.3.5.7) 1143
range.access (26.3) 1195
range.access.begin (26.3.2) 1195
range.access.begin (26.3.4) 1196
range.access.end (26.3.3) 1196
range.access.end (26.3.5) 1196
range.access.end (26.3.7) 1226
range.access.object (26.7.2) 1224
range.adaptors (26.7) 1224
range.adaptors.general (26.7.1) 1224
range.adjacent (26.7.27) 1301
range.adjacent.iterator (26.7.27.3) 1302
range.adjacent.overview (26.7.27.1) 1301
range.adjacent.sentinel (26.7.27.4) 1305
range.adjacent.transform (26.7.28) 1306
range.adjacent.transform.iterator (26.7.28.3) 1308
range.adjacent.transform.overview (26.7.28.1) 1306
range.adjacent.transform.sentinel (26.7.28.4) 1310
range.adjacent.transform.view (26.7.28.2) 1306
range.adjacent.view (26.7.27.2) 1301
range.all (26.7.6) 1227
range.all.general (26.7.6.1) 1227
range.as.const (26.7.22) 1278
range.as.const.overview (26.7.22.1) 1278
range.as.const.view (26.7.22.2) 1279
range.as.rvalue (26.7.7) 1228
range.as.rvalue.overview (26.7.7.1) 1228
range.as.rvalue.view (26.7.7.2) 1229
range.cartesian (26.7.33) 1334
range.stride (26.7.32) 1328
range.stride.iterator (26.7.32.3) 1330
range.stride.overview (26.7.32.1) 1328
range.stride.view (26.7.32.2) 1329
range.subrange (26.5.4.1) 1204
range.subrange.access (26.5.4.3) 1206
range.subrange.ctor (26.5.4.2) 1206
range.subrange.general (26.5.4.1) 1204
range.take (26.7.10) 1239
range.take.overview (26.7.10.1) 1239
range.take.sentinel (26.7.10.3) 1241
range.take.view (26.7.10.2) 1239
range.take.while (26.7.11) 1242
range.take.while.overview (26.7.11.1) 1242
range.take.while.sentinel (26.7.11.3) 1243
range.take.while.view (26.7.11.2) 1242
range.transform (26.7.9) 1233
range.transform.iterator (26.7.9.3) 1234
range.transform.overview (26.7.9.1) 1233
range.transform.sentinel (26.7.9.4) 1238
range.transform.view (26.7.9.2) 1233
range.utility (26.5.1) 1202
range.utility.conv (26.5.7.1) 1208
range.utility.conv.adaptors (26.5.7.3) 1210
range.utility.conv.general (26.5.7.1) 1208
range.utility.conv.to (26.5.7.2) 1209
range.utility.general (26.5.1) 1202
range.utility.helpers (26.5.2) 1202
range.view (26.4.4) 1200
range.zip (26.7.25) 1290
range.zip.iterator (26.7.25.3) 1292
range.zip.overview (26.7.25.1) 1290
range.zip.sentinel (26.7.25.4) 1295
range.zip.transform (26.7.26) 1296
range.zip.transform.iterator (26.7.26.3) 1297
range.zip.transform.overview (26.7.26.1) 1296
range.zip.transform.sentinel (26.7.26.4) 1300
range.zip.transform.view (26.7.26.2) 1296
range.zip.view (26.7.25.2) 1290
ranges (Clause 26) 1186
ranges.general (26.1) 1186
ranges.syn (26.2) 1186
ratio (21.4) 695
ratio.arithmetic (21.4.4) 697
ratio.comparison (21.4.5) 697
ratio.general (21.4.1) 695
ratio.ratio (21.4.3) 696
ratio.si (21.4.6) 698
ratio.syn (21.4.2) 695
rcu.syn (33.11.2.2) 2027
re (Clause 32) 1896
re.alg (32.10) 1918
re.alg.match (32.10.2) 1918
re.alg.replace (32.10.4) 1921
re.alg.search (32.10.3) 1920
re.badexp (32.5) 1905
re.const (32.4) 1902
re.const.general (32.4.1) 1902
re.err (32.4.4) 1904
re.except (32.10.1) 1918
re.general (32.1) 1896
re.grammar (32.12) 1928
re.iter (32.11) 1922
re.matchflag (32.4.3) 1902
re.regex (32.7) 1907
re.regex.assign (32.7.3) 1910
re.regex.construct (32.7.2) 1909
re.regex.general (32.7.1) 1907
re.regex.locale (32.7.5) 1911
re.regex.nonnmb (32.7.7) 1911
re.regex.operations (32.7.4) 1911
re.regex.swap (32.7.6) 1911
re.register (32.11.1) 1923
re.register.cnstr (32.11.1.2) 1923
re.register.comp (32.11.1.3) 1924
re.register.deref (32.11.1.4) 1924
re.register.general (32.11.1.1) 1923
re.register.incr (32.11.1.5) 1924
re.req (32.2) 1896
re.results (32.9) 1913
re.results.acc (32.9.5) 1916
re.results.all (32.9.7) 1918
re.results.const (32.9.2) 1915
re.results.form (32.9.6) 1917
re.results.general (32.9.1) 1914
re.results.nonnmember (32.9.9) 1918
re.results.size (32.9.4) 1916
re.results.state (32.9.3) 1916
re.results.swap (32.9.8) 1918
re.submatch (32.8) 1911
re.submatch.general (32.8.1) 1911
re.submatch.members (32.8.2) 1912
re.submatch.op (32.8.3) 1912
re.syn (32.3) 1898
re.synopt (32.4.2) 1902
re.tokiter (32.11.2) 1925
re.tokiter.cnstr (32.11.2.2) 1927
re.tokiter.comp (32.11.2.3) 1927
re.tokiter.deref (32.11.2.4) 1927
re.tokiter.general (32.11.2.1) 1925
re.tokiter.incr (32.11.2.5) 1927
re.traits (32.6) 1905
readable.traits (25.3.2.2) 1129
reduce (27.10.4) 1457
reentrancy (16.4.6.9) 520
refwrap (22.10.6) 788
refwrap.access (22.10.6.4) 789
refwrap.assign (22.10.6.3) 789
refwrap.common.ref (22.10.6.8) 790
refwrap.comparisons (22.10.6.6) 789
refwrap.const (22.10.6.2) 789
refwrap.general (22.10.6.1) 788
refwrap.helpers (22.10.6.7) 790
refwrap.invoke (22.10.6.5) 789
replacement.functions (16.4.5.6) 516
requirements (16.4) 499
requirements.general (16.4.1) 499
res.on.arguments (16.4.5.9) 518
specialized.destroy (27.11.9) 1472
sstream.syn (31.8.1) 1805
stable.sort (27.8.2.2) 1428
stack (24.6.8) 1034
stack.cons (24.6.8.3) 1036
stack.cons.alloc (24.6.8.4) 1036
stack.defn (24.6.8.2) 1034
stack.mod (24.6.8.5) 1036
stack.ops (24.6.8.6) 1036
stack.special (24.6.8.7) 1037
stack.syn (24.6.3) 1026
stacktrace (19.6) 600
stacktrace.basic (19.6.4) 602
stacktrace.basic.cmp (19.6.4.4) 605
stacktrace.basic.cons (19.6.4.2) 604
stacktrace.basic.hash (19.6.6) 606
stacktrace.basic.mod (19.6.4.5) 605
stacktrace.basic.nonmem (19.6.4.6) 605
stacktrace.basic.obs (19.6.4.3) 604
stacktrace.entry (19.6.3) 601
stacktrace.entry.cmp (19.6.3.5) 602
stacktrace.entry.cons (19.6.3.2) 602
stacktrace.entry.obs (19.6.3.3) 602
stacktrace.entry.overview (19.6.3.1) 601
stacktrace.format (19.6.5) 606
stacktrace.general (19.6.1) 600
stacktrace.syn (19.6.2) 600
std.exceptions (19.2) 587
std.exceptions.general (19.2.1) 587
std.ios.manip (31.5.5) 1767
std.iterator.tags (25.4.2) 1148
std.modules (31.4.2.4) 501
stdalign.h.syn (17.14.4) 572
stdatomic.h.syn (33.5.12) 1980
stdbool.h.syn (17.14.5) 572
stdexcept.syn (19.2.2) 587
stdfloat.syn (17.4.2) 539
stmt.ambig (8.9) 176
stmt.block (8.4) 168
stmt.break (8.7.2) 174
stmt.cont (8.7.3) 174
stmt.dcl (8.8) 175
stmt.do (8.6.3) 172
stmt.expr (8.3) 168
stmt.for (8.6.4) 172
stmt.goto (8.7.6) 175
stmt.if (8.2) 168
stmt.iterator (8.6) 171
stmt.iterator.general (8.6.1) 171
stmt.jump (8.7) 173
stmt.jump.general (8.7.1) 174
stmt.label (8.2) 168
stmt.pre (8.1) 167
stmt.return (8.6.5) 173
stmt.return.coroutine (8.7.5) 175
stmt.select (8.5) 168
stmt.select.general (8.5.1) 168
stmt.stmt (Clause 8) 167
stmt.switch (8.5.3) 170
stmt.while (8.6.2) 172
stopcallback (33.3.5) 1938
stopcallback.cons (33.3.5.2) 1939
stopcallback.general (33.3.5.1) 1938
stopsource (33.3.4) 1936
stopsource.cons (33.3.4.2) 1937
stopsource.general (33.3.4.1) 1936
stopsource.member (33.3.4.3) 1938
stopsource.member.nonmembers (33.3.4.4) 1938
stoptoken (33.3.3) 1935
stoptoken.cons (33.3.3.2) 1935
stoptoken.general (33.3.3.1) 1935
stoptoken.member (33.3.3.3) 1936
stoptoken.nonmembers (33.3.3.4) 1936
stream.buffers (31.6) 1769
stream.iterators (25.6) 1770
stream.types (31.2.2) 1749
streambuf (31.6.3) 1770
streambuf.assign (31.6.3.4.1) 1773
streambuf.buffer (31.6.3.3.2) 1772
streambuf.cons (31.6.3.2) 1772
streambuf.general (31.6.3.1) 1770
streambuf.get.area (31.6.3.4.2) 1774
streambuf.locales (31.6.3.3.1) 1772
streambuf.members (31.6.3.3) 1772
streambuf.protected (31.6.3.4) 1773
streambuf.pub.get (31.6.3.3.3) 1773
streambuf.pub.back (31.6.3.3.4) 1773
streambuf.pub.put (31.6.3.3.5) 1773
streambuf.put.area (31.6.3.4.3) 1774
streambuf.reqts (31.6.2) 1769
streambuf.syn (31.6.1) 1769
streambuf.virt.buffer (31.6.3.5.2) 1774
streambuf.virt.get (31.6.3.5.3) 1775
streambuf.virt.locales (31.6.3.5.1) 1774
streambuf.virt.back (31.6.3.5.4) 1776
streambuf.virt.put (31.6.3.5.5) 1776
streambuf.virt.virtuals (31.6.3.5) 1774
string.access (23.4.3.6) 885
string.accessors (23.4.3.8.1) 892
string.append (23.4.3.7.2) 886
string.assign (23.4.3.7.3) 887
string.capacity (23.4.3.5) 883
string.classes (23.4) 872
string.classes.general (23.4.1) 872
string.cpp (23.4.4.2) 896
string.compare (23.4.3.8.4) 893
string.containsKey (23.4.3.8.5) 881
string.contains (23.4.3.8.7) 894
string.conversions (23.4.5) 898
string.copy (23.4.3.7.7) 891
string.endsWith (23.4.3.8.6) 894
string.erase (23.4.3.7.5) 889

Cross-references

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2130
Cross-references

thread.condition.condvarany.general (33.7.5.1) 2004
thread.condition.general (33.7.1) 2000
thread.condition.nonmember (33.7.3) 2000
thread.condvarany.intwait (33.7.5.3) 2006
thread.condvarany.wait (33.7.5.2) 2005
thread.coord (33.9) 2009
thread.coord.general (33.9.1) 2009
thread.general (33.1) 1931
thread.jthread.class (33.4.4) 1943
thread.jthread.class.general (33.4.4.1) 1943
thread.jthread.cons (33.4.4.2) 1944
thread.jthread.mem (33.4.4.3) 1945
thread.jthread.special (33.4.4.5) 1946
thread.jthread.stop (33.4.4.4) 1946
thread.latch (33.9.2) 2009
thread.latch.class (33.9.2.3) 2009
thread.latch.general (33.9.2.1) 2009
thread.lock (33.6.5) 1990
thread.lock.algorithm (33.6.6) 1998
thread.lock.general (33.6.5.1) 1990
thread.lock.guard (33.6.5.2) 1990
thread.lockscoped (33.6.5.3) 1991
thread.lock.shared (33.6.5.5) 1995
thread.lock.shared.cons (33.6.5.5.2) 1996
thread.lock.shared.general (33.6.5.5.1) 1995
thread.lock.shared.locking (33.6.5.5.3) 1997
thread.lock.shared.mod (33.6.5.5.4) 1998
thread.lock.shared.obs (33.6.5.5.5) 1998
thread.lock.unique (33.6.5.4) 1991
thread.lock.unique.cons (33.6.5.4.2) 1992
thread.lock.unique.general (33.6.5.4.1) 1991
thread.lock.unique.locking (33.6.5.4.3) 1993
thread.lock.unique.mod (33.6.5.4.4) 1994
thread.lock.unique.obs (33.6.5.4.5) 1995
thread.mutex (33.6) 1981
thread.mutex.class (33.6.4.2.2) 1984
thread.mutex.general (33.6.1) 1982
thread.mutex.requirements (33.6.4) 1982
thread.mutex.requirements.general (33.6.4.1) 1982
thread.mutex.requirements.mutex (33.6.4.2) 1982
thread.mutex.requirements.mutex.general (33.6.4.2.1) 1983
thread.once (33.6.7) 1989
thread.once.callonce (33.6.7.2) 1989
thread.once.onceflag (33.6.7.1) 1999
thread.req (33.2) 1931
thread.req.exception (33.2.2) 1931
thread.req.lockable (33.2.5) 1932
thread.req.lockable.basic (33.2.5.2) 1933
thread.req.lockable.general (33.2.5.1) 1932
thread.req.lockable.req (33.2.5.3) 1933
thread.req.lockable.shared (33.2.5.5) 1934
thread.req.lockable.shared.timed (33.2.5.6) 1934
thread.req.lockable.timed (33.2.5.4) 1933
thread.req.native (33.2.3) 1931
thread.req.paramname (33.2.1) 1931
thread.req.timing (33.2.4) 1931
thread.sema (33.8) 2007
thread.sema.cut (33.8.3) 2007
thread.sema.general (33.8.1) 2007
thread.sharedmutex.class (33.6.4.4.2) 1988
thread.sharedmutex.requirements (33.6.4.4) 1987
thread.sharedmutex.requirements.general (33.6.4.1) 1988
thread.sharedtimedmutex.class (33.6.4.5.2) 1989
thread.sharedtimedmutex.requirements (33.6.4.5) 1988
thread.sharedtimedmutex.requirements.general (33.6.4.5.1) 1988
thread.stoptoken (33.3) 1934
thread.stoptoken.intro (33.3.1) 1934
thread.stoptoken.syn (33.3.2) 1935
thread.syn (33.4.2) 1939
thread.thread.algorithm (33.4.3.8) 1943
thread.thread.assign (33.4.3.5) 1942
thread.thread.class (33.4.3) 1940
thread.thread.class.general (33.4.3.1) 1940
thread.thread.constructor (33.4.3.3) 1941
thread.thread.destructor (33.4.3.4) 1942
thread.thread.id (33.4.3.2) 1940
thread.thread.member (33.4.3.6) 1942
thread.thread.static (33.4.3.7) 1943
thread.thread.this (33.4.5) 1946
thread.threads (33.4) 1939
thread.threads.general (33.4.1) 1939
thread.timedmutex.class (33.6.4.3.2) 1985
thread.timedmutex.requirements (33.6.4.3) 1986
thread.timedmutex.requirements.general (33.6.4.3.1) 1985
time (Clause 29) 1609
time.12 (29.10) 1677
time.cal (29.8) 1646
time.cal.day (29.8.3) 1646
time.cal.day.members (29.8.3.2) 1647
time.cal.day.nonmembers (29.8.3.3) 1647
time.cal.dayoverview (29.8.3.1) 1646
time.cal.general (29.8.1) 1646
time.cal.last (29.8.2) 1646
time.cal.md (29.8.9) 1656
time.cal.md.members (29.8.9.2) 1657
time.cal.md.nonmembers (29.8.9.3) 1657
time.cal.mdoverview (29.8.9.1) 1656
time.cal.mdlast (29.8.10) 1657
time.cal.month (29.8.4) 1648
time.cal.month.members (29.8.4.2) 1649
time.cal.month.nonmembers (29.8.4.3) 1649
time.cal.monthoverview (29.8.4.1) 1648
time.cal.mwd (29.8.11) 1658
time.cal.mwd.members (29.8.11.2) 1659
time.cal.mwd.nonmembers (29.8.11.3) 1659
time.cal.mwdoverview (29.8.11.1) 1658
time.cal.mwdlast (29.8.12) 1659
time.cal.mwdlast.members (29.8.12.2) 1659

Cross-references

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2133
Cross-references from ISO C++ 2023

All clause and subclause labels from ISO C++ 2023 (ISO/IEC 14882:2023, Programming Languages — C++) are present in this document, with the exceptions described below.

container.gen.reqmts see container.requirements.general

depr.arith.conv.enum removed
depr.codecvt.syn removed
depr.conversions removed
depr.conversions.buffer removed
depr.conversions.general removed
depr.conversions.string removed
depr.default.allocators removed
depr.istrstream removed
depr.istrstream.cons removed
depr.istrstream.general removed
depr.istrstream.members removed
depr.locale.stdct removed
depr.locale.stdct.general removed
depr.locale.stdct.req removed
depr.mem.poly.allocators mem see mem.poly.allocators mem

depr.ostrstream removed
depr.ostrstream.cons removed
depr.ostrstream.general removed
depr.ostrstream.members removed
depr.res.on.required removed
depr.str.strstreams removed
depr.string.capacity removed
depr.str.stream removed
depr.strstream.cons removed
depr.strstream.dest removed
depr.strstream.general removed
depr.strstream.oper removed
depr.strstream.syn removed
depr.strstreambuf removed
depr.strstreambuf.cons removed
depr.strstreambuf.general removed
depr.strstreambuf.members removed
depr.strstreambuf.virtuals removed
depr.util.smartptr.shared.atomic removed

mismatch see alg.mismatch
Index

Constructions whose name appears in *monospaced italics* are for exposition only.

Symbols

- *, see operator, indirection, *see declarator*, pointer
- +, see operator, unary plus, *see operator*, addition
- ++, see operator, increment
- -, see operator, comma
- --, see operator, decrement
- ->, see operator, class member access
- ->*, see operator, pointer to member
- .*, see operator, pointer to member
- . . . , see ellipsis
- /, see operator, division
- : bit-field declaration, 300
  label specifier, 168
- ::, see operator, scope resolution
- ::*, see declarator, pointer-to-member
- <, see operator, less than
- <=, see operator, less than or equal to
- <=, see operator, three-way comparison
- =, see assignment operator
- ==, see operator, equality
- >, see operator, greater than
- >=, see operator, greater than or equal to
- >>, see operator, right shift
- ?; see operator, conditional expression
- [], see operator, subscripting, *see declarator*, array
- # operator, 481, 483
- ## operator, 484
- #define, 481
- #elif, 476
- #elifdef, 477
- #elifndef, 477
- #else, 477
- #endif, 477
- #error, see preprocessing directive, error
- #if, 476, 519
- #ifdef, 477
- #ifndef, 477
- #include, 477, 504
- #line, see preprocessing directive, line control
- #pragma, see preprocessing directive, pragma
- #undef, 486, 516
- %, see operator, remainder
- &, see operator, address-of, *see operator*, bitwise
  AND, *see declarator*, reference
- &&, see operator, logical AND
- ~, see operator, bitwise exclusive OR
- \, see backslash character
- {}
  block statement, 168
  class declaration, 277
  class definition, 277
  enum declaration, 241
  initializer list, 221
- _, see character, underscore
- __cplusplus, 487
- __cpp_aggregate_bases, 488
- __cpp_aggregate_nsdmi, 488
- __cpp_aggregate_paren_init, 488
- __cpp_alias_templates, 488
- __cpp_aligned_new, 488
- __cpp_attributes, 488
- __cpp_auto_cast, 488
- __cpp_binary_literals, 488
- __cpp_capture_star_this, 488
- __cpp_char8_t, 488
- __cpp_concepts, 488
- __cpp_conditional_explicit, 488
- __cpp_consteval, 488
- __cpp_constexpr, 488
- __cpp_constexpr_dynamic_alloc, 488
- __cpp_constexpr_in_decltype, 488
- __cpp_constinit, 488
- __cpp_declarator, 488
- __cpp_declaration, 488
- __cpp_designated_initializers, 488
- __cpp_enumerator_attributes, 488
- __cpp_explicit_this_parameter, 488
- __cpp_fold_expressions, 488
- __cpp_generic_lambdas, 488
- __cpp_guaranteed_copy_elision, 488
- __cpp_if_consteval, 488
- __cpp_if_constexpr, 488
- __cpp_impl_coroutine, 488
- __cpp_impl_destroying_delete, 488
- __cpp_impl_three_way_comparison, 488
- __cpp_implicit_move, 488
- **, see operator, indirection, *see declarator*, pointer
- *+, see operator, increment
- -+, see operator, decrement
- -+, see operator, subtraction
- ->, see operator, class member access
- ->*, see operator, pointer to member
- .*, see operator, pointer to member
- . . . , see ellipsis
- /, see operator, division
- : bit-field declaration, 300
  label specifier, 168
- ::, see operator, scope resolution
- ::*, see declarator, pointer-to-member
- <, see operator, less than
- <=, see operator, less than or equal to
- <=, see operator, three-way comparison
- =, see assignment operator
- ==, see operator, equality
- >, see operator, greater than
- >=, see operator, greater than or equal to
- >>, see operator, right shift
- ?; see operator, conditional expression
- [], see operator, subscripting, *see declarator*, array
- # operator, 481, 483
- ## operator, 484
- #define, 481
- #elif, 476
- #elifdef, 477
- #elifndef, 477
- #else, 477
- #endif, 477
- #error, see preprocessing directive, error
- #if, 476, 519
- #ifdef, 477
- #ifndef, 477
- #include, 477, 504
- #line, see preprocessing directive, line control
- #pragma, see preprocessing directive, pragma
- #undef, 486, 516
- %, see operator, remainder
- &, see operator, address-of, *see operator*, bitwise
  AND, *see declarator*, reference
- &&, see operator, logical AND
- ~, see operator, bitwise exclusive OR
- \, see backslash character
extended, 73
fundamental, 72
new-extended, 73
stricter, 73
stronger, 73
weaker, 73
alignment requirement
implementation-defined, 72
alignment-specifier, 257, 2049
alignof, 140
  keyword, 21, 37, 72, 73, 136, 140, 427, 428, 2041
allocated type, see type, allocated
allocation
  alignment storage, 143
  implementation-defined bit-field, 300
allocation function, 70
class-specific, 300
allocator-aware container, see container, allocator-aware
alternate form
format string, 830
alternative token, see token, alternative
ambiguity
  base class member, 46
  class conversion, 48
  declaration type, 182
  declaration versus cast, 201
  declaration versus expression, 176
  function declaration, 219
  member access, 46
  overloaded function, 339
  parentheses and, 141
ambiguous, 45
ambiguous conversion sequence, see conversion sequence, ambiguous
Amendment 1, 516
and
  keyword, 18, 21, 2035, 2095
  and-expression, 153, 2042
  and_eq
    keyword, 18, 21, 2035, 2095
anonymous union, 304
  member, see member, anonymous union
  variable, see variable, anonymous union
appearance-ordered, 94
appertain, 224, 258
argv, 93
argument, 3, 518, 519, 589
  access checking and default, 315
  binding of default, 215
  evaluation of default, 215, 216
  example of default, 214, 215
  function call expression, 3
  function-like macro, 3
  overloaded operator and default, 369
  reference, 127
  scope of default, 216
  template, 383
template instantiation, 3
throw expression, 3
type checking of default, 215
argument and name hiding
default, 216
argument and virtual function
default, 216
argument forwarding call wrapper, 787
argument list
  empty, 210
  variable, 210
argument passing, 127
  reference and, 226
argument substitution, see macro, argument substitution
argument type
  unknown, 210
argument-dependent lookup, see lookup, argument-dependent
argv, 93
arithmetic
  pointer, 149
  unsigned, 79
array
  backing, 232
  bound, 208
  const, 83
  delete, 145
  element, 208
  handler of type, 467
  new, 142
  parameter of type, 210
  sizeof, 140
  template parameter of type, 378
array
  as aggregate, 945
  contiguous storage, 945
  creation, 947
  initialization, 945, 946
  tuple interface to, 947
  zero sized, 946
array size
  default, 208
array type, 208
arrow operator, see operator, class member access
as-if rule, 11
asm
  implementation-defined, 254
  keyword, 21, 254, 2049
asm-declaration, 254, 2049
assembler, 254
assignment
  and lvalue, 157
  conversion by, 157
  copy, see assignment operator, copy
  move, 5, see assignment operator, move
  reference, 226
assignment operator
  copy, 286, 291–293
hidden, 292
implicitly declared, 291
non-trivial, 292
trivial, 292
virtual bases and, 293
move, 286, 291–293
hidden, 292
implicitly declared, 291
non-trivial, 292
trivial, 292
overloaded, 369
assignment-expression, 157, 2042
assignment-operator, 157, 2042
associated, 1934
associated constraints, 392
associative container, see container, associative
associative containers
exception safety, 930
requirements, 930
unordered, see unordered associative
containers
assumption, 259
asynchronous provider, 2014
asynchronous return object, 2014
at least as constrained, 394
at least as specialized as, see more specialized
atexit, 95
atomic
notifying operation, 1954
operation, 87–92
smart pointers, 1972–1977
waiting operation, 1954
eligible to be unblocked, 1954
atomic constraint, see constraint, atomic
identical, 390
attached
declaration, 267
entity, 59
attempt, 1505
attribute, 257–261
alignment, 259
carries dependency, 260
deprecated, 261
fallthrough, 261
indeterminate, 262
likely, 262
maybe unused, 263
no unique address, 265
nodiscard, 264
noretturn, 264
syntax and semantics, 257
unlikely, 262
attribute, 257, 2050
attribute-argument-clause, 257, 2050
attribute-declaration, 180, 2045
attribute-list, 257, 2050
attribute-namespace, 257, 2050
attribute-scoped-token, 257, 2050
attribute-specifier, 257, 2049
attribute-specifier-seq, 257, 2049
attribute-token, 257, 2050
attribute-using-prefix, 257, 2049
attributed-identifier, 179, 2044
attributed-identifier-list, 179, 2044
auto
keyword, 21, 112, 118, 151, 167, 173, 177,
195–198, 200–202, 209, 213, 214, 337,
438, 2046, 2074, 2081, 2090
automatic storage duration, see storage duration,
amagnetic
await expression
final, 238
initial, 238
await-expression, 138, 2041
B
backing array, see array, backing
backslash character, 25
bad_alloc, 144
bad_cast, 131
bad_typeid, 131
balanced-token, 257, 2050
balanced-token-seq, 257, 2050
cbarrier
phase synchronization point, 2011
barrier phase, 2011
base characteristic, 668
base class, 306, 307
dependent, 424
direct, 306
indirect, 306
non-virtual, 307
private, 316
protected, 316
public, 316
virtual, 307
base class subobject, 62
base prefix, 832
base-2 representation, 79
base-clause, 306, 2051
base-specifier, 306, 2052
base-specifier-list, 306, 2052
basic character set, see character set, basic
basic literal character set, see character set, basic
liter al
basic-c-char, 24, 2036
basic-s-char, 27, 2037
BasicFormatter, 835
behavior
conditionally-supported, 4, 11
default, 4, 494
erroneous, 4
implementation-defined, 5, 11
locale-specific, 5
observable, 11
on receipt of signal, 87
required, 7, 494

Index
Index

body
function, 234
Bond
James Bond, 119
bool
keyword, 21, 80, 101, 103–106, 112, 130, 137–140, 151, 152, 154, 163, 169, 181, 184, 185, 191, 469, 841, 2046, 2088, 2095
Boolean literal, 29
boolean literal, see literal, boolean
Boolean type, 80
boolean-literal, 29, 2038
bound argument entity, 787
bound arguments, 802
bound, of array, 208
brace-or-equal-initializer, 217, 2047
braced-init-list, 217, 2048
brains
names that want to eat your, 515
break
keyword, 21, 171, 174, 464, 2043
buckets, 931
built-in candidate, 344
built-in operators, see operators, built-in
byte, 62, 139
C
C
linkage to, 255
standard library, 3
c-char, 24, 2036
c-char-sequence, 23, 2036
C++ library headers
importable, 500
C++ library modules, 502
call
dependent, 422
nodiscard, 264
operator function, 368
call pattern, 787
call signature, 787
call wrapper, 787
forwarding, 787
perfect forwarding, 787
simple, 787
type, 787
call-compatible, 126
callable object, see object, callable
callable type, see type, callable, 804
candidate, 339
aggregate deduction, 349
usable, 340
candidate initializer, 385
capture
implicit, 118
capture, 117, 2039
capture-default, 117, 2039
capture-list, 117, 2039
Index

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2143

captured, 119
by copy, 120
by reference, 120
carries a dependency, 88
case
keyword, 21, 168, 170, 171, 176, 2043
cast
base class, 133
const, 135, 147
derived class, 133
dynamic, 130, 549
construction and, 333
destruction and, 333
integer to pointer, 134
lvalue, 132, 134
pointer to integer, 134
pointer-to-function, 134
pointer-to-member, 135
reference, 132, 135
reinterpret, 134, 147
integer to pointer, 134
lvalue, 134
pointer to integer, 134
pointer-to-function, 134
pointer-to-member, 135
reference, 135
static, 132, 147
lvalue, 132
reference, 132
undefined pointer-to-function, 134
cast-expression, 147, 2041
casting, 128
casting away constness, 136
catch, 464
keyword, 21, 464, 570, 2054
category tag, 1148
cats
interfering with canines, 548
<ccomplex>
absence thereof, 516, 2071
class
81, 277–338
abstract, 313
base, 516, 520, 521
cast to incomplete, 148
constructor and abstract, 313
current, 107
definition, 34
derived, 520
implicit-lifetime, 279
linkage of, 58
linkage specification, 256
local, see local class, 305
member function, see member function, class
nested, 302
polymorphic, 309
scope of enumerator, 243
standard-layout, 78, 278
templated, 376
trivial, 78, 278
trivially copyable, 78, 278
union-like, 305
unnamed, 185, 277
variant member of, 305
character, 3
decimal-point, 497
fill, 829
formatted as escaped, 838
multibyte, 497
null, 16
signed, 79
source file, 13
terminating null, 497
underscore, 20, 516
in identifier, 20
character literal, see literal, character
character sequence, 497
character set, 14–17
basic, 14
basic literal, 16, 62
execution, 497
translation, 14
character string, 27
character string literal, 483
character type, see type, character
character-literal, 23, 2036
checking
point of error, 419
syntax, 419
chunks, 658
<char>
absence thereof, 516, 2071
char
implementation-defined sign of, 79
keyword, 21, 24, 27, 63, 66, 76–80, 83, 84, 92,
99, 143, 181, 191, 226, 465, 1705, 1867,
2046, 2062
char-like object, 857
char-like type, 857
char16_t, see type, char16_t
keyword, 3, 21, 24, 27, 80, 84, 103, 104, 106,
139, 191, 192, 219, 226, 491, 705, 837,
903, 1847, 1857, 1957, 1957, 1966, 2046, 2072,
2080, 2095, 2103
char32_t, see type, char32_t
keyword, 3, 21, 24, 27, 80, 84, 103, 104, 106,
139, 191, 192, 219, 226, 491, 705, 837,
903, 1847, 1857, 1957, 1966, 2046, 2072,
2080, 2095, 2103
char8_t, see type, char8_t
keyword, 3, 21, 24, 27, 79, 80, 84, 103, 104,
106, 191, 192, 219, 226, 491, 705, 837,
904, 1847, 1857, 1957, 1957, 1966, 2046, 2066,
2103
<ccomplex>
absence thereof, 516, 2071
class, 81, 277–338
abstract, 313
base, 516, 520, 521
cast to incomplete, 148
constructor and abstract, 313
current, 107
definition, 34
derived, 520
implicit-lifetime, 279
linkage of, 58
linkage specification, 256
local, see local class, 305
member function, see member function, class
nested, 302
polymorphic, 309
scope of enumerator, 243
standard-layout, 78, 278
templated, 376
trivial, 78, 278
trivially copyable, 78, 278
union-like, 305
unnamed, 185, 277
variant member of, 305
class member access operator function, see operator function, class member access

class name
   elaborated, 192, 280
   point of declaration, 281
typedef, 185, 281
class object
   member, 283
   sizeof, 140
class object copy, see constructor, copy
class object initialization, see constructor
class scope, see scope, class
class-head, 277, 2050
class-head-name, 277, 2051
class-key, 277, 2051
class-name, 277, 2050
class-or-decltype, 306, 2052
class-specifier, 277, 2050
class-virt-specifier, 277, 2051
closure object, 112
closure type, 112
co-await, 138
   keyword, 21, 138, 156, 240, 368, 2066
co_return, 175
   keyword, 21, 110, 175, 238, 2066
co_yield, 155
   keyword, 21, 2066
code unit, 16
<codecvt>
   absence thereof, 516, 2060
coherence
   read-read, 90
   read-write, 90
   write-read, 90
   write-write, 90
coherence-ordered before, 1952
collating element, 4
comma operator, see operator, comma
comment, 17–18
   /* */. 18
   //, 18
common comparison type, 338
common initial sequence, 284
compare-expression, 150, 2042
comparison
   pointer, 152
   pointer to function, 152
   undefined pointer, 150
comparison category types, 557
comparison operator function, see operator function, comparison
compatible for subsumption, see subsumption, compatible for
compatible with
   shared_ptr, 636
compilation
   separate, 13
compiler control line, see preprocessing directive
compl
linkage of, 58
const object, see object, const
undefined change to, 190
const volatile object, see object, const volatile
const-default-constructible, 218
const-qualified, 83
const-volatile-qualified, 83
const_cast, see cast, const
keyword, 21, 75, 125, 127, 135, 136, 147, 148,
381, 418, 427, 428, 911, 1135, 2040, 2093
constant, 21, 107
enumeration, 242
null pointer, 105
constant destruction, see destruction, constant
constant expression, 158, see expression, constant
permitted result of, 163
constant initialization, 93
constant iterator, 1127
constant subexpression, 4
constant-expression, 158, 2042
constant-initialized, 158
consteval
keyword, 21, 93, 112, 114, 164, 169, 170, 182,
186, 187, 204, 285, 287, 312, 336, 405,
437, 2039, 2043, 2045, 2066
consteval if statement, see statement, consteval if
constexpr
keyword, 21, 33, 93, 112, 114, 161, 162, 164,
168–170, 173, 182, 186–188, 204, 217,
285, 287, 288, 290, 292, 293, 299, 336,
374, 405, 420, 437, 520, 532, 743, 788,
853, 1168, 1178, 1180, 2039, 2043, 2045,
2073, 2078, 2080, 2098
constexpr function, 187
constexpr if, 169
constexpr iterator, 1128
constexpr-suitable, 187
constexpr-unknown, 161
constinit
keyword, 21, 182, 188, 204, 2045, 2066
constituent expression, 85
constraint, 389
associated, see associated constraints
atomic, 390
fold expanded, 392
immediately-declared, 377
normalization, 393–394
satisfaction
atomic, 391
conjunction, 389
disjunction, 389
subsumption, 394
constraint-expression, 392, 2053
constraint-logical-and-expression, 375, 2052
constraint-logical-or-expression, 375, 2052
construction, 331–333
dynamic cast and, 333
member access, 331
move, 6
pointer to member or base, 332
typeid operator, 333
virtual function call, 332
constructor, 286
address of, 287
array of class objects and, 324
converting, 296
copy, 74, 286, 288–290, 498
elision, 333
implicitly declared, 289
non-trivial, 290
trivial, 290
default, 286, 287
non-trivial, 288
trivial, 288
delegating, 325
exception handling, see exception handling,
constructors and destructors
explicit call, 287
implicitly invoked, 288
inheritance of, 287
inherited, 250
move, 286, 288–290
elision, 333
implicitly declared, 289
non-trivial, 290
trivial, 290
non-trivial, 287
target, 325
union, 303
constructor, conversion by, see conversion,
user-defined
contained value
any, 753
optional, 729
variant, 742
container, 907
allocator-aware, 911
associative, 923
contiguous, 910
reversible, 910
sequence, 914
unordered associative, 931
contains a value
optional, 729
context
non-deduced, 456
type-only, 418
contextually converted constant expression of type
bool, see conversion, contextual
contextually converted to bool, see conversion,
contextual to bool
contextually implicitly converted, 101
contiguous container, see container, contiguous
continue
and handler, 464
and try block, 464
keyword, 21, 172, 174, 464, 2043
control line, see preprocessing directive

Index
control-flow-limited statement, see statement, control-flow-limited
control-line, 473, 2054
controlling expression, see expression, controlling
conventions, 495
lexical, 13–31
conversion
argument, 210
array-to-pointer, 102
better, 362
bool, 104
boolean, 106
class, 295
contextual, 101
contextual to bool, 101
contextual to constant expression of type bool, 163
deduced return type of user-defined, 298
derived-to-base, 357
floating to integral, 104
function pointer, 105
function-to-pointer, 102
implementation-defined pointer integer, 134
implicit, 101, 295
implicit user-defined, 296
inheritance of user-defined, 298
integer rank, 84
integral, 104
integral to floating, 104
lvalue-to-rvalue, 101, 2089
narrowing, 233
null member pointer, 105
null pointer, 105
overload resolution and, 353
overload resolution and pointer, 367
pointer, 105
pointer-to-member, 105
void*, 105
qualification, 103
return type, 174
standard, 101–106
temporary materialization, 102
to signed, 104
to unsigned, 104
user-defined, 295–297
usual arithmetic, 106
virtual user-defined, 298
conversion explicit type, see casting
conversion function, see conversion, user-defined, see function, conversion
conversion rank, 358
floating-point, 84
conversion sequence
ambiguous, 358
better, 362
implicit, 356
indistinguishable, 363
standard, 101
user-defined, 358
worse, 362
conversion-declarator, 297, 2051
conversion-function-id, 297, 2051
conversion-type-id, 297, 2051
converted bit-field, see bit-field, converted
converted constant expression, see expression, converted constant
converting constructor, see constructor, converting copy
class object, see constructor, copy, see assignment operator, copy
copy deduction candidate, 348
copy elision, see constructor, copy, elision
copy-initialization, 218
copy-list-initialization, 228
copyable_function::is-callable-from, 810
core constant expression, see expression, core constant
coroutine, 237
await expression, 238
promise type, 237
resumer, 238
suspend point, 139
coroutine return, see co_return
coroutine state, 238
coroutine-return-statement, 175, 2043
correspond, 40
corresponding object parameter, see object parameter, corresponding
corresponding overloads, 40
corresponding signature, see signature, corresponding
counted range, see range, counted
Cpp17Allocator, 508
Cpp17BasicLockable, 1933
Cpp17BidirectionalIterator, 1143
Cpp17BinaryTypeTrait, 668
Cpp17Clock, 1623
Cpp17CopyAssignable, 505
Cpp17CopyConstructible, 505
Cpp17CopyInsertable into X, 912
Cpp17DefaultConstructible, 505
Cpp17DefaultInsertable into X, 911
Cpp17Destructible, 505
Cpp17EmplaceConstructible into X from args, 912
Cpp17EqualityComparable, 505
Cpp17Erasable from X, 912
Cpp17ForwardIterator, 1143
Cpp17Hash, 508
Cpp17InputIterator, 1141
Cpp17Iterator, 1140
Cpp17LessThanComparable, 505
Cpp17Lockable, 1933
Cpp17MoveAssignable, 505
Cpp17MoveConstructible, 505
Cpp17MoveInsertable into X, 911
Cpp17NullablePointer, 507
Index
Index
decrement operator
  overloaded, see overloading, decrement operator
decrement operator function, see operator function, decrement
deducible template, see template, deducible
deduction
  class template argument, 398
  class template arguments, 128, 191, 198, 348
deduction substitution loci, 447
  placeholder type, 197
deduction guide
    freestanding item, 499
deduction substitution loci, 447
deduction-guide, 398, 2053
default
  keyword, 21, 168, 170, 171, 234, 2043, 2048
default access control, see access control, default
  argument overload resolution and, 353
default argument instantiation, 436
default constructor, see constructor, default
default member initializer, 283
  default memory resource pointer, 658
default template argument, see template argument, default
default-initialization, 218
default-inserted, 911
defaulted, 236
defered function, see function, deferred
definable item, see item, definable
define, 33
defined, 475
defined-macro-expression, 475, 2055
defining-type-id, 201, 2047
defining-type-specifier, 189, 2045
defining-type-specifier-seq, 189, 2045
definition, 33
  alternate, 517
class, 277, 282
class name as type, 279
  constructor, 234
coroutine, 237
declaration as, 181
deleted, 236
  function, 234–237
deleted, 236
  explicitly-defaulted, 235
local class, 305
  member function, 285
  namespace, 245
  nested class, 302
  program semantics affected by, 435
  pure virtual function, 313
  scope of class, 280
  static member, 299
  virtual function, 311
definition domain, 37
definitions, 3–9
deleter, 625
denormalized value, see number, subnormal
dependency-ordered before, 88
dependent base class, see base class, dependent
dependent call, see call, dependent
dependent member of the current instantiation,
  see current instantiation, dependent
  member of the
dependent name, see name, dependent
dereferenceable iterator, see iterator, dereferenceable
dereferencing, see indirection
derivation, see inheritance
derived class, 306–313
  most, see most derived class
derived object
  most, see most derived object
designated-initializer-clause, 217, 2048
designated-initializer-list, 217, 2048
designator, 217, 2048
destringization, 490
destroying operator delete, see operator delete, destroying
destruction, 331–333
  constant, 162
dynamic cast and, 333
  member access, 331
  pointer to member or base, 332
typeid operator, 333
  virtual function call, 332
destructor, 293, 498
  address of, 293
default, 293
  exception handling, see exception handling, constructors and destructors
  explicit call, 294
  implicit call, 294
  non-trivial, 294
  program termination and, 294
  prospective, 293
  pure virtual, 294
selected, 293
union, 303
virtual, 294
diagnosable rules, 10
diagnostic message, see message, diagnostic
diagonal, 1570
difference type, 1127
digit, 20, 2034
digit-sequence, 26, 2037
digraph, see token, alternative, 18
direct base class, see base class, direct
direct member, see member, direct
direct-initialization, 219
direct-list-initialization, 228
direct-non-list-initialization, 228
directed acyclic graph, see DAG
directive, preprocessing, see preprocessing
directive-introducing token, see token, directive-introducing
directory, 1846
directory-separator, 1854
discarded
declaration, 272
discarded statement, 169
discarded-value expression, 100
disjunction, 389
disqualifying declaration, see declaration, disqualifying
disqualifying parameter, see parameter, disqualifying
distribution, see random number distribution
do
keyword, 21, 171, 172, 2043
dogs
obliviousness to interference, 548
domain error, 1552
dominance
virtual base class, 47
dot
filename, 1855
dot operator, see operator, class member access
dot-dot
filename, 1855
double
keyword, 21, 26, 72, 80, 84, 104, 191, 841, 2046
dynamic binding, see function, virtual
dynamic extent, see extent, dynamic
dynamic initialization, see initialization, dynamic
dynamic type, see type, dynamic
dynamic_cast, see cast, dynamic
keyword, 21, 37, 66, 67, 75, 125, 130, 131, 147, 160, 328, 329, 333, 381, 418, 427, 465, 470, 549, 555, 571, 2040
E
E (complete elliptic integrals), 1554
E (incomplete elliptic integrals), 1555
ECMA-262, 1896
ECMAScript, 1903, 1928
Ei (exponential integrals), 1556
eligible special member function, see special member function, eligible
eligible to be unblocked, 1954
elision
copy, see constructor, copy, elision
copy constructor, see constructor, copy, elision
move constructor, see constructor, move, elision
ellipsis
conversion sequence, 128, 359
overload resolution and, 353
elliptic integrals
complete Π, 1554
complete E, 1554
complete K, 1553
incomplete Π, 1556
incomplete E, 1555
incomplete F, 1555
else
keyword, 21, 169, 170, 2043
else-group, 473, 2054
empty-declaration, 180, 2045
enclosed by statement, 167
enclosing scope, see scope, enclosing
enclosing statement, 167
enclosing-name-space-specifier, 245, 2049
encoded character type, 1847
encoding
literal, 16
ordinary literal, 16
registered character, 1742
alias, 1742
wide literal, 16
encoding-prefix, 23, 2036
end-of-file, 783
endif-line, 473, 2055
engine, see random number engine
game adaptor, see random number engine
game adaptor
entity, 32
associated, 51
belong, 39
freestanding item, 499
implicitly movable, 110
Index

©ISO/IEC 2150
explicit type conversion, see casting
explicit-instantiation, 437, 2053
explicit-object-parameter-declaration, 210
explicit-specialization, 439, 2053
explicit-specifier, 184, 2045
explicitly captured, 117
explicitly initialized elements
aggregate, 221
exponent-part, 26, 2037
exponential integrals Ei, 1556
export
keyword, 21, 267, 474, 478, 479, 2050, 2055, 2082
export-declaration, 267, 2050
exposure, 60
expr-or-braced-init-list, 217, 2048
expression, 97–166
additive operators, 149
alignof, 140
assignment and compound assignment, 157
await, 138
bitwise AND, 153
bitwise exclusive OR, 153
bitwise inclusive OR, 154
cast, 128, 147–148
class member access, 128
comma, 157
conditional operator, 154
const cast, 135
constant, 158, 163
controlling, 171
converted constant, 163
core constant, 158
decrement, 130, 138
delete, 145
destructor call, 111
domain, 574
dynamic cast, 130
equality operators, 152
equality-preserving, 574
equivalent, see equivalent, expressions
fold, 122
function call, 126
functionally equivalent, see functionally equivalent, expressions
immediate-escalating, 164
increment, 130, 138
integral constant, 162
lambda, 111–122
left-shift-operator, 150
logical AND, 154
logical OR, 154
multiplicative operators, 149
new, 140
noexcept, 140
order of evaluation of, 97(parenthesized, 107
pointer-to-member, 148
pointer-to-member constant, 137 postfix, 125–136
potentially constant evaluated, 166
potentially evaluated, 35
primary, 106–125
pseudo-destructor call, 111
reference, 99
reinterpret cast, 134
relational operators, 151
requires, 122–125
right-shift-operator, 150
rvalue reference, 98
sizeof, 139
spaceship, 150
static cast, 132
subscription, 126
three-way comparison, 150
throw, 156
type identification, 131
type-dependent, 422
unary, 136–140
unary operator, 136
value-dependent, 422
yield, 155
expression, 157, 2042
expression-equivalent, 5
expression-list, 125, 2040
expression-statement, 168, 2043
extend, see namespace, extend
extended alignment, see alignment, extended
extended integer type, see type, extended integer
extended signed integer type, see type, extended signed integer
extended unsigned integer type, see type, extended unsigned integer
extent
dynamic, 1079
static, 1079
extern, 182
keyword, 21, 33, 43, 58, 70, 183, 184, 204, 206, 226, 255, 257, 283, 437, 2045, 2049, 2053, 2087, 2089
linkage of, 183
extern "C", 504, 516
extern "C++", 504, 516
extern template, see instantiation, explicit
external linkage, see linkage, external
F
F (incomplete elliptic integrals), 1555
facet, 1705
fallback-separator, 1855
false
keyword, 21, 80, 104–106, 123, 124, 137–139, 151–154, 2095
feature-test macro, see macro, feature-test
field width
estimated, 828
minimum, 828
field width units, see units, field width
file, 1846
file attributes, 1873
   cached, 1873
file system, 1846
file system race, 1847
file, source, see source file
filename, 1855
filename, 1854
fill character, see character, fill
final, 20
   keyword, 20, 277, 281, 310, 2051
final await expression, see await expression, final
final overrider, 309
final suspend point, see suspend point, final
finite state machine, 5
float
   keyword, 21, 26, 80, 84, 104, 101, 841, 2046
floating-point conversion rank, see conversion rank, floating-point
floating-point literal, see literal, floating-point
floating-point promotion, 104
floating-point type, see type, floating-point
floating-point-literal, 25, 2037
floating-point-suffix, 26, 2037
fold
   binary, 122
   unary, 122
fold expanded constraint, see constraint, fold expanded
fold-expression, 122, 2040
fold-operator, 122, 2040
for
   keyword, 21, 43, 76, 167, 171–173, 1880, 2043, 2062
for-range-declaration, 171, 2043
for-range-initializer, 171, 2043
format specification
   format string, 828
format specifier, 5
format string, 827
Formatter, 836
formatter
   debug-enabled specialization of, 837
formatting locale, see locale, formatting
forward, 703
forward progress guarantees
   concurrent, 91
   delegation of, 92
   parallel, 91
   weakly parallel, 92
forwarding reference, 452
fractional-constant, 25, 2037
free store, see also delete, see also new, 300
freestanding deleted function, see function
   freestanding deleted
   freestanding implementation, see implementation, freestanding
   freestanding item, 498
friend
   virtual and, 311
   access specifier and, 320
   class access and, 319
   inheritance and, 320
   local class and, 321
   template and, 404
friend
   keyword, 21, 182, 186, 204, 281, 287, 293, 336, 2045, 2051
friend function
   access and, 318
   inline, 320
   linkage of, 58
   member function and, 318
   nested class, 303
friend-type-declaration, 281, 2051
friend-type-specifier, 282, 2051
friend-type-specifier-list, 281, 2051
full-expression, 85
function, see also friend function, see also inline
   function, see also member function, see also virtual function
   addressable, 514
   allocation, 71, 141
   conversion, 297
   deallocation, 72
   deferred, 2022
   definition, 34
   deleted, 236
   freestanding deleted, 498
   global, 516, 519
   handler, 5
   handler of type, 467
   immediate, 164
   immediate-escalating, 164
   inline, 188
   linkage specification overloaded, 256
   modifier, 5
   named by expression or conversion, 35
   needed for constant evaluation, 166
   non-template, 212
   observer, 6
   operator, 368
      template, 368
      overload resolution and, 340
   overloaded, see overloading
      parameter of type, 210
   pointer to member, 148
   program semantics affected by the existence
      of a function definition, 435
   replacement, 7
   reserved, 7
   template parameter of type, 378
   templated, 376
   viable, 339
   virtual, 308–312
   override, 309
   pure, 313
virtual function call, 126
virtual member, 516
waiting, 2014
function argument, see argument
function call, 127
    recursive, 128
    undefined, 134
function call operator
    overloaded, 370
function call operator function, see operator
    function, function call
function object, 783
    binders, 801–803
    mem_fn, 803
    reference_wrapper, 788
    type, 783
    wrapper, 803–815
function parameter, see parameter
function parameter pack, 401
function parameter scope, see scope, function
    parameter
function pointer type, 82
function return, see return
function return type, see return type
function try block, see exception handling
    function try block
function-body, 234, 2048
function-definition, 234, 2048
function-like macro, see macro, function-like
function-local predefined variable, see variable
    function-local predefined
function-specifier, 184, 2045
function-try-block, 464, 2053
function_ref::is-invocable-using, 813
functionally equivalent
    expressions, 411
    template-heads, 412
functions
    candidate, 429
fundamental alignment, see alignment,
    fundamental
fundamental type, 80
    destructor and, 295
fundamental type conversion, see conversion
    user-defined
future
    shared state, 2014

G
generated destructor, see destructor, default
generic lambda, 112
generic parameter type placeholder, 195
global module, see module, global
    global module fragment, 271
global namespace, see namespace, global
    global scope, see scope, global
    global-module-fragment, 271, 2050
glvalue, 98
goto
    and handler, 464
    and try block, 464
    initialization and, 175
    keyword, 21, 160, 172, 174, 175, 464, 2043
grammar, 2033
    regular expression, 1928
group, 473, 2054
    group-part, 473, 2054

H
H_n (Hermite polynomials), 1556
h-char, 19, 2034
h-char-sequence, 19, 2034
h-pp-tokens, 475, 2055
h-preprocessing-token, 475, 2055
handle
    native, 1829
    handler, see exception handling, handler
    handler, 464, 2054
    handler-seq, 464, 2053
    happens after, 89
    happens before, 89
    hard link, 1846
    has-attribute-expression, 475, 2055
    has-include-expression, 475, 2055
hash
    instantiation restrictions, 818
    hash code, 931
    hash function, 930
    hash tables, see unordered associative containers
hazard pointer, 2029
    associated, 2029
    unassociated, 2029
hazard-protectable, 2029
header, 500
    C, 516, 519, 573
    C library, 504
    C++ library, 500
    importable, 270
    name, 19
    header unit, 270
        preprocessing, 479
    header-name, 19, 2034
    header-name-tokens, 475, 2055
headers
    C library, 571
    heap with respect to comp and proj, 1444
Hermite polynomials H_n, 1556
hex-quad, 16, 2033
hexadecimal-digit, 22, 2036
hexadecimal-digit-sequence, 22, 2035
hexadecimal-escape-sequence, 24, 2036
hexadecimal-floating-point-literal, 25, 2037
hexadecimal-fractional-constant, 26, 2037
hexadecimal-literal, 22, 2035
hexadecimal-prefix, 22, 2035
high-order bit, 62
hosted implementation, see implementation, hosted
hosted library facilities, see library facilities, hosted

I
Iν (Bessel functions), 1554
id-expression, 108
id-expression, 108, 2038
identical
atomic constraints, see atomic constraint, identical
identifier, 19–20, 109, 180
identifier, 19, 2034
identifier-continue, 19, 2034
identifier-list, 474, 2055
identifier-start, 19, 2034
if
keyword, 21, 101, 169, 170, 172, 1483, 2043
if-group, 473, 2054
if-section, 473, 2054
ill-formed program, see program, ill-formed
immediate function, see function, immediate
immediate function context, 164
immediate invocation, 164
immediate scope, see scope, immediate
immediate subexpression, 85
immediate-escalating, 164
conversion, see conversion, immediate-escalating
expression, see expression, immediate-escalating
function, see function, immediate-escalating
implementation
freestanding, 10, 87, 92, 487, 502–504, 1952
hosted, 10, 487, 502
implementation limits, see limits, implementation
implementation-defined behavior, see behavior, implementation-defined
implementation-dependent, 438, 526, 1782, 1793
implementation-generated, 34
implicit conversion, see conversion, implicit
implicit conversion sequence, see conversion sequence, implicit
implicit object member function, see member function, implicit object
implicit object parameter, see object parameter, implicit
implicit-lifetime class, see class, implicit-lifetime
implicit-lifetime type, see type, implicit-lifetime
implicitly movable entity, see entity, implicitly movable
implicitly-declared default constructor, see constructor, default, 287
implied object argument, 340
implicit conversion sequences, 340
non-static member function and, 340
import, 270
import, 20, 504
keyword, 18, 20, 474, 479, 2055
importable C++ library headers, see C++ library headers, importable
importable header, see header, importable inclusion
conditional, see preprocessing directive, conditional inclusion
source file, see preprocessing directive, source-file inclusion
inclusive-or-expression, 154, 2042
incomplete, 149
incomplete type, see type, incomplete
incompletely-defined object type, see object type, incompletely-defined
increment operator
overloaded, see overloading, increment operator
increment operator function, see operator function, increment
incrementable, 1136
indeterminate value, see value, indeterminate
indeterminately sequenced, 86
index
multidimensional, 1077
index space
multidimensional, 1077
indirect base class, see base class, indirect
indirection, 136
inheritance, 306
using-declaration and, 250
init-capture, 117, 2040
init-capture pack, 121, 401
init-declarator, 199, 2046
init-declarator-list, 199, 2046
init-statement, 167, 2043
initial await expression, see await expression, initial
initial suspend point, see suspend point, initial
initialization, 93, 217–234
aggregate, 221
array, 221
array of class objects, 225, 324
automatic, 175, 176
base class, 325, 326
by inherited constructor, 329
character array, 226
class object, see also constructor, 221,
324–330
const, 189, 220
const member, 326
constant, 93
constructor and, 324
copy, 218
default, 217
default constructor and, 324
definition and, 181
direct, 218
dynamic, 93

Index ©ISO/IEC 2154
Index

N4986

dynamic block-scope, 176
dynamic non-block, 94
explicit, 324
jump past, 175
list-initialization, 228–234
local static, 176
local thread_local, 176
member, 325
member function call during, 328
member object, 326
order of, 94, 307
order of base class, 327
order of member, 327
order of virtual base class, 327
overloaded assignment and, 324
parameter, 126
reference, 206, 226
reference member, 326
static, 93
static and thread, 93
static member, 299
union, 225
vacuous, 65
virtual base class, 290
zero-initialization, 93, 217
initializer
  base class, 234
  member, 234
  pack expansion, 329
  scope of member, 328
  temporary and declarator, 74
initializer, 217, 2047
initializer-clause, 217, 2048
initializer-list, 217, 2048
initializer-list constructor, 229
initializing declaration, 220
injected-class-name, 277
inline, 519
inline
  keyword, 21, 93, 182, 188, 204, 245, 246, 285,
  287, 293, 374, 405, 437, 517, 2045, 2049
  linkage of, 58
inline function, see function, inline, 188
inline namespace, see namespace, inline
inline namespace set, 246
inline variable, see variable, inline
instantiation
  explicit, 437
  point of, 428
  template implicit, 433
instantiation context, 274
instantiation units, 14
int
  keyword, 21, 24, 78, 79, 82–84, 92, 99, 100,
  103, 104, 142, 191, 841, 1829, 2046, 2089,
  2092, 2093
  integer literal, see literal, integer
  integer type, 80
  integer-class type, see type, integer-class
integer-like, 1135
integer-literal, 22, 2035
integer-suffix, 22, 2036
integral constant expression, see expression, integral constant
integral promotion, 104
integral type, 80
  implementation-defined sizeof, 78
inter-thread happens before, 89
interface dependency, 271
internal linkage, see linkage, internal
invalid iterator, see iterator, invalid
invalid pointer value, see value, invalid pointer invocation
  macro, 481
invocation sequence, 600
INVOKED, 787
item
  definable, 34
  freestanding, see freestanding item
iteration statement
  trivially empty, 171
iteration-statement, 171, 174, 2043
iterator, 1127
  constexpr, 1128
  dereferenceable, 1127
  invalid, 1128
  past-the-end, 1127
J
  j_n (spherical Bessel functions), 1557
  J_n (Bessell functions), 1554
  Jessie, 296
jump-statement, 174, 2043
K
  K (complete elliptic integrals), 1553
  K_n (Bessell functions), 1555
key parameter, see parameter, key
  keyword, 20, 2033
  keyword, 20, 2035
  known to be initialized, 467
L
  L_n (Laguerre polynomials), 1556
  L^m_n (associated Laguerre polynomials), 1553
  label, 175
  case, 168, 170
  default, 168, 170
  scope of, 168
  label, 168, 2043
  label-seq, 168, 2043
  labeled-statement, 168, 2043
Laguerre polynomials
  L_n, 1556
  L^m_n, 1553
lambda scope, see scope, lambda
lambda-capture, 117, 2039

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2155
Index

lambda-declarator, 111, 2039
lambda-expression, 111, 2039
lambda-introducer, 111, 191, 2039
lambda-specifier, 112, 2039
lambda-specifier-seq, 112, 2039
language linkage, 255
lattice, see DAG, see subobject layout
  bit-field, 300
class object, 284, 307
layout mapping, 1082
layout mapping policy, 1084
layout-compatible
class, 284
enumeration, 243
layout-compatible type, see type, layout-compatible
left shift
  undefined, 150
left shift operator, see operator, left shift
left-pad, 842
Legendre functions $Y^m_\ell$, 1557
Legendre polynomials
  $P_\ell$, 1556
  $P^m_\ell$, 1553
letter, 497
lexical conventions, see conventions, lexical
LIA-1, 532
library
  C standard, 492, 497, 500, 504, 571, 2094, 2095
  C++ standard, 491, 516–518, 520, 521
library call
  non-constant, 6
library clauses, 12
library facilities
  hosted, 502
lifetime, 65
limits
  implementation, 5
line number, 486
line splicing, 13
linear algebra linear algebra value types, see linear algebra value types, linear algebra
linear algebra value types
  linear algebra, 1571
link, 1846
linkage, 32, 33, 58–60
    const and, 58
    external, 58, 504, 516
    implementation-defined object, 257
    inline and, 58
    internal, 58
    module, 58
    no, 58, 59
  static and, 58
linkage specification, see specification, linkage
  linkage-specification, 255, 2049
list-initialization, 228

literal, 21–31, 107
  base of integer, 22
  boolean, 29
char16_t, 24
char32_t, 24
char8_t, 24
  character, 23, 24
    ordinary, 24
    UTF-16, 24
    UTF-32, 24
    UTF-8, 24
    wide, 24
  complex, 1483
  constant, 21
  float, 26
  floating-point, 25, 26
  integer, 21, 23
long, 22, 23
long double, 26
multicharacter, 24
narrow-character, 28
operator, 374
  raw, 374
  template, 374
  template numeric, 374
  template string, 374
pointer, 29
string, 26, 27
  char16_t, 27
  char32_t, 27
  narrow, 28
  ordinary, 27
  raw, 17, 27
  undefined change to, 28
  UTF-16, 27
  UTF-32, 27
  UTF-8, 27
  wide, 27
suffix identifier, 374
type of character, 24
type of floating-point, 26
type of integer, 23
unsigned, 22, 23
user-defined, 29

literal encoding, see encoding, literal
literal type, see type, literal
literal-operator-id, 374, 2052
living dead
  name of, 515
local class, see class, local
friend, 321
  member function in, 285
local entity, see entity, local
local scope, see scope, block
local variable
  destruction of, 174
locale, 1896, 1898, 1903
formatting, 1691

©ISO/IEC
2156
memory location, 62
memory management, see delete, see new
memory model, 62
message
diagnostic, 4, 10
minimum field width, see field width, minimum model
concept, 518
modifiable, 99
modification order, 88
module, 267
exported, 270
global, 267
named, 266
reserved name of, 266
module, 20
keyword, 18, 20, 473, 474, 478, 2054, 2055
module implementation unit, 266
module interface unit, 266
module linkage, see linkage, module
module partition, 266
module unit, 266
module unit purview, see purview, module unit
module-declaration, 266, 2050
module-file, 473, 2054
module-import-declaration, 270, 2050
module-name, 266, 2050
module-name-qualifier, 266, 2050
module-partition, 266, 2050
more constrained, 394
more cv-qualified, 83
more specialized, 408, 455
class template, 408
function template, 455
most derived class, 63
most derived object, 63
bit-field, 64
zero size subobject, 64
move
class object, see constructor, move, see assignment operator, move
move, 703
move-eligible, 110
move_only_function::is-callable-from, 807
multi-pass guarantee, 1139, 1143
multibyte character, see character, multibyte
multicharacter literal, see literal, multicharacter
multidimensional index, see index,
multidimensional
multidimensional index space, see index space,
multidimensional
multiple inheritance, 306, 307
virtual and, 311
multiple threads, see threads, multiple
multiplicative-expression, 149, 2041
mutable, 182
keyword, 21, 109, 112, 114, 121, 129, 137, 148,
183, 184, 190, 204, 299, 2039, 2045
mutable iterator, 1127
mutex types, 1983

N

n_n (spherical Neumann functions), 1557
N_\nu (Neumann functions), 1555
n-char, 14, 2033
n-char-sequence, 16, 2033
name, 20, 32, 60, 108
address of cv-qualified, 137
bound, 39
dependent, 422
elaborated
enum, 192
length of, 20
macro, see macro, name
predefined macro, see macro, predefined
qualified, 52, 53
reserved, 515
same, 32
terminal, 109
unqualified, 48, 49
zombie, 515
name class, see class name
name hiding, 42, 110, 175
using-declaration and, 253
name-declaration, 179, 2044
named module, see module, named
named-name-space-definition, 245, 2049
named-universal-character, 16, 2033
namespace, 500
alias, 247
definition, 245
extend, 245
global, 20, 245
inline, 246
unnamed, 246
namespace
keyword, 21, 245–247, 2049
namespace scope, see scope, namespace
namespace-alias, 247, 2049
namespace-alias-definition, 247, 2049
namespace-body, 245, 2049
namespace-definition, 245, 2049
namespace-name, 245, 2049
namespacees, 245–249
NaN, 1552
narrow character type, see type, narrow character
narrowing conversion, see conversion, narrowing
native encoding, 1856
native handle, see handle, native
native pathname format, 1852
NDEBUG, 504
necessarily reachable, see reachable, necessarily needed
exception specification, 471
needed for constant evaluation, 166
nested class, see class, nested
local class, 306
nested within, 63
nested-name-specifier, 110, 2039
nested-namespace-definition, 245, 2049
nested-requirement, 125, 2040

Neumann functions
  Nν, 1555
  nν, 1557
new, 70, 140, 141
  array of class objects and, 144
  constructor and, 144
  default constructor and, 144
  exception and, 144
  initialization and, 144
  keyword, 21, 65, 70–72, 140–142, 144, 145,
    163, 201, 368, 427, 471, 544, 571, 634,
    2029, 2041
operator
  replaceable, 517
  scoping and, 142
  storage allocation, 140
  type of, 300
  unspecified constructor and, 144
  unspecified order of evaluation, 144
new-declarator, 141, 2041
new-expression, 140, 2041
  placement, 143
new-extended alignment, see alignment, new-extended
new-initializer, 141, 2041
new-line, 140, 2041
new-placement, 140, 2041
new-type-id, 141, 2041
new_handler, 71
  no linkage, see linkage, no
  node handle, 919
nodeclspec-function-declaration, 179, 2044
nodelistcall, see call, nodiscard
nodelistcall type, see type, nodiscard
noexcept, 140
  keyword, 21, 80, 86, 100, 105, 115, 124, 140,
    209, 359, 427, 428, 458, 459, 461, 469,
    471, 521, 649, 739, 751, 818, 1216, 1699,
    2040, 2041, 2054, 2071, 2080, 2083
noexcept-expression, 140, 2041
noexcept-specifier, 469, 2054
nominable, 42
non-initialization odr-use, see odr-use, non-initialization
non-member candidate, 344
non-object parameter, see parameter, non-object
non-object-parameter-type-list, 211
non-shared lock, see lock, non-shared
non-static data member, see data member, non-static
non-static member, see member, non-static
non-static member function, see member function, non-static
non-template function, see function, non-template
non-throwing exception specification, 469
non-virtual base class, see base class, non-virtual
nondigit, 19, 2034
nonzero-digit, 22, 2035
noptr-abstract-declarator, 201, 2047
noptr-abstract-pack-declarator, 201, 2047
noptr-declarator, 200, 2046
noptr-new-declarator, 141, 2041
normal distributions, 1516–1521
normal form
  constraint, 393
  path, 1855
normalization
  constraint, see constraint, normalization
  path, see path, normalization
normative references, see references, normative
not
  keyword, 18, 21, 2035, 2095
not_eq
  keyword, 18, 21, 2035, 2095
notation
  syntax, 12
NTBS, 497
  empty, 497
  length, 497
  static, 497
  value, 497
NTCTS, 6
NTMBS, 497
static, 497
null character, see character, null
null member pointer conversion, see conversion, null member pointer
null pointer conversion, see conversion, null pointer
null pointer value, see value, null pointer
null statement, see statement, null
null wide character, see wide-character, null
nullptr
  keyword, 21, 29, 239, 524, 543, 644, 661, 749,
    756, 920, 976, 1180, 1182, 1743, 1766,
number
  preprocessing, 19
  subnormal, 532, 534, 2099
numeric type, see type, numeric
numeric-escape-sequence, 24, 2036
numeric_limits, 530
O
object, see also object model, 32, 62
  byte copying and, 76–77
  callable, 787
  complete, 62
  const, 83
  const volatile, 83
  definition, 34
  destructor and placement of, 295
destructor static, 95
exception, see exception handling, exception
object
implicit creation, 64
linkage specification, 257
local static, 70
nested within, 63
nonzero size, 63
potentially non-unique, 64
providing storage for, 63
reified, 1195
suitable created, 64
unnamed, 287
volatile, 83
zero size, 63
object class, see class object
object expression, 129, 148
object lifetime, 65–68
object model, 62–65
object parameter, see parameter, object
corresponding, 40
implicit, 340
object pointer type, 82
object temporary, see temporary
object type, 78
incompletely-defined, 77
object-like macro, see macro, object-like
observable behavior, see behavior, observable
octal-digit, 22, 2035
octal-escape-sequence, 24, 2036
octal-literal, 22, 2035
odr-usable, 36
odr-use, 35
non-initialization, 94
one-definition rule, 34–39
opaque-enum-declaration, 241, 2048
operating system dependent, 1847
operator, 20–21, 368
**=, 157
+=, 157
-=, 157
/=, 157
<<=, 157
>>=, 157
%=, 157
&=, 157
^=, 157
|=, 157
addition, 149
additive, 149
address-of, 136
assignment, 157, 498
bitwise, 153
bitwise AND, 153
bitwise exclusive OR, 153
bitwise inclusive OR, 154
cast, 136, 201
class member access, 128
comma, 157
comparison
secondary, 338
conditional expression, 154
copy assignment, see assignment operator, copy
decrement, 130, 136, 138
defaulted comparison operator function, 336
division, 149
equality, 152
defaulted, 337
deleted, 336
function call, 126, 368
greater than, 151
greater than or equal to, 151
implementation, 368
increment, 130, 136, 138
indirection, 136
inequality, 152
defaulted, 338
left shift, 150
less than, 151
less than or equal to, 151
logical AND, 154
logical negation, 136, 137
logical OR, 154
move assignment, see assignment operator, move
multiplication, 149
multiplicative, 149
ośćes’ complement, 136, 137
overloaded, 97, 368
pointer to member, 148
 pragmac, see macro, pragma operator
precedence of, 97
relational, 151
defaulted, 338
remainder, 149
right shift, 150
scope resolution, 53, 110, 142, 285, 306, 312
side effects and comma, 158
side effects and logical AND, 154
side effects and logical OR, 154
sizeof, 136, 139
spaceship, 150
subscripting, 126, 368
subtraction, 149
three-way comparison, 150
defaulted, 337
deleted, 336
unary, 136
unary minus, 136, 137
unary plus, 136, 137
operator, 368, 2052
operator
keyword, 21, 65, 70–72, 76, 137, 138, 142, 146,
272, 297, 341, 343–347, 352, 354, 357,
364, 368–371, 374, 423, 425, 2029, 2051, 2052
operator delete
destroying, 72

operator delete, see also delete, 142, 146
operator function, see function, operator
  binary, 369
  class member access, 370
  comparison, 369
  decrement, 371
  equality, 369
  function call, 370
  increment, 370
  prefix unary, 369
  relational, 369
  simple assignment, 369
  subscripting, 370
  three-way comparison, 369
operator new, see also new, 142
operator overloading, see overloading, operator
operator use
  scope resolution, 299
operator-function-id, 368, 2052
operator-or-punctuator, 21, 2035
operators
  built-in, 97
  optimization of temporary, see temporary, elimination of
  optional object, 726
or
  keyword, 18, 21, 2035, 2095
or_eq
  keyword, 18, 21, 2035, 2095
order of evaluation in expression, see expression, order of evaluation of
order of execution
  base class constructor, 288
  base class destructor, 294
  constructor and array, 324
  constructor and static data members, 324
  destructor, 294
  destructor and array, 294
  member constructor, 288
  member destructor, 294
ordering
  function template partial, see template, function, partial ordering
  ordinary character type, see type, ordinary character
  ordinary literal encoding, see encoding, ordinary literal
  over-aligned type, see type, over-aligned
  overflow, 97
  undefined, 97
overload resolution, 339
overload set, 45
overloaded function, see overloading
  address of, 137, 366
overloaded operator, see overloading, operator
  inheritance of, 368
overloading, 212, 280, 339–373, 410
  address of overloaded function, 366
  argument lists, 340–353
assignment operator, 369
binary operator, 369
built-in operators and, 371
candidate functions, 340–353
decrement operator, 371
degenerate of, 339
function call operator, 370
increment operator, 370
member access operator, 370
operator, 368–371
resolution, 339–366
  best viable function, 353–369
  better viable function, 353
  contexts, 339
  function call syntax, 341–343
  function template, 462
  implicit conversions and, 356–366
  initialization, 347, 348
  operators, 344
  template, 412
  viable functions, 353–369
  subscripting operator, 370
  user-defined literal, 373
  using directive and, 249
  using-declaration and, 253
overloads
  floating-point, 1483
  override, see function, virtual, override
override, 20
  keyword, 20, 281, 310, 2051
overrider
  final, 309
own, 625
owning
  hazard pointer, 2031
P
  $P_l$ (Legendre polynomials), 1556
  $P_l^m$ (associated Legendre polynomials), 1553
  pack, 401
    unexpanded, 402
    pack expansion, 401
    pattern, 401
  pack-index-expression, 111, 2039
  pack-index-specifier, 191, 2046
  padding bits, 77
  padding width, see width, padding
pair
  tuple interface to, 706
parallel algorithm, 1349
parallel forward progress guarantees, 92
parameter, 6
  catch clause, 6
  disqualifying, 583
  explicit object, 211
  function, 6
  function-like macro, 6
key, 583
macro, 481
non-object, 211
object, 211
reference, 206
scope of, 44
template, 6, 33
void, 210
parameter declaration, 33
parameter list
variable, 128, 210
parameter mapping, 390
parameter-declaration, 210, 2047
parameter-declaration-clause, 209, 2047
parameter-declaration-list, 209, 2047
parameter-type-list, 210
parameterized type, see template
parameters-and-qualifiers, 200, 2046
parent directory, 1846
parent scope, see scope, parent
past-the-end iterator, see iterator, past-the-end
path, 1851
absolute, 1851
normalization, 1855
relative, 1851
path equality, 1866
path-format-spec, 1866
pathname, 1852
pathname, 1854
pathname resolution, 1852
pattern, see pack expansion, pattern
perfect forwarding call wrapper, see call wrapper,
perfect forwarding
period, 497
permissible types, see types, permissible
phase completion step, 2011
phase synchronization point, see barrier, phase
synchronization point
phases of translation, see translation, phases
Π (complete elliptic integrals), 1554
Π (incomplete elliptic integrals), 1556
piecewise construction, 708
placeholder type deduction, 197
placeholder-type-specifier, 195, 2046
placeholders
freestanding item, 803
placement new-expression, see new-expression,
placement
plain lock-free atomic operation, 571
pm-expression, 148, 2041
POD, 2100
point, 82
point of
macro definition, see macro, point of
definition
macro import, see macro, point of import
macro undefinition, see macro, point of
undefined
pointer, see also void*
composite pointer type, 99
strict total order, 5
zero, see value, null pointer
pointer literal, see literal, pointer
pointer past the end of, 82
pointer to, 82
pointer to member, 81, 148, 207
pointer-interconvertible, 82
pointer-literal, 29, 2038
Poisson distributions, 1511–1516
polymorphic class, see class, polymorphic
pool resource classes, 658
pools, 658
population, 1425
POSIX, 491
possibly-reclaimable, 2029
postfix ++ and --
overloading, 370
postfix ++, 130
postfix --, 130
postfix-expression, 125, 2040
potential results, 35
potentially concurrent, 90
potentially conflict, 41
potentially constant evaluated, 166
potentially evaluated, 35
potentially non-unique object, see object,
potentially non-unique
potentially-constant, 158
potentially-evaluated subexpression, see
subexpression, potentially-evaluated
potentially-overlapping subexpression, see
subexpression, potentially-evaluated
potentially-throwing
exception specification, 469
expression, 470
pp-global-module-fragment, 473, 2054
pp-import, 479, 2055
pp-module, 478, 2055
pp-module-name, 479
pp-module-name-qualifier, 479
pp-module-partition, 479
pp-number, 19, 2034
pp-private-module-fragment, 473, 2054
pp-tokens, 474, 2055
precede, see declaration, precede
precedence of operator, see operator, precedence
of
preferred-separator, 1855
prefix
L, 27
R, 27
prefix ++ and --
overloading, 370
prefix ++, 138
prefix --, 138
prefix unary operator function, see operator
function, prefix unary

Index
preprocessing, 475
preprocessing directive, 473–490
   conditional inclusion, 475
diagnostic, 486
error, 486
header inclusion, 477
import, 479
line control, 486
macro control, see macro replacement
module, 478
null, 487
pragma, 486
source-file inclusion, 477
warning, 486
preprocessing translation unit, see translation
unit, preprocessing
preprocessing-file, 473, 2054
preprocessing-op-or-punc, 20, 2035
preprocessing-operator, 20, 2035
preprocessing-token, 17, 2034
primary equivalence class, 6
primary module interface unit, 266
primary template, see template, primary
primary-expression, 106, 2038
private, see access control, private
   keyword, 21, 273, 306, 316, 317, 473, 2050,
   2052, 2054
private-module-fragment, 273, 2050
program, 58
   ill-formed, 5
   startup, 92–95
   termination, 95–96
   well-formed, 9, 11
program execution, 11, 84–96
   abstract machine, 11
   as-if rule, see as-if rule
program semantics
   affected by the existence of a variable or
   function definition, 435
projection, 6
promise object, 238
promise type, see coroutine, promise type
promoted integral type, 371
promotion
   bool to int, 104
   default argument promotion, 128
   floating-point, 104
   integral, 103
prospective destructor, see destructor, prospective
protected, see access control, protected
   keyword, 21, 306, 316, 2052
protection, see access control, 520
protection epoch, see epoch, protection
prototype parameter
   concept, 417
   provides storage, 63
prvalue, 98
pseudo-destructor, 111
ptr-abstract-declarator, 201, 2047
ptr-declarator, 200, 2046
ptr-operator, 200, 2047
ptrdiff_t, 150
   implementation-defined type of, 150
public, see access control, public
   keyword, 21, 306, 316, 317, 2052
punctuator, 20–21
pure-specifier, 281, 2051
purview
   global module, 267
   module unit, 267
   named module, 267
Q
q-char, 19, 2034
q-char-sequence, 19, 2034
qualification
   explicit, 52
qualification-combined type, see type,
   qualification-combined
qualification-decomposition, 103
qualified name, see name, qualified
qualified-id, 110, 2039
qualified-name-specifier, 247, 2049
R
r-char, 27, 2037
r-char-sequence, 27, 2037
random number distribution
   requirements, 1491–1493
random number distributions
   Bernoulli, 1508–1511
   normal, 1516–1521
   Poisson, 1511–1516
   sampling, 1521–1526
   uniform, 1506–1507
random number engine
   requirements, 1488–1490
   with predefined parameters, 1501–1502
random number engine adaptor
   with predefined parameters, 1501–1502
random number generation, 1483–1527
   distributions, 1505–1526
   engines, 1493–1501
   predefined engines and adaptors, 1501–1502
   requirements, 1486–1493
   synopsis, 1484–1486
   utilities, 1503–1505
random number generator, see uniform random
   bit generator
range, 1128
   accessible, 1104
   counted, 1128, 1275
   valid, 1128
   valid, 1128
rank, 1077
rank index, 1077
raw string literal, 27
Index

raw-string, 27, 2037
recu-protectable, 2026
reachable
declaraiton, 275
necessarily
translation unit, 275
translation unit, 275
reachable from, 1128
declaraiton, 275
ready, 1914, 2015
reclaimed, 2029
ref-qualifier, 200, 2047
reference, 81
assignment to, 157
call by, 127
forwarding, 451
lvalue, 81
null, 206
rvalue, 81
sizeof, 140
reference collapsing, 207
reference-compatible, 65
reference-related, 226
references
normative, 2
region of RCU protection, 2026
register
keyword, 20, 21, 2074, 2090
register storage class, 2074
registered character encoding, see encoding, registered character
regular expression, 1896–1930
grammar, 1928
matched, 5
requirements, 1896
regular expression traits, 1928
requirements, 1896, 1905
transform_primary, 1897, 1930
reified object, see object, reified
reinterpret_cast, see cast, reinterpret
keyword, 21, 75, 82, 125, 134, 135, 147, 148,
160, 381, 418, 427, 428, 2040
relational operator function, see operator function, relational
relational-expression, 151, 2042
relative path, see path, relative
relative-path, 1854
release sequence, 88
remainder operator, see operator, remainder
remote time zone database, 1680
replacement
macro, see macro, replacement
replacement field
format string, 827
replacement-list, 474, 2055
representation
object, 77
value, 77
represents the address, 82
requirement
compound, 124
nested, 125
simple, 123
type, 124
requirement, 122, 2040
requirement-body, 122, 2040
requirement-parameter-list, 122, 2040
requirement-seq, 122, 2040
requirements, 493
container, 906, 931, 945, 946, 1914
not required for unordered associated containers, 930
iterator, 1127
numeric type, 1475
random number distribution, 1491–1493
random number engine, 1488–1490
regular expression traits, 1896, 1905
seed sequence, 1487–1488
sequence, 1914
uniform random bit generator, 1488
unordered associative container, 931
requires
keyword, 21, 122–125, 375, 2040, 2052
requires-clause, 375, 2052
trailing, 200
requires-expression, 122, 2040
rescanning and replacement, see macro, rescanning and replacement
reserved identifier, 20
reset, 625
resolution, see overloading, resolution
restriction, 518, 519, 521
address of bit-field, 300
anonymous union, 304
bit-field, 300
constructor, 287
destructor, 293
extern, 183
local class, 306
operator overloading, 368
overloading, 368
pointer to bit-field, 300
reference, 206
static, 183
static member local class, 306
union, 303
result
glvalue, 99
prvalue, 99
result object, 99
rethrow, see exception handling, rethrow
retired, 2029
return, 174
and handler, 464
and try block, 464
constructor and, 174
Index

keyword, 21, 80, 93, 101, 112, 127, 174, 464, 466, 469, 2043
reference and, 226
return statement, see return
type, 212
covariant, 310
return-type-requirement, 124, 2040
reversible container, see container, reversible
rewritten candidate, 344
right shift operator, see operator, right shift
root-directory, 1854
root-name, 1854
rounding, 104
rvalue, 98
lvalue conversion to, see conversion,
lvalue-to-rvalue, 2089
rvalue reference, 206
S
s-char, 27, 2037
s-char-sequence, 26, 2037
sample, 1425
sampling distributions, 1521–1526
satisfy, see constraint, satisfaction
scalar type, see type, scalar
scope, 1, 32, 39–45, 180
anonymous union at namespace, 304
block, 43
class, 44
declarations and, see locus
destructor and exit from, 174
enclosing, 39
enumeration, 45
function parameter, 44
function prototype, see scope, function
parameter
global, 39
handler, 43
immediate, 39
inhabit, 39
intervene, 39
iteration-statement, 171
lambda, 44
macro definition, see macro, scope of
definition
name lookup and, see lookup, name
namespace, 44
parent, 39
search, 46
single, 46
selection-statement, 169
target, 39
template parameter, 45
scope resolution operator, see operator, scope
resolution
scoped enumeration, see enumeration, scoped
search, 46
single, 46
secondary comparison operator, 338
seed sequence, 1487
requirements, 1487–1488
selected destructor, see destructor, selected
selection-statement, 169, 2043
semantics
class member, 128
sentinel, 1128
separate compilation, see compilation, separate
separate translation, see compilation, separate
sequence
sorted
with respect to a comparator, 1427
with respect to a comparator and
projection, 1427
sequence container, see container, sequence
sequenced after, 86
sequenced before, 86
sequencing operator, see operator, comma
shared lock, see lock, shared, 1987
shared mutex types, 1987
shared state, see future, shared state
shared timed mutex type, 1988
shift operator
left, see operator, left shift
right, see operator, right shift
shift-expression, 150, 2041
short
keyword, 21, 78–80, 84, 191, 2046
typedef and, 182
side effects, 11, 74, 86, 88–90, 168, 327, 333, 482,
520
visible, 89
sign, 26, 2037
signal, 87
signal-safe
_exit, 540
abort, 540
evaluation, see evaluation, signal-safe
forward, 703
initializer_list functions, 556
memcpy, 902
memmove, 902
move, 703
move_if_noexcept, 703
numeric_limits members, 532
quick_exit, 541
signal, 571
type traits, 667
signature, 7, 8
corresponding, 40
signed
keyword, 21, 78–80, 84, 191, 2046
typedef and, 182
signed integer representation
two’s complement, 79, 243, 696, 1959, 1968
signed integer type, see type, signed integer
signed-integer-class type, see type,
signed-integer-class

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2165
signed-integer-like, 1135
significand, 26
similar types, 103
simple assignment operator function, see operator function, simple assignment
simple call wrapper, 787
simple-capture, 117, 2039
simple-declaration, 179, 2044
simple-escape-sequence, 24, 2036
simple-escape-sequence-char, 24, 2036
simple-hexadecimal-digit-sequence, 16, 2033
simple-ocital-digit-sequence, 24, 2036
simple-requirement, 123, 2040
simple-template-id, 380, 2053
simple-type-specifier, 191, 2046
simply happens before, 89
single search, see search, single
size of a multidimensional index space, 1077
size-suffix, 22, 2036
size_t, 140
sizeof keyword, 21, 37, 77, 136, 139, 140, 202, 427, 428, 2041, 2088
smart pointers, 634–649
source file, 13, 504, 516
source file character, see character, source file
special member function, see constructor, see assignment operator, see destructor eligible, 286
special-declaration, 179, 2044
specialization, 432
class template partial, 405
declared, 433
program-defined, 6
template, 431
template explicit, 439
specification
linkage, 255–257
extern, 255
implementation-defined, 255
nesting, 255
template argument, 444
specifications
C standard library exception, 521
C++, 521
specifier, 182–199
consteval, 186
constexpr, 186
function, 186, 187
cv-qualified, 189
declaration, 182
explicit, 184
friend, 186, 520
function, 184
inline, 188
storage class, 182
type, see type specifier
typedef, 185
virtual, 184
specifier access, see access specifier
spherical harmonics $Y_m^\ell$, 1557
stable algorithm, 8, 520
stack unwinding, 466
stacktrace, 600
stacktrace entry, 600
standard
structure of, 12
standard integer type, see type, standard integer
standard signed integer type, see type, standard signed integer
standard unsigned integer type, see type, standard unsigned integer
standard-layout class, see class, standard-layout
standard-layout struct, see struct, standard-layout
standard-layout type, see type, standard-layout
standard-layout union, see union, standard-layout
start
program, 94
startup
program, 504, 517
state, 753
state entity, 787
statement, 167–178
continue in for, 172
break, 174
compound, 168
consteval if, 170
continue, 174
control-flow-limited, 168
declaration, 175
declaration in switch, 171
declaration in while, 172
do, 171, 172
empty, 168
enclosed by, 167
enclosing, 167
expression, 168
fallthrough, 261
for, 171, 172
goto, 168, 174, 175
if, 168, 169
iteration, 171–173
jump, 174
labeled, 168
null, 168
range based for, 173
selection, 168–171
switch, 168, 170, 174
while, 171, 172
statement, 167, 2043
statement-seq, 168, 2043
static, 182
destruction of local, 176
keyword, 21, 58, 70, 93, 112, 114, 182, 183, 188, 204, 210, 282, 283, 299–301, 304, 532, 1963, 2039, 2045, 2089, 2090
linkage of, 58, 183
static data member, see data member, static
static extent, see extent, static
static initialization, see initialization, static
static member, see member, static
static member function, see member function, static
static storage duration, see storage duration, static
static type, see type, static
static_assert, 181
failed, 181
keyword, 21, 180, 2044, 2080, 2095
static_assert-declaration, 180, 2044
static_assert-message, 179, 2044
static_cast, see cast, static
keyword, 21, 37, 66, 75, 98, 125, 132–135, 147, 148, 218, 337, 381, 418, 419, 427, 428, 513, 1630, 2040
STATICALLY-WIDEN, 1609
<stdnoreturn.h>
absence thereof, 500, 2095
stop request, 1934
stop state, 1934
storage
reachable through a pointer value, 83
storage class, 32
storage duration, 69–72
automatic, 69, 70
class member, 72
dynamic, 69–71, 142
local object, 70
static, 69, 70
thread, 69, 70
storage management, see delete, see new
storage-class-specifier, 183, 2045
string
formatted as escaped, 838
null terminator, 875
null-terminated byte, see NTBS
null-terminated character type, 6
null-terminated multibyte, see NTMBS
type of, 27
string literal, see literal, string
string-literal, 26, 2037
stringize, see # operator
stringizing argument, 483
strongly happens before, 89
<stringstream>
absence thereof, 516, 2061
struct
standard-layout, 279
struct
keyword, 21, 193, 241, 277, 279, 280, 314, 316, 317, 680, 690, 711, 2048, 2051, 2087, 2090, 2093
structural type, see type, structural
structure tag, see class name
structured binding, 240
structured binding declaration, 180, 240
structured-binding-declaration, 179, 2044
sub-expression
regular expression, 8
subexpression, 85
potentially-evaluated, 85
subnormal number, see number, subnormal
subobject, see also object model, 62
initialized, known to be, 467
subscript expression, see expression, subscript
subscripting operator
overloaded, 370
subscripting operator function, see operator function, subscripting
subsequence rule
overloading, 363
substatement, 167
substitutability, 558
subsume, see constraint, subsumption
subsumption
compatible for, 392
subtraction
implementation-defined pointer, 150
subtraction operator, see operator, subtraction
suffix
F, 26
f, 26
L, 23, 26
l, 23, 26
U, 23
u, 23
suitable created object, see object, suitable created
summary
compatibility with C, 2085
compatibility with ISO C++ 2003, 2079
compatibility with ISO C++ 2011, 2077
compatibility with ISO C++ 2014, 2073
compatibility with ISO C++ 2017, 2065
compatibility with ISO C++ 2020, 2061
compatibility with ISO C++ 2023, 2058
syntax, 2033
surrogate call function, 343
suspend point, 139
final, 238
initial, 238
swappable, 506
swappable with, 505
switch
and handler, 464
and try block, 464
keyword, 21, 101, 167–171, 174, 176, 261, 2043, 2056
symbolic link, 1846
synchronize with, 88
synonym, 247
type name as, 185
syntax
class member, 128
synthesized three-way comparison, see three-way comparison, synthesized

T
target constructor, see constructor, target
target object, 787
target scope, see scope, target
template, 375–463
  alias, 415
class, 396
deducible, 191
deducible arguments of, 350
function, 443
  abbreviated, 212
corresponding object parameter, 40
corresponding signature, 40
key parameter of, 583
partial ordering, 412
member function, 397
primary, 396
static data member, 375
variable, 375
template, 375
template argument
default, 379
template instantiation, 431
template name
  linkage of, 376
template parameter, 33
template parameter object, 378
template parameter pack, 401
template parameter scope, see scope, template parameter
template-argument, 380, 2053
template-argument-equivalent, 395
template-argument-list, 380, 2053
template-declaration, 375, 2052
template-head, 375, 2052
template-id, 380, 2053
valid, 382
template-name, 380, 2053
template-parameter, 376, 2053
template-parameter-list, 375, 2052
templated, 376
templated class, see class, templated
templated function, see function, templated
templated variable, see variable, templated
temporary, 73
  constructor for, 74
destruction of, 74
destructor for, 74
elimination of, 73, 333
implementation-defined generation of, 73
order of destruction of, 74
terminal name, see name, terminal
terminal, 471, 472
called, 156, 466, 470, 471
termination
  program, 93, 96
terminology
  pointer, 82
text representation, 1941
text-line, 473, 2055
this, 107
thread, 87
thread of execution, 87
thread storage duration, see storage duration, thread
thread_local, 182
  keyword, 21, 70, 183, 204, 283, 299, 437, 439, 2045, 2080
threads
  multiple, 87–92
<threads.h>
  absence thereof, 500, 2095
three-way comparison
  synthesized, 337
three-way comparison operator function, see operator function, three-way comparison
throw, 156
  keyword, 3, 21, 156, 427, 2042
throw-expression, 156, 2042
throwing, see exception handling, throwing
timed mutex types, 1985
to-unsigned-like, 1195
token, 18
  alternative, 18
directive-introducing, 474
preprocessing, 17–18
token, 18, 2034
trailing requires-clause, see requires-clause, trailing
to-trailing-return-type, 200, 2047
traits, 8
transform
  regular expression traits, 1897, 1930
translation
  phases, 13–14
  separate, see compilation, separate
translation character set, see character set, translation
translation unit, 14, 58
  name and, 33
preprocessing, 13
to-trailing
translation-unit, 58, 2038
transparently replaceable, 67
triangle
  lower, 1570

Index
upper, 1570
trigraph sequence, 2073
trivial class, see class, trivial
trivial infinite loop, see loop, trivial infinite
trivial type, see type, trivial
trivially copyable class, see class, trivially copyable
trivially copyable type, see type, trivially copyable
trivially empty iteration statement, see iteration statement, trivially empty
true
keyword, 21, 80, 104–106, 123, 137, 139, 151–154, 158, 469, 471, 946, 968, 1857, 2095
truncation, 104
try
keyword, 21, 464, 466, 2053
try block, see exception handling, try block
try-block, 464, 2053
TU-local
tuple
and pair, 706
type, 32, 76–83
allocated, 140
arithmetic, 80
promoted, 371
array, 81
bitmask, 496, 497
Boolean, 80
callable, 787
char, 79
char16_t, 24, 27, 80, 84
cchar32_t, 24, 27, 80, 84
char8_t, 24, 79
charaet, 79, 80
character container, 4
class and, 277
compound, 81
const, 189
destination, 219
double, 80
dynamic, 4
enumerated, 496
example of incomplete, 77
extended integer, 79
extended signed integer, 78
extended unsigned integer, 79
float, 80
floating-point, 80
extended, 80
standard, 80
function, 81, 209, 210
fundamental, 80
implementation-defined sizeof, 78
implicit-lifetime, 78
incomplete, 34, 37, 42, 77, 101, 126, 128, 130, 137, 139, 140, 145, 306
incompletely-defined object, 77
int, 78
integer-class, 1135
integral, 80
promoted, 371
layout-compatible, 78
literal, 78
long, 78
long double, 80
long long, 78
narrow character, 79
nodiscard, 264
numeric, 1475
ordinary character, 79
over-aligned, 73
pointer, 81
polymorphic, 308
program-defined, 6
qualification-combined, 103
referenceable, 7
scalar, 78
short, 78
signed char, 78, 79
signed integer, 78
signed-integer-class, 1135
similar, see similar types
standard integer, 79
standard signed integer, 78
standard unsigned integer, 78
standard-layout, 78
static, 8
structural, 378
trivial, 78
trivially copyable, 76, 78
underlying, 79
char16_t, 80, 104
cchar32_t, 80, 104
cchar8_t, 79
enumeration, 103, 242
fixed, 242
wchar_t, 79, 104
unsigned, 78
unsigned char, 78, 79
unsigned int, 78
unsigned integer, 79
unsigned long, 78
unsigned long long, 78
unsigned short, 78
unsigned-integer-class, 1135
void, 80
volatile, 189
wchar_t, 24, 27, 79, 84
type checking
argument, 127
type concept, see concept, type
type conversion, explicit, see casting
type generator, see template
type name, 201
type pun, 135
type specifier
auto, 195
bool, 191
char, 191
char16_t, 191
char32_t, 191
cost, 189
dcltype, 193
dcltype(auto), 195
double, 191
eclaborated, 57, 192
enum, 192
float, 191
int, 191
long, 191
short, 191
signed, 191
simple, 190
unsigned, 191
void, 191
volatile, 189, 190
wchar_t, 191
type-accessible, 99
type-constraint, 377, 2053
type-id, 201, 2047
type-name, 191, 2046
type-only
  context, see context, type-only
  lookup, see lookup, type-only
type-parameter, 377, 2053
type-parameter-key, 377, 2053
type-requirement, 124, 2040
type-specifier, 189, 2045
type-specifier-seq, 189, 2045
type_info, 131
typedef
  function, 212
typedef
  keyword, 21, 33, 77, 181, 182, 185, 269, 1493, 1502, 1625, 1854
  typedef name for linkage purposes, 185
typedef-name, 185, 2045
  freestanding item, 499
typeid, 131
  construction and, 333
  destruction and, 333
  keyword, 21, 37, 67, 80, 118, 125, 131, 132, 160, 427, 428, 465, 470, 2040, 2080
typename, 192
  keyword, 21, 124, 191, 249, 250, 350, 377, 381, 418, 419, 425, 2040, 2049, 2053
typename-specifier, 418, 2053
types
  implementation-defined, 496
  permissible, 341

U

U
  keyword, 99
ud-suffix, 30, 2038
unary fold, 122
unary left fold, 122
unary operator
  interpretation of, 369
  overloaded, 369
unary right fold, 122
unary-expression, 136, 2041
unary-operator, 136, 2041
unblock, 8
undefined, 7, 515, 516, 518, 1537, 1541, 1544, 1545, 1763, 1798, 1804
undefined behavior, see behavior, undefined
underlying type, see type, underlying
unevaluated operand, 100
unevaluated-string, 29, 2038
uniform distributions, 1506–1507
uniform random bit generator
  requirements, 1488
union, 303
  standard-layout, 279
union, 81, 303
    anonymous, 304
    global anonymous, 304
    keyword, 21, 193, 277, 297, 303, 304, 314, 2051, 2090, 2093
union-like class, see class, union-like
unique pointer, 625
unit
  translation, 504, 516
units
    field width, 828
universal-character-name, 16, 2033
Unix time, 1636
unnamed bit-field, see bit-field, unnamed
unnamed class, see class, unnamed
unnamed-namespace-definition, 245, 2049
unordered associative container, see container, unordered associative
unordered associative containers, 931
    complexity, 930
    equality function, 930
    equivalent keys, 930, 931, 1008, 1019
    exception safety, 941
    hash function, 930
    iterator invalidation, 940
    iterators, 940
    lack of comparison functions, 930
    requirements, 930, 931, 940, 941
    unique keys, 930, 931, 1000, 1014
unordered_map
    element access, 1006
    unique keys, 1000
unordered_multimap
    equivalent keys, 1008
unordered_multiset
   equivalent keys, 1019
unordered_set
   unique keys, 1014
unqualified name, see name, unqualified
unqualified-id, 109, 2039
unscoped enumeration, see enumeration, unscoped
unsequenced, 86
unsigned
   keyword, 21, 63, 66, 76-80, 84, 99, 103, 104,
      143, 191, 226, 841, 2046, 2062
typedef and, 182
unsigned integer type, see type, unsigned integer
unsigned-integer-class type, see type,
   unsigned-integer-class
unsigned-integer-like, 1135
unsigned-suffix, 22, 2036
unspecified, 543, 544, 549, 1429, 1811
unspecified behavior, see behavior, unspecified
unwinding stack, 466
upper triangle, see triangle, upper
uppercase, 20, 497
upstream allocator, 658
usable
   binary operator expression, 336
usable candidate, see candidate, usable
usable in constant expressions, 158
user-defined conversion sequence, see conversion
   sequence, user-defined
user-defined literal, see literal, user-defined
overloaded, 373
user-defined-character-literal, 29, 2038
user-defined-floating-point-literal, 29, 2038
user-defined-integer-literal, 29, 2038
user-defined-literal, 29, 2038
user-provided, 236
uses-allocator construction, 618
using
   keyword, 21, 179, 244, 246, 247, 249, 257,
      2044, 2049
using-declaration, 249-254
using-declaration, 249, 2049
using-declarator, 249, 2049
using-declarator-list, 249, 2049
using-directive, 247-249
using-directive, 247, 2049
using-enum-declaration, 244, 2049
using-enum-declarator, 244, 2049
usual arithmetic conversions, see conversion, usual
   arithmetic
usual deallocation function, 72
UTF-16, 16, 226, 1857, 2086, 2103
UTF-32, 16, 226, 1857, 2086, 2103
UTF-8, 16, 62, 226, 860, 904, 1857, 2066, 2072,
   2086, 2103

V
va-opt-replacement, 482, 2055
vacuous initialization, see initialization, vacuous
valid but unspecified state, 9
valid in the context of, 82
valid range, see range, valid
value, 77
call by, 127
denormalized, see number, subnormal
erroneous, 68
indeterminate, 68
invalid pointer, 82
null member pointer, 105
null pointer, 82, 105
undefined unrepresentable integral, 104
valid in the context of an evaluation, 82
value category, 98
value computation, 74, 86-87, 90, 130, 144, 157
value type, 1127
value-initialization, 218
variable, 32
active, 175
anonymous union, 304
decision, 167
function-local predefined, 234
indeterminate uninitialized, 217
inline, 188
needed for constant evaluation, 166
program semantics affected by the existence
   of a variable definition, 435
templated, 376
variable arguments, 482
variable template
definition of, 375
variant member, 305
vectorization-unsafe, 1349
virt-specifier, 281, 2051
virt-specifier-seq, 281, 2051
virtual
   keyword, 21, 126, 184, 197, 204, 210, 293, 294,
      299, 306-308, 311, 336, 400, 521, 2045,
      2052
virtual base class, see base class, virtual
virtual function, see function, virtual, see function,
   virtual
virtual function call, 312
constructor and, 332
destructor and, 332
undefined pure, 313
visible side effects, see side effects, visible
void
   keyword, 21, 37, 66, 71-73, 77, 78, 80-83,
      98-100, 105, 126, 128-130, 132, 134, 135,
      137, 138, 145, 152, 154, 156, 160, 174,
      175, 191, 192, 196, 197, 206, 208, 210,
      212, 234, 264, 297, 299, 366, 378, 386,
      419, 447, 449, 450, 456, 466, 467, 494,
      561, 580, 590, 616, 639, 675, 677-683,
void*
  type, 83
void&. 206
volatile, 83
  constructor and, 287
destructor and, 293
  implementation-defined, 190
  keyword, 21, 83, 86, 90, 129, 200, 2047, 2093
volatile object, see object, volatile
volatile-qualified, 83

W
waiting function, see function, waiting
wchar_t, see type, wchar_t
  keyword, 3, 21, 24, 27, 79, 80, 84, 103, 104,
   106, 139, 191, 192, 219, 226, 489, 491,
   497, 523, 524, 705, 837, 848, 903, 1609,
   1705, 1726, 1749, 1752, 1829, 1847, 1854,
   1856, 1858, 1867, 1896, 1898, 1957, 1966,
   2046, 2072, 2086, 2095, 2103
weakly parallel forward progress guarantees, 92
well-formed program, see program, well-formed
while
whitespace, 17, 18
wide literal encoding, see encoding, wide literal
wide-character, 24
  null, 16
wide-character set
  execution, 497
width, 78, 300
  of integer-class type, 1135
  padding, 828
worse conversion sequence, see conversion
  sequence, worse

X
xor
  keyword, 18, 21, 2035, 2095
xor_eq
  keyword, 18, 21, 2035, 2095
xvalue, 98

Y
Y^n_l (spherical associated Legendre functions),
       1557
yield-expression, 155, 2042

Z
zero
  division by undefined, 97
  remainder undefined, 97
  undefined division by, 149
Index of grammar productions

The first bold page number for each entry is the page in the general text where the grammar production is defined. The second bold page number is the corresponding page in the Grammar summary (Annex A). Other page numbers refer to pages where the grammar production is mentioned in the general text.

abstract-declarator, 199, 201, 201, 202, 210, 213, 214, 2047
abstract-pack-declarator, 201, 2047
access-specifier, 306, 306, 315–317, 2052
additive-expression, 149, 2041
alias-declaration, 33, 42, 179, 185, 201, 211, 269, 272, 282, 375, 396, 415, 2044
alignment-specifier, 73, 257, 258, 259, 402, 403, 2049, 2092
and-expression, 153, 2042
asm-declaration, 160, 180, 254, 254, 2049
assignment-expression, 126, 157, 180, 197, 221, 240, 299, 324, 347, 590, 2042
assignment-operator, 157, 2042
attribute, 257, 258, 402, 2050
attribute-argument-clause, 257, 258–265, 2050
attribute-declaration, 33, 180, 182, 2045
attribute-list, 257, 258, 402, 2050
attribute-namespace, 257, 258, 2050
attribute-scoped-token, 257, 258, 2050
attribute-specifier, 257, 258, 2049, 2092
attribute-token, 20, 257, 258–265, 476, 516, 2050
attribute-using-prefix, 257, 258, 2049
attribute-identifier, 179, 204, 2044
attributed-identifier-list, 179, 240, 241, 2044
await-expression, 87, 138, 138, 139, 160, 237, 238, 570, 2041
balanced-token, 257, 2050
balanced-token-seq, 254, 257, 258, 2050
base-clause, 278, 306, 432, 2051
basic-c-char, 24, 25, 2036
basic-s-char, 27, 28, 2037
binary-digit, 22, 22, 2035
binary-exponent-part, 26, 26, 2037
binary-literal, 22, 23, 2035
block-declaration, 32, 179, 2044
boolean-literal, 29, 2038
brace-or-equal-initializer, 85, 181, 197, 217, 217, 218, 221, 282, 283, 287, 288, 299, 426, 2047
braced-init-list, 73, 85, 128, 142, 157, 166, 175, 197, 217, 218–221, 223, 228, 229, 232, 324, 326, 328, 349, 385, 422, 427, 2048, 2057, 2074
c-char, 24, 24, 2036
c-char-sequence, 13, 16, 23, 24, 25, 2036
capture, 117, 117, 402, 2039
capture-default, 36, 117, 117, 118, 120, 2039, 2067, 2097
capture-list, 117, 402, 2039
cast-expression, 122, 138, 147, 147, 148, 166, 301, 369, 402, 403, 428, 2041
character-literal, 16, 23, 24, 25, 476, 481, 483, 1711, 2036, 2077, 2086
class-head, 42, 259, 277, 277, 2050
class-head-name, 44, 110, 277, 277, 278, 2051
class-key, 57, 180, 193, 277, 277–279, 303, 317, 397, 2051
class-name, 12, 45, 180, 185, 193, 277, 277, 280, 281, 293, 2050
class-or-decltype, 53, 278, 306, 306, 325, 349, 418, 2052
class-specifier, 32, 42, 44, 46, 61, 180, 189, 277, 277, 283, 286, 2050
class-virt-specifier, 277, 278, 678, 2051
compare-expression, 150, 2042
compound-requirement, 124, 124, 125, 2040
computed-type-specifier, 52, 109–111, 138, 191, 294, 2046
concept-definition, 33, 43, 416, 416, 417, 2053
concept-name, 43, 60, 271, 377, 383, 416, 2053
conditional-escape-sequence, 24, 25, 29, 2037
conditional-escape-sequence-char, 24, 2037
conditional-expression, 4, 154, 154, 160, 2042
conditionally-supported-directive, 473, 474, 482, 2055
constant-expression, 3, 85, 111, 141, 158, 158, 165, 170, 171, 181, 184, 191, 208, 242, 259, 283, 300, 341, 386, 396, 469, 494, 2042

Index of grammar productions ©ISO/IEC 2173
<table>
<thead>
<tr>
<th>Production Type</th>
<th>Index Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-parameter, type-parameter-key, type-requirement</td>
<td>377, 124, 418, 2053</td>
</tr>
<tr>
<td>type-specifier, type-specifier-seq</td>
<td>141, 189, 2045</td>
</tr>
<tr>
<td>typedef-name</td>
<td>12, 124, 2053</td>
</tr>
<tr>
<td>unary-expression, unary-operator</td>
<td>131, 136, 2041</td>
</tr>
<tr>
<td>unevaluated-string</td>
<td>29, 2038</td>
</tr>
<tr>
<td>universal-character-name</td>
<td>13, 16, 29, 30, 374, 2033</td>
</tr>
<tr>
<td>unnamed-namespaces-definition</td>
<td>43, 245, 2049</td>
</tr>
<tr>
<td>unqualified-id</td>
<td>50, 53, 109, 29, 30, 374, 2039</td>
</tr>
<tr>
<td>unsigned-suffix</td>
<td>29, 2036</td>
</tr>
<tr>
<td>user-defined-character-literal</td>
<td>29, 30, 2038</td>
</tr>
<tr>
<td>user-defined-floating-point-literal</td>
<td>29, 30, 2038</td>
</tr>
<tr>
<td>user-defined-integer-literal</td>
<td>29, 30, 2038</td>
</tr>
<tr>
<td>user-defined-string-literal</td>
<td>16, 29, 30, 107, 2038</td>
</tr>
<tr>
<td>using-declarator</td>
<td>29, 30, 31, 374, 2038</td>
</tr>
<tr>
<td>using-declarator-list</td>
<td>249, 2049</td>
</tr>
<tr>
<td>using-directive</td>
<td>33, 155, 160, 237, 1344, 2042</td>
</tr>
<tr>
<td>using-enum-declaration</td>
<td>33, 244, 2049</td>
</tr>
<tr>
<td>va-opt-replacement</td>
<td>482, 2055</td>
</tr>
<tr>
<td>virt-specifier</td>
<td>281, 2051</td>
</tr>
<tr>
<td>yield-expression</td>
<td>138, 155, 2051</td>
</tr>
</tbody>
</table>
Index of library headers

The bold page number for each entry refers to the page where the synopsis of the header is shown.

<assert.h>, 504, 590, 2005
<assert.h>, 2005
<assert.h>, 504, 590, 2005
<assert.h>, 2005
<assert.h>, 504, 590, 2005
<assert.h>, 2005
<cassert>, 504, 590, 2005
<ctype.h>, 900, 1710
<cerrno>, 516, 528, 591, 594, 2100
<cfenv>, 1475, 1476, 2082
<cstdio>, 80, 526, 537, 538
<cmath>, 527, 530, 822, 2071, 2076
<chrono>, 527, 1609, 2082
<cinttypes.h>, 1894, 1895, 2082
<climits>, 62, 80, 526, 537, 537
<locale.h>, 1740, 2095
<cmath>, 527–529, 572, 1545, 1551, 1552, 2071
<compare>, 527, 530, 557, 2071
<complex>, 527, 572, 1476, 1477, 2071
<complex.h>, 572, 572, 573, 2095
<concepts>, 527, 575, 2071
<condition_variable.h>, 1701, 2095
<cstdlib>, 527, 565, 565, 2071
<csetjmp>, 516, 570, 570, 2096
<ctype.h>, 570, 571
<csignal>, 210, 516, 570, 570
<csignal>, 210, 516, 570, 570
<csignal>, 210, 516, 570, 570
<ctime>, 540, 1752–1754, 1759, 1832, 1893, 1894, 2095
<ctime>, 95, 96, 523, 524, 527, 540, 541, 544, 570, 573, 607, 625, 903, 1474, 1526, 1552, 1721, 2095, 2096
<ctime>, 497, 527, 902, 2095
<ctime>, 1699, 1700, 1702, 2095
<ctype.h>, 572, 900
<cuchar>, 516, 903, 903, 2082, 2095
<cuchar>, 516, 528, 860, 902, 903, 2095
<cwchar>, 516, 901
<debugging>, 517, 527, 856, 2059
<dequeue>, 526, 527, 529, 941, 942, 1183
<errno.h>, 572, 591
<exception>, 530, 552
<execution>, 527, 820, 821, 2076
<expected>, 527, 528, 756, 2063
<fenv.h>, 572, 1476
<filesystem>, 527, 1545, 2076, 2103
<flat_map>, 527, 1024, 1026, 1183, 2063
<flat_set>, 527, 1024, 1027, 1183, 2063
<float.h>, 538, 572
<format>, 527, 824, 838, 2071, 2103
<formatter>, 526–529, 941, 942, 1183, 2082
<fstream>, 528, 1828, 1829, 1891
<functional>, 526–530, 783
<future>, 2012, 2082
<generator>, 528, 1186, 1341, 2063
<hazard_pointer>, 528, 2030, 2059
<initializer_list>, 2082
<initializer_list>, 556
<inplace_vector>, 528, 941, 944, 1183, 2059
<inttypes.h>, 572, 1895
<ioanip>, 529, 1778, 1799, 1801
<iop>, 528, 1754
<iostream>, 1750, 1752
<iostream>, 1752, 1752, 1753, 1759
<iostream.h>, 501, 572, 572, 573, 2095
<iostream>, 527, 1777, 1779
<iterator>, 526–530, 1119, 1183, 1195, 2102
<iostream>, 528, 2009, 2071
<limits>, 80, 526, 527, 530, 2099
<limits.h>, 537, 572
<list.h>, 528, 1559, 2059
<ltdl>, 526–529, 941, 943, 1183
<locale.h>, 527, 1701, 1702
<locale.h>, 572, 1740
<map>, 526–530, 978, 978, 1183
#include>, 572, 1551
<mdspan>, 528–530, 1071, 1077, 2063
<memory>, 526–530, 607, 607, 1467, 1972
<memory_resource>, 529, 653, 2076
<mutex>, 529, 1982, 2082
<new>, 71, 502, 527, 528, 541
<numbers>, 528, 1558, 2071
<numeric>, 526–529, 1453
<optional>, 527–529, 726, 2076
<ostream>, 527, 529, 1778, 1790
<print>, 529, 1779, 2063
<queue>, 526, 527, 1024, 1025
<random>, 529, 1473, 1484, 2082
Index of library headers

<ranges>, 526, 528, 529, 723, 1186, 1195, 2071, 2101
<ratio>, 528, 529, 695, 2082
<rcu>, 529, 2027, 2059
<regex>, 529, 1183, 1898, 1898, 2082
<scoped_allocator>, 526, 662, 2082
<semaphore>, 529, 2007, 2071
<set>, 526–529, 978, 979, 1183
<setjmp.h>, 570, 572
<shared_mutex>, 529, 1982, 2079
<signal.h>, 571, 572
<source_location>, 529, 549, 2071
<span>, 529, 530, 1071, 1071, 1183, 2071
<sstream>, 530, 1805, 2061, 2063
<stdalign.h>, 572, 573, 2095, 2099, 2099
<stdarg.h>, 570, 572
<stdatomic.h>, 530, 572, 573, 1980, 1981, 2063
<stdbool.h>, 572, 572, 573, 2088, 2095, 2099, 2099
<stddef.h>, 523, 524, 572, 2096
<stdexcept>, 587
<stdfloat>, 80, 81, 539, 539, 2063
<stdint.h>, 539, 572, 1895
<stdio.h>, 572, 1894
<stdlib.h>, 524, 572, 573
<stop_token>, 528, 1935, 2071
<streambuf>, 1769, 1769
<string>, 526, 527, 529, 530, 850, 872, 1183
<string.h>, 572, 902
<string_view>, 527, 528, 530, 862, 1183, 2076
<syncstream>, 530, 1841, 1842, 2071
<system_error>, 528, 592, 594, 2082
<text_encoding>, 530, 1741, 2059
<tgmath.h>, 572, 572, 573, 2095
<thread>, 527, 528, 1939, 2082
<time.h>, 572, 1700
<tuple>, 526–530, 702, 712, 712, 723, 2082, 2101
<typeindex>, 2082
<type_traits>, 526–530, 668, 2082, 2100
<typeindex>, 818
<typeinfo>, 527, 548
<uchar.h>, 572, 903
<unordered_map>, 526–530, 998, 998, 1183, 2082
<unordered_set>, 526–529, 998, 999, 1183, 2082
<utility>, 506, 526–530, 699, 712, 723, 2083, 2099, 2101
<valarray>, 1527, 1529
<variant>, 527, 528, 530, 740, 2076, 2101
<vector>, 526–529, 941, 943, 1183
<version>, 526, 526, 530, 2071
<wchar.h>, 572, 903
<wctype.h>, 572, 901
Index of library names

Constructions whose name appears in italics are for exposition only.

Symbols

advance-bwd
  concat_view::iterator, 1272

advance-fwd
  concat_view::iterator, 1271

cmp-name
  text_encoding, 1743

de-ice, 1112

first_, 1112

last_, 1112

prev
  concat_view::iterator, 1271

satisfy
  concat_view::iterator, 1271

src-indices, 1112

_EXIT, 523, 540
_IOFBF, 1893
_IOLBF, 1893
__IONBF, 1893
__alignas_is_defined, 2099
__bool_true_false_are_defined, 2099
__cpp_lib_adaptor_iterator_pair_- constructor, 526
__cpp_lib_addressof_constexpr, 526
__cpp_lib_algorithm_default_value_type, 526
__cpp_lib_algorithm_iterator_- requirements, 526
__cpp_lib_allocate_at_least, 526
__cpp_lib_allocator_traits_is_always_- equal, 526
__cpp_lib_any, 526
__cpp_lib_apply, 526
__cpp_lib_array_constexpr, 526
__cpp_lib_atomic_ref, 526
__cpp_lib_assume_aligned, 526
__cpp_lib_associative_heterogeneous_- erasure, 526
__cpp_lib_associative_heterogeneous_- insertion, 526
__cpp_lib_assume_aligned, 526
__cpp_lib_atomic_flag_test, 526
__cpp_lib_atomic_float, 526
__cpp_lib_atomic_is_always_lock_free, 526
__cpp_lib_atomic_lock_free_type_aliases, 526
__cpp_lib_atomic_min_max, 526
__cpp_lib_atomic_ref, 526
__cpp_lib_atomic_shared_ptr, 526
__cpp_lib_atomic_value_initialization, 526
__cpp_lib_atomic_wait, 526
__cpp_lib_barrier, 526

__cpp_lib_bind_back, 526
__cpp_lib_bind_front, 526
__cpp_lib_bit_cast, 526
__cpp_lib_bitops, 526
__cpp_lib_bitset, 526
__cpp_lib_bool_constant, 526
__cpp_lib_bounded_array_traits, 527
__cpp_lib_boyer_moore_searcher, 527
__cpp_lib_byte, 527
__cpp_lib_byteswap, 527
__cpp_lib_char8_t, 527
__cpp_lib_chrono, 527
__cpp_lib_chrono_uds, 527
__cpp_lib_clamp, 527
__cpp_lib_common_reference, 527
__cpp_lib_common_reference_wrapper, 527
__cpp_lib_complex_uds, 527
__cpp_lib_concepts, 527
__cpp_lib_constexpr_algorithms, 527
__cpp_lib_constexpr_bitset, 527
__cpp_lib_constexpr_charconv, 527
__cpp_lib_constexpr_cmath, 527
__cpp_lib_constexpr_complex, 527
__cpp_lib_constexpr_dynamic_alloc, 527
__cpp_lib_constexpr_functional, 527
__cpp_lib_constexpr_iterator, 527
__cpp_lib_constexpr_memory, 527
__cpp_lib_constexpr_new, 527
__cpp_lib_constexpr_numeric, 527
__cpp_lib_constexpr_string, 527
__cpp_lib_constexpr_string_view, 527
__cpp_lib_constexpr_tuple, 527
__cpp_lib_constexpr_typeinfo, 527
__cpp_lib_constexpr_utility, 527
__cpp_lib_constexpr_vector, 527
__cpp_lib_constrained_equality, 527
__cpp_lib_containers_ranges, 527
__cpp_lib_copyable_function, 527
__cpp_lib_coroutine, 527
__cpp_lib_debugging, 527
__cpp_lib_destroying_delete, 527
__cpp_lib_enable_shared_from_this, 527
__cpp_lib_endian, 527
__cpp_lib_erase_if, 527
__cpp_lib_exchange_function, 527
__cpp_lib_execution, 527
__cpp_lib_expected, 527
__cpp_lib_filesystem, 527
__cpp_lib_flat_map, 527
__cpp_lib_filesystem, 527
__cpp_lib_format, 527
N4986

Index of library names

©ISO/IEC
2183
coroutine_handle<noop_coroutine_promise>, 569
addressof, 625
adjacent
views, 1301
adjacent_difference, 1464
adjacent_find, 1400
adjacent_transform
views, 1306
adjacent_transform_view, 1306
begin, 1307
end, 1307
size, 1307
adjacent_view, 1301
begin, 1301
end, 1301
size, 1301
adopt_lock, 1990
adopt_lock_t, 1990
advance, 1149, 1150
subrange, 1207
advance_to
basic_format_context, 842
basic_format_parse_context, 840
aliases
text_encoding, 1743
aliases_view
text_encoding, 1744
align, 617
align_val_t, 541
aligned_alloc, 523, 625, 2096
aligned_storage, 2100
aligned_storage_t, 2100
aligned_union, 2101
aligned_union_t, 2100
alignment_of, 684
alignment_of_v, 674
all
bitset, 782
views, 1227
all_of, 1394
all_t, 1186
allocate
allocator, 624
allocator_traits, 623
memory_resource, 654
polymorphic_allocator, 656
scoped_allocator_adaptor, 665
allocate_at_least
allocator, 624
allocator_traits, 623
allocate_bytes
polymorphic_allocator, 656
allocate_object
polymorphic_allocator, 656
allocate_shared, 640–642
allocator, 623
allocate, 624
allocate_at_least, 624
deallocate, 624
difference_type, 623
operator=, 623
operator==, 624
propagate_on_container_move_all
assignment, 623
size_type, 623
value_type, 623
allocator_arg, 618
allocator_arg_t, 618
allocator_traits, 621
allocate, 623
allocate_at_least, 623
const_pointer, 622
const_void_pointer, 622
construct, 623
deallocate, 623
destroy, 623
difference_type, 622
is_always_equal, 623
max_size, 623
pointer, 622
propagate_on_container_copy_all
assignment, 622
propagate_on_container_move_all
assignment, 622
propagate_on_container_swap, 623
rebind_alloc, 623
select_on_container_copy_construction, 623
size_type, 622
void_pointer, 622
allocator_type
allocator-aware containers, 912
basic_string, 875
alpha
gamma_distribution, 1514
always_noconv
codecvt, 1715
ambiguous
local_info, 1682
ambiguous_local_time, 1681
constructor, 1681
and_then
expected, 768
expected<void>, 775
optional, 735
any
constructor, 753, 754
destructor, 754
emplace, 754, 755
has_value, 755
operator=, 754
reset, 755
swap, 755
type, 755
any (member)
bitset, 782
any_cast, 756
<table>
<thead>
<tr>
<th>Library Name</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>any_of</td>
<td>1394</td>
</tr>
<tr>
<td>append</td>
<td>886, 887</td>
</tr>
<tr>
<td>append_range</td>
<td>886, 976</td>
</tr>
<tr>
<td>apply</td>
<td>722</td>
</tr>
<tr>
<td>apply_givens_rotation</td>
<td>1586</td>
</tr>
<tr>
<td>arg</td>
<td>1483</td>
</tr>
<tr>
<td>asin</td>
<td>1545</td>
</tr>
<tr>
<td>asinl</td>
<td>1545</td>
</tr>
<tr>
<td>asinf</td>
<td>1545</td>
</tr>
<tr>
<td>asinh</td>
<td>1545</td>
</tr>
<tr>
<td>asinhf</td>
<td>1545</td>
</tr>
<tr>
<td>assert</td>
<td>590</td>
</tr>
<tr>
<td>assign</td>
<td>885</td>
</tr>
<tr>
<td>assign_range</td>
<td>888</td>
</tr>
<tr>
<td>assignable_from</td>
<td>579</td>
</tr>
<tr>
<td>at</td>
<td>2022</td>
</tr>
<tr>
<td>atexit</td>
<td>95, 523, 540</td>
</tr>
<tr>
<td>atf</td>
<td>1545</td>
</tr>
<tr>
<td>atan</td>
<td>1545</td>
</tr>
<tr>
<td>atan2</td>
<td>1545</td>
</tr>
<tr>
<td>atan2f</td>
<td>1545</td>
</tr>
<tr>
<td>atan2l</td>
<td>1545</td>
</tr>
<tr>
<td>atanf</td>
<td>1545</td>
</tr>
<tr>
<td>atanh</td>
<td>1545</td>
</tr>
<tr>
<td>atanhf</td>
<td>1545</td>
</tr>
<tr>
<td>atanhl</td>
<td>1545</td>
</tr>
<tr>
<td>atanh</td>
<td>1545</td>
</tr>
<tr>
<td>atexit</td>
<td>95, 523, 540</td>
</tr>
<tr>
<td>atof</td>
<td>523</td>
</tr>
<tr>
<td>atoi</td>
<td>523</td>
</tr>
<tr>
<td>atol</td>
<td>523</td>
</tr>
<tr>
<td>atoll</td>
<td>523</td>
</tr>
<tr>
<td>atomic</td>
<td>1961, 1962</td>
</tr>
<tr>
<td>basic_format_context</td>
<td>842</td>
</tr>
<tr>
<td>basic_string_view</td>
<td>867</td>
</tr>
<tr>
<td>basic_stacktrace</td>
<td>605</td>
</tr>
<tr>
<td>basic_string</td>
<td>885</td>
</tr>
<tr>
<td>basic_string_view</td>
<td>867</td>
</tr>
<tr>
<td>barrier</td>
<td>2012</td>
</tr>
<tr>
<td>barrier</td>
<td>2012</td>
</tr>
<tr>
<td>barrier</td>
<td>2012</td>
</tr>
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</tr>
<tr>
<td>barrier</td>
<td>2012</td>
</tr>
<tr>
<td>barrier</td>
<td>2012</td>
</tr>
</tbody>
</table>
compare_exchange_weak, 1963
constructor, 1962
exchange, 1963
is_always_lock_free, 1963
is_lock_free, 1963
load, 1963
notify_all, 1965
notify_one, 1965
operator type, 1963
operator=, 1963
store, 1963
value_type, 1961
wait, 1965

atomic<floating-point-type>, 1968
compare_exchange_strong, 1963
compare_exchange_weak, 1963
closest, 1962
exchange, 1963
fetch_add, 1969
fetch_sub, 1969
is_always_lock_free, 1963
is_lock_free, 1963
load, 1963
notify_all, 1965
notify_one, 1965
operator floating-point-type, 1963
operator+=, 1969
operator-=, 1969
operator=, 1963
store, 1963
wait, 1965

atomic<integral-type>, 1966
compare_exchange_strong, 1963
compare_exchange_weak, 1963
closest, 1962
exchange, 1963
fetch_add, 1967
fetch_and, 1967
fetch_max, 1967
fetch_min, 1967
fetch_or, 1967
fetch_xor, 1967
is_always_lock_free, 1963
is_lock_free, 1963
load, 1963
notify_all, 1965
notify_one, 1965
operator integral-type, 1963
operator++, 1971, 1972
operator-=, 1968
operator+=, 1971, 1972
operator-=, 1972
operator=, 1968, 1969, 1971
operator=, 1963
store, 1963
wait, 1965

atomic<shared_ptr<T>>, 1972
compare_exchange_strong, 1974
compare_exchange_weak, 1974
closest, 1973
exchange, 1974
is_always_lock_free, 1963
is_lock_free, 1963
load, 1974
notify_all, 1975
notify_one, 1975
operator shared_ptr<T>, 1974
operator=, 1973
store, 1973
wait, 1974
atomic<T>>, 1970, 1971
compare_exchange_strong, 1963
compare_exchange_weak, 1963
closest, 1962
exchange, 1963
fetch_add, 1971
fetch_max, 1971
fetch_min, 1971
fetch_sub, 1971
is_always_lock_free, 1963
is_lock_free, 1963
load, 1963
notify_all, 1965
notify_one, 1965
operator T*, 1963
operator+=, 1968, 1969, 1971
operator-=, 1972
operator=, 1968, 1969, 1971
operator=, 1963
store, 1963
wait, 1965
atomic<weak_ptr<T>>, 1975
compare_exchange_strong, 1976
compare_exchange_weak, 1976
closest, 1975
exchange, 1976
is_always_lock_free, 1963
is_lock_free, 1963
load, 1976
notify_all, 1977
notify_one, 1977
operator weak_ptr<T>, 1976
operator=, 1976
store, 1976
wait, 1977
atomic_bool, 1952, 1980
ATOMIC_BOOL_LOCK_FREE, 1953
atomic_char, 1952, 1980
atomic_char16_t, 1952, 1980
ATOMIC_CHAR16_T_LOCK_FREE, 1953
atomic_char32_t, 1952, 1980
ATOMIC_CHAR32_T_LOCK_FREE, 1953
atomic_char8_t, 1952, 1980
ATOMIC_CHAR8_T_LOCK_FREE, 1953
atomic_compare_exchange_strong, 1953
atomic_compare_exchange_strong_explicit, 1963, 1981
atomic_compare_exchange_weak, 1953
atomic_compare_exchange_weak_explicit, 1963, 1981
atomic_exchange_explicit, 1963, 1981
atomic_fetch_and, 1967, 1981
atomic_fetch_and_explicit, 1967, 1981
atomic_fetch_or, 1967, 1981
atomic_fetch_or_explicit, 1967, 1981
atomic_fetch_xor, 1967, 1981
atomic_fetch_xor_explicit, 1967, 1981
atomic_flag, 1980
clear, 1978
constructor, 1978
test, 1978
test_and_set, 1978
wait, 1978
atomic_flag_clear, 1978, 1981
atomic_flag_clear_explicit, 1978, 1981
atomic_flag_test, 1978
atomic_flag_test_and_set, 1978, 1981
atomic_flag_test_and_set_explicit, 1978, 1981
atomic_flag_test_explicit, 1978
atomic_flag_wait, 1978
atomic_flag_wait_explicit, 1978
atomic_init, 2104
atomic_int, 1952, 1980
atomic_int16_t, 1952, 1980
atomic_int32_t, 1952, 1980
atomic_int64_t, 1952, 1980
atomic_int8_t, 1952, 1980
atomic_int_fast16_t, 1952, 1981
atomic_int_fast32_t, 1952, 1981
atomic_int_fast64_t, 1952, 1981
atomic_int_fast8_t, 1952, 1981
atomic_int_least16_t, 1952, 1981
atomic_int_least32_t, 1952, 1981
atomic_int_least64_t, 1952, 1981
atomic_int_least8_t, 1952, 1980
atomic_intmax_t, 1952, 1981
atomic_int_ptr_t, 1952, 1981
atomic_is_lock_free, 1963, 1981
atomic_llong, 1952, 1980
atomic_load_explicit, 1963, 1981
atomic_long, 1952, 1980
atomic_long_long, 1952, 1980
atomic_store_strong_explicit, 1963, 1981
atomic_store字第, 1963, 1981
atomic_test_and_set, 1956
atomic_test_and_set_explicit, 1956
operator\^=, 1950
operator\|=, 1950
required_alignment, 1955
store, 1956
atomic_ref<T\*>, 1960
compare_exchange_strong, 1956
compare_exchange_weak, 1956
compiler, 1956
exchange, 1956
fetch_add, 1961
fetch_max, 1961
fetch_min, 1961
fetch_sub, 1961
is\_always\_lock\_free, 1956
is\_lock\_free, 1956
load, 1956
operator T\*, 1956
operator++, 1961
operator\+=, 1961
operator\-=, 1961
operator\|=, 1961
required_alignment, 1955
store, 1956
atomic_ref<T\>
notify\_all, 1957
notify\_one, 1957
wait, 1957
atomic\_schar, 1952, 1980
atomic\_short, 1952, 1980
ATOMIC\_SHORT\_LOCK\_FREE, 1953
atomic\_signal\_fence, 1980, 1981
atomic\_signed\_lock\_free, 1952
atomic\_size\_t, 1952, 1981
atomic\_store, 1963, 1981
atomic\_store\_explicit, 1963, 1981
atomic\_thread\_fence, 1979, 1981
atomic\_uchar, 1952, 1980
atomic\_uint, 1952, 1980
atomic\_uint\_16\_t, 1952, 1980
atomic\_uint\_32\_t, 1952, 1980
atomic\_uint\_64\_t, 1952, 1980
atomic\_uint\_8\_t, 1952, 1980
atomic\_uint\_fast\_16\_t, 1952, 1981
atomic\_uint\_fast\_32\_t, 1952, 1981
atomic\_uint\_fast\_64\_t, 1952, 1981
atomic\_uint\_fast\_8\_t, 1952, 1981
atomic\_uint\_least\_16\_t, 1952, 1981
atomic\_uint\_least\_32\_t, 1952, 1981
atomic\_uint\_least\_64\_t, 1952, 1981
atomic\_uint\_least\_8\_t, 1952, 1980
atomic\_uint\_max\_t, 1952, 1981
atomic\_uint\_ptr\_t, 1952, 1981
atomic\_ullong, 1952, 1980
atomic\_ulong, 1952, 1980
atomic\_unsigned\_lock\_free, 1952
atomic\_ushort, 1952, 1980
ATOMIC\_VAR\_INIT, 2104
atomic\_wchar\_t, 1952, 1980
ATOMIC\_WCHAR\_T\_LOCK\_FREE, 1953
atto, 696
auto\_ptr
zombie, 515
auto\_ptr\_ref
zombie, 515
await\_ready
suspend\_always, 569
suspend\_never, 569
await\_resume
suspend\_always, 569
suspend\_never, 569
await\_suspend
suspend\_always, 569
suspend\_never, 569
awk
syntax\_option\_type, 1902, 1903
B
b
cauchy\_distribution, 1519
extreme\_value\_distribution, 1516
uniform\_int\_distribution, 1506
uniform\_real\_distribution, 1507
weibull\_distribution, 1515
back
basic\_string, 885
basic\_string\_view, 868
span, 1076
view\_interface, 1204
back\_insert\_iterator, 1156
composer, 1156
operator*, 1156
operator++, 1156
operator\=, 1156
back\_ inserter, 1156
bad
basic\_ios, 1767
bad\_alloc, 144, 543, 546, 547
composer, 546
what, 546
bad\_any\_cast, 752
what, 752
bad\_array\_new\_length, 546
composer, 546
what, 547
bad\_cast, 131, 548, 549
composer, 549
what, 549
bad\_exception, 553
composer, 553
what, 553
bad\_expected\_access, 759
composer, 759
error, 759
what, 759
bad\_function\_call, 803
what, 803
flush, 1798
init, 1793
operator<<, 1794–1799
operator=, 1793
put, 1798
seekp, 1794
sentry, 1793
swap, 1793
tellp, 1794
write, 1798

basic_ostream::sentry, 1793
constructor, 1793
destructor, 1793
operator bool, 1793

basic_ostream<char>, 1778
basic_ostream<wchar_t>, 1778
basic_ostringstream, 1750, 1815
constructor, 1816, 1817
rdbuf, 1818
str, 1818
view, 1818

basic_ostringstream<char>, 1805
constructor, 1816
rdbuf, 1828
span, 1828
swap, 1828

basic_spanbuf, 1822
constructor, 1823
operator=, 1823
seekoff, 1824
seekpos, 1824
setbuf, 1825
span, 1824
swap, 1823

basic_spanstream, 1827
constructor, 1828
rdbuf, 1828
span, 1828
swap, 1828

basic_stacktrace, 602
at, 605
begin, 605
cbegin, 605
cend, 605
const_iterator, 604
constructor, 604
crbegin, 605
crend, 605
current, 604

empty, 605
dep, 605
get_allocator, 604
max_size, 605
operator<<, 606
operator=, 604
operator=>, 605
operator<<, 605
operator[]], 605
rbegin, 605
rend, 605
size, 605
swap, 605
to_string, 606

basic_streambuf, 1750, 1770
constructor, 1772
destructor, 1772
eback, 1774
eptr, 1774
egptr, 1774
gbump, 1774
getloc, 1772
gptr, 1774
imbue, 1774
in_avail, 1773
operator=, 1773
overflow, 1777
pbackfail, 1776
pbase, 1774
pbump, 1774
pbset, 1774
pubimbue, 1772
pubseekoff, 1772
pubseekpos, 1773
pubsetbuf, 1772
pubsync, 1773
sbumpc, 1773
seekoff, 1775
seekpos, 1775
setbuf, 1775
setg, 1774
setp, 1774
sgetc, 1773
sgetn, 1773
showmanyc, 1775
snexe, 1773
sputbackc, 1773
sputc, 1773
sputc, 1773
underflow, 1775
xsgetn, 1775
xsputc, 1776

basic_streambuf<char>, 1769
basic_streambuf<wchar_t>, 1769
basic_string, 875, 894, 1806
allocator_type, 875
append, 886, 887
append_range, 886
assign, 887, 888
assign_range, 888
at, 885
back, 885
begin, 883
c_str, 892
capacity, 884
cbegin, 883
cend, 883
clear, 885
clear, 885
compare, 893, 894
const_iterator, 875
cost_pointer, 875
cost_reference, 875
const_reverse_iterator, 875
constructor, 881, 882
contains, 894
copy, 891
crbegin, 883
crend, 883
data, 892
difference_type, 875
empty, 885
end, 883
ends_with, 894
erase, 889, 890, 898
erase_if, 898
find, 892, 893
find_first_not_of, 892, 893
find_first_of, 892, 893
find_last_not_of, 892, 893
find_last_of, 892, 893
front, 885
get_allocator, 892
ggetline, 897, 898
hash, 900
insert, 888, 889
insert_range, 889
iterator, 875
length, 883
max_size, 884
operator basic_string_view, 892
operator+, 894–896
operator=, 885, 886
operator<<, 897
operator<<, 911
operator=, 882, 883
operator>>, 897
operator[], 885
pointer, 875
pop_back, 890
push_back, 887
rbegin, 883
reference, 875
rend, 883
replace, 890, 891
replace_with_range, 891
reserve, 884
resize, 884
resize_and_overwrite, 884
reverse_iterator, 875
rfind, 892, 893
shrink_to_fit, 884
size, 883
size_type, 875
starts_with, 894
substr, 893
swap, 892, 897
traits_type, 875
value_type, 875
basic_string_view, 863
at, 867
back, 868
begin, 867
cbegin, 867
cend, 867
compare, 868, 869
const_iterator, 863, 866
const_pointer, 863
const_reference, 863
const_reverse_iterator, 863
constructor, 865, 866
contains, 869
copy, 868
crbegin, 867
crend, 867
data, 868
difference_type, 863
empty, 867
end, 867
ends_with, 869
find, 870
find_first_not_of, 870
find_first_of, 870
find_last_not_of, 870
find_last_of, 870
front, 867
iterator, 863
length, 867
max_size, 867
operator<<, 871
operator<<, 871
operator<<, 871
operator[], 867
pointer, 863
rbegin, 867
reference, 863
remove_prefix, 863
remove_suffix, 863
rend, 867
reverse_iterator, 863
rfind, 870
size, 867
size_type, 863
starts_with, 869
substr, 868
swap, 868
traits_type, 863
value_type, 863
basic_stringbuf, 1750, 1806
constructor, 1807, 1808
get_allocator, 1810
operator=, 1809
overflow, 1811
pbackfail, 1811
seekoff, 1811
seekpos, 1812
str, 1810
swap, 1809
underflow, 1811
view, 1810
basic_stringbuf<char>, 1805
basic_stringbuf<wchar_t>, 1805
basic_stringstream, 1750, 1818
constructor, 1819, 1820
rdbuf, 1821
str, 1821
swap, 1820
view, 1821
basic_stringstream<char>, 1805
basic_stringstream<wchar_t>, 1805
basic_syncbuf, 1750, 1842
constructor, 1842, 1843
destructor, 1843
emit, 1843
get_allocator, 1844
get_wrapped, 1844
operator=, 1843
set_emit_on_sync, 1844
swap, 1843, 1844
sync, 1844
before

type_info, 549
before_begin

forward_list, 954
begin, 556, 1195
adjacent_transform_view, 1307
adjacent_view, 1301
array, 945
basic_format_parse_context, 840
basic_stacktrace, 605
basic_string, 883
basic_string_view, 867
chunk_view, 1312, 1316
common_view, 1276
concat_view, 1268
containers, 908
directory_iterator, 1877
drop_view, 1245
drop_while_view, 1246
elements_view, 1280
tenumerate_view, 1285
filter_view, 1230
generator, 1342
initializer_list, 556
iota_view, 1214
join_view, 1246
lazy_split_view, 1258
lazy_split_view::outer_iterator::value_type, 1262
match_results, 1917
optional, 734
path, 1865
recursive_directory_iterator, 1880
repeat_view, 1220
reverse_view, 1278
single_view, 1212
slide_view, 1320
span, 1077
subrange, 1206
sys_info, 1682
take_view, 1239
take_while_view, 1242
text_encoding::aliases_view, 1744
transform_view, 1234
tzdb_list, 1679
unordered associative containers, 939
valarray, 1545
zip_transform_view, 1296
zip_view, 1290
begin(C&), 1183
begin(initializer_list<E>), 556
begin(T (&)[N]), 1183
bernoulli_distribution, 1508
constructor, 1508
p, 1508
result_type, 1508
beta, 1553
gamma_distribution, 1514
betal, 1553
betaf, 1553
betal, 1553
bfloat16_t, 539
bidirectional_iterator, 1139
bidirectional_iterator_tag, 1148
bidirectional_range, 1201
big

depend, 855
binary_function
zombie, 515
binary_negate
zombie, 515
binary_search, 1434
binary_semaphore, 2007
bind, 801–802
bind1st
zombie, 515
bind2nd
zombie, 515
bind_back, 800
bind_front, 800
binder1st
zombie, 515

Index of library names ©ISO/IEC 2193
complex, 1482

category
  error_code, 597
  error_condition, 599
locale, 1704
cauchy_distribution, 1519
  a, 1519
  b, 1519
  constructor, 1519
result_type, 1519
cbefore_begin
  forward_list, 954
cbegin, 1196
  basic_stacktrace, 605
  basic_string, 883
  basic_string_view, 867
containers, 908
  tzdb_list, 1679
unordered associative containers, 939
cbegin(const C&), 1184
cbrt, 1545
cbrtf, 1545
cbrtl, 1545
cdata, 1199
ceil, 1545
  duration, 1630
  time_point, 1635
cceil, 1545
cceil, 1545
cend, 1196
  basic_stacktrace, 605
  basic_string, 883
  basic_string_view, 867
containers, 908
  tzdb_list, 1679
unordered associative containers, 939
cend(const C&), 1184
centi, 696
cerr, 1753
CHAR_BIT, 537
char_class_type
  regex_traits, 1905
CHAR_MAX, 537
CHAR_MIN, 537
char_traits, 859–862
  char_type, 859
  int_type, 859
  state_type, 859
char_type
  basic_format_context, 841
  basic_format_parse_context, 840
  char_traits, 859
chars_format, 822
  fixed, 822
  general, 822
  hex, 822
  scientific, 822
check_arg_id
  basic_format_parse_context, 841
check_dynamic_spec
  basic_format_parse_context, 841
check_dynamic_spec_integral
  basic_format_parse_context, 841
check_dynamic_spec_string
  basic_format_parse_context, 841
chi_squared_distribution, 1518
  constructor, 1518
  n, 1519
  result_type, 1519
choose, 1609
  earliest, 1609
  latest, 1609
chrono, 1609
chunk
  views, 1311
chunk_by
  views, 1326
chunk_by_view
  pred, 1327
chunk_view
  begin, 1312, 1316
  end, 1312, 1316
  size, 1312, 1316
chunk_view::inner_iterator, 1314
chunk_view::outer_iterator, 1313
chunk_view::outer_iterator::value_type, 1314
cin, 1753
clamp, 1450
classic
  locale, 1708
classic_table
  ctype<char>, 1714
clear
  atomic_flag, 1978
  basic_ios, 1766
  basic_string, 885
  error_code, 597
  error_condition, 598
  forward_list, 956
  ordered associative containers, 928
  path, 1860
  sequence containers, 916
unordered associative containers, 938
clearerr, 1893
clock, 1699
clock_cast, 1646
clock_t, 1699
clock_time_conversion, 1643
  operator(), 1644, 1645
CLOCKS_PER_SEC, 1699
clog, 1753
close
  basic_filebuf, 1833
  basic_fstream, 1841
  basic_ifstream, 1837
  basic_ofstream, 1839
  messages, 1739

Index of library names
cmp_equal, 704
cmp_greater, 705
cmp_greater_equal, 705
cmp_less, 705
cmp_less_equal, 705
cmp_not_equal, 705
code
  future_error, 2014
  system_error, 600
codecvt, 1714
  always_noconv, 1715
  do_always_noconv, 1717
  do_encoding, 1717
  do_in, 1716
  do_length, 1717
  do_max_length, 1717
  do_out, 1716
  do_unshift, 1717
  encoding, 1715
  in, 1715
  length, 1715
  max_length, 1715
  out, 1715
  unshift, 1715
codecvtbyname, 1717
codecvtmode
  zombie, 515
codecvt_utf16
  zombie, 515
codecvt_utf8
  zombie, 515
codecvt_utf8_utf16
  zombie, 515
collate, 1727
  compare, 1727
  do_compare, 1727
  do_hash, 1728
  do_transform, 1728
  hash, 1727
  syntax_option_type, 1902, 1903, 1929
  transform, 1727
collatebyname, 1728
column_major, 1572
column_major_t, 1572
combine
  locale, 1707
common
  views, 1276
common_comparison_category, 561
common_comparison_category_t, 557
common_iterator, 1169
  constructor, 1170
  iter_move, 1172
  iter_swap, 1172
  operator*, 1171
  operator++, 1171
  operator-, 1172
  operator->, 1171
  operator=, 1170
  operator==, 1172
common_range, 1202
common_reference, 690
common_reference_t, 671
common_reference_with, 578
common_type, 691, 1625, 1628
tuple, 725
common_type_t, 671
common_view, 1276
  base, 1276
  begin, 1276
  constructor, 1277
  end, 1276
  size, 1276
common_with, 578
comp
  map::value_compare, 980
  multimap::value_compare, 987
comp_ellint_1, 1553
comp_ellint_1f, 1553
comp_ellint_1l, 1553
comp_ellint_2, 1554
comp_ellint_2f, 1554
comp_ellint_2l, 1554
comp_ellint_3, 1554
comp_ellint_3f, 1554
comp_ellint_3l, 1554
compare
  atomic, 1963
  atomic<floating-point-type>, 1963
  atomic<integer-type>, 1963
  atomic<shared_ptr<T>>, 1974
  atomic<T*>, 1963
  atomic<weak_ptr<T>>, 1976
  atomic_ref, 1956
  atomic_ref<floating-point-type>, 1956
  atomic_ref<integer-type>, 1956
  atomic_ref<T*>, 1956
compare_exchange_strong
  atomic, 1963
  atomic<floating-point-type>, 1963
  atomic<integer-type>, 1963
  atomic<shared_ptr<T>>, 1974
  atomic<T*>, 1963
  atomic<weak_ptr<T>>, 1976
  atomic_ref, 1956
  atomic_ref<floating-point-type>, 1956
  atomic_ref<integer-type>, 1956
  atomic_ref<T*>, 1956
compare_exchange_weak
  atomic, 1963
  atomic<floating-point-type>, 1963
  atomic<integer-type>, 1963
  atomic<shared_ptr<T>>, 1974
  atomic<T*>, 1963
  atomic<weak_ptr<T>>, 1976
  atomic_ref, 1956
  atomic_ref<floating-point-type>, 1956
  atomic_ref<integer-type>, 1956
  atomic_ref<T*>, 1956
compare_partial_orderFallback, 564
compare_strong_orderFallback, 564
compare_three_way, 795
compare_weak_orderFallback, 564

Index of library names

© ISO/IEC

2196
Index of library names

complex, 1478
abs, 1481
acos, 1481
acosh, 1481
arg, 1481
asin, 1481
asinh, 1481
atan, 1481
atanh, 1482
cacos, 1481
acosh, 1481
casin, 1481
casinh, 1482
catan, 1481
catanh, 1482
conj, 1481
constructor, 1479
cos, 1482
cosh, 1482
exp, 1482
get, 1483
imag, 1479, 1481
log, 1482
log10, 1482
norm, 1481
operator"**", 1483
operator"*", 1480
operator"==", 1479, 1480
operator"-", 1480
operator"-", 1479
operator/, 1480
operator/, 1479, 1480
operator<<, 1480
operator="=", 1479
operator"==", 1480
operator>>, 1480
polar, 1481
pow, 1482
proj, 1481
real, 1479, 1481
sin, 1482
sinh, 1482
sqrt, 1482
tan, 1482
tanh, 1482
value_type, 1478
concat
path, 1859, 1860
concat_view, 1267
begin, 1268
constructor, 1268
end, 1269
iterator, 1269
size, 1269
concat_view::iterator

advance-bwd, 1272
advance-fwd, 1271
prev, 1271
satisfy, 1271
constructor, 1272
iter_move, 1275
iter_swap, 1275
operator*, 1272
operator+, 1274
operator++, 1272
operator+=, 1273
operator--, 1274
operator--, 1273
operator<, 1273
operator<=, 1273
operator[][], 1273
condition_variable, 2001
constructor, 2001
destructor, 2001
notify_all, 2002
notify_one, 2002
wait, 2002
wait_for, 2003
wait_until, 2002, 2003
condition_variable_any, 2004
constructor, 2005
destructor, 2005
notify_all, 2005
notify_one, 2005
wait, 2005
wait_for, 2006
wait_until, 2005, 2006
conditional_t, 671
conj, 1483
complex, 1481
conjugate_transposed, 1585
conjugated, 1581
conjugated_accessor, 1580
access, 1581
constructor, 1581
offset, 1581
conjunction, 693
conjunction_v, 675
const_iterator, 1159
basic_format_parse_context, 840
basic_stacktrace, 604
basic_string, 875
basic_string_view, 863, 866
containers, 907
optional, 734
const_local_iterator
unordered associative containers, 932
const_mem_fun1_ref_t
zombie, 515
const_mem_fun1_t
zombie, 515
const_mem_fun_ref_t
zombie, 515

concat_view::iterator
const_mem_fun_t
  zombie, 515
const_pointer
  allocator_traits, 622
  basic_string, 875
  basic_string_view, 863
  scoped_allocator_adaptor, 663
const_pointer_cast
  shared_ptr, 644
const_reference
  basic_string, 875
  basic_string_view, 863
  containers, 907
const_reverse_iterator
  basic_string, 875
  basic_string_view, 863
  reversible containers, 910
const_sentinel, 1159
const_void_pointer
  allocator_traits, 622
  scoped_allocator_adaptor, 663
constant_range, 1202
construct
  allocator_traits, 623
  polymorphic_allocator, 657
  scoped_allocator_adaptor, 665
construct_at, 1472
constructible_from, 581
consume
  memory_order, 1952
consume_header
  zombie, 515
contains, 1395
  basic_string, 894
  basic_string_view, 869
  ordered associative containers, 928
  unordered associative containers, 938
contains_subrange, 1395
contiguous_iterator, 1140
contiguous_iterator_tag, 1148
contiguous_range, 1202
converted
  zombie, 516
convertible_to, 578
copy, 1409, 1410, 1587
  basic_string, 891
  basic_string_view, 868
  path, 1881
copy_backward, 1411
copy_constructible, 582
copy_file, 1883
copy_if, 1410
copy_n, 1410
copy_options, 1868
copy_systime, 1883
copyable, 585
copyable_function, 810
  constructor, 811
  destructor, 812
operator bool, 812
operator(), 812
operator=, 812
operator==, 812
swap, 812
copyfmt
  basic_ios, 1765
copysign, 1545
copysignf, 1545
copysignl, 1545
coroutine_handle, 566
  address, 567
  constructor, 567
  destroy, 568
  done, 567
  from_address, 567
  from_promise, 567
  hash, 568
  operator bool, 567
  operator coroutine_handle>, 567
  operator!=, 568
  operator(), 568
  operator<, 568
  operator<=, 568
  operator==, 568
  promise, 568
  promise<noop_coroutine_promise>, 568
  resume, 568
coroutine_traits, 565
cos, 1545
  complex, 1482
  valarray, 1538
cosf, 1545
cosh, 1545
  complex, 1482
  valarray, 1538
coshf, 1545
coshl, 1545
cosl, 1545
count, 1401
  bitset, 782
  counted_iterator, 1175
  duration, 1627
  ordered associative containers, 928
  unordered associative containers, 938
count_down
  latch, 2010
count_if, 1401
counted
  views, 1275
<table>
<thead>
<tr>
<th>Name</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>counted_iterator</td>
<td>1173</td>
</tr>
<tr>
<td>base</td>
<td>1175</td>
</tr>
<tr>
<td>constructor</td>
<td>1174, 1175</td>
</tr>
<tr>
<td>count</td>
<td>1175</td>
</tr>
<tr>
<td>iter_move</td>
<td>1177</td>
</tr>
<tr>
<td>iter_swap</td>
<td>1177</td>
</tr>
<tr>
<td>operator*</td>
<td>1175</td>
</tr>
<tr>
<td>operator++</td>
<td>1175</td>
</tr>
<tr>
<td>operator+=</td>
<td>1176</td>
</tr>
<tr>
<td>operator-</td>
<td>1176</td>
</tr>
<tr>
<td>operator--</td>
<td>1176</td>
</tr>
<tr>
<td>operator-&gt;</td>
<td>1175</td>
</tr>
<tr>
<td>operator&lt;&gt;</td>
<td>1177</td>
</tr>
<tr>
<td>operator=</td>
<td>1175</td>
</tr>
<tr>
<td>operator==</td>
<td>1177</td>
</tr>
<tr>
<td>operator[]</td>
<td>1175</td>
</tr>
<tr>
<td>counting_semaphore</td>
<td>2008</td>
</tr>
<tr>
<td>acquire</td>
<td>2008</td>
</tr>
<tr>
<td>max</td>
<td>2008</td>
</tr>
<tr>
<td>release</td>
<td>2008</td>
</tr>
<tr>
<td>try_acquire</td>
<td>2008</td>
</tr>
<tr>
<td>try_acquire_for</td>
<td>2009</td>
</tr>
<tr>
<td>try_acquire_until</td>
<td>2009</td>
</tr>
<tr>
<td>countl_one</td>
<td>855</td>
</tr>
<tr>
<td>countl_zero</td>
<td>855</td>
</tr>
<tr>
<td>countr_one</td>
<td>855</td>
</tr>
<tr>
<td>countr_zero</td>
<td>855</td>
</tr>
<tr>
<td>cout</td>
<td>1753</td>
</tr>
<tr>
<td>cbegin</td>
<td>1197</td>
</tr>
<tr>
<td>basic_stacktrace</td>
<td>605</td>
</tr>
<tr>
<td>basic_string</td>
<td>883</td>
</tr>
<tr>
<td>basic_string_view</td>
<td>867</td>
</tr>
<tr>
<td>reversible containers</td>
<td>911</td>
</tr>
<tr>
<td>cbegin(const C&amp; c)</td>
<td>1194</td>
</tr>
<tr>
<td>create_directories</td>
<td>1884</td>
</tr>
<tr>
<td>create_directory</td>
<td>1884</td>
</tr>
<tr>
<td>create_directory_symlink</td>
<td>1884</td>
</tr>
<tr>
<td>create_hard_link</td>
<td>1885</td>
</tr>
<tr>
<td>create_symlink</td>
<td>1885</td>
</tr>
<tr>
<td>cref</td>
<td>790</td>
</tr>
<tr>
<td>cshift</td>
<td>1536</td>
</tr>
<tr>
<td>ctime</td>
<td>1699</td>
</tr>
<tr>
<td>ctype</td>
<td>1709</td>
</tr>
<tr>
<td>do_is</td>
<td>1710</td>
</tr>
<tr>
<td>do_narrow</td>
<td>1710</td>
</tr>
<tr>
<td>do_scan_is</td>
<td>1710</td>
</tr>
<tr>
<td>do_scan_not</td>
<td>1710</td>
</tr>
<tr>
<td>do_tolower</td>
<td>1710</td>
</tr>
<tr>
<td>do_toupper</td>
<td>1710</td>
</tr>
<tr>
<td>do_widen</td>
<td>1710</td>
</tr>
<tr>
<td>is</td>
<td>1710</td>
</tr>
<tr>
<td>narrow</td>
<td>1710</td>
</tr>
<tr>
<td>narrow</td>
<td>1710</td>
</tr>
<tr>
<td>scan_is</td>
<td>1710</td>
</tr>
<tr>
<td>scan_not</td>
<td>1710</td>
</tr>
<tr>
<td>table</td>
<td>1713</td>
</tr>
<tr>
<td>table</td>
<td>1713</td>
</tr>
<tr>
<td>tolower</td>
<td>1713</td>
</tr>
<tr>
<td>toupper</td>
<td>1713</td>
</tr>
<tr>
<td>widen</td>
<td>1713</td>
</tr>
<tr>
<td>ctype_base</td>
<td>1709</td>
</tr>
<tr>
<td>do_scan_is</td>
<td>1711</td>
</tr>
<tr>
<td>ctype_byname</td>
<td>1712</td>
</tr>
<tr>
<td>curr_symbol</td>
<td>1712</td>
</tr>
<tr>
<td>moneypunct</td>
<td>1738</td>
</tr>
<tr>
<td>current</td>
<td>604</td>
</tr>
<tr>
<td>basic_stacktrace</td>
<td>604</td>
</tr>
<tr>
<td>current_exception</td>
<td>554</td>
</tr>
<tr>
<td>current_path</td>
<td>1885</td>
</tr>
<tr>
<td>current_zone</td>
<td>1670</td>
</tr>
<tr>
<td>tzdb</td>
<td>1678</td>
</tr>
<tr>
<td>cv_status</td>
<td>2000</td>
</tr>
<tr>
<td>cyl_bessel_i</td>
<td>1554</td>
</tr>
<tr>
<td>cyl_bessel_if</td>
<td>1554</td>
</tr>
<tr>
<td>cyl_bessel_il</td>
<td>1554</td>
</tr>
<tr>
<td>cyl_bessel_j</td>
<td>1554</td>
</tr>
<tr>
<td>cyl_bessel_jf</td>
<td>1554</td>
</tr>
<tr>
<td>cyl_bessel_jl</td>
<td>1554</td>
</tr>
<tr>
<td>cyl_bessel_k</td>
<td>1555</td>
</tr>
<tr>
<td>cyl_bessel_kf</td>
<td>1555</td>
</tr>
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<td>cyl_bessel_kl</td>
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</tr>
<tr>
<td>cyl_neumann</td>
<td>1555</td>
</tr>
<tr>
<td>cyl_neumannf</td>
<td>1555</td>
</tr>
<tr>
<td>cyl_neumannl</td>
<td>1555</td>
</tr>
<tr>
<td>D</td>
<td>1207</td>
</tr>
<tr>
<td>dangling</td>
<td>1207</td>
</tr>
<tr>
<td>data</td>
<td>1198</td>
</tr>
<tr>
<td>array</td>
<td>946</td>
</tr>
<tr>
<td>basic_string</td>
<td>892</td>
</tr>
<tr>
<td>basic_string_view</td>
<td>868</td>
</tr>
<tr>
<td>inplace_vector</td>
<td>976</td>
</tr>
<tr>
<td>single_view</td>
<td>1212</td>
</tr>
</tbody>
</table>
Index of library names

span, 1077
vector, 968
data(C& c), 1184
data(initializer_list<E>), 1185
data(T (&array)[N]), 1185
date
  leap_second, 1689
date_order
time_get, 1729
day, 1646
  constructor, 1647
  from_stream, 1648
  hash, 1699
  month_day, 1657
  ok, 1647
  operator unsigned, 1647
  operator"d, 1648
  operator+, 1648
  operator++, 1647
  operator=, 1647
  operator-, 1648
  operator--, 1647
  operator->, 1647
  operator, 1648
  operator<<, 1648
  operator<=, 1648
  operator==, 1647
  year_month_day, 1664
  year_month_day_last, 1666
days, 1609
DBL_DECIMAL_DIG, 537
DBL_DIG, 537
DBL_EPSILON, 537
DBL_HAS_SUBNORM, 537
DBL_MANT_DIG, 537
DBL_MAX, 537
DBL_MAX_10_EXP, 537
DBL_MAX_EXP, 537
DBL_MIN, 537
DBL_MIN_10_EXP, 537
DBL_MIN_EXP, 537
DBL_TRUE_MIN, 537
deallocate
  allocator, 624
  allocator_traits, 623
  memory_resource, 654
  polymorphic_allocator, 656
  scoped_allocator_adaptor, 665
deallocate_bytes
  polymorphic_allocator, 656
deallocate_object
  polymorphic_allocator, 656
debug_string
  range_format, 826
dec, 1768, 1796
deca, 696
decay, 690
decay-copy, 495
decay_t, 671
deci, 696

DECIMAL_DIG, 537
decimal_point
  moneypunct, 1738
  nummpunct, 1726
declare_no_pointers
  zombie, 515
declare_reachable
  zombie, 515
dclval, 704
default_accessor
  access, 1106
  constructor, 1106
  offset, 1106
default_delete
  constructor, 626
  operator(), 626
default_error_condition
  error_category, 595
  error_code, 597
default_initializable, 582
default_random_engine, 1502
default_searcher, 816
  constructor, 816
  operator(), 816
default_sentinel, 1125
default_sentinel_t, 1173
default_zone
  zoned_traits<time_zone*, 1684
defaultfloat, 1769
defer_lock, 1990
defer_lock_t, 1990
delete
  operator, 517, 543–546, 625
denorm_min
  numeric_limits, 534
densities
  piecewise_constant_distribution, 1524
  piecewise_linear_distribution, 1526
depth
  recursive_directory_iterator, 1879
deque, 947
  allocator_type, 912
  assign, 916
  assign_range, 916
  begin, 908
  cbegin, 908
  cend, 908
  clear, 916
  const_iterator, 907
  const_reference, 907
  const_reverse_iterator, 910
  constructor, 949, 950
  crbegin, 911
crend, 911
difference_type, 907
demplace, 914, 950
empty, 909
end, 908
erase, 915, 951
erase_if, 951
get_allocator, 912
insert, 915, 950
insert_range, 915
iterator, 907
max_size, 909
operator!=, 908
operator==, 908
operator=, 907, 913
operator==, 908
push_back, 950
push_front, 950
rbegin, 910
reference, 907
rend, 911
resize, 950
reverse_iterator, 910
shrink_to_fit, 950
size, 909
size_type, 907
swap, 908, 913
value_type, 907
derived_from, 577
description
stacktrace_entry, 602
destroy, 1472
allocator_traits, 623
coroutine_handle, 568
coroutine_handle<noop_coroutine_-
promise>, 569
polymorphic_allocator, 657
scoped_allocator_adaptor, 665
destroy_at, 1472
destroy_n, 1473
destroying_delete, 541
destroying_delete_t, 541
destructible, 581
detach
jthread, 1945
thread, 1943
dextents, 1082
difference_type
allocator, 623
allocator_traits, 622
basic_string, 875
basic_string_view, 863
containers, 907
pointer_traits, 616
scoped_allocator_adaptor, 665
difftime, 1699
digits
numeric_limits, 532
digits10
numeric_limits, 533
dims, 1082
directory_entry, 1872
assign, 1873
constructor, 1873
exists, 1874
filesize, 1875
hard_link_count, 1875
is_block_file, 1874
is_character_file, 1874
is_directory, 1874
is_fifo, 1874
is_other, 1874
is_regular_file, 1874
is_socket, 1875
is_symlink, 1875
last_write_time, 1875
operator const filesystem::path&, 1874
operator<<, 1875
operator==, 1875
operator==, 1875
path, 1874
refresh, 1874
replace_filename, 1873
status, 1875
symlink_status, 1875
directory_iterator, 1876
begin, 1877
constructor, 1877
end, 1877
increment, 1877
operator++, 1877
operator=, 1877
directory_options, 1870
disable_recursion_pending
recursive_directory_iterator, 1880
disable_sized_range, 1200
disable_sized_sentinel_for, 1138
move_iterator, 1125
reverse_iterator, 1124
disabled
range_format, 826
discard_block_engine, 1498
constructor, 1499
result_type, 1498
discrete_distribution, 1521, 1522
constructor, 1522, 1523
probabilities, 1523
result_type, 1522
disjunction, 693
disjunction_v, 675
distance, 1149, 1150
div, 523, 1894
div_sat, 1467
div_t, 523
divides, 792
operator(), 792
divides<>, 792
operator(), 792
do_allocate
memory_resource, 654
monotonic_buffer_resource, 662
synchronized_pool_resource, 660
unsynchronized_pool_resource, 660
do_always_noconv
Index of library names

codecvt, 1717
do_close
message, 1740
do_compare
collate, 1727
do_curr_symbol
moneypunct, 1738
do_date_order
time_get, 1730
do_deallocate
memory_resource, 654
monotonic_buffer_resource, 662
synchronized_pool_resource, 660
unsynchronized_pool_resource, 660
do_decimal_point
moneypunct, 1738
numpunct, 1726
do_encoding
codecvt, 1717
do_falsename
numpunct, 1726
do_frac_digits
moneypunct, 1738
do_get
messages, 1740
money_get, 1734
num_get, 1719, 1721
time_get, 1731
do_get_date
time_get, 1731
do_get_monthname
time_get, 1731
do_get_time
time_get, 1730
do_get_weekday
time_get, 1731
do_get_year
time_get, 1731
do_grouping
moneypunct, 1738
numpunct, 1726
do_hash
collate, 1728
do_in
codecvt, 1716
do_is
cctype, 1710
do_is_equal
memory_resource, 655
monotonic_buffer_resource, 662
synchronized_pool_resource, 660
unsynchronized_pool_resource, 660
do_length
codecvt, 1717
do_max_length
codecvt, 1717
do_narrow, 1713
cctype, 1711
cctype<char>, 1714
do_neg_format
moneypunct, 1738
do_negative_sign
moneypunct, 1738
do_open
messages, 1740
do_out
codecvt, 1716
do_pos_format
moneypunct, 1738
do_positive_sign
moneypunct, 1738
do_put
money_put, 1736
num_put, 1722, 1725
time_put, 1733
do_scan_is
cctype_base, 1711
do_scan_not
cctype, 1711
do_thousands_sep
moneypunct, 1738
numpunct, 1726
do_tolower
cctype, 1711
cctype<char>, 1714
do_toupper
cctype, 1711
cctype<char>, 1714
do_transform
collate, 1728
do_truename
numpunct, 1726
do_unshift
numpunct, 1726
done
coroutine_handle, 567
coroutine_handle<noop_coroutine_-_promise>, 569
dot, 1588
dotc, 1588
double_t, 1545
drop
views, 1243
drop_view, 1244
base, 1244
begin, 1245
constructor, 1245
end, 1244
size, 1244
drop_while
views, 1245
drop_while_view, 1245
base, 1245
Index of library names
common_view, 1276
concat_view, 1269
containers, 908
directory_iterator, 1877
drop_view, 1244
drop_while_view, 1245
elements_view, 1280
enumerate_view, 1285
filter_view, 1230
generator, 1342
initializer_list, 556
iota_view, 1214, 1215
join_view, 1246
lazy_split_view, 1258
lazy_split_view::outer_iterator::value_type, 1262
match_results, 1917
optional, 734
path, 1865
recursive_directory_iterator, 1880
repeat_view, 1220
reverse_view, 1278
single_view, 1212
slide_view, 1320
span, 1077
subrange, 1206
sys_info, 1682
take_view, 1239
take_while_view, 1242
text_encoding::aliases_view, 1744
transform_view, 1234
tzdb_list, 1679
unordered associative containers, 939
valarray, 1545
zip_transform_view, 1296
zip_view, 1290
end(C&), 1183
end(initializer_list<E>), 557
end(T (&)[N]), 1183
endian, 855
big, 855
little, 855
native, 855
endl, 1796, 1798
ends, 1799
ends_with, 1407
basic_string, 894
basic_string_view, 869
ENETDOWN, 591
ENETRESET, 591
ENETUNREACH, 591
ENFILE, 591
ENOBUFFS, 591
ENODATA, 2100
ENODEV, 591
ENOENT, 591
ENOEXEC, 591
ENOLCK, 591
ENOLINK, 591
ENOMEM, 591
ENOMSG, 591
ENOPROTOOPT, 591
ENOSPC, 591
ENOSR, 2100
ENOSTR, 2100
ENOSYS, 591
ENOTCONN, 591
ENOTDIR, 591
ENOTEMPTY, 591
ENOTRECOVERABLE, 591
ENOTSOCK, 591
ENOTSUP, 591
ENOTTY, 591
entropy
random_device, 1503
enumerate
views, 1285
enumerate_view, 1285
begin, 1285
end, 1285
size, 1285
enumerate_view::iterator, 1286
base, 1288
constructor, 1288
index, 1288
operator+, 1289
operator++, 1288
operator+=, 1288
operator-, 1289
operator=, 1288
operator=, 1288
operator<<, 1289
operator==, 1289
operator==, 1289
operator==, 1289
environment

environment_is

text_encoding, 1743
ENXIO, 591
EOF, 1893
eof

basic_ios, 1767
EOPNOTSUPP, 591
EOVERFLOW, 591
EOWNERDEAD, 591
EPERM, 591
EPIPE, 591
epptr

basic_streambuf, 1774
EPROTO, 591
EPROTONOSUPPORT, 591
EPROTOTYPE, 591
epsilon

Index of library names
Index of library names

numeric_limits, 533

equal, 1403
   istreambuf_iterator, 1182
   strong_ordering, 560
equal_range, 1433
   ordered associative containers, 929
   unordered associative containers, 938
equal_to, 793, 795
   operator(), 793
equal_to<>, 793
   operator(), 793
equality_comparable, 584
equality_comparable_with, 584
equivalence_relation, 586
equivalent, 1885
   error_category, 595
   partial_ordering, 558
   strong_ordering, 560
   weak_ordering, 559
erANGE, 591
erase
   basic_string, 889, 890, 898
   deque, 951
   forward_list, 958
   inplace_vector, 977
   list, 962, 964
   ordered associative containers, 927, 928
   sequence containers, 915
   unordered associative containers, 937
   vector, 969
erase_after
   forward_list, 956
   tzdb_list, 1679
erase_if
   basic_string, 898
   deque, 951
   flat_map, 1049
   flat_multimap, 1056
   flat_multiset, 1070
   flat_set, 1063
   forward_list, 958
   inplace_vector, 977
   list, 964
   multimap, 990
   multiset, 998
   set, 994
   unordered_map, 1008
   unordered_multimap, 1014
   unordered_multiset, 1024
   unordered_set, 1019
   vector, 969
erf, 1545
erfc, 1545
erfcf, 1545
erfcl, 1545
erff, 1545
erfl, 1545
EROFS, 591
errc, 592
   make_error_code, 597
   make_error_condition, 599
ererrno, 591
error
   bad_expected_access, 759
   expected, 768
   expected<void>, 775
   unexpected, 758
error_category, 592, 594
   constructor, 594
default_error_condition, 595
destructor, 594
equivalent, 595
   message, 595
   name, 595
   operator<>, 595
   operator=, 595
error_code, 592, 596
   assign, 597
   category, 597
   clear, 597
   constructor, 596, 597
default_error_condition, 597
   hash, 599
   message, 597
   operator bool, 597
   operator<, 597
   operator<>, 599
   operator=, 597
   operator==, 599
   value, 597
error_condition, 592, 598
   assign, 598
   category, 599
   clear, 598
   constructor, 598
   message, 599
   operator bool, 599
   operator<, 599
   operator=, 598
   operator==, 599
   value, 599
error_or
   expected, 768
   expected<void>, 775
error_type, 1904, 1905
   expected, 760
   expected<void>, 770
   regex_constants, 1904, 1905
ESPIPE, 591
ESRCH, 591
ETIME, 2100
ETIMEDOUT, 591
ETXTBSY, 591
EWOULDBLOCK, 591
exa, 696
exception, 552
   constructor, 552
©ISO/IEC
Index of library names © ISO/IEC 2207
Index of library names

a, 1516
b, 1516
constructor, 1516
result_type, 1515

F
fabs, 1545
fabsf, 1545
fabsl, 1545
facet
locale, 1705
fail
basic_ios, 1767
failed
ostreambuf_iterator, 1183
failure
ios_base, 1757
false_type, 675
falsename
numpunct, 1726
fclose, 1833, 1893
fdim, 1545
fdimf, 1545
fdiml, 1545
FE_ALL_EXCEPT, 1475
FE_DFL_ENV, 1475
FE_DIVBYZERO, 1475
FE_DOWNWARD, 1475
FE_INEXACT, 1475
FE_INVALID, 1475
FE_OVERFLOW, 1475
FE_TONEAREST, 1475
FE_TOWARDZERO, 1475
FE_UPWARD, 1475
FE_UNDERFLOW, 1475
femto, 696
fenv_t, 1475
fegetenv, 1475
fegetexceptflag, 1475
fesetenv, 1475
fesetround, 1475
fetch_add
atomic<floating-point-type>, 1969
atomic<integral-type>, 1967
atomic<T*>, 1971
atomic_ref<floating-point-type>, 1960
atomic_ref<integral-type>, 1958
atomic_ref<T*>, 1961
fetch_and
atomic<integral-type>, 1967
atomic_ref<integral-type>, 1958
fetch_max
atomic<integral-type>, 1967
atomic<T*>, 1971
atomic_ref<integral-type>, 1958
atomic_ref<T*>, 1961
fetch_min
atomic<integral-type>, 1967
atomic<T*>, 1971
atomic_ref<integral-type>, 1958
atomic_ref<T*>, 1961
fetch_or
atomic<integral-type>, 1967
atomic_ref<integral-type>, 1958
fetch_sub
atomic<floating-point-type>, 1969
atomic<integral-type>, 1967
atomic<T*>, 1971
atomic_ref<floating-point-type>, 1960
atomic_ref<integral-type>, 1958
atomic_ref<T*>, 1961
fetch_xor
atomic<integral-type>, 1967
atomic_ref<integral-type>, 1958
fetestexcept, 1475
feupdateenv, 1475
fexcep_t, 1475
fflush, 1893
fgetc, 1893
fgetpos, 1893
fgets, 1893
fgetwc, 902
fgetws, 902
FILE, 1893
file_clock, 1641
now, 1642
file_size, 1886
directory_entry, 1875
file_status, 1871
constructor, 1871
permissions, 1871, 1872
type, 1871
file_time, 1609
from_stream, 1642
operator<<, 1642
file_type, 1868
filebuf, 1750, 1828
filename
path, 1863
FILENAME_MAX, 1893
filesystem_error, 1867
constructor, 1867, 1868
path1, 1868
path2, 1868
what, 1868
fill, 1417
array, 946
basic_ios, 1765
fill_n, 1417
filter
views, 1229
filter_view, 1230
  base, 1230
  begin, 1230
  constructor, 1230
  end, 1230
  iterator, 1231
  pred, 1230
  sentinel, 1232
filter_view::iterator
  base, 1232
  constructor, 1231
  iter_move, 1232
  iter_swap, 1232
  operator*, 1232
  operator++, 1232
  operator--, 1232
  operator->, 1232
filter_view::sentinel
  base, 1233
  constructor, 1233
final_suspend
generator::promise_type, 1343
find, 1397
  basic_string, 892, 893
  basic_string_view, 870
  ordered associative containers, 928
  unordered associative containers, 938
find_end, 1399
find_first_not_of
  basic_string, 892, 893
  basic_string_view, 870
find_first_of, 1400
  basic_string, 892, 893
  basic_string_view, 870
find_if, 1397
find_if_not, 1397
find_last, 1398
find_last_not_of
  basic_string, 892, 893
  basic_string_view, 870
find_last_of
  basic_string, 892, 893
  basic_string_view, 870
first
  local_info, 1682
  span, 1075, 1076
first_argument_type
  zombie, 515
fisher_distribution
result_type, 1520
fisher_f_distribution, 1520
  constructor, 1520
m, 1520
n, 1520
fixed, 1769
  chars_format, 822
flag_type
  basic_regex, 1911
flags
  ios_base, 1709, 1759
flat_map, 1037
  at, 1045
  constructor, 1043, 1044
  emplace, 1045
  erasure_if, 1049
  extract, 1048
  insert, 1046
  insert_or_assign, 1047, 1048
  insert_range, 1046
  max_size, 1045
  operator<=>, 911
  operator[], 1045
  replace, 1048
  size, 1045
  swap, 1048
  try_emplace, 1047
flat_multimap, 1049
  constructor, 1055
  erasure_if, 1056
  operator<=>, 911
flat_multiset, 1063
  constructor, 1068, 1069
  emplace, 1069
  erasure_if, 1070
  extract, 1070
  insert, 1069
  operator<=>, 911
  replace, 1070
  swap, 1070
flat_map, 1056, 1057
  constructor, 1061, 1062
  erasure_if, 1063
  insert, 1062, 1063
  insert_range, 1063
  operator<=>, 911
  replace, 1063
  swap, 1063
flatset
  extract, 1063
  insert, 1062
flip
  bitset, 781
    vector<bool>, 971
  float128_t, 539
  float16_t, 539
  float32_t, 539
  float64_t, 539
  float_denorm_style, 2099
    numeric_limits, 2099
  float_round_style, 530, 531
  float_t, 1545
  floating_point, 579
  floor, 1545
    duration, 1630
    time_point, 1635
empty, 909
end, 908
erase, 915, 958
erase_after, 956
erase_if, 958
front, 954
get_allocator, 912
insert, 915
insert_after, 955, 956
insert_range, 915
insert_range_after, 955
iterator, 907
max_size, 909
merge, 958
operator!=, 908
operator<>: 911
operator==, 907, 913
operator==, 908
pop, 955
prepend_range, 955
push_front, 955
reference, 907
remove, 957
remove_if, 957
resize, 956
reverse, 958
size, 909
size_type, 907
sort, 958
splice_after, 956, 957
swap, 908, 913
unique, 957
value_type, 907
forward_range, 1201
FP_FAST_FMA, 1545
FP_FAST_FMAF, 1545
FP_FAST_FMAL, 1545
FP_ILOGB0, 1545
FP_ILOGBNAN, 1545
FP_INFINITY, 1545
FP_NAN, 1545
FP_NORMAL, 1545
FP_SUBNORMAL, 1545
FP_ZERO, 1545
fpclassify, 1545
fpos, 1750, 1755, 1762
state, 1762
fpos_t, 1893
fprintf, 1893
fputc, 1893
fputs, 1893
fputwc, 902
fputws, 902
frac_digits
moneypunct, 1738
freopen, 1893
frequ, 1545
frexp, 1545
frexpf, 1545
frexpl, 1545
from_address
coroutine_handle, 567
from_bytes
zombie, 516
from_chars, 823, 824
from_chars_result, 822
ec, 822
ptr, 822
from_promise
coroutine_handle, 567
from_stream
day, 1648
duration, 1632
date_time, 1642
gps_time, 1641
local_time, 1643
month, 1650
month_day, 1657
sys_time, 1636
tai_time, 1640
utc_time, 1638
weekday, 1655
year, 1652
year_month, 1662
year_month_day, 1665
from_sys
tai_clock, 1637
from_time_t
day, 1648
duration, 1632
date_time, 1642
gps_time, 1641
local_time, 1643
month, 1650
month_day, 1657
sys_time, 1636
tai_time, 1640
utc_time, 1638
weekday, 1655
year, 1652
year_month, 1662
year_month_day, 1665
from_utc
gps_clock, 1641
tai_clock, 1639
from_utc
gps_clock, 1641
tai_clock, 1639
from_utc
gps_clock, 1641
tai_clock, 1639
front
basic_string, 885
basic_string_view, 867
forward_list, 954
span, 1076
tzdb_list, 1679
view_interface, 1204
front_insert_iterator, 1157
constructor, 1157
operator*, 1157
operator++, 1157
operator==, 1157
front_insert
operator*, 1157
operator++, 1157
operator==, 1157
fscanf, 1893
fseek, 1832, 1893
fsetpos, 1893
fstream, 1750, 1828
ftell, 1893
function, 803
constructor, 804, 805
destructor, 806
invocation, 806
operator bool, 806

Index of library names
Index of library names
shared_ptr, 644
unique_ptr, 629
get_future
   packaged_task, 2025
   promise, 2016
get_id
   jthread, 1946
   this_thread, 1946
   thread, 1943
get_if, 748, 749
   variant, 748, 749
get_info
   time_zone, 1683
   zoned_time, 1688
get_leap_second_info, 1638
get_local_time
   zoned_time, 1688
get_money, 1801
get_monthname
get_time, 1730
generic
get_newHandler, 517, 547
get_pointer_safety
   zombie, 515
get_return_object
   generator::promise_type, 1343
get_stop_source
   jthread, 1946
get_stop_token
   jthread, 1946
get_sys_time
   zoned_time, 1688
get_temporary_buffer
   zombie, 515
get_terminate, 517, 553
get_time, 1802
   time_get, 1729
get_time_zone
   zoned_time, 1688
globals
get_token
   stop_source sc, 1938
get_tzdb, 1679
get_tzdb_list, 1679
get_unexpected
   zombie, 515
get_weekday
   time_get, 1730
get_wrapped
   basic_syncbuf, 1844
get_year
   time_get, 1730
getc, 1893
getchar, 1893
getenv, 523, 570
globline
   basic_istream, 1786, 1787
   basic_string, 897, 898
getloc, 1907
   basic_regex, 1911
   basic_streambuf, 1772
ios_base, 1760
gets
   zombie, 515
getwc, 902
getwchar, 902
giga, 696
global
   locale, 1708
gmtime, 1699
good
   basic_ios, 1767
gps_clock, 1640
      from_utc, 1641
      now, 1641
      to_utc, 1641
gps_seconds, 1609
gps_time, 1609
      from_stream, 1641
      operator<<, 1641
gptr
   basic_streambuf, 1774
greater, 793, 796
      operator(), 793
      partial_ordering, 558
      strong_ordering, 560
      weak_ordering, 559
greater<, 794
      operator(), 794
greater_equal, 794, 796
      operator(), 794
      greater_equal<, 794
      operator(), 794
grep
   syntax_option_type, 1902, 1903
grouping
   moneypunct, 1738
   numpunct, 1726
gslice, 1540
      constructor, 1541
      size, 1541
      start, 1541
      stride, 1541
gslice_array, 1542
      operator**, 1542
      operator+=, 1542
      operator-=, 1542
      operator/=, 1542
      operator<<, 1542
      operator=, 1542
      operator>>=, 1542
      operator^=, 1542
      operator|, 1542
      value_type, 1542
H
handle
  basic_format_arg, 849
hard_link_count, 1886
directory_entry, 1875
hardware_concurrency
  jthread, 1946
  thread, 1943
hardware_constructive_interference_size, 548
hardware_destructive_interference_size, 548
has_denorm_loss
  numeric_limits, 2099
has_extension
  path, 1864
has_facet
  locale, 1708
has_filename
  path, 1864
has_infinity
  numeric_limits, 534
has_parent_path
  path, 1864
has_quiet_NaN
  numeric_limits, 534
has_relative_path
  path, 1864
has_root_directory
  path, 1863
has_root_name
  path, 1863
has_root_path
  path, 1863
has_signaling_NaN
  numeric_limits, 534
has_single_bit, 854
has_stem
  path, 1864
has_unique_object_representations, 682, 684
has_value
  any, 755
  expected, 767
  expected<void>, 775
  optional, 739
has_virtual_destructor, 682
has_virtual_destructor_v, 674
hash, 818
  basic_string, 900
  collate, 1727
coroutine_handle, 568
day, 1699
duration, 1699
error_code, 599
leap_second, 1699
monostate, 751
month, 1699
month_day, 1699
month_day_last, 1699
month_weekday, 1699
month_weekday_last, 1699
optional, 739
shared_ptr, 649
string_view, 871
text_encoding, 1748
thread::id, 1941
time_point, 1699
type_index, 820
u16string_view, 871
u32string_view, 871
u8string_view, 871
unique_ptr, 649
variant, 751
weekday, 1699
weekday_indexed, 1699
weekday_last, 1699
wstring_view, 871
year, 1699
year_month, 1699
year_month_day, 1699
year_month_day_last, 1699
year_month_weekday, 1699
year_month_weekday_last, 1699
zoned_time, 1699
hash_code, 782
type_index, 819
type_info, 549
hash_function
unordered associative containers, 934
hash_value
  path, 1866
hasher
unordered associative containers, 932
hazard_pointer
constructor, 2031
destructor, 2031
empty, 2031
operator=, 2031
protect, 2031
reset_protection, 2032
swap, 2032
try_protect, 2031
hazard_pointer_obj_base
  retire, 2030
hecto, 696
hermite, 1556
hermitef, 1556
hermitel, 1556
hermitian_matrix_rank_1_update, 1598, 1599
hermitian_matrix_rank_2_update, 1599
hermitian_matrix_rank_2k_update, 1605
hermitian_matrix_rank_k_update, 1604
hermitian_matrix_vector_product, 1594
hex, 1768
  chars_format, 822
hexfloat, 1769
hh_mm_ss
Index of library names

hours, 1677
is_negative, 1676
minutes, 1677
operator precision, 1677
seconds, 1677
subseconds, 1677
to_duration, 1677
high_resolution_clock, 1643
hms, 1675
holds_alternative, 748
variant, 748
hours, 1609
hh_mm_ss, 1677
HUGE_VAL, 1545
HUGE_VALF, 1545
HUGE_VALL, 1545
hypot, 1545
3-argument form, 1552
hypotf, 1545
hypotl, 1545

I
case
    syntax_option_type, 1902, 1903
id
    locale, 1706
text_encoding, 1744
thread, 1940
identity, 799
ifstream, 1750, 1828
ignore, 721
    basic_istream, 1787
ilogb, 1545
ilogbf, 1545
ilogbl, 1545
imag, 1483
complex, 1479, 1481
imaxabs, 1894
imaxdiv, 1894
imaxdiv_t, 1894
imbue, 1907
    basic_filebuf, 1835
    basic_ios, 1765
    basic_regex, 1911
    basic_streambuf, 1774
    ios_base, 1760
implicit_unit_diagonal, 1573
implicit_unit_diagonal_t, 1573
in
    codecvt, 1715
in_avail
    basic_streambuf, 1773
in_place, 702
in_place_index, 702
in_place_index_t, 702
in_place_t, 702
in_place_type, 702
in_place_type_t, 702
in_range, 705
includes, 1439
inclusive_scan, 1461, 1462
increment
    directory_iterator, 1877
    recursive_directory_iterator, 1880
incrementable, 1136
incrementable_traits, 1128
independent_bits_engine, 1499
    result_type, 1499
index
    enumerate_view:::iterator, 1288
variant, 747
weekday_indexed, 1655
year_month_weekday, 1669
index_sequence, 700
index_sequence_for, 700
indirect_array, 1544
    operator**, 1544
    operator**, 1544
    operator-=, 1544
    operator=, 1544
    operator<<, 1544
    operator<<, 1544
    operator%=, 1544
    operator%=, 1544
    operator/=, 1544
    operator/=, 1544
    value_type, 1544
indirect_binary_predicate, 1145
indirect_equivalence_relation, 1145
indirect_result_t, 1121
indirect_strict_weak_order, 1145
indirect Unary predicate, 1145
indirectly_comparable, 1147
indirectly_copyable, 1146
indirectly_copyable_storable, 1147
indirectly_movable, 1146
indirectly_movable_storable, 1146
indirectly_readeable, 1134
indirectly_readable, 1129
indirectly_readeable_traits, 1129
indirectly_regular Unary invocable, 1145
indirectly_swappable, 1147
indirectly Unary invocable, 1145
indirectly_writable, 1134
INFINITY, 1545
infinity
    numeric_limits, 534
Init
    ios_base, 1759
init
    basic_ios, 1764, 1781
    basic_ostream, 1793
initializer_list, 556
begin, 556
constructor, 556
end, 556
size, 556
inner_allocator
   scoped_allocator_adaptor, 665
inner_allocator_type
   scoped_allocator_adaptor, 664
inner_product, 1458
inout_ptr, 653
inout_ptr_t, 652
  constructor, 652
destructor, 652
inplace_merge, 1438
inplace_vector, 972
  append_range, 976
capacity, 975
  constructor, 975
data, 976
emplace
emplace_back, 976
erase, 977
erase_if, 977
insert, 976
insert_range, 976
max_size, 975
pop_back, 977
push_back, 976
reserve, 977
resize, 975
shrink_to_fit, 977
try_append_range, 977
try_emplace_back, 976
try_push_back, 976
unchecked_emplace_back, 977
unchecked_push_back, 977
input_iterator, 1138
input_iterator_tag, 1148
input_or_output_iterator, 1137
input_range, 1201
insert
  basic_string, 888, 889
deque, 950
flat_map, 1046
flat_multiset, 1069
flat_set, 1062, 1063
flatset, 1062
inplace_vector, 976
list, 962
map, 985
multimap, 990
ordered associative containers, 925, 926
  sequence containers, 915
set, 994
unordered associative containers, 935, 936
unordered_map, 1006
unordered_multimap, 1013, 1014
unordered_set, 1019
vector, 968
insert_after
  forward_list, 955, 956
insert_iterator, 1157
constructor, 1158
operator*, 1158
operator++, 1158
operator~, 1158
insert_or_assign
  flat_map, 1047, 1048
  map, 985, 986
unordered_map, 1007, 1008
insert_range
  basic_string, 889
  flat_map, 1046
  flat_set, 1063
  inplace_vector, 976
  sequence containers, 915
  unordered associative containers, 936
insert_range_after
  forward_list, 955
inserter, 1158
int16_t, 538
int32_t, 538
int64_t, 538
int8_t, 538
int_fast16_t, 538
int_fast32_t, 538
int_fast64_t, 538
int_fast8_t, 538
int_least16_t, 538
int_least32_t, 538
int_least64_t, 538
int_least8_t, 538
INT_MAX, 537
INT_MIN, 537
int_type
  char_traits, 859
  integer_sequence, 667
    value_type, 667
  integral, 579
  integral_constant, 675
    value_type, 675
  internal, 1768
  intervals
    piecewise_constant_distribution, 1524
    piecewise_linear_distribution, 1526
intmax_t, 538
intptr_t, 538
invalid_argument, 587, 588, 779, 780
  constructor, 588
invocable, 585
INVOKE, 787, 788
invoke, 788
invoke_r, 788
invoke_result, 690
invoke_result_t, 671
io_errc, 1754
  make_error_code, 1769
  make_error_condition, 1769
io_state
  zombie, 515
ios, 1750, 1755
ios_base, 1755
  constructor, 1761
destructor, 1762
failure, 1757
flags, 1709, 1759
fmtflags, 1757, 1800
imbed, 1760
Init, 1759
iostream_category, 1769
iostate, 1757
iword, 1761
openmode, 1757
precision, 1709, 1760
pword, 1761
register_callback, 1761
seekdir, 1759
setf, 1759
sync_with_stdio, 1760
unsetf, 1760
width, 1709, 1760
xalloc, 1761
ios_base::failure, 1757
  constructor, 1757
ios_base::Init, 1759
  constructor, 1759
destructor, 1759
iostate
  ios_base, 1757
iostream_category, 1769
iota, 1465
  views, 1212
iota_view, 1212
  begin, 1214
corstructor, 1214
empty, 1215
end, 1214, 1215
size, 1215
iota_view::iterator
  constructor, 1216
operator*, 1216
operator+, 1217, 1218
operator++, 1216
operator+=, 1217
operator-, 1218
operator--, 1216
operator-=, 1217
operator<, 1217
operator<=, 1217
operator>=, 1217
operator==, 1217
operator+=, 1217
operator-=, 1217
operator<, 1217
operator<=, 1217
operator>=, 1217
operator==, 1217
operator[](), 1217
iota_view::sentinel
  constructor, 1218
operator==, 1218
is
cctype, 1710
cctype<char>, 1713
is_vector<bool_reference, 972
is_absolute
path, 1864
is_abstract, 678
is_abstract_v, 672
is_aggregate, 678
is_aggregate_v, 673
is_always_equal
  allocator_traits, 623
  scoped_allocator_adaptor, 664
is_always_exhaustive
  layout_right_padded::mapping, 1103
is_always_lock_free
  atomic, 1963
    atomic-floating-point-type>, 1963
    atomic<integral-type>, 1963
    atomic<shared_ptr<T>>, 1963
    atomic<T*>, 1963
    atomic<weak_ptr<T>>, 1963
    atomic_ref, 1956
    atomic_ref<floating-point-type>, 1956
    atomic_ref<integral-type>, 1956
    atomic_ref<T*>, 1956
is_am, 1677
is_arithmetic, 676
is_arithmetic_v, 672
is_array, 676
is_array_v, 673
is_base_of, 675
is_base_of_v, 673
is_block_file
  directory_entry, 1886
  directory_entry, 1874
is_bound
  numeric_limits, 1801
is_bounded
  array, 678
  array_v, 673
is_bind_expression
  directory_entry, 1886
  directory_entry, 1874
is_class, 1886, 1887
  directory_entry, 1874
is_class_v, 672
is_clock, 1625
is_clock_v, 1609
is_compound, 677
is_compound_v, 672
is_const, 677
is_const_v, 672
is_constant_evaluated, 694
is_constructible, 678, 684
is_constructible_v, 673
is_convertible, 686, 687
is_convertible_v, 674
is_copy_assignable, 679
is_copy_assignable_v, 673
is_copy_constructible, 678
is_copy_constructible_v, 673
Index of library names
is_corresponding_member, 694
is_debugger_present, 856
is_default_constructible, 678
is_default_constructible_v, 673
is_destructible, 680
is_destructible_v, 673
is_directory, 1887
directory_entry, 1874
is_empty
class, 678
function, 1887
is_empty_v, 672
is_enum, 676
is_enum_v, 672
is_eq, 557
is_equal
memory_resource, 654
is_error_code_enum, 592
is_error_condition_enum, 592
is_exact
numeric_limits, 533
is_execution_policy, 821
is_execution_policy_v, 820
is_exhaustive
layout_right_padded::mapping, 1104
layout_stride::mapping, 1093
is_fifo, 1887
directory_entry, 1874
is_final, 678
is_final_v, 673
is_floating_point, 676
is_floating_point_v, 672
is_function, 676
is_function_v, 672
is_fundamental, 677
is_fundamental_v, 672
is_geq, 557
is_gt, 557
is_gteq, 557
is_heap, 1446
is_heap_until, 1446
is_iec559
numeric_limits, 534
is_implicit_lifetime, 682
is_implicit_lifetime_v, 674
is_integer
numeric_limits, 533
is_integral, 676
is_integral_v, 672
is_invocable, 686
is_invocable_r, 686
is_invocable_r_v, 674
is_invocable_v, 674
is_layout_compatible, 686
is_layout_compatible_v, 674
is_leap
year, 1651
is_literal_type
zombie, 515
is_literal_type_v
zombie, 515
is_lock_free
atomic, 1963
atomic<floating-point-type>, 1963
atomic<integral-type>, 1963
atomic<shared_ptr<T>>, 1963
atomic<T*>, 1963
atomic<weak_ptr<T>>, 1963
atomic_ref, 1956
atomic_ref<floating-point-type>, 1956
atomic_ref<integral-type>, 1956
atomic_ref<T*>, 1956
is_lt, 557
is_lteq, 557
is_lvalue_reference, 676
is_lvalue_reference_v, 672
is_member_function_pointer, 676
is_member_function_pointer_v, 672
is_member_object_pointer, 676
is_member_object_pointer_v, 672
is_member_pointer, 677
is_member_pointer_v, 672
is_modulo
numeric_limits, 535
is_move_assignable, 679
is_move_assignable_v, 673
is_move_constructible, 679
is_move_constructible_v, 673
is_negative
hh_mm_ss, 1676
is_neq, 557
is_nothrow_assignable, 682
is_nothrow_assignable_v, 674
is_nothrow_constructible, 681
is_nothrow_convertible, 686
is_nothrow_convertible_v, 674
is_nothrow_copy_assignable, 682
is_nothrow_copy_assignable_v, 674
is_nothrow_copy_constructible, 681
is_nothrow_default_constructible, 681
is_nothrow_destructible, 682
is_nothrow_destructible_v, 674
is_nothrow_invocable, 686
is_nothrow_invocable_r, 686
is_nothrow_invocable_v, 674
is_nothrow_move_assignable, 682
is_nothrow_move_assignable_v, 674
is_nothrow_move_constructible, 681
is_nothrow_swappable, 682
is_nothrow_swappable_v, 674
is_nothrow_swappable_with, 682
is_nothrow_swappable_with_v, 674
is_null_pointer, 676
is_null_pointer_v, 672
is_object, 677
is_object_v, 672
is_open
basic_filebuf, 1831
Index of library names

basic_fstream, 1841
basic_ifstream, 1837
basic_ofstream, 1839
is_other, 1887
directory_entry, 1874
is_partitioned, 1434
is_permutation, 1404, 1405
is_placeholder, 801
is_placeholder_v, 785
is_pm, 1677
is_pod, 2100
is_pointer, 676
is_pointer_interconvertible_base_of, 686
is_pointer_interconvertible_with_class, 694
is_pointer_v, 672
is_polymorphic, 678
is_polymorphic_v, 673
is_reference, 676
is_reference_v, 672
is_regular_file, 1888
directory_entry, 1874
is_relative
path, 1864
is_rvalue_reference, 676
is_rvalue_reference_v, 672
is_same_v, 674
is_scalar, 677
is_scalar_v, 672
is_scoped_enum, 678
is_scoped_enum_v, 673
is_signed
class, 678
numeric_limits, 533
is_signed_v, 673
is_socket, 1888
directory_entry, 1875
is_sorted, 1430, 1431
is_sorted_until, 1431
is_standard_layout, 677
is_standard_layout_v, 672
is_swappable, 680
is_swappable_v, 673
is_swappable_with, 680
is_swappable_with_v, 673
is_symlink, 1888
directory_entry, 1875
is_trivial, 677
is_trivial_v, 672
is_trivially_assignable, 681
is_trivially_assignable_v, 673
is_trivially_constructible, 680
is_trivially_copy_assignable, 681
is_trivially_copy_constructible, 681
is_trivially_copyable, 677
is_trivially_copyable_v, 672
is_trivially_default_constructible, 680
is_trivially_destructible, 681
is_trivially_destructible_v, 673
is_trivially_move_assignable, 681
is_trivially_move_constructible, 681
is_unbounded_array, 678
is_unbounded_array_v, 673
is_union, 676
is_union_v, 672
is_unsigned, 678
is_unsigned_v, 673
is_virtual_base_of, 686
is_virtual_base_of_v, 674
is_void, 675
is_void_v, 672
is_volatile, 677
is_volatile_v, 672
is_within_lifetime, 695
isalnum, 900, 1708
isalpha, 900, 1708
isblank, 900, 1708
iscntrl, 900, 1708
isctype
regex_traits, 1906
regular expression traits, 1929
isdigit, 900, 1708
isfinite, 1545
isgraph, 900, 1708
isgreater, 1545
isgreaterequal, 1545
isinf, 1545
isless, 1545
islessequal, 1545
islessgreater, 1545
islower, 900, 1708
isnan, 1545
isnormal, 1545
iso_encoding
weekday, 1654
isspanstream, 1821
isprint, 900, 1708
ispunct, 900, 1708
isspace, 900, 1708
istream, 1750, 1777
istream_iterator, 1178
constructor, 1178, 1179
destructor, 1179
operator*, 1179
operator++, 1179
operator->, 1179
operator==, 1179
istreambuf_iterator, 1180, 1750
constructor, 1181, 1182
equal, 1182
operator*, 1182
operator++, 1182
operator==, 1182
proxy, 1181
istringstream, 1750, 1805
istream
zombie, 515
isunordered, 1545

©ISO/IEC
2219
isupper, 900, 1708
iswalnum, 901
iswblank, 901
iswcntrl, 901
iswctype, 901
iswdigit, 901
iswgraph, 901
iswlower, 901
iswprint, 901
iswpunct, 901
iswspace, 901
iswupper, 901
iswxdigit, 901
iter_common_reference_t, 1120
iter_const_reference_t, 1159
iter_difference_t, 1129
iter_move, 1133
    common_iterator, 1172
    concat_view::iterator, 1275
    counted_iterator, 1177
    filter_view::iterator, 1232
    move_iterator, 1167
    reverse_iterator, 1155
    stride_view::iterator, 1333
iter_reference_t, 1119
iter_rvalue_reference_t, 1120
iter_swap, 1133, 1413
    common_iterator, 1172
    concat_view::iterator, 1275
    counted_iterator, 1177
    filter_view::iterator, 1232
    join_view::iterator, 1251
    lazy_split_view::inner_iterator, 1264
    move_iterator, 1167
    reverse_iterator, 1155
    stride_view::iterator, 1334
iter_value_t, 1130
iterator, 2102
    basic_format_context, 841
    basic_format_parse_context, 840
    basic_string, 875
    basic_string_view, 863
    concat_view, 1269
    containers, 907
    filter_view, 1231
    optional, 734
    path, 1865
    span, 1077
    transform_view::iterator, 1236
iterator_category
    iterator_traits, 1130
iterator_traits, 1130
    iterator_category, 1130
    pointer, 1130
    reference, 1130
iword
    ios_base, 1761

J
    jmp_buf, 570
    join
        jthread, 1945
        thread, 1943
        views, 1246
    join_view, 1246
        base, 1246
        begin, 1246
        constructor, 1247
        end, 1246
    join_view::::iterator
        constructor, 1250
        iter_swap, 1251
        operator++, 1250
        operator--, 1250, 1251
        operator->, 1250
        operator==, 1251
    join_view::sentinel
        constructor, 1251
        operator==, 1251
    join_with
        views, 1252
    joinable
        jthread, 1945
        thread, 1943
    jthread, 1943
        constructor, 1944, 1945
        destructor, 1945
        detach, 1945
        get_id, 1946
        get_stop_source, 1946
        get_stop_token, 1946
        hardware_concurrency, 1946
        join, 1945
        joinable, 1945
        operator=, 1945
        request_stop, 1946
        swap, 1945, 1946

K
    k
        negative_binomial_distribution, 1511
    key_comp
        ordered associative containers, 924
    key_compare
        ordered associative containers, 923
    key_eq
        unordered associative containers, 934
    key_equal
        unordered associative containers, 932
    key_type
        ordered associative containers, 923
        unordered associative containers, 932
    keys
        views, 1192
        keys_view, 1192
        kill_dependency, 1953
kilo, 696
knuth_b, 1502

L
L_tmpnam, 1893
labs, 523
laguerre, 1556
laguerref, 1556
laguerrel, 1556
lambda
  exponential_distribution, 1513
largest_required_pool_block
  pool_options, 659
last
  span, 1075, 1076
last_spec, 1646
last_write_time, 1888
directory_entry, 1875
latch
  arrive_and_wait, 2010
  constructor, 2010
  count_down, 2010
  max, 2010
  try_wait, 2010
  wait, 2010
latest
  choose, 1609
launder, 547
layout_blas_packed, 1573
layout_blas_packed::mapping
  constructor, 1574, 1575
  operator(), 1575
  operator==, 1575
  required_span_size, 1575
  stride, 1575
layout_left::mapping
  constructor, 1086, 1087
  operator(), 1087
  operator==, 1087
  required_span_size, 1087
  stride, 1087
  submdspan-mapping-impl, 1114
layout_leftspan::mapping
  constructor, 1096–1098
  submdspan-mapping-impl, 1116
layout_right::mapping
  constructor, 1088, 1089
  operator(), 1090
  operator==, 1090
  required_span_size, 1090
  stride, 1090
  submdspan-mapping-impl, 1115
layout_rightspan::mapping
  constructor, 1101–1103
  is_always_exhaustive, 1103
  is_exhaustive, 1104
  operator(), 1103
  operator==, 1104
required_span_size, 1103
strides, 1103
submdspan-mapping-impl, 1116
layout_stride::mapping
  constructor, 1092
  is_exhaustive, 1093
  operator(), 1093
  operator==, 1093
  required_span_size, 1093
  submdspan-mapping-impl, 1115
layout_transpose, 1582
layout_transpose::mapping
  constructor, 1583
  operator==, 1584
  stride, 1583
lazy_split
  views, 1258
lazy_split_view, 1258
  base, 1258
  begin, 1258
  constructor, 1259
  end, 1258
lazy_split_view::inner-iterator, 1262
  base, 1263
  constructor, 1263
  iter_swap, 1264
  operator++, 1263
  operator==, 1263
lazy_split_view::outer-iterator, 1260
  constructor, 1260, 1261
  operator*, 1261
  operator++, 1261
  operator==, 1261
lazy_split_view::outer-iterator::value_type, 1261
  begin, 1262
  constructor, 1262
  end, 1262
LC_ALL, 1740
LC_COLLATE, 1740
LC_CTYPE, 1740
LC_MONETARY, 1740
LC_NUMERIC, 1740
LC_TIME, 1740
lcm, 1466
lconv, 1740
LDBL_DECIMAL_DIG, 537
LDBL_DIG, 537
LDBL_EPSILON, 537
LDBL_HAS_SUBNORM, 537
LDBL_MANT_DIG, 537
LDBL_MAX, 537
LDBL_MAX_10_EXP, 537
LDBL_MAX_EXP, 537
LDBL_MAX, 537
LDBL_MIN, 537
LDBL_MIN_10_EXP, 537
LDBL_MIN_EXP, 537
ldexp, 1545
ldexpf, 1545
ldexpl, 1545
ldiv, 523
ldiv_t, 523
leap_second, 1688
date, 1689
hash, 1699
operator<, 1689
operator<=, 1690
operator<>, 1689, 1690
operator==, 1689
operator>, 1690
operator>=, 1690
value, 1689
leap_second_info, 1638
left, 1768
legendre, 1556
legendref, 1556
legendrel, 1556
length
basic_string, 883
basic_string_view, 867
codecvt, 1715
match_results, 1916
regex_traits, 1906
sub_match, 1912
length_error, 587, 588
constructor, 588
lerp, 1552
less, 794, 796
operator(), 794
partial_ordering, 558
strong_ordering, 560
weak_ordering, 559
less<>, 794
operator(), 794
less_equal, 794, 796
operator(), 794
less_equal<>, 795
operator(), 795
lexically_normal
path, 1864
lexically_proximate
path, 1865
lexically_relative
path, 1864
lexicographical_compare, 1450
lexicographical_compare_three_way, 1451,
1452
lgamma, 1545
lgammaf, 1545
lgammal, 1545
linear_congruential_engine, 1494
constructor, 1495
result_type, 1494
list, 958
allocator_type, 912
assign, 916
assign_range, 916
begin, 908
cbegin, 908
cend, 908
clear, 916
const_iterator, 907
const_reference, 907
const_reverse_iterator, 910
constructor, 961
crbegin, 911
crend, 911
difference_type, 907
emplace, 914
empty, 909
end, 908
erase, 915, 962, 964
erase_if, 964
get_allocator, 912
insert, 915, 962
insert_range, 915
iterator, 907
max_size, 909
merge, 964
operator! =, 908
operator<>, 911
operator==, 907, 913
operator==, 908
rbegin, 910
reference, 907
remove, 963
rend, 911
resize, 961
reverse, 964
reverse_iterator, 910
size, 909
size_type, 907
sort, 964
splice, 962, 963
swap, 908, 913
unique, 963
value_type, 907
literal
text_encoding, 1743
little
endian, 855
little_endian
zombie, 515
llabs, 523
lldiv, 523
lldiv_t, 523
LONGLONG_MAX, 537
LONGLONG_MIN, 537
llrint, 1545
llrintf, 1545
llrintl, 1545
llround, 1545
llroundf, 1545
llroundl, 1545
load
atomic, 1963
Index of library names

M

m

  fisher_f_distribution, 1520
  lognormal_distribution, 1518
make12, 1677
make24, 1677
make_any, 755
make_const_iterator, 1124
make_const_sentinel, 1124
make_error_code
  errc, 597
  future_errc, 2014
  io_errc, 1769
make_error_condition
  errc, 599
  future_errc, 2014
  io_errc, 1769
make_exception_ptr
  future_errc, 2014
  io_errc, 1769
make_format_args, 850
make_from_tuple, 722
make_hazard_pointer, 2032
make_heap, 1445
make_index_sequence, 700
make_integer_sequence, 667
make_move_iterator, 1168
make_obj_using_allocator, 621
make_optional, 739
make_pair, 710
make_preferred
  path, 1860
make_ready_at_thread_exit
  packaged_task, 2025
make_reverse_iterator, 1155
make_shared, 640–642
make_signed, 688
make_signed_t, 670
make_tuple, 721
tuple, 721
make_unique, 632
make_unsigned, 689
make_unsigned_t, 670
make_wformat_args, 850
malloc, 523, 625, 2096
map, 980
  allocator_type, 912
  at, 984
begin, 908
cbegin, 908
cend, 908
clear, 928
const_iterator, 907
const_reference, 907
const_reverse_iterator, 910
constructor, 923, 924, 984
contains, 928
count, 928
crbegin, 911
crend, 911
difference_type, 907
emplace, 924, 925
emplace_hint, 925
empty, 909
end, 908
equal_range, 929
erase, 927, 928
erase_if, 986
extract, 926, 927
find, 928
get_allocator, 912
insert, 925, 926, 985
insert_or_assign, 985, 986
iterator, 907
key_comp, 924
key_compare, 923
key_type, 923
lower_bound, 928, 929
mapped_type, 923
max_size, 909
merge, 927
node_type, 923
operator!=, 908
operator<, 984
operator<=, 911
operator<=>, 913
operator==, 927, 913
operator==, 908, 984
range_format, 826
rbegin, 910
reference, 907
rend, 911
reverse_iterator, 910
size, 909
size_type, 907
swap, 908, 913
try_emplace, 985
upper_bound, 929
value_comp, 924
value_compare, 923
value_type, 907, 923
map::value_compare
  comp, 980
operator(), 980
mapped_type
  ordered associative containers, 923
  unordered associative containers, 932
mark_count
  basic_regex, 1911
mask_array, 1543
  operator**, 1543
  operator+=, 1543
  operator-=, 1543
  operator/=, 1543
  operator<<=, 1543
  operator>>, 1543
operator[], 1543
operator[], 1543
operator%, 1543
operator&=, 1543
operator&=, 1543
unordered associative containers, 939
max_digits10
numeric_limits, 533
max_element, 1449
max_exponent
numeric_limits, 534
max_exponent10
numeric_limits, 534
max_length
codecvt, 1715
max_load_factor
unordered associative containers, 940
max_size
allocator_traits, 623
array, 945
basic_stacktrace, 605
basic_string, 884
basic_string_view, 867
containers, 909
flat_map, 1045
inplace_map, 1045
match_results, 1916
scoped_allocator_adaptor, 665
MB_CUR_MAX, 523
MB_LEN_MAX, 537
mblen, 523, 903
mbrlen, 902, 904
mbstowcs, 904
mbtowc, 902, 904
mbsinit, 902, 903
mbstowcs, 902
mbstate_t, 902, 903
mbstowcs, 523, 903
mbtowc, 523, 904
mdspan
constructor, 1108–1110
empty, 1111
operator[], 1110
size, 1111
swap, 1111
mean
normal_distribution, 1517
poisson_distribution, 1512
student_t_distribution, 1521
mega, 696
mem_fn, 803
mem_fun
zombie, 515
mem_fun1_ref_t
zombie, 515
mem_fun1_t
zombie, 515
mem_fun_ref
zombie, 515
mem_fun_ref_t
zombie, 515
mem_fun_t
  zombie, 515
memchr, 901
memcmp, 901
memcpy, 901
memmove, 901
memory_order, 1952, 1980
  acq_rel, 1952
  acquire, 1952
  consume, 1952
  relaxed, 1952
  release, 1952
  seq_cst, 1952
memory_order_acq_rel, 1952, 1980
memory_order_acquire, 1952, 1980
memory_order_consume, 1952, 1980
memory_order_relaxed, 1952, 1980
memory_order_release, 1952, 1980
memory_order_seq_cst, 1952, 1980
memory_resource, 654
  allocate, 654
  deallocate, 654
  destructor, 654
  doAllocate, 654
  do_deallocate, 654
  do_is_equal, 655
  is_equal, 654
  operator=, 654
  operator==, 655
memset, 901
merge, 1437
  forward_list, 958
  list, 964
  ordered associative containers, 927
  unordered associative containers, 937
mergeable, 1147
mersenne_twister_engine, 1495
  constructor, 1496
  result_type, 1495
message
  do_close, 1740
  error_category, 595
  error_code, 597
  error_condition, 599
messages, 1739
  close, 1739
  do_get, 1740
  do_open, 1740
  get, 1739
  open, 1739
messages_byname, 1740
mib
  text_encoding, 1743
micro, 696
microseconds, 1609
midpoint, 1466
milli, 696
milliseconds, 1609
min, 1447
duration, 1628
duration_values, 1625
numeric_limits, 532
time_point, 1634
valarray, 1535
year, 1652
min_element, 1449
min_exponent
  numeric_limits, 533
  min_exponent10
  numeric_limits, 533
minmax, 1448
minmax_element, 1450
minstd_rand, 1501
minstd_rand0, 1501
minus, 791
  operator(), 791
  minus<>, 791
  operator(), 791
minutes, 1609
hh_mm_ss, 1677
mismatch, 1402
mktime, 1699
modf, 1545
modff, 1545
modfl, 1545
modulus, 792
  operator(), 792
  modulus<>, 792
  operator(), 792
money_get, 1734
  do_get, 1734
  get, 1734
money_put, 1735
  do_put, 1736
  put, 1736
moneypunct, 1736
  curr_symbol, 1738
  decimal_point, 1738
  do_curr_symbol, 1738
  do_decimal_point, 1738
  do_frac_digits, 1738
  do_grouping, 1738
  do_neg_format, 1738
  do_negative_sign, 1738
  do_pos_format, 1738
  do_positive_sign, 1738
  do_thousands_sep, 1738
  frac_digits, 1738
  grouping, 1738
  negative_sign, 1738
  positive_sign, 1738
  thousands_sep, 1738
moneypunct_byname, 1738
monostate, 751
  hash, 751
  operator<=>, 751
  operator==, 751
monotonic_buffer_resource, 661
constructor, 661
destructor, 661
do_allocate, 662
do_deallocate, 662
do_is_equal, 662
release, 662
upstream_resource, 662

month, 1648
constructor, 1649
from_stream, 1650
hash, 1699
month_day, 1657
month_day_last, 1658
month_weekday, 1659
month_weekday_last, 1660
ok, 1649
operator unsigned, 1649
operator+, 1649, 1650
operator++, 1649
operator*=, 1649
operator-, 1650
operator--, 1649
operator-, 1649
operator<<, 1650
operator<<, 1649
operator>>, 1649
operator==, 1649
year_month, 1661
year_month_day, 1663
year_month_day_last, 1666
year_month_weekday, 1669
year_month_weekday_last, 1671

month_day, 1656
constructor, 1657
day, 1657
from_stream, 1657
hash, 1699
month, 1657
ok, 1657
operator<<, 1657
operator>>, 1657
operator==, 1657

month_day_last, 1658
constructor, 1658
hash, 1699
month, 1658
ok, 1658
operator<<, 1658
operator>>, 1658
operator==, 1658
year_month_day_last, 1666

month_weekday, 1658
constructor, 1659
hash, 1699
month, 1659
ok, 1659
operator<<, 1659
operator==, 1659
weekday_indexed, 1659
month_weekday_last, 1659

constructor, 1660
hash, 1699
month, 1660
ok, 1660
operator<<, 1660
operator==, 1660
weekday_last, 1660
months, 1609
movable, 585
move
algorithm, 1412
basic_ios, 1766
function, 703
move_backward, 1412
move_constructible, 582
move_if_noexcept, 704
move_iterator, 1164
base, 1165, 1166
constructor, 1165
iter_move, 1167
iter_swap, 1167
operator*, 1166
operator+, 1166, 1167
operator++, 1166
operator-=, 1166
operator-, 1166, 1167
operator==, 1166
operator+=, 1166
operator+=, 1166
operator-=, 1166
operator==, 1166
operator++, 1166, 1167
operator+=, 1166
operator-=, 1166
operator==, 1166
operator++, 1166
operator+=, 1166
operator-=, 1166
operator==, 1166
operator++, 1166
operator+=, 1166
operator-=, 1166
operator==, 1166
move_only_function, 807
constructor, 808
destructor, 809
operator bool, 809
operator(), 809
operator=, 809
operator==, 809
swap, 809
move_sentinel, 1168
base, 1168
constructor, 1168
operator=, 1168
operator+=, 1168
operator-=, 1168
operator==, 1168
operators, 1168
mt19937, 1501
mt19937_64, 1502
mul_sat, 1467
multiline
syntax_option_type, 1903
multimap, 987
allocator_type, 912
begin, 908
cbegin, 908
cend, 908
Index of library names

- time_zone_link, 1690
- type_index, 820
- type_info, 549
- N0_1545
- nan, 1545
- nanf, 1545
- nanl, 1545
- nano, 696
- nanoseconds, 1609
- narrow
  - basic_ios, 1765
  - ctype, 1710
  - ctype<char>, 1713
- native
  - endian, 855
  - path, 1861
- native_handle
  - basic_filebuf, 1833
  - basic_fstream, 1841
  - basic_ifstream, 1837
  - basic_ofstream, 1839
  - stacktrace_entry, 602
- native_handle_type, 1829
- NDEBUG, 504
- nearbyint, 1545
- nearbyintf, 1545
- nearbyintl, 1545
- negate, 792
  - operator(), 792
  - negate>, 792
  - operator(), 792
- negation, 694
- negation_v, 675
- negative_binomial_distribution, 1510
  - constructor, 1511
  - k, 1511
  - p, 1511
  - result_type, 1510
- negative_sign
  - moneypunct, 1738
- nested_exception, 555
  - constructor, 555
  - nested_ptr, 555
  - rethrow_if_nested, 555
  - rethrow_nested, 555
  - throw_with_nested, 555
- nested_ptr
  - nested_exception, 555
- new
  - operator, 517, 542–544, 546, 625
  - new_delete_resource, 657
- new_handler, 547
- new_object
  - polymorphic_allocator, 657
- next
  - 1149, 1151
  - subrange, 1207
- next_arg_id
  - basic_format_parse_context, 840
  - next_permutation, 1452
- nextafter, 1545
- nextafterf, 1545
- nextafterl, 1545
- nexttoward, 1545
- nexttowardf, 1545
- nexttowardl, 1545
- noboolalpha, 1767
- node_type
  - ordered associative containers, 923
  - unordered associative containers, 932
  - noemit_on_flush, 1799
- none
  - bitset, 782
- none_of, 1395
- nonexistent
  - local_info, 1682
  - nonexistent_local_time, 1680
    - constructor, 1680
- nontype, 702
- nontype_t, 702
- noop_coroutine, 569
- noop_coroutine_handle, 565
- noop_coroutine_promise, 568
- norm, 1483
  - complex, 1481
- normal_distribution, 1516
  - constructor, 1517
  - mean, 1517
  - result_type, 1516
  - stddev, 1517
  - noshowbase, 1767
  - noshowpunct, 1767
  - noshowpos, 1767
  - noskipws, 1768
  - nostopstate, 1936
  - nostopstate_t, 1936
  - nosubs
    - syntax_option_type, 1902, 1903
- not1
  - zombie, 515
- not2
  - zombie, 515
- not_equal_to, 793, 795
  - operator(), 793
  - not_equal_to>, 793
  - operator(), 793
- not_fn, 799, 800
- noexcept, 541
- noexcept_t, 541
- notify_all
  - atomic, 1665
    - atomic<floating-point-type>, 1665
    - atomic<integral-type>, 1665
    - atomic<shared_ptr<T>>, 1975
  - atomic<T>, 1975
  - atomic<weak_ptr<T>>, 1977
  - atomic_ref<T>, 1957
  - condition_variable, 2002
  - condition_variable_any, 2005

© ISO/IEC 2229
Index of library names
Index of library names
Index of library names
counted_iterator, 1176

day, 1648
duration, 1627, 1634
elements_view::iterator, 1284
enumerate_view::iterator, 1289
iota_view::iterator, 1217, 1218
month, 1649, 1650
move_iterator, 1166, 1167
repeat_view::iterator, 1222
reverse_iterator, 1153, 1155
stride_view::iterator, 1333
time_point, 1634
transform_view::iterator, 1237
valarray, 1534, 1536
weekday, 1654
year, 1651, 1652
year_month, 1661, 1662
year_month_day, 1664, 1665
year_month_day_last, 1667
year_month_weekday, 1669
year_month_weekday_last, 1671, 1672

day, 1647
duration, 1627
elements_view::iterator, 1283
enumerate_view::iterator, 1288
filter_view::iterator, 1232
front_insert_iterator, 1157
generator::iterator, 1346
insert_iterator, 1158
iota_view::iterator, 1216
istream_iterator, 1179
istreambuf_iterator, 1182
join_view::iterator, 1250
lazy_split_view::inner_iterator, 1263
lazy_split_view::outer_iterator, 1261
month, 1649
move_iterator, 1166
ostream_iterator, 1180
ostreambuf_iterator, 1183
recursive_directory_iterator, 1880
regex_iterator, 1924, 1925
regex_token_iterator, 1927, 1928
repeat_view::iterator, 1221
reverse_iterator, 1153
stride_view::iterator, 1332
time_point, 1633
transform_view::iterator, 1236
weekday, 1653
year, 1651

operator++
atomic<integral-type>, 1971, 1972
atomic<T*>, 1971, 1972
atomic_ref<integral-type>, 1961
atomic_ref<T*>, 1961
back_insert_iterator, 1156
basic_const_iterator, 1162
basic_istream_view::iterator, 1223
common_iterator, 1171
counted_view::iterator, 1272
counted_iterator, 1175
day, 1647
directory_iterator, 1877
duration, 1627
elements_view::iterator, 1283
enumerate_view::iterator, 1288
filter_view::iterator, 1232
front_insert_iterator, 1157
generator::iterator, 1346
insert_iterator, 1158
iota_view::iterator, 1216
istream_iterator, 1179
istreambuf_iterator, 1182
join_view::iterator, 1250
lazy_split_view::inner_iterator, 1263
lazy_split_view::outer_iterator, 1261
month, 1649
move_iterator, 1166
ostream_iterator, 1180
ostreambuf_iterator, 1183
recursive_directory_iterator, 1880
regex_iterator, 1924, 1925
regex_token_iterator, 1927, 1928
repeat_view::iterator, 1221
reverse_iterator, 1153
stride_view::iterator, 1332
time_point, 1633
transform_view::iterator, 1236
weekday, 1653
year, 1651

operator--
atomic<floating-point-type>, 1969
atomic<integral-type>, 1968
atomic<T*>, 1968, 1969, 1971
atomic_ref<floating-point-type>, 1960
atomic_ref<integral-type>, 1959
atomic_ref<T*>, 1961
basic_const_iterator, 1162
basic_string, 885, 886
complex, 1479
catat_view::iterator, 1273
counted_iterator, 1176
day, 1647
duration, 1628
elements_view::iterator, 1283
enumerate_view::iterator, 1288
gslice_array, 1542
indirect_array, 1544
iota_view::iterator, 1217
mask_array, 1543
month, 1649
move_iterator, 1166
path, 1859, 1860
repeat_view::iterator, 1221
reverse_iterator, 1154
slice_array, 1540
stride_view::iterator, 1332
time_point, 1634
transform_view::iterator, 1237
valarray, 1534, 1535
weekday, 1654
year, 1651
year_month, 1661
year_month_day, 1666
year_month_weekday, 1668
year_month_weekday_last, 1670, 1671

operator-
atomic<integral-type>, 1971, 1972
atomic<T*>, 1971, 1972
atomic_ref<integral-type>, 1961
atomic_ref<T*>, 1961
back_insert_iterator, 1156
basic_const_iterator, 1162
basic_istream_view::iterator, 1223
common_iterator, 1171
counted_view::iterator, 1272
counted_iterator, 1175
day, 1647
directory_iterator, 1877
duration, 1627
elements_view::iterator, 1283
enumerate_view::iterator, 1288
filter_view::iterator, 1232
front_insert_iterator, 1157
generator::iterator, 1346
insert_iterator, 1158
iota_view::iterator, 1216
istream_iterator, 1179
istreambuf_iterator, 1182
join_view::iterator, 1250
lazy_split_view::inner_iterator, 1263
lazy_split_view::outer_iterator, 1261
month, 1649
move_iterator, 1166
ostream_iterator, 1180
ostreambuf_iterator, 1183
recursive_directory_iterator, 1880
regex_iterator, 1924, 1925
regex_token_iterator, 1927, 1928
repeat_view::iterator, 1221
reverse_iterator, 1153
stride_view::iterator, 1332
time_point, 1633
transform_view::iterator, 1236
weekday, 1653
year, 1651

Index of library names
©ISO/IEC
2233
transform_view::sentinel, 1238, 1239
valarray, 1534, 1536
weekday, 1654
year, 1651, 1652
year_month, 1661, 1662
year_month_day, 1664, 1665
year_month_day_last, 1667
year_month_weekday, 1669
year_month_weekday_last, 1671, 1672
operator--
atomic<integral-type>, 1972
atomic<internal-type>, 1961
atomic_ref<integer-type>, 1960
basic_const_iterator, 1162
counted_iterator, 1176
day, 1647
duration, 1627
elements_view::iterator, 1283
enumerate_view::iterator, 1288
filter_view::iterator, 1232
iota_view::iterator, 1216
join_view::iterator, 1250, 1251
month, 1649
move_iterator, 1166
repeat_view::iterator, 1221
reverse_iterator, 1153, 1154
stride_view::iterator, 1332
time_point, 1633
transform_view::iterator, 1237
weekday, 1653
year, 1651
operator--
atomic<floating-point-type>, 1969
atomic<internal-type>, 1968
atomic<internal-type>, 1960
atomic_ref<internal-type>, 1959
atomic_ref<internal-type>, 1961
basic_const_iterator, 1162
complex, 1479
concat_view::iterator, 1273
counted_iterator, 1176
day, 1647
duration, 1628
elements_view::iterator, 1283
enumerate_view::iterator, 1288
gslice_array, 1542
indirect_array, 1544
iota_view::iterator, 1217
mask_array, 1543
month, 1649
move_iterator, 1166
repeat_view::iterator, 1221
reverse_iterator, 1154
slice_array, 1540
stride_view::iterator, 1332
time_point, 1634
transform_view::iterator, 1237
valarray, 1534, 1536
weekday, 1654
year, 1651
year_month, 1661
year_month_day, 1663
year_month_day_last, 1666
year_month_weekday, 1668
year_month_weekday_last, 1670, 1671
operator->
basic_const_iterator, 1162
counted_iterator, 1175
elementary, 767
filter_view::iterator, 1232
istream_iterator, 1179
join_view::iterator, 1250
move_iterator, 2102
optional, 734
regex_iterator, 1924
regex_token_iterator, 1927
reverse_iterator, 1153
shared_ptr, 639
unique_ptr, 629
operator/=complex, 1479, 1480
duration, 1629
path, 1866
valarray, 1536
operator/=complex, 1479, 1480
duration, 1628
gslice_array, 1542
indirect_array, 1544
mask_array, 1543
path, 1859
slice_array, 1540
valarray, 1534, 1535
operator<
basic_const_iterator, 1163
concat_view::iterator, 1273
duration, 1629
elements_view::iterator, 1284
iota_view::iterator, 1217
leap_second, 1689
map, 984
move_iterator, 1167
multimap, 990
multiset, 998
optional, 737, 738
partial_ordering, 558, 559
queue, 1030
reverse_iterator, 1154
set, 994
stack, 1037
stride_view::iterator, 1333
strong_ordering, 561
sys_time, 1689
time_point, 1634
transform_view::iterator, 1237
type_index, 819
unique_ptr, 633
valarray, 1537
variant, 749
vector, 966
weak_ordering, 560
operator<<
   basic_ostream, 1794–1797, 1799
   basic_stacktrace, 606
   basic_string, 897
   basic_string_view, 871
   bitset, 781, 783
   byte, 525
   complex, 1480
day, 1648
directory_entry, 1875
duration, 1631
error_code, 597
file_time, 1642
gps_time, 1641
guarded_ptr, 644
directory_stacktrace, 606
sub_match, 1913
sys_days, 1636
sys_info, 1682
sys_time, 1636
tai_time, 1639
thread::id, 1941
unique_ptr, 634
utc_time, 1638
valarray, 1536
weekday, 1654
weekday_indexed, 1656
weekday_last, 1656
year, 1652
year_month, 1662
year_month_day, 1665
year_month_day_last, 1667
year_month_weekday, 1670
year_month_weekday_last, 1672
zoned_time, 1688
operator<<=
   bitset, 780
   byte, 525
gslice_array, 1542
indirect_array, 1544
mask_array, 1543
slice_array, 1540
valarray, 1534, 1535
operator<=, 2099
   basic_const_iterator, 1163
duration, 1629
elements_view::iterator, 1284
iota_view::iterator, 1217
leap_second, 1690
move_iterator, 1167
optional, 737, 739
partial_ordering, 558, 559
queue, 1030
reverse_iterator, 1154
stack, 1037
stride_view::iterator, 1333
strong_ordering, 561
sys_time, 1690
time_point, 1634
transform_view::iterator, 1237
type_index, 819
unique_ptr, 633
valarray, 1537
variant, 749
weak_ordering, 560
operator<<>
   basic_ostream, 1794–1797, 1799
   basic_stacktrace, 606
   basic_string_view, 871
   bitset, 781, 783
day, 1648
directory_entry, 1875
duration, 1631
error_code, 597
file_time, 1642
sys_days, 1636
sys_info, 1682
sys_time, 1636
tai_time, 1639
thread::id, 1941
unique_ptr, 634
valarray, 1537
weekday, 1654
weekday_indexed, 1656
weekday_last, 1656
year, 1652
year_month, 1662
year_month_day, 1665
year_month_day_last, 1667
year_month_weekday, 1670
year_month_weekday_last, 1672
zoned_time, 1688
time_zone_link, 1691
transform_view::iterator, 1237
tuple, 724
type_index, 819
unique_ptr, 633, 634
variant, 749
weak_ordering, 560
year, 1652
year_month, 1661
year_month_day, 1664
year_month_day_last, 1667
operator=
  allocator, 623
  allocator-aware containers, 913
  any, 754
  atomic, 1963
  atomic<floating-point-type>, 1963
  atomic<integral-type>, 1963
  atomic<shared_ptr<T>>, 1973
  atomic<T>, 1963
  atomic<weak_ptr<T>>, 1976
  atomic_ref, 1956
  atomic_ref<floating-point-type>, 1956
  atomic_ref<integral-type>, 1956
  atomic_ref<T>, 1956
  back_insert_iterator, 1156
  basic_filebuf, 1831
  basic_istream, 1790
  basic_ostream, 1781
  basic_regex, 1910
  basic_spanbuf, 1823
  basic_stacktrace, 604
  basic_streambuf, 1773
  basic_string, 882, 883
  basic_stringbuf, 1809
  basic_systimebuf, 1843
  common_iterator, 1170
  complex, 1479
  containers, 907
  copyable_function, 812
  coroutine_handle, 567
  counted_iterator, 1175
  directory_iterator, 1877
  enable_shared_from_this, 649
  error_code, 597
  error_condition, 598
  exception, 552
  expected, 764, 765
  expected<void>, 773, 774
  front_insert_iterator, 1157
  function, 805, 806
  function_ref, 814
  future, 2019
  generator, 1342
  generator::iterator, 1345
  gslice_array, 1542
  hazard_pointer, 2031
  indirect_array, 1544, 1545
insert_iterator, 1158
jthread, 1945
locale, 1707
mask_array, 1543
match_results, 1916
memory_resource, 654
move_iterator, 1165
move_only_function, 809
move_sentinel, 1168
optional, 730–732
ostream_iterator, 1180
ostreambuf_iterator, 1183
packaged_task, 2025
pair, 708, 709
path, 1858
promise, 2016
recursive_directory_iterator, 1879
reference_wrapper, 789
reverse_iterator, 1153
shared_future, 2021
shared_lock, 1997
shared_ptr, 638
slice_array, 1540
span, 1075
stop_source, 1937
stop_token, 1936
thread, 1942
tuple, 719–721
unique_lock, 1993
unique_ptr, 629, 631
valarray, 1532
variant, 744, 745
weak_ptr, 646
zoned_time, 1687, 1688
operator==
  allocator, 624
  basic_const_iterator, 1162
  basic_istream_view::iterator, 1224
  basic_stacktrace, 605
  basic_string_view, 871
  bitset, 782
  common_iterator, 1172
  complex, 1480
  concat_view::iterator, 1273
  containers, 908
  copyable_function, 812
  coroutine_handle, 568
  counted_iterator, 1177
  day, 1647
  directory_entry, 1875
duration, 1629
function, 805, 806
gslice_array, 1542
hazard_pointer, 2031
indirect_array, 1544, 1545
jthread, 1945
locale, 1707
mask_array, 1543
match_results, 1916
memory_resource, 654
move_iterator, 1165
move_only_function, 809
move_sentinel, 1168
optional, 730–732
ostream_iterator, 1180
ostreambuf_iterator, 1183
packaged_task, 2025
pair, 708, 709
path, 1858
promise, 2016
recursive_directory_iterator, 1879
reference_wrapper, 789
reverse_iterator, 1153
shared_future, 2021
shared_lock, 1997
shared_ptr, 638
slice_array, 1540
span, 1075
stop_source, 1937
stop_token, 1936
thread, 1942
tuple, 719–721
unique_lock, 1993
unique_ptr, 629, 631
valarray, 1532
variant, 744, 745
weak_ptr, 646
zoned_time, 1687, 1688
operator==
  allocator, 624
  basic_const_iterator, 1162
  basic_istream_view::iterator, 1224
  basic_stacktrace, 605
  basic_string_view, 871
  bitset, 782
  common_iterator, 1172
  complex, 1480
  concat_view::iterator, 1273
  containers, 908
  copyable_function, 812
  coroutine_handle, 568
  counted_iterator, 1177
  day, 1647
  directory_entry, 1875
  duration, 1629
  function, 805, 806
  gslice_array, 1542
  hazard_pointer, 2031
  indirect_array, 1544, 1545
Index of library names

N4986

expected<void>, 777
extents, 1081
filter_view::iterator, 1232
filter_view::sentinel, 1233
function, 806
generator::iterator, 1346
iota_view::iterator, 1217
iota_view::sentinel, 1218
istream_iterator, 1179
istreambuf_iterator, 1182
join_view::iterator, 1251
join_view::sentinel, 1251
function, 806
generator::iterator, 1346
iota_view::iterator, 1217
iota_view::sentinel, 1218
istream_iterator, 1179
istreambuf_iterator, 1182
join_view::iterator, 1251
join_view::sentinel, 1251
layout_blas_packed::mapping, 1575
layout_left::mapping, 1087
layout_right::mapping, 1090
layout_right_padded::mapping, 1104
layout_stride::mapping, 1093
layout_transpose::mapping, 1584
lazy_split_view::inner_iterator, 1263
lazy_split_view::outer_iterator, 1261
leap_second, 1689
locale, 1707
map, 984
match_results, 1918
memory_resource, 655
monostate, 751
month, 1649
month_day, 1657
month_day_last, 1658
month_weekday, 1659
month_weekday_last, 1660
move_iterator, 1166
move_only_function, 809
multimap, 990
multiset, 998
optional, 737, 738
pair, 710
partial_ordering, 558
path, 1866
polymorphic_allocator, 657
queue, 1030
regex_iterator, 1924
regex_token_iterator, 1925, 1927
repeat_view::iterator, 1222
reverse_iterator, 1154
scoped_allocator_adaptor, 665
set, 994
shared_ptr, 643
stack, 1037
stacktrace_entry, 602
stop_source, 1938
stop_token, 1936
stride_view::iterator, 1332, 1333
strong_ordering, 561
sub_match, 1913
sys_time, 1689
take_view::sentinel, 1241
take_while_view::sentinel, 1243
text_encoding, 1744
thread::id, 1941
time_point, 1634
time_zone, 1684
time_zone_link, 1690
transform_view::iterator, 1237
tuple, 724
type_index, 819
type_info, 549
unexpected, 758
unique_ptr, 633
unreachable_sentinel_t, 1177
valarray, 1537
variant, 749
vector, 966
weak_ordering, 560
weekday, 1654
weekday_indexed, 1655
weekday_last, 1656
year, 1652
year_month, 1661
year_month_day, 1664
year_month_day_last, 1666
year_month_weekday, 1669
year_month_weekday_last, 1671
zoned_time, 1688
operator>, 2099
basic_const_iterator, 1163
duration, 1629
elements_view::iterator, 1284
iota_view::iterator, 1217
leap_second, 1690
move_iterator, 1167
optional, 737–739
partial_ordering, 558, 559
queue, 1030
reverse_iterator, 1154
stack, 1037
stride_view::iterator, 1333
strong_ordering, 561
sys_time, 1690
time_point, 1634
transform_view::iterator, 1237
type_index, 819
unique_ptr, 633
valarray, 1537
variant, 749
weak_ordering, 560
operator>=, 2100
basic_const_iterator, 1163
duration, 1629
elements_view::iterator, 1284
iota_view::iterator, 1217
leap_second, 1690
move_iterator, 1167
optional, 738, 739
partial_ordering, 558, 559
queue, 1030
reverse_iterator, 1154

©ISO/IEC
2237
Index of library names

© ISO/IEC
2238

stack, 1037
stride_view::iterator, 1333
strong_ordering, 561
sys_time, 1690
time_point, 1635
transform_view::iterator, 1237
type_index, 819
unique_ptr, 633, 634
valarray, 1537
variant, 749
weak_ordering, 560
operator>>, basic_istream, 1782–1785, 1789
basic_string, 897
bitset, 781, 783
byte, 525
complex, 1480
path, 1866
valarray, 1536
operator>>=
bitset, 781
byte, 525
gslice_array, 1542
indirect_array, 1544
mask_array, 1543
slice_array, 1540
valarray, 1534, 1535
operator[]

basic_const_iterator, 1162
basic_stacktrace, 605
basic_string, 885
basic_string_view, 867
bitset, 781
concat_view::iterator, 1273
counted_iterator, 1175
flat_map, 1045
indirect_array, 1544
iota_view::iterator, 1217
map, 984
mask_array, 1543
match_results, 1917
mdspan, 1110
move_iterator, 1166
repeat_view::iterator, 1222
reverse_iterator, 1153
shared_ptr, 639
span, 1076
unique_ptr, 632
unordered_map, 1006
valarray, 1532–1534
weekday, 1654
operator%
duration, 1629
valarray, 1536
operator%=
duration, 1628
gslice_array, 1542
indirect_array, 1544
mask_array, 1543

slice_array, 1540
valarray, 1534, 1535
operator&
bitset, 783
byte, 525
valarray, 1536
operator&=
atomic<integral-type>, 1968
atomic_ref<integral-type>, 1959
bitset, 780
byte, 525
gslice_array, 1542
indirect_array, 1544
mask_array, 1543
slice_array, 1540
valarray, 1534, 1535
operator&&
valarray, 1537
operator~
bitset, 783
byte, 526
valarray, 1536
operator~=
atomic<integral-type>, 1968
atomic_ref<integral-type>, 1959
bitset, 780
byte, 525
gslice_array, 1542
indirect_array, 1544
mask_array, 1543
slice_array, 1540
valarray, 1534, 1535
operator|
bitset, 783
byte, 525
valarray, 1536
operator|=
atomic<integral-type>, 1968
atomic_ref<integral-type>, 1959
bitset, 780
byte, 525
gslice_array, 1542
indirect_array, 1544
mask_array, 1543
slice_array, 1540
valarray, 1534, 1535
operator||
valarray, 1537
optimize
syntax_option_type, 1902, 1903
optional, 727
and_then, 735
begin, 734
const_iterator, 734
constructor, 729, 730
destructor, 730
emplace, 733
end, 734
has_value, 735
hash, 739
iterator, 734
operator bool, 735
operator!=, 737, 738
operator*, 734, 735
operator->, 734
operator<, 737, 738
operator<=, 737, 739
operator==, 737, 738
operator>, 737–739
operator>=, 738, 739
operator\=, 730–732
operator==, 737–739
operator\=, 737–739
operator\=>, 738, 739
or\_else, 736
reset, 736
swap, 733, 739
transform, 736
value, 735
value\_or, 735
value\_type, 727
options
  recursive\_directory\_iterator, 1879
  synchronized\_pool\_resource, 660
  unsynchronized\_pool\_resource, 660
or\_else
  expected, 769
  expected\lt void\gt, 776
  optional, 736
ospan\_stream, 1821
ostream, 1750, 1778
ostream\_iterator, 1179
  constructor, 1180
  operator\*, 1180
  operator\+=, 1180
  operator\=, 1180
ostream\_buf\_iterator, 1182, 1750
  constructor, 1183
  failed, 1183
  operator\*, 1183
  operator\+=, 1183
  operator\=, 1183
ostream\_stream, 1750, 1805
ostream\_stream
  zombie, 515
osync\_stream, 1750, 1841
out
  basic\_format\_context, 842
codecv\_t, 1715
  format\_to\_n\_result, 824
out\_of\_range, 587, 589, 779–782
  constructor, 589
out\_ptr, 651
out\_ptr\_t, 650
  constructor, 650
destructor, 650

outer\_allocator
  scoped\_allocator\_adaptor, 665
outer\_allocator\_type
  scoped\_allocator\_adaptor, 663
output\_iterator, 1138
output\_iterator\_tag, 1148
output\_range, 1201
overflow
  basic\_filebuf, 1834
  basic\_streambuf, 1777
  basic\_stringbuf, 1811
overflow\_error, 587, 589, 779, 782
  constructor, 590
owner\_before
  shared\_ptr, 639
  weak\_ptr, 646
owner\_equal, 648
  operator\(\), 648
  shared\_ptr, 639
  weak\_ptr, 647
owner\_hash, 647
  operator\(\), 648
  shared\_ptr, 639
  weak\_ptr, 646
owner\_less, 647
  operator\(\), 647
owns\_lock
  shared\(\), 1998
  unique\_lock, 1995

P
p
  bernoulli\_distribution, 1508
  binomial\_distribution, 1509
  geometric\_distribution, 1510
  negative\_binomial\_distribution, 1511
packaged\_task, 2024
  constructor, 2024, 2025
  destructor, 2025
  get\_future, 2025
  make\_ready\_at\_thread\_exit, 2025
  operator\(\), 2025
  operator\=, 2025
  reset, 2026
  swap, 2025, 2026
  valid, 2025
pair, 706, 720
  constructor, 707, 708
  get, 711
  operator\\=, 710
  operator\+=, 708, 709
  operator\=, 710
  swap, 710
pair\_wise
  views, 1193
pairwise\_transform
  views, 1193
par, 821
<table>
<thead>
<tr>
<th>Library Name</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>execution</td>
<td>821</td>
</tr>
<tr>
<td>par_unseq</td>
<td>821</td>
</tr>
<tr>
<td>param</td>
<td></td>
</tr>
<tr>
<td>seed_seq</td>
<td>1505</td>
</tr>
<tr>
<td>parent_path</td>
<td>1802</td>
</tr>
<tr>
<td>parse</td>
<td>1695–1699</td>
</tr>
<tr>
<td>formatter</td>
<td>845–847</td>
</tr>
<tr>
<td>range-default-formatter</td>
<td>844</td>
</tr>
<tr>
<td>partial_order</td>
<td>564</td>
</tr>
<tr>
<td>partial_ordering</td>
<td>558</td>
</tr>
<tr>
<td>equivalent</td>
<td>558</td>
</tr>
<tr>
<td>greater</td>
<td>558</td>
</tr>
<tr>
<td>less</td>
<td>558</td>
</tr>
<tr>
<td>operator&lt;</td>
<td>558</td>
</tr>
<tr>
<td>operator&lt;=</td>
<td>558</td>
</tr>
<tr>
<td>operator&lt;&gt;</td>
<td>558</td>
</tr>
<tr>
<td>operator==</td>
<td>558</td>
</tr>
<tr>
<td>operator&gt;</td>
<td>558</td>
</tr>
<tr>
<td>operator&gt;=</td>
<td>558</td>
</tr>
<tr>
<td>unordered</td>
<td>558</td>
</tr>
<tr>
<td>partial_sort</td>
<td>1428</td>
</tr>
<tr>
<td>partial_sort_copy</td>
<td>1429</td>
</tr>
<tr>
<td>partial_sum</td>
<td>1460</td>
</tr>
<tr>
<td>partition</td>
<td>1435</td>
</tr>
<tr>
<td>partition_copy</td>
<td>1436</td>
</tr>
<tr>
<td>partition_point</td>
<td>1436</td>
</tr>
<tr>
<td>path</td>
<td>1851</td>
</tr>
<tr>
<td>append</td>
<td>1859</td>
</tr>
<tr>
<td>assign</td>
<td>1858</td>
</tr>
<tr>
<td>begin</td>
<td>1865</td>
</tr>
<tr>
<td>c_str</td>
<td>1861</td>
</tr>
<tr>
<td>clear</td>
<td>1860</td>
</tr>
<tr>
<td>compare</td>
<td>1862</td>
</tr>
<tr>
<td>concat</td>
<td>1859, 1860</td>
</tr>
<tr>
<td>constructor</td>
<td>1857, 1858</td>
</tr>
<tr>
<td>copy</td>
<td>1881</td>
</tr>
<tr>
<td>directory_entry</td>
<td>1874</td>
</tr>
<tr>
<td>empty</td>
<td>1863</td>
</tr>
<tr>
<td>end</td>
<td>1865</td>
</tr>
<tr>
<td>extension</td>
<td>1863</td>
</tr>
<tr>
<td>filename</td>
<td>1863</td>
</tr>
<tr>
<td>generic_string</td>
<td>1861, 1862</td>
</tr>
<tr>
<td>generic_u16string</td>
<td>1862</td>
</tr>
<tr>
<td>generic_u32string</td>
<td>1862</td>
</tr>
<tr>
<td>generic_u8string</td>
<td>1862</td>
</tr>
<tr>
<td>generic_wstring</td>
<td>1862</td>
</tr>
<tr>
<td>has_extension</td>
<td>1864</td>
</tr>
<tr>
<td>has_filename</td>
<td>1864</td>
</tr>
<tr>
<td>has_parent_path</td>
<td>1864</td>
</tr>
<tr>
<td>has_relative_path</td>
<td>1864</td>
</tr>
<tr>
<td>has_root_directory</td>
<td>1863</td>
</tr>
<tr>
<td>has_root_name</td>
<td>1863</td>
</tr>
<tr>
<td>has_root_path</td>
<td>1863</td>
</tr>
<tr>
<td>has Stem</td>
<td>1864</td>
</tr>
<tr>
<td>hash_value</td>
<td>1866</td>
</tr>
<tr>
<td>is_absolute</td>
<td>1864</td>
</tr>
<tr>
<td>is_relative</td>
<td>1864</td>
</tr>
<tr>
<td>iterator</td>
<td>1865</td>
</tr>
<tr>
<td>lexically_normal</td>
<td>1864</td>
</tr>
<tr>
<td>lexically_proximate</td>
<td>1865</td>
</tr>
<tr>
<td>lexically_relative</td>
<td>1864</td>
</tr>
<tr>
<td>make_preferred</td>
<td>1860</td>
</tr>
<tr>
<td>native</td>
<td>1861</td>
</tr>
<tr>
<td>operator string_type</td>
<td>1861</td>
</tr>
<tr>
<td>operator+=</td>
<td>1859, 1860</td>
</tr>
<tr>
<td>operator/</td>
<td>1866</td>
</tr>
<tr>
<td>operator/=</td>
<td>1859</td>
</tr>
<tr>
<td>operator&lt;&lt;</td>
<td>1865</td>
</tr>
<tr>
<td>operator==</td>
<td>1866</td>
</tr>
<tr>
<td>operator=</td>
<td>1858</td>
</tr>
<tr>
<td>operator-=</td>
<td>1866</td>
</tr>
<tr>
<td>parent_path</td>
<td>1862</td>
</tr>
<tr>
<td>preferred_separator</td>
<td>1854</td>
</tr>
<tr>
<td>relative_path</td>
<td>1862</td>
</tr>
<tr>
<td>remove</td>
<td>1890</td>
</tr>
<tr>
<td>remove_filename</td>
<td>1860</td>
</tr>
<tr>
<td>replace_extension</td>
<td>1861</td>
</tr>
<tr>
<td>replace_filename</td>
<td>1860</td>
</tr>
<tr>
<td>root_directory</td>
<td>1862</td>
</tr>
<tr>
<td>root_name</td>
<td>1862</td>
</tr>
<tr>
<td>root_path</td>
<td>1862</td>
</tr>
<tr>
<td>stem</td>
<td>1863</td>
</tr>
<tr>
<td>string</td>
<td>1861</td>
</tr>
<tr>
<td>swap</td>
<td>1861, 1866</td>
</tr>
<tr>
<td>u16string</td>
<td>1861</td>
</tr>
<tr>
<td>u32string</td>
<td>1861</td>
</tr>
<tr>
<td>u8string</td>
<td>1861</td>
</tr>
<tr>
<td>value_type</td>
<td>1854</td>
</tr>
<tr>
<td>wstring</td>
<td>1861</td>
</tr>
<tr>
<td>path1</td>
<td></td>
</tr>
<tr>
<td>filesystem_error</td>
<td>1868</td>
</tr>
<tr>
<td>path2</td>
<td></td>
</tr>
<tr>
<td>filesystem_error</td>
<td>1868</td>
</tr>
<tr>
<td>pbackfail</td>
<td></td>
</tr>
<tr>
<td>basic_filebuf</td>
<td>1833</td>
</tr>
<tr>
<td>basic_streambuf</td>
<td>1776</td>
</tr>
<tr>
<td>basic_stringbuf</td>
<td>1811</td>
</tr>
<tr>
<td>pbase</td>
<td></td>
</tr>
<tr>
<td>basic_streambuf</td>
<td>1774</td>
</tr>
<tr>
<td>pbump</td>
<td></td>
</tr>
<tr>
<td>basic_streambuf</td>
<td>1774</td>
</tr>
<tr>
<td>pcount</td>
<td></td>
</tr>
<tr>
<td>zombie</td>
<td>516</td>
</tr>
<tr>
<td>peek</td>
<td></td>
</tr>
<tr>
<td>basic_istream</td>
<td>1787</td>
</tr>
<tr>
<td>perm_options</td>
<td>1870</td>
</tr>
<tr>
<td>permissions</td>
<td>1889</td>
</tr>
<tr>
<td>file_status</td>
<td>1871, 1872</td>
</tr>
<tr>
<td>perms</td>
<td>1870</td>
</tr>
<tr>
<td>permutable</td>
<td>1147</td>
</tr>
<tr>
<td>perror</td>
<td>1893</td>
</tr>
<tr>
<td>peta</td>
<td>696</td>
</tr>
<tr>
<td>pico</td>
<td>696</td>
</tr>
<tr>
<td>piecewise_constant_distribution</td>
<td>1523</td>
</tr>
</tbody>
</table>
Index of library names

PRIoN, 1894
PRIoPTR, 1894
priority_queue, 1030
    constructor, 1032–1034
    emplace, 1034
    pop, 1034
    push, 1034
    push_range, 1034
    swap, 1034
PRIuFASTN, 1894
PRIuLEASTN, 1894
PRIuMAX, 1894
PRIuN, 1894
PRIuPTR, 1894
PRIxFASTN, 1894
PRIxLEASTN, 1894
PRIxMAX, 1894
PRIxN, 1894
PRIxPTR, 1894
probabilities
    discrete_distribution, 1523
proj
    complex, 1481
    projected, 1145
promise, 2015
    constructor, 2016
    coroutine_handle, 568
    coroutine_handle<noop_coroutine_-
promise>, 569
destructor, 2016
get_future, 2016
operator=, 2016
set_exception, 2017
set_exception_at_thread_exit, 2017
set_value, 2016
set_value_at_thread_exit, 2017
swap, 2016, 2017
uses_allocator, 2016
propagate_on_container_copy_assignment
    allocator_traits, 622
    scoped_allocator_adaptor, 664
propagate_on_container_move_assignment
    allocator_traits, 623
    allocator_traits, 622
    scoped_allocator_adaptor, 664
propagate_on_container_swap
    allocator_traits, 623
    scoped_allocator_adaptor, 664
protect
    hazard_pointer, 2031
proximate, 1889
proxy
    istreambuf_iterator, 1181
ptr
    from_chars_result, 822
    to_chars_result, 822
ptr_fun
    zombie, 515
ptrdiff_t, 522
pubimbue
    basic_streambuf, 1772
    pubseekoff
    basic_streambuf, 1772
    pubseekpos
    basic_streambuf, 1773
    pubsetbuf
    basic_streambuf, 1772
    pubsync
    basic_streambuf, 1773
push
    priority_queue, 1034
    push_back
    basic_string, 1034
    deque, 950
    inplace_vector, 976
    push_front
    deque, 950
    forward_list, 955
    push_heap, 1444
    push_range
    priority_queue, 1034
    queue, 1030
    stack, 1036
put
    basic_ostream, 1798
    money_put, 1736
    num_put, 1722
    time_put, 1732
    put_money, 1801
    put_time, 1802
    putback
    basic_istream, 1788
    putc, 1893
    putchar, 1893
    putenv, 570
    puts, 1893
    putwc, 902
    putwchar, 902
    pword
    ios_base, 1761
Q
qsort, 523, 1474
quecto, 696, 698
quetta, 696, 698
queue, 1028
    constructor, 1029, 1030
    operator<, 1030
    operator<=, 1030
    operator<> , 1030
    operator==, 1030
    operator>>, 1030
    operator>, 1030

©ISO/IEC
2242
<table>
<thead>
<tr>
<th>Operator</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;=</td>
<td>1030</td>
</tr>
<tr>
<td>push_range</td>
<td>1030</td>
</tr>
<tr>
<td>swap</td>
<td>1030</td>
</tr>
<tr>
<td>quick_exit</td>
<td>523, 541</td>
</tr>
<tr>
<td>quiet_NaN</td>
<td>numeric_limits, 534</td>
</tr>
<tr>
<td>quoted</td>
<td>1803</td>
</tr>
</tbody>
</table>

**R**
- radix
  - numeric_limits, 533
- raise, 570
- rand, 523, 1526
  - discouraged, 1527
- RAND_MAX, 523
- random_access_iterator, 1139
- random_access_iterator_tag, 1148
- random_access_range, 1201
- random_device, 1502
  - constructor, 1503
  - entropy, 1503
  - operator(), 1503
  - result_type, 1502
- random_shuffle
  - zombie, 515
- range, 1199
- range-default-formatter, 845–847
  - constructor, 846, 847
  - format, 846, 847
  - parse, 845–847
  - set_brackets, 845
  - set_separator, 845
- range_error, 587, 589
  - constructor, 589
- range_format, 826
  - debug_string, 826
  - disabled, 826
  - map, 826
  - sequence, 826
  - set, 826
  - string, 826
- range_formatter, 843
  - format, 845
  - parse, 844
  - set_brackets, 844
  - set_separator, 844
- ranges
  - to, 1209, 1210
- rank, 685
- rank_v, 674
- ranlux24, 1502
- ranlux24_base, 1502
- ranlux48, 1502
- ranlux48_base, 1502
- ratio, 695, 696
- ratio_add, 697
- ratio_divide, 697
- ratio_equal, 697
- ratio_equal_v, 696
- ratio_greater, 698
- ratio_greater_equal, 698
- ratio_greater_equal_v, 696
- ratio_greater_v, 696
- ratio_less, 697
- ratio_less_equal, 698
- ratio_less_equal_v, 696
- ratio_less_v, 696
- ratio_multiply, 697
- ratio_not_equal, 697
- ratio_not_equal_v, 696
- ratio_subtract, 697
- raw_storage_iterator
  - zombie, 515
- rbegin, 1196
  - basic_stacktrace, 605
  - basic_string, 883
  - basic_string_view, 867
  - reversible containers, 910
  - span, 1077
- rbegin(C&), 1184
- rbegin(initializer_list<E>), 1184
- rbegin(T (&array)[N]), 1184
- rcu_barrier, 2028
- rcu_default_domain, 2028
- rcu_domain
  - lock, 2028
  - try_lock, 2028
  - unlock, 2028
- rcu_retire, 2029
- rcu_synchronize, 2028
- rdbuf
  - basic_fstream, 1841
  - basic_ifstream, 1837
  - basic_ios, 1765
  - basic_ifstream, 1826
  - basic_istream, 1815
  - basic_ofstream, 1839
  - basic_ofstream, 1826
  - basic_ostringstream, 1818
  - basic_spanstream, 1828
  - basic_stringstream, 1821
- rdstate
  - basic_ios, 1766
- read
  - basic_istream, 1787
  - read_symlink, 1889
  - readsome
  - basic_istream, 1788
  - ready
  - match_results, 1916
  - real, 1483
  - complex, 1479, 1481
  - realloc, 523, 625, 2096
  - rebinding
    - expected, 760
    - expected<void>, 770
    - pointer_traits, 616
Index of library names
Index of library names

result_of
  zombie, 515
result_of_t
  zombie, 515
result_type
  bernoulli_distribution, 1508
  binomial_distribution, 1508
  cauchy_distribution, 1519
  chi_squared_distribution, 1518
  discard_block_engine, 1498
  discrete_distribution, 1522
  exponential_distribution, 1512
  extreme_value_distribution, 1515
  fisher_distribution, 1520
  function, 803
  gamma_distribution, 1513
  geometric_distribution, 1509
  independent_bits_engine, 1499
  linear_congruential_engine, 1494
  lognormal_distribution, 1517
  mersenne_twister_engine, 1495
  negative_binomial_distribution, 1510
  normal_distribution, 1516
  piecewise_constant_distribution, 1523
  piecewise_linear_distribution, 1525
  poisson_distribution, 1511
  random_device, 1502
  seed_seq, 1503
  shuffle_order_engine, 1500
  student_t_distribution, 1521
  subtract_with_carry_engine, 1497
  uniform_int_distribution, 1506
  uniform_real_distribution, 1507
  weibull_distribution, 1511
resume
  coroutine_handle, 568
  coroutine_handle<noop_coroutine_promise>, 569
rethrow_exception, 554
rethrow_if_nested
  nested_exception, 555
rethrow_nested
  nested_exception, 555
retire
  hazard_pointer_obj_base, 2030
return_temporary_buffer
  zombie, 515
reverse, 1422
  forward_list, 958
  list, 964
  views, 1277
reverse_copy, 1423
reverse_iterator, 1151
  base, 1153
  basic_string, 875
  basic_string_view, 863
  constructor, 1152, 1153
  iter_move, 1155
  iter_swap, 1155
make_reverse_iterator non-member
  function, 1155
operator!=, 1154
operator*, 1153
operator+, 1153, 1155
operator++, 1153
operator+=, 1154
operator=, 1153, 1155
operator=, 1154
operator->, 1153
operator<, 1154
operator<=, 1154
operator>=, 1154
operator[], 1153
reverse_view, 1278
  base, 1278
  begin, 1278
  constructor, 1278
  end, 1278
  size, 1278
rewind, 1893
rfind
  basic_string, 892, 893
  basic_string_view, 870
riemann_zeta, 1557
riemann_zetaf, 1557
riemann_zetal, 1557
right, 1768
rint, 1545
rintf, 1545
rintl, 1545
ronna, 696, 698
ronto, 696, 698
root_directory
  path, 1862
root_name
  path, 1862
root_path
  path, 1862
rotate, 1423
  rotate_copy, 1424
  rotl, 854
  rotr, 854
  round, 1545
  duration, 1630
  time_point, 1635
round_error
  numeric_limits, 533
  round_indeterminate, 531
  round_style
    numeric_limits, 535
  round_to_nearest, 531
  round_toward_infinity, 531
round_toward_neg_infinity, 531
round_toward_zero, 531
roundf, 1545
roundl, 1545
row_major, 1572
row_major_t, 1572
runtime_error, 587, 589
        constructor, 589
S

    lognormal_distribution, 1518
same_as, 577
sample, 1424
saturated_cast, 1467
save
sys_info, 1682
sbumpc
    basic_streambuf, 1773
scalbln, 1545
scalblnf, 1545
scalblnl, 1545
scalbn, 1545
scalbnf, 1545
scalbnl, 1545
scale, 1587
scaled, 1580
scaled_accessor, 1579
        access, 1580
        constructor, 1579, 1580
        offset, 1580
scan_is
    ctype, 1710
    ctype<char>, 1713
scan_not
    ctype, 1710
    ctype<char>, 1713
scanf, 1893
SCHAR_MAX, 537
SCHAR_MIN, 537
scientific, 1769
        chars_format, 822
SCNdFASTN, 1894
SCNdLEASTN, 1894
SCNdMAX, 1894
SCNdN, 1894
SCNdPTR, 1894
SCNiFASTN, 1894
SCNiLEASTN, 1894
SCNiMAX, 1894
SCNiN, 1894
SCNiPTR, 1894
SCNuFASTN, 1894
SCNuLEASTN, 1894
SCNuMAX, 1894
SCNuN, 1894
SCNuPTR, 1894
scoped_allocator_adaptor, 663
        allocate, 665
        const_pointer, 663
        const_void_pointer, 663
        construct, 665
        constructor, 664
        deallocate, 665
        destroy, 665
difference_type, 663
inner_allocator, 665
inner_allocator_type, 664
is_always_equal, 664
max_size, 665
operator==, 665
outer_allocator, 665
outer_allocator_type, 663
pointer, 663
propagate_on_container_copy_assignment, 664
propagate_on_container_move_assignment, 664
propagate_on_container_swap, 664
select_on_container_copy_construction, 665
        size_type, 663
        value_type, 663
        void_pointer, 663
scoped_lock, 1991
        constructor, 1991
destructor, 1991
search, 1405–1407
search_n, 1406, 1407
second
        local_info, 1682
        second_argument_type
zombie, 515
seconds, 1609
        hh_mm_ss, 1677
seed_seq, 1503
        constructor, 1503, 1504
generate, 1504
param, 1505
result_type, 1503
size, 1504
SEEK_CUR, 1893
seek_dir
zombie, 515
SEEK_END, 1893
SEEK_SET, 1893
seekdir
Index of library names

ios_base, 1759
seekg, 1759
seekoff, 1759
seekp, 1759
seekpos, 1759
select_on_container_copy_construction, 1759
semiregular, 1844
sentinel, 1844
sentinel_for, 1844
sentry, 1844
seq, 1844
seq_cst, 1844
sequence, 1844
set, 1844
bitset, 1844
begin, 1844
cbegin, 1844
cend, 1844
clear, 1844
const_iterator, 1844
const_reference, 1844
const_reverse_iterator, 1844
constructor, 1844
destructor, 1844
contains, 1844
count, 1844
crbegin, 1844
crend, 1844
difference_type, 1844
decimal, 1844
emplace, 1844
emplace_hint, 1844
empty, 1844
end, 1844
equal_range, 1844
erase, 1844
erase_if, 1844
extract, 1844
find, 1844
get_allocator, 1844
insert, 1844
iterator, 1844
key_comp, 1844
key_compare, 1844
key_type, 1844
lower_bound, 1844
mapped_type, 1844
max_size, 1844
merge, 1844
node_type, 1844
operator!, 1844
operator<=, 1844
operator<, 1844
operator<=>, 1844
operator<=, 1844
operator==, 1844
range_format, 1844
rbegin, 1844
reference, 1844
rend, 1844
reverse_iterator, 1844
size, 1844
size_type, 1844
swap, 1844
upper_bound, 1844
value_comp, 1844
value_compare, 1844
value_type, 1844
set (member)
<table>
<thead>
<tr>
<th>Function</th>
<th>Declaration</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>set_value_at_thread_exit</td>
<td>promise, 2017</td>
<td></td>
</tr>
<tr>
<td>setbase</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>setbuf</td>
<td>1893</td>
<td></td>
</tr>
<tr>
<td>basic_filebuf</td>
<td>1834</td>
<td></td>
</tr>
<tr>
<td>basic_spanbuf</td>
<td>1825</td>
<td></td>
</tr>
<tr>
<td>basic_streambuf</td>
<td>1775, 1812</td>
<td></td>
</tr>
<tr>
<td>setenv</td>
<td>570</td>
<td></td>
</tr>
<tr>
<td>set</td>
<td>ios_base, 1759</td>
<td></td>
</tr>
<tr>
<td>setfill</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>setg</td>
<td>basic_streambuf, 1774</td>
<td></td>
</tr>
<tr>
<td>setiosflags</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>setjmp</td>
<td>516, 570</td>
<td></td>
</tr>
<tr>
<td>setlocale</td>
<td>1740</td>
<td></td>
</tr>
<tr>
<td>setp</td>
<td>basic_streambuf, 1774</td>
<td></td>
</tr>
<tr>
<td>setprecision</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>setstate</td>
<td>basic_ios, 1766</td>
<td></td>
</tr>
<tr>
<td>setup_givens_rotation</td>
<td>1586</td>
<td></td>
</tr>
<tr>
<td>setvbuf</td>
<td>1893</td>
<td></td>
</tr>
<tr>
<td>setw</td>
<td>1801</td>
<td></td>
</tr>
<tr>
<td>sgetc</td>
<td>basic_streambuf, 1773</td>
<td></td>
</tr>
<tr>
<td>sgetn</td>
<td>basic_streambuf, 1773</td>
<td></td>
</tr>
<tr>
<td>share</td>
<td>future, 2019</td>
<td></td>
</tr>
<tr>
<td>shared_from_this</td>
<td>enable_shared_from_this, 649</td>
<td></td>
</tr>
<tr>
<td>shared_future</td>
<td>constructor, 2020, 2021</td>
<td></td>
</tr>
<tr>
<td>destructor, 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>get</td>
<td>2021</td>
<td></td>
</tr>
<tr>
<td>operator=, 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>valid, 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wait, 2022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wait_for, 2022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wait_until, 2022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shared_lock</td>
<td>constructor, 1996, 1997</td>
<td></td>
</tr>
<tr>
<td>destructor, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lock, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mutex, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator bool, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator=, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>owns_lock, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>release, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>swap, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>try_lock, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>try_lock_for, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>try_lock_until, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlock, 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shared_mutex, 1988</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shared_ptr</td>
<td>634, 649</td>
<td></td>
</tr>
<tr>
<td>const_pointer_cast, 644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>constructor, 636, 637</td>
<td></td>
<td></td>
</tr>
<tr>
<td>destructor, 638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dynamic_pointer_cast, 643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>get, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>get_deleter, 644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hash, 649</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator bool, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator*, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator-&gt;, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator&lt;&lt;, 644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator&lt;=, 643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator&lt;, 638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator=, 643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operator[]=, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>owner_before, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>owner_equal, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>owner_hash, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reinterpret_pointer_cast, 644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reset, 638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>static_pointer_cast, 643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>swap, 638, 643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>use_count, 639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shared_timed_mutex, 1989</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shift</td>
<td>valarray, 1536</td>
<td></td>
</tr>
<tr>
<td>shift_left, 1425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shift_right, 1426</td>
<td></td>
<td></td>
</tr>
<tr>
<td>showbase, 1767</td>
<td></td>
<td></td>
</tr>
<tr>
<td>showmanyc</td>
<td>basic_filebuf, 1833</td>
<td></td>
</tr>
<tr>
<td>basic_streambuf, 1775, 1833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>showpoint, 1767</td>
<td></td>
<td></td>
</tr>
<tr>
<td>showpos, 1767</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shrink_to_fit</td>
<td>basic_string, 884</td>
<td></td>
</tr>
<tr>
<td>deque, 950</td>
<td></td>
<td></td>
</tr>
<tr>
<td>inplace_vector, 977</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vector, 968</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHRT_MAX, 537</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHRT_MIN, 537</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shuffle, 1425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shuffle_order_engine, 1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>constructor, 1501</td>
<td></td>
<td></td>
</tr>
<tr>
<td>result_type, 1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sig_atomic_t, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIG_DFL, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIG_ERR, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIG_IGN, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGABRT, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGFPE, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGILL, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGINT, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>signal, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>signalingNaN</td>
<td>numeric_limits, 534</td>
<td></td>
</tr>
<tr>
<td>signbit, 1545</td>
<td></td>
<td></td>
</tr>
<tr>
<td>signed_integral, 579</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGSEGV, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIGTERM, 570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sin, 1545</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Index of library names
Index of library names

basic_spanbuf, 1824
basic_spanstream, 1828
begin, 1077
constructor, 1073–1075
data, 1077
deduction guide, 1075
empty, 1076
end, 1077
first, 1075, 1076
front, 1076
iterator, 1077
last, 1075, 1076
operator=, 1075
rbegin, 1077
rend, 1077
size, 1076
size_bytes, 1076
subspan, 1075, 1076
spanbuf, 1821
spanstream, 1821
sph_bessel, 1557
sph_besself, 1557
sph_bessell, 1557
sph_legendre, 1557
sph_legendref, 1557
sph_legendrel, 1557
sph_neumann, 1557
sph_neumannf, 1557
sph_neumannl, 1557
splice
list, 962, 963
splice_after
forward_list, 956, 957
split_view
constructor, 1265
sprintf, 1893
sputback
basic_streambuf, 1773
sputc
basic_streambuf, 1773
sputn
basic_streambuf, 1773
sqrt, 1545
complex, 1482
valarray, 1538
sqrtf, 1545
sqrtl, 1545
rand, 523, 1526
sscanf, 1893
ssize, 1198
ssize(C& c), 1184
ssize(T (&array)[N]), 1184
stable_partition, 1435
stable_sort, 1428
stack, 1034
constructor, 1036
operator<, 1037
operator<=, 1037
operator><, 1037
operator>>, 1037
operator==, 1037
operator>, 1037
operator>=, 1037
push_range, 1036
swap, 1037
stacktrace_entry, 601
constructor, 602
description, 602
native_handle, 602
operator bool, 602
operator<<, 606
operator==, 602
source_file, 602
source_line, 602
start
gslice, 1541
slice, 1539
start_lifetime_as, 617
start_lifetime_as_array, 618
starts_with, 1407
basic_string, 894
basic_string_view, 869
state
fpos, 1762
state_type
car_traits, 859
static_extent
extents, 1081
static_pointer_cast
shared_ptr, 643
status, 1891
directory_entry, 1875
status_known, 1892
stdev
normal_distribution, 1517
stderr, 1893
stdin, 1893
stdout, 1893
steady_clock, 1642
stem
path, 1863
stod, 899
stof, 899
stoi, 898, 899
stol, 898, 899
stold, 899
stoll, 898, 899
stop_callback, 1938
constructor, 1939
destructor, 1939
stop_possible
stop_source, 1938
stop_token, 1936
stop_requested
stop_source, 1938
stop_token, 1936
stop_source, 1936
constructor, 1937
destructor, 1937
operator=, 1937
operator==, 1937
request_stop, 1938
stop_possible, 1938
stop_requested, 1938
swap, 1938
stop_source sc
get_token, 1938
stop_token, 1935
constructor, 1936
destructor, 1936
operator=, 1936
operator==, 1936
stop_possible, 1936
stop_requested, 1936
swap, 1936
store
atomic, 1963
atomic<floating-point-type>, 1963
atomic<integral-type>, 1963
atomic<shared_ptr<T>>, 1973
atomic<T>, 1963
atomic<weak_ptr<T>>, 1976
atomic_ref, 1956
atomic_ref<floating-point-type>, 1956
atomic_ref<integral-type>, 1956
atomic_ref<T*>, 1956
storssc
zombie, 516
stoul, 898, 899
stoull, 898, 899
str
basic_istringstream, 1815
basic_ostringstream, 1818
basic_stringbuf, 1810
basic_stringstream, 1821
match_results, 1916
sub_match, 1912
strcat, 901
strchr, 901
strcoll, 901
strcpyp, 901
strcspn, 901
streambuf, 1750, 1769
streamoff, 1749, 1762
streampos, 1750
streamsize, 1749
strerror, 901
strftime, 1699, 1733
strict
zombie, 515
strict_weak_order, 586
stride
gslice, 1541
layout_blas_packed::mapping, 1575
layout_left::mapping, 1087
layout_right::mapping, 1090
layout_transpose::mapping, 1583
slice, 1539
stride_view, 1330
stride_view
constructor, 1329
size, 1330
stride, 1330
stride_view::iterator
base, 1332
constructor, 1331
iter_move, 1333
iter_swap, 1334
operator+, 1333
operator++, 1332
operator+=, 1332
operator-, 1333
operator--, 1332
operator-=, 1332
operator<, 1333
operator<=, 1333
operator<>, 1333
operator<=, 1333
operator==, 1333
operator>, 1333
operator>=, 1333
strided_slice, 1111
strides
layout_right_padded::mapping, 1103
string, 874
operator"s, 900
path, 1861
range_format, 826
string_view
hash, 871
operator"sv, 871
stringbuf, 1750, 1805
stringstream, 1750, 1805
strlen, 901
strncat, 901
strncpy, 901
strong_order, 563
strong_ordering, 560
operator partial_ordering, 561
operator weak_ordering, 561
operator<, 561
operator<=, 561
operator<>, 561
operator<=, 561
operator==, 561
operator>, 561
operator>=, 561
strpbrk, 901
strrchr, 901
strspn, 901
strstr, 901
zombie, 515
Index of library names

© ISO/IEC 2252
strstreambuf
    zombie, 515
strtod, 523
strtof, 523
strtoimax, 1894
strtok, 901
strtol, 523
strtold, 523
strtoll, 523
strtoul, 523
strtoull, 523
strtoumax, 1894
strxfrm, 901
student_t_distribution, 1521
    constructor, 1521
    mean, 1521
    result_type, 1521
sub_match, 1911
    compare, 1912
    constructor, 1912
    length, 1912
    operator basic_string, 1912
    operator<<, 1913
    operator>>>, 1913
    operator==, 1913
    str, 1912
    swap, 1912
sub_sat, 1467
submdspan, 1117
submdspan-mapping-impl
    layout_left::mapping, 1114
    layout_left_padded::mapping, 1116
    layout_right::mapping, 1115
    layout_right_padded::mapping, 1116
    layout_stride::mapping, 1115
submdspan_extents, 1113
submdspan_mapping_result, 1112
subrange, 1204
    advance, 1207
    begin, 1206
    constructor, 1206
    empty, 1206
    end, 1206
    get, 1207
    next, 1207
    operator PairLike, 1206
    prev, 1207
    size, 1206
subrange_kind, 1188
    sized, 1188
    unsized, 1188
subseconds
    hh_mm_ss, 1677
subspan
    span, 1075, 1076
substr
    basic_string, 893
    basic_string_view, 868
subtract_with_carry_engine, 1496, 1497
    constructor, 1497, 1498
    result_type, 1497
suffix
    match_results, 1917
sum
    valarray, 1535
sungetc
    basic_streambuf, 1773
suspend_always, 569
    await_ready, 569
    await_resume, 569
    await_suspend, 569
suspend_never, 569
    await_ready, 569
    await_resume, 569
    await_suspend, 569
swap, 580, 702
    allocator-aware containers, 913
    any, 755
    array, 946
    basic_filebuf, 1831
    basic_fstream, 1841
    basic_ifstream, 1837
    basic_ios, 1766
    basic_iosstream, 1790
    basic_ispanstream, 1826
    basic_istream, 1843
    basic_istreamstream, 1814, 1815
    basic_ofstream, 1838, 1839
    basic_ospanstream, 1827
    basic_osstream, 1793
    basic_ostringstream, 1817, 1818
    basic_regex, 1911
    basic_spanbuf, 1823, 1824
    basic_spanstream, 1828
    basic_stacktrace, 605
    basic_streambuf, 1774
    basic_string, 892, 897
    basic_string_view, 868
    basic_stringbuf, 1809
    basic_stringstream, 1820
    basic_synctfio, 1843, 1844
    containers, 908
    copyable_function, 812
    expected, 766, 767
    expected<voice>, 774, 775
    flat_map, 1048
    flat_multiset, 1070
    flat_set, 1063
    function, 806
    hazard_pointer, 2032
    jthread, 1945, 1946
    match_results, 1918
    mdspan, 1111
    move_only_function, 809
    optional, 733, 739
    packaged_task, 2025, 2026
    pair, 710
    path, 1861, 1866
priority_queue, 1034
promise, 2016, 2017
queue, 1030
shared_lock, 1998
shared_ptr, 638, 643
stack, 1037
stop_source, 1938
stop_token, 1936
sub_match, 1912
thread, 1942, 1943
tuple, 721, 725
unexpected, 758
unique_lock, 1995
unique_ptr, 630
valarray, 1535, 1538
variant, 747, 751
vector, 968
vector<bool>, 971
weak_ptr, 646, 647
swap(unique_ptr&, unique_ptr&), 632
swap_elements, 1587
swap_ranges, 1413
swappable, 580
swappable_with, 580
swprintf, 902
swscanf, 902
symlink_status, 1892
directory_entry, 1875
symmetric_matrix_product, 1600–1602
symmetric_matrix_rank_1_update, 1598
symmetric_matrix_rank_2_update, 1599
symmetric_matrix_rank_2k_update, 1604
symmetric_matrix_rank_k_update, 1604
symmetric_matrix_vector_product, 1594

sync
basic_filebuf, 1835
basic_istream, 1788
basic_streambuf, 1775
basic_syncbuf, 1844

car, 1689

car, 523, 570

car_category, 594, 596
car_clock, 1635
from_time_t, 1636
rep, 1636
to_time_t, 1636
car_error, 592, 600
code, 600
constructor, 600
what, 600

car:
binomial_distribution, 1509
table
ctype<char>, 1713
tai_clock, 1639
from_utc, 1639
now, 1639
to_utc, 1639
tai_seconds, 1609
tai_time, 1609
from_stream, 1640
operator<<, 1639
take
views, 1239
take_view, 1239
base, 1239
begin, 1239
constructor, 1241
end, 1239
size, 1239
take_view::sentinel
base, 1241
constructor, 1241
operator==, 1241
take_while, 1242
views, 1242
take_while_view, 1242
base, 1242
begin, 1242
constructor, 1243
end, 1242
pred, 1243
take_while_view::sentinel
constructor, 1243
operator==, 1243
tan, 1545
complex, 1482
valarray, 1538
tanf, 1545
tanh, 1545
complex, 1482
valarray, 1538
tanhf, 1545
tanhl, 1545
tgamma, 1545
tgammaf, 1545
tgammal, 1545
tellg
basic_istream, 1788
tellp
basic_ostream, 1794
temp_directory_path, 1892
tera, 696
terminate, 540, 541, 553
terminate_handler, 517, 553
test
atomic_flag, 1978
bitset, 782
test_and_set
atomic_flag, 1978
text_encoding, 1741
comp_name, 1743
aliases, 1743
aliases_view, 1744
constructor, 1742
environment, 1743
environment_is, 1743
hash, 1748
id, 1744
literal, 1743
mib, 1743
name, 1743
operator==, 1744
text_encoding::aliases_view
begin, 1744
end, 1744
tgamma, 1545
tgammaf, 1545
tgamma, 1545
tgammaf, 1545
tgammal, 1545
this_thread
get_id, 1946
sleep_for, 1947
sleep_until, 1946
yield, 1946
thousands_sep
money_punct, 1738
num_punct, 1726
thread, 1940
constructor, 1941, 1942
destructor, 1942
detach, 1943
get_id, 1943
hardware_concurrency, 1943
id, 1940
join, 1943
joinable, 1943
operator==, 1942
swap, 1942, 1943
thread::id, 1940
constructor, 1941
operator<<, 1941
operator<<>, 1941
operator==, 1941
three_way_comparable, 562
three_way_comparable_with, 562
throw_with_nested
nested_exception, 555
tie, 721
basic_ios, 1765
tuple, 721
time, 1699
time_get, 1728
date_order, 1729
do_date_order, 1730
do_get, 1731
do_get_date, 1731
do_get_monthname, 1731
do_get_time, 1730
do_get_weekday, 1731
do_get_year, 1731
get, 1730
get_date, 1729
get_monthname, 1730
get_time, 1729
get_weekday, 1730
get_year, 1730
time_get_byname, 1732
time_point, 1632
ceil, 1635
compiler, 1633
floor, 1635
hash, 1699
max, 1634
min, 1634
operator+, 1634
operator++, 1633

Index of library names © ISO/IEC 2255
<table>
<thead>
<tr>
<th>Function</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>operator+=</td>
<td>1634</td>
</tr>
<tr>
<td>operator-</td>
<td>1634</td>
</tr>
<tr>
<td>operator-=</td>
<td>1633</td>
</tr>
<tr>
<td>operator&lt;</td>
<td>1634</td>
</tr>
<tr>
<td>operator&lt;=</td>
<td>1634</td>
</tr>
<tr>
<td>operator==</td>
<td>1634</td>
</tr>
<tr>
<td>operator&gt;</td>
<td>1634</td>
</tr>
<tr>
<td>operator&gt;=</td>
<td>1635</td>
</tr>
<tr>
<td>round</td>
<td>1635</td>
</tr>
<tr>
<td>time_point_cast</td>
<td>1635</td>
</tr>
<tr>
<td>time_since_epoch</td>
<td>1633</td>
</tr>
<tr>
<td>time_point_cast</td>
<td>1635</td>
</tr>
<tr>
<td>time_point</td>
<td>1635</td>
</tr>
<tr>
<td>time_put</td>
<td>1732</td>
</tr>
<tr>
<td>do_put</td>
<td>1733</td>
</tr>
<tr>
<td>put</td>
<td>1732</td>
</tr>
<tr>
<td>time_put_byname</td>
<td>1733</td>
</tr>
<tr>
<td>time_since_epoch</td>
<td>1633</td>
</tr>
<tr>
<td>time_t</td>
<td>1699</td>
</tr>
<tr>
<td>TIME_UTC</td>
<td>1699</td>
</tr>
<tr>
<td>time_zone</td>
<td>1683</td>
</tr>
<tr>
<td>get_info</td>
<td>1683</td>
</tr>
<tr>
<td>name</td>
<td>1683</td>
</tr>
<tr>
<td>operator&lt;=&gt;</td>
<td>1684</td>
</tr>
<tr>
<td>operator==</td>
<td>1684</td>
</tr>
<tr>
<td>to_local</td>
<td>1684</td>
</tr>
<tr>
<td>to_sys</td>
<td>1683</td>
</tr>
<tr>
<td>to_zone_link</td>
<td>1690</td>
</tr>
<tr>
<td>name</td>
<td>1690</td>
</tr>
<tr>
<td>operator&lt;=&gt;</td>
<td>1691</td>
</tr>
<tr>
<td>operator==</td>
<td>1690</td>
</tr>
<tr>
<td>target</td>
<td>1690</td>
</tr>
<tr>
<td>timed_mutex</td>
<td>1986</td>
</tr>
<tr>
<td>timespec</td>
<td>1699</td>
</tr>
<tr>
<td>timespec_get</td>
<td>1699</td>
</tr>
<tr>
<td>tinyness_before</td>
<td>535</td>
</tr>
<tr>
<td>numeric_limits</td>
<td>535</td>
</tr>
<tr>
<td>tm</td>
<td>1983</td>
</tr>
<tr>
<td>TMP_MAX</td>
<td>1893</td>
</tr>
<tr>
<td>tmpfile</td>
<td>1893</td>
</tr>
<tr>
<td>tmpnam</td>
<td>1893</td>
</tr>
<tr>
<td>to</td>
<td>1210</td>
</tr>
<tr>
<td>ranges</td>
<td>1210</td>
</tr>
<tr>
<td>to_address</td>
<td>617</td>
</tr>
<tr>
<td>pointer_traits</td>
<td>617</td>
</tr>
<tr>
<td>to_array</td>
<td>947</td>
</tr>
<tr>
<td>to_bytes</td>
<td>516</td>
</tr>
<tr>
<td>zombie</td>
<td>516</td>
</tr>
<tr>
<td>to_char</td>
<td>823</td>
</tr>
<tr>
<td>to_char_result</td>
<td>822</td>
</tr>
<tr>
<td>ec</td>
<td>822</td>
</tr>
<tr>
<td>ptr</td>
<td>822</td>
</tr>
<tr>
<td>to_duration</td>
<td>1677</td>
</tr>
<tr>
<td>hh_mm_ss</td>
<td>1677</td>
</tr>
<tr>
<td>to_integer</td>
<td>526</td>
</tr>
<tr>
<td>byte</td>
<td>526</td>
</tr>
<tr>
<td>to_local</td>
<td></td>
</tr>
<tr>
<td>time_zone</td>
<td>1683</td>
</tr>
<tr>
<td>to_string</td>
<td>899</td>
</tr>
<tr>
<td>basic_stacktrace</td>
<td>606</td>
</tr>
<tr>
<td>bitset</td>
<td>782</td>
</tr>
<tr>
<td>to_sys</td>
<td>1683</td>
</tr>
<tr>
<td>utc_clock</td>
<td>1637</td>
</tr>
<tr>
<td>to_time_t</td>
<td>1636</td>
</tr>
<tr>
<td>system_clock</td>
<td>1636</td>
</tr>
<tr>
<td>to_ulong</td>
<td>782</td>
</tr>
<tr>
<td>bitset</td>
<td>782</td>
</tr>
<tr>
<td>to_underlying</td>
<td>705</td>
</tr>
<tr>
<td>to_utc</td>
<td></td>
</tr>
<tr>
<td>gpc_clock</td>
<td>1641</td>
</tr>
<tr>
<td>tai_clock</td>
<td>1639</td>
</tr>
<tr>
<td>to_wstring</td>
<td>899</td>
</tr>
<tr>
<td>tolower</td>
<td>1708</td>
</tr>
<tr>
<td>ctype</td>
<td>1710</td>
</tr>
<tr>
<td>ctype&lt;char&gt;</td>
<td>1713</td>
</tr>
<tr>
<td>totally_ordered</td>
<td>584</td>
</tr>
<tr>
<td>totally_ordered_with</td>
<td>585</td>
</tr>
<tr>
<td>toupper</td>
<td>1708</td>
</tr>
<tr>
<td>ctype</td>
<td>1710</td>
</tr>
<tr>
<td>ctype&lt;char&gt;</td>
<td>1713</td>
</tr>
<tr>
<td>towctrans</td>
<td>901</td>
</tr>
<tr>
<td>towlower</td>
<td>901</td>
</tr>
<tr>
<td>towupper</td>
<td>901</td>
</tr>
<tr>
<td>traits_type</td>
<td></td>
</tr>
<tr>
<td>basic_string</td>
<td>875</td>
</tr>
<tr>
<td>basic_string_view</td>
<td>863</td>
</tr>
<tr>
<td>transform</td>
<td>1413</td>
</tr>
<tr>
<td>collate</td>
<td>1727</td>
</tr>
<tr>
<td>expected</td>
<td>769</td>
</tr>
<tr>
<td>expected&lt;void&gt;</td>
<td>776</td>
</tr>
<tr>
<td>optional</td>
<td>736</td>
</tr>
<tr>
<td>regex_traits</td>
<td>1906</td>
</tr>
<tr>
<td>views</td>
<td>1233</td>
</tr>
<tr>
<td>transform_error</td>
<td></td>
</tr>
<tr>
<td>expected</td>
<td>770</td>
</tr>
<tr>
<td>expected&lt;void&gt;</td>
<td>777</td>
</tr>
<tr>
<td>transform_exclusive_scan</td>
<td>1462</td>
</tr>
<tr>
<td>transform_inclusive_scan</td>
<td>1463</td>
</tr>
<tr>
<td>transform_primary</td>
<td></td>
</tr>
<tr>
<td>regex_traits</td>
<td>1906</td>
</tr>
<tr>
<td>transform_reduce</td>
<td>1459</td>
</tr>
<tr>
<td>transform_view</td>
<td>1233</td>
</tr>
<tr>
<td>base</td>
<td>1233</td>
</tr>
<tr>
<td>begin</td>
<td>1234</td>
</tr>
<tr>
<td>constructor</td>
<td>1234</td>
</tr>
<tr>
<td>end</td>
<td>1234</td>
</tr>
<tr>
<td>size</td>
<td>1233</td>
</tr>
<tr>
<td>transform_view::iterator</td>
<td></td>
</tr>
<tr>
<td>base</td>
<td>1236</td>
</tr>
<tr>
<td>constructor</td>
<td>1236</td>
</tr>
<tr>
<td>iterator</td>
<td>1236</td>
</tr>
<tr>
<td>operator+</td>
<td>1237</td>
</tr>
<tr>
<td>operator++</td>
<td>1236</td>
</tr>
</tbody>
</table>
erase_after, 1679
front, 1679

U
u16streampos, 1750
u16string, 874
  operator"s, 900
  path, 1861
u16string_view
    hash, 871
    operator"sv, 871
u32streampos, 1750
u32string, 874
  operator"s, 900
  path, 1861
u32string_view
    hash, 871
    operator"sv, 871
u8path, 2103
u8string, 874
  operator"s, 900
  path, 1861
u8string_view
    hash, 871
    operator"sv, 871
UCHAR_MAX, 537
uflow
  basic_filebuf, 1833
  basic_streambuf, 1776
uint16_t, 538
uint32_t, 538
uint64_t, 538
uint8_t, 538
uint_fast16_t, 538
uint_fast32_t, 538
uint_fast64_t, 538
uint_fast8_t, 538
UINT_MAX, 537
uintmax_t, 538
uintptr_t, 538
ULLONG_MAX, 537
ULONG_MAX, 537
unary_function
  zombie, 515
unary_negate
  zombie, 515
uncaught_exception
  zombie, 515
uncaught_exceptions, 472, 554
unchecked_emplace_back
  inplace_vector, 977
unchecked_push_back
  inplace_vector, 977
undeclare_no_pointers
  zombie, 515
undeclare_reachable
  zombie, 515
underflow
  basic_filebuf, 1833
  basic_streambuf, 1775
  basic_stringbuf, 1811
underlying_error, 587, 590
  constructor, 590
underlying_type, 690
underlying_type_t, 671
unexpected, 756
unexpected_t, 756
unexpected, 757
  constructor, 758
  error, 758
  operator==, 758
  swap, 758
unexpected_handler
  zombie, 515
unexpected_type
  expected, 760
    expected<void>, 770
unget
  basic_istream, 1788
ungetc, 1893
ungetwc, 902
unhandled_exception
  generator::promise_type, 1344
uniform_int_distribution, 1506
    a, 1506
    b, 1506
    constructor, 1506
    result_type, 1506
uniform_random_bit_generator, 1488
uniform_real_distribution, 1507
    a, 1507
    b, 1507
    constructor, 1507
    result_type, 1507
uninitialized_construct_using_allocator, 621
uninitialized_copy, 1469, 1470
uninitialized_copy_n, 1470
uninitialized_default_construct, 1468
uninitialized_default_construct_n, 1468
uninitialized_fill, 1471
uninitialized_fill_n, 1472
uninitialized_move, 1470
uninitialized_move_n, 1471
uninitialized_value_construct, 1469
uninitialized_value_construct_n, 1469
unique, 1420
    forward_list, 957
    list, 963
    local_info, 1682
    unique_copy, 1421
    unique_lock, 1991
      constructor, 1992, 1993
Index of library names

destructor, 1993
destructor, 1995
lock, 1993
mutex, 1995
operator bool, 1995
operator=, 1995
owns_lock, 1995
release, 1995
swap, 1995
try_lock, 1994
try_lock_for, 1994
try_lock_until, 1994
unlock, 1994
unique_ptr, 626, 630, 637
constructor, 627, 628, 631
destructor, 628
get, 629
get_deleter, 629
hash, 649
operator bool, 629
operator*, 629
operator-, 633
operator<, 633
operator<=, 633
operator/=, 633
operator[] operator[], 629, 631
operator==, 633
operator>, 633
operator><, 633, 634
operator<, 633, 634
operator<,, 633, 634
operator=, 629, 631
operator==, 633
operator>, 633
operator><, 633
operator[] operator[], 632
release, 630
reset, 630, 632
swap, 630

unlock
rcu_domain, 2028
shared_lock, 1998
unique_lock, 1994
unordered
partial_ordering, 558
unordered_map, 998, 1000, 1001
allocator_type, 912
at, 1006
begin, 908, 939
bucket, 939
bucket_count, 938
bucket_size, 939
cbegin, 908, 939
cend, 908, 939
clear, 938
cost_iterator, 907
cost_local_iterator, 932
cost_reference, 907
cost_reverse_iterator, 910
constructor, 932, 1005
contains, 938
count, 938
crbegin, 911
crend, 911
difference_type, 907
emplace, 934, 935
emplace_hint, 935
empty, 909
end, 908, 939
equal_range, 938
erase, 937
erase_if, 1008
extract, 936, 937
find, 938
get_allocator, 912
hash_function, 934
hasher, 932
insert, 935, 936, 1006
insert_or_assign, 1007, 1008
insert_range, 936
iterator, 907
key_eq, 934
key_equal, 932
load_factor, 940
local_iterator, 932
mapped_type, 932
max_bucket_count, 939
max_load_factor, 940
max_size, 909
merge, 937
node_type, 932
operator!=, 908
operator=, 907, 913
operator==, 908
operator[], 1006
rbegin, 910
reference, 907
rehash, 940
rend, 911
reserve, 940
reverse_iterator, 910
size, 909
size_type, 907
swap, 908, 913
try_emplace, 1006, 1007
value_type, 907, 932
unordered_multimap, 998, 1008, 1009
allocator_type, 912
begin, 908, 939
bucket, 939
bucket_count, 938
bucket_size, 939
cbegin, 908, 939
cend, 908, 939
clear, 938
cost_iterator, 907
cost_local_iterator, 932
cost_reference, 907
cost_reverse_iterator, 910
constructor, 932, 1005
contains, 938
count, 938
crbegin, 911
crend, 911
Index of library names

difference_type, 907
emplace, 934, 935
emplace_hint, 935
empty, 909
end, 908, 939
equal_range, 938
erase, 937
erase_if, 1019
extract, 936, 937
find, 938
get_allocator, 912
hash_function, 934
hasher, 932
insert, 935, 936, 1019
insert_range, 936
iterator, 907
key_eq, 934
key_equal, 932
key_type, 932
load_factor, 940
local_iterator, 932
mapped_type, 932
max_bucket_count, 939
max_load_factor, 940
max_size, 909
merge, 937
node_type, 932
operator!=, 908
operator=, 907, 913
operator==, 908
rbegin, 910
reference, 907
rehash, 940
rend, 911
reserve, 940
reverse_iterator, 910
size, 909
size_type, 907
swap, 908, 913
value_type, 907, 932
unreachable, 705
unreachable_sentinel, 1125
unreachable_sentinel_t, 1177
operator==, 1177
unsetf
   ios_base, 1760
unshift
codecvt, 1715
unsigned_integral, 579
unsized
   subrange_kind, 1188
unsynchronized_pool_resource, 658
constructor, 660
destructor, 660
do_allocate, 660
do_deallocate, 660
do_is_equal, 660
options, 660
release, 660
upstream_resource, 660
unwrap_ref_decay, 691, 783
unwrap_ref_decay_t, 783
unwrap_reference, 691
upper_bound, 1433
   ordered associative containers, 929
upper_triangle, 1572
upper_triangle_t, 1572
uppercase, 1708
upstream_resource
   monotonic_buffer_resource, 662
   synchronized_pool_resource, 660
   unsynchronized_pool_resource, 660
use_count
   shared_ptr, 639
   weak_ptr, 646
use_facet
   locale, 1708
uses_allocator, 618
uses_allocator<tuple>, 725
uses_allocator_construction_args, 619, 620
uses_allocator_v, 608
USHRT_MAX, 537
utc_clock, 1637
   from_sys, 1637
   now, 1637
   to_sys, 1637
utc_seconds, 1609
utc_time, 1609
   from_stream, 1638
   operator<<, 1638
V
   va_arg, 570
   va_copy, 570
   va_end, 516, 570
   va_list, 516, 570
   va_start, 570
valarray, 1529, 1542
   abs, 1538
   acos, 1538
   apply, 1536
   asin, 1538
   atan, 1538
   atan2, 1538
   begin, 1545
   constructor, 1531, 1532
   cos, 1538
   cosh, 1538
   cshift, 1536
destructor, 1532
   end, 1545
destructor, 1532
   end, 1545
   exp, 1538
   log, 1538
   log10, 1538
   max, 1535
   min, 1535

©ISO/IEC 2261
Index of library names

capacity, 967
cbegin, 908
cend, 908
clear, 916
const_iterator, 907
const_reference, 907
const_reverse_iterator, 910
constructor, 967
crbegin, 911
crend, 911
data, 968
difference_type, 907
emplace, 914
empty, 909
end, 908
erase, 915, 969
erase_if, 969
get_allocator, 912
insert, 915, 968
insert_range, 915
iterator, 907
max_size, 909
operator!=, 908
operator<, 966
operator<>, 911
operator=, 907, 913
operator==, 908, 906
rbegin, 910
reference, 907
rend, 911
reserve, 967
resize, 968
reverse_iterator, 910
shrink_to_fit, 968
size, 909
size_type, 907
swap, 908, 913, 968
value_type, 907
vector<bool>, 969
flip, 971
reference, 970
swap, 971
vector_abs_sum, 1590
vector_idx_abs_max, 1590
vector_sum_of_squares, 1589
vector_two_norm, 1589
vformat, 834
vformat_to, 834
vprintf, 1893
vfscanf, 1893
vfwprintf, 902
vfwscanf, 902
view, 1200
    basic_istringstream, 1815
    basic_ostringstream, 1818
    basic_stringbuf, 1810
    basic_stringstream, 1821
view_interface, 1203
back, 1204
viewable_range, 1202
views
    adjacent, 1301
    adjacent_transform, 1306
    all, 1227
    as_rvalue, 1228
    chunk, 1311
    chunk_by, 1326
    common, 1276
    counted, 1275
    drop, 1243
    drop_while, 1245
    elements, 1279
    empty, 1188
    enumerate, 1285
    filter, 1229
    iota, 1212
    join, 1246
    join_with, 1252
    keys, 1192
    lazy_split, 1258
    pairwise, 1193
    pairwise_transform, 1193
    repeat, 1219
    reverse, 1277
    single, 1211
    slide, 1320
    take, 1239
    take_while, 1242
    transform, 1233
    values, 1192
    zip, 1290
    zip_transform, 1296
visit, 750
    basic_format_arg, 849
    variant, 750, 751
visit_format_arg, 2103
void_pointer
    allocator_traits, 622
    scoped_allocator_adaptor, 663
void_t, 671
vprintf_nonunicode, 1797, 1805
vprintf_nonunicode_buffered, 1805
vprintf_unicode, 1797, 1804
vprintf_unicode_buffered, 1804
vprintf, 1893
vsprintf, 1893
vsscanf, 1893
vswprintf, 902
vswscanf, 902
vwprintf, 902
vwscanf, 902
Index of library names

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Index of library names

<table>
<thead>
<tr>
<th>Name</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic</td>
<td>1965</td>
</tr>
<tr>
<td>atomic&lt;floating-point-type&gt;</td>
<td>1965</td>
</tr>
<tr>
<td>atomic&lt;integral-type&gt;</td>
<td>1965</td>
</tr>
<tr>
<td>atomic&lt;T&gt;</td>
<td>1965</td>
</tr>
<tr>
<td>atomic&lt;weak_ptr&lt;T&gt;&gt;</td>
<td>1977</td>
</tr>
<tr>
<td>atomic_flag</td>
<td>1978</td>
</tr>
<tr>
<td>atomic_ref&lt;T&gt;</td>
<td>1957</td>
</tr>
<tr>
<td>barrier</td>
<td>2012</td>
</tr>
<tr>
<td>condition_variable</td>
<td>2002</td>
</tr>
<tr>
<td>condition_variable_any</td>
<td>2005</td>
</tr>
<tr>
<td>future</td>
<td>2019</td>
</tr>
<tr>
<td>latch</td>
<td>2010</td>
</tr>
<tr>
<td>shared_future</td>
<td>2022</td>
</tr>
<tr>
<td>wait</td>
<td></td>
</tr>
<tr>
<td>condition_variable</td>
<td>2003</td>
</tr>
<tr>
<td>future</td>
<td>2019</td>
</tr>
<tr>
<td>shared_future</td>
<td>2022</td>
</tr>
<tr>
<td>weak_from_this</td>
<td></td>
</tr>
<tr>
<td>enable_shared_from_this</td>
<td>649</td>
</tr>
<tr>
<td>weak_order</td>
<td>563</td>
</tr>
<tr>
<td>weak_ordering</td>
<td>559</td>
</tr>
<tr>
<td>equivalent</td>
<td>559</td>
</tr>
<tr>
<td>greater</td>
<td>559</td>
</tr>
<tr>
<td>less</td>
<td>559</td>
</tr>
<tr>
<td>operator partial_ordering</td>
<td>559</td>
</tr>
<tr>
<td>operator&lt;</td>
<td>560</td>
</tr>
<tr>
<td>operator&lt;=</td>
<td>560</td>
</tr>
<tr>
<td>operator&lt;=&gt;</td>
<td>560</td>
</tr>
<tr>
<td>operator==</td>
<td>560</td>
</tr>
<tr>
<td>operator&gt;</td>
<td>560</td>
</tr>
<tr>
<td>operator&gt;=</td>
<td>560</td>
</tr>
<tr>
<td>weak_ptr</td>
<td>637, 644, 649</td>
</tr>
<tr>
<td>constructor</td>
<td>645</td>
</tr>
<tr>
<td>destructor</td>
<td>646</td>
</tr>
<tr>
<td>expired</td>
<td>646</td>
</tr>
<tr>
<td>lock</td>
<td>646</td>
</tr>
<tr>
<td>operator=</td>
<td>646</td>
</tr>
<tr>
<td>owner_before</td>
<td>646</td>
</tr>
<tr>
<td>owner_equal</td>
<td>647</td>
</tr>
<tr>
<td>owner_hash</td>
<td>646</td>
</tr>
<tr>
<td>reset</td>
<td>646</td>
</tr>
<tr>
<td>swap</td>
<td>646, 647</td>
</tr>
<tr>
<td>use_count</td>
<td>646</td>
</tr>
<tr>
<td>weakly_canonical</td>
<td>1892</td>
</tr>
<tr>
<td>weakly_incrementable</td>
<td>1135</td>
</tr>
<tr>
<td>weekday</td>
<td>1652</td>
</tr>
<tr>
<td>c_encoding</td>
<td>1654</td>
</tr>
<tr>
<td>constructor</td>
<td>1653</td>
</tr>
<tr>
<td>from_stream</td>
<td>1655</td>
</tr>
<tr>
<td>hash</td>
<td>1699</td>
</tr>
<tr>
<td>iso_encoding</td>
<td>1654</td>
</tr>
<tr>
<td>ok</td>
<td>1654</td>
</tr>
<tr>
<td>operator+</td>
<td>1654</td>
</tr>
<tr>
<td>operator++</td>
<td>1653</td>
</tr>
<tr>
<td>operator+=</td>
<td>1654</td>
</tr>
<tr>
<td>operator-</td>
<td>1654</td>
</tr>
<tr>
<td>operator--</td>
<td>1653</td>
</tr>
<tr>
<td>operator-=</td>
<td>1654</td>
</tr>
<tr>
<td>operator&lt;&lt;</td>
<td>1654</td>
</tr>
<tr>
<td>operator[]</td>
<td>1654</td>
</tr>
<tr>
<td>weekday Indexed</td>
<td>1655</td>
</tr>
<tr>
<td>weekday Last</td>
<td>1656</td>
</tr>
<tr>
<td>year_month_weekday</td>
<td>1669</td>
</tr>
</tbody>
</table>
Index of library names

operator-=, 1651
operator<<, 1652
operator==, 1652
year_month, 1661
year_month_day, 1663
year_month_day_last, 1666
year_month_weekday, 1669
year_month_weekday_last, 1671
year_month, 1660
constructor, 1660
from_stream, 1662
hash, 1699
month, 1661
ok, 1661
operator+, 1661, 1662
operator-=, 1661
operator-, 1661, 1662
operator==, 1661
operator<<, 1662
operator<=>, 1661
operator==, 1661
year, 1661
year_month_day, 1662
constructor, 1663
day, 1664
from_stream, 1665
hash, 1699
month, 1663
ok, 1664
operator local_days, 1664
operator sys_days, 1664
operator+=, 1664, 1665
operator-=, 1664, 1665
operator==, 1663
operator<<, 1665
operator<=>, 1664
operator==, 1664
year, 1663
year_month_day_last, 1665
constructor, 1666
day, 1666
hash, 1699
month, 1666
month_day_last, 1666
ok, 1666
operator local_days, 1666
operator sys_days, 1666
operator+, 1667
operator+=, 1666
operator-, 1667
operator-=, 1666
operator<<, 1667
operator<=>, 1667
operator==, 1666
year, 1666
year_month_weekday, 1667
constructor, 1668
hash, 1699
index, 1669
month, 1669
ok, 1669
operator local_days, 1669
operator sys_days, 1669
operator+, 1669
operator+=, 1668
operator-, 1669
operator-=, 1668
operator<<, 1670
operator==, 1669
weekday, 1669
weekday_indexed, 1669
year, 1669
year_month_weekday_last, 1670
constructor, 1670
hash, 1699
month, 1671
ok, 1671
operator local_days, 1671
operator sys_days, 1671
operator+, 1671, 1672
operator+=, 1670, 1671
operator-, 1671, 1672
operator-=, 1670, 1671
operator<<, 1672
operator==, 1671
weekday, 1671
weekday_last, 1671
year, 1671
years, 1609
yield
tthis_thread, 1946
yield_value
generator::promise_type, 1344
yocto, 696, 698
yotta, 696, 698
Z
zepto, 696, 698
zero
duration, 1628
duration_values, 1624
zetta, 696, 698
zip
views, 1290
zip_transform
views, 1296
zip_transform_view, 1296
begin, 1296
del, 1296
size, 1296
zip_view, 1290
begin, 1290
del, 1290
size, 1290
zoned_time, 1684
constructor, 1686–1687
get_info, 1688
get_local_time, 1688
get_sys_time, 1688
get_time_zone, 1688
hash, 1699
operator local_time, 1688
operator sys_time, 1688
operator<<, 1688
operator=, 1687, 1688
operator==, 1688
zoned_traits, 1684
zoned_traits<const time_zone*> default_zone, 1684
locate_zone, 1684
Index of library concepts

The bold page number for each entry is the page where the concept is defined. Other page numbers refer to pages where the concept is mentioned in the general text. Concepts whose name appears in *italics* are for exposition only.

**advanceable**, 1212, 1213, 1214–1218
**all-bidirectional**, 1227, 1268, 1292–1294
**all-forward**, 1227, 1270–1272, 1292, 1293
**all-random-access**, 1227, 1268, 1270, 1273, 1274, 1292–1294, 1337, 1340
**assignable_from**, 576, 579, 579, 580, 585, 916, 1137, 1146, 1147, 1150, 1153, 1165, 1168–1170, 1173, 1175, 1362

**bidirectional-common**, 1252, 1254, 1255, 1257
**bidirectional_iterator**, 1121, 1123, 1127, 1139, 1139, 1150–1152, 1159, 1161, 1162, 1165, 1174, 1176, 1196, 1197, 1201, 1205, 1207, 1348, 1362–1365, 1372, 1380, 1382, 1391, 1408, 1409, 1411, 1412, 1422, 1423, 1526, 1435, 1438, 1452, 1918, 1920


**boolean-testable**, 495, 505, 508, 561, 562, 564, 582, 583, 583, 584, 586, 710, 724, 1141, 1144, 1438, 1931

**boolean-testable-impl**, 582, 582, 583

**borrowed_range**, 1074, 1199, 1200, 1205–1208, 1744, 1825, 1826

**can-reference**, 1119, 1119, 1120, 1130, 1137, 1171, 1190, 1193, 1233, 1235, 1238, 1296, 1297, 1300, 1308, 1310

**cartesian-is-sized-sentinel**, 1334, 1337, 1340

**cartesian-product-common-arg**, 1334, 1334, 1335

**cartesian-product-is-bidirectional**, 1334, 1336, 1337, 1339

**cartesian-product-is-common**, 1334, 1335

**cartesian-product-is-random-access**, 1334, 1336, 1337, 1339, 1340

**cartesian-product-is-sized**, 1334, 1335, 1336

**common_range**, 1191, 1202, 1202, 1204, 1209, 1229, 1230, 1234, 1247–1253, 1255, 1259, 1264, 1268, 1269, 1276, 1278, 1281, 1286, 1290, 1294, 1297, 1301, 1302, 1307, 1316, 1320, 1322, 1327, 1329, 1334, 1335

**common_reference_with**, 576, 578, 578–580, 1105, 1134, 1145, 1268, 1342, 2063

**common_with**, 576, 578, 579, 1124, 1174, 1176, 1177

**compares-as**, 561, 562

**comparison-common-type-with**, 562, 583, 584

**comparison-common-type-with-impl**, 583, 583

**concat-indirectly-readable**, 1267, 1268, 1268

**concat-indirectly-readable-impl**, 1268, 1268

**concat-is-bidirectional**, 1267, 1268, 1268, 1270, 1271, 1273

**concat-is-random-access**, 1267, 1268, 1268, 1270, 1271, 1273, 1274

**concatitable**, 1252, 1253, 1257, 1267, 1268, 1268, 1269

**const-formattable-range**, 826, 826

**constant_iterator**, 1124, 1159, 1159, 1160, 1162, 1196, 1197, 1202

**constant_range**, 1192, 1202, 1202, 1279


**contiguous_iterator**, 734, 866, 867, 910, 1073–1075, 1077, 1121, 1127, 1140, 1140, 1161, 1162, 1173–1175, 1198, 1202, 1203, 1276, 1545

**contiguous_range**, 866, 1074, 1075, 1201, 1202, 1202, 1227, 1228

**convertible-to-non-slicing**, 1204, 1205, 1206


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index-pair-like

indirectly-readable-impl

indirectly_binary_left_foldable

indirectly_binary_left_foldable_impl

indirectly_binary_right_foldable

indirectly_readable_impl

indirectly_comparable

indirectly_binary_predicate

indirectly_equivalence_relation

indirectly_strict_weak_order

indirectly_unary_predicate

indirectly_binary_left_foldable_

indirectly_binary_right_foldable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

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indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_

indirectly_readable_impl_

indirectly_comparable_
zip-is-common, 1290, 1291
# Index of implementation-defined behavior

The entries in this index are rough descriptions; exact specifications are at the indicated page in the general text.

#pragma, 486

additional execution policies supported by parallel algorithms, 821, 1351
additional file_type enumerators for file systems supporting additional types of file, 1869
additional formats for time_get::do_get_date, 1731
additional supported forms of preprocessing directive, 474
algorithms for producing the standard random number distributions, 1505
alignment, 72
alignment additional values, 73
alignment of bit-fields within a class object, 300
allocation of bit-fields within a class object, 300
argument values to construct ios_base::failure, 1766
assignability of placeholder objects, 802
barrier phrase completion without wait, 2011
behavior of iostream classes when traits::pos_type is not streampos or when traits::off_type is not streamoff, 1749
behavior of non-standard attributes, 258
bits in a byte, 62
character encoding scheme of the environment, 1743
choice of larger or smaller value of floating-point-literal, 26
code unit sequence for conditional-escape-sequence, 29
column value of source_location::current, 551
conversions between pointers and integers, 134
converting function pointer to object pointer and vice versa, 135
default configuration of a pool, 660
default next_buffer_size for a monotonic_buffer_resource, 661
default number of buckets in unordered_map, 1005, 1006
default number of buckets in unordered_multimap, 1013
default number of buckets in unordered_multiset, 1023, 1024
default number of buckets in unordered_set, 1018
default semantics of is_debugger_present, 856
default value for least_max_value template parameter of counting_semaphore, 2007
defining main in freestanding environment, 92
definition and meaning of __STDC__, 489, 2094
definition and meaning of __STDC_VERSION__, 489
definition of NULL, 524, 2095
derived type for typeid, 131
determination of kind of input file, 13
diagnostic message, 4
dynamic initialization of static inline variables before main, 95
dynamic initialization of static variables before main, 94, 95
dynamic initialization of thread-local variables before entry, 95
effect of calling associated Laguerre polynomials with n >= 128 or m >= 128, 1553
effect of calling associated Legendre polynomials with l >= 128, 1553
effect of calling basic_filebuf::setbuf with nonzero arguments, 1834
effect of calling basic_filebuf::sync when a get area exists, 1835
effect of calling basic_streambuf::setbuf with nonzero arguments, 1812
effect of calling cylindrical Bessel functions of the first kind with nu >= 128, 1554
effect of calling cylindrical Neumann functions with nu >= 128, 1555
effect of calling Hermite polynomials with n >= 128, 1556
effect of calling ios_base::sync_with_stdio after any input or output operation on standard streams, 1760
effect of calling irregular modified cylindrical Bessel functions with nu >= 128, 1555
effect of calling Laguerre polynomials with n >= 128, 1556
effect of calling Legendre polynomials with l >= 128, 1556
effect of calling regular modified cylindrical Bessel functions with nu >= 128, 1554
effect of calling spherical associated Legendre functions with l >= 128, 1557
effect of calling spherical Bessel functions with n >= 128, 1557

Index of implementation-defined behavior © ISO/IEC 2273
Index of implementation-defined behavior
resuming a coroutine on a different execution agent, 567
return type of \texttt{cartesian\_product\_view::size}, 1336
return value of \texttt{bad\_alloc::what}, 546
return value of \texttt{bad\_any\_cast::what}, 752
return value of \texttt{bad\_array\_new\_length::what}, 547
return value of \texttt{bad\_cast::what}, 549
return value of \texttt{bad\_exception::what}, 553
return value of \texttt{bad\_function\_call::what}, 803
return value of \texttt{bad\_optional\_access::what}, 737
return value of \texttt{bad\_typeid::what}, 549
return value of \texttt{bad\_variant\_access::what}, 751
return value of \texttt{bad\_weak\_ptr::what}, 634
return value of \texttt{char\_traits<char16\_t>::eof}, 861
return value of \texttt{char\_traits<char32\_t>::eof}, 861
return value of \texttt{char\_traits<char8\_t>::eof}, 860
return value of \texttt{exception::what}, 553
return value of \texttt{source\_location::current}, 550
return value of \texttt{type\_info::name()}, 549
search locations for " header, 478
search locations for < > header, 477
semantics of an access through a volatile glvalue, 190
semantics of \texttt{breakpoint}, 856
semantics of linkage specifiers, 255
semantics of parallel algorithms invoked with implementation-defined execution policies, 1351
semantics of \texttt{stacktrace\_entry::native\_handle}, 602
semantics of \texttt{token} parameter and default token value used by \texttt{random\_device} constructors, 1503
sequence of places searched for a header, 477
set of aliases of a known registered character encoding, 1742
set of character container types that \texttt{iostreams} templates can be instantiated for, 1705, 1749
set of integer-class types, 1135
signedness of \texttt{char}, 191
\texttt{sizeof} applied to fundamental types other than \texttt{char}, \texttt{signed char}, and \texttt{unsigned char}, 139
stack unwinding before invocation of \texttt{std::terminate}, 468, 472
\texttt{stacktrace\_entry::native\_handle\_type}, 601
startup and termination in freestanding environment, 92
strict total order over pointer values, 5
string resulting from \texttt{\_func\_}, 234

support for extended alignments, 73
support for \texttt{module\_import\_declarations} with non-C++ language linkage, 255
supported input files, 13
supported multibyte character encoding rules, 860
supported \texttt{root\_names} in addition to any operating system dependent \texttt{root\_names}, 1854, 1855
text of \texttt{\_DATE\_} when date of translation is not available, 487
text of \texttt{\_TIME\_} when time of translation is not available, 488
threads and program points at which deferred dynamic initialization is performed, 94, 95
transcoding of a formatted path when \texttt{charT} and \texttt{path::value\_type} differ, 1867
type of a directory-like file, 1876, 1878
type of \texttt{array::const\_iterator}, 945
type of \texttt{array::iterator}, 945
type of \texttt{basic\_stacktrace::const\_iterator}, 602
type of \texttt{basic\_stacktrace::difference\_type}, 603
type of \texttt{basic\_stacktrace::size\_type}, 603
type of \texttt{basic\_string::const\_iterator}, 875
type of \texttt{basic\_string::iterator}, 875
type of \texttt{basic\_string\_view::const\_iterator}, 863, 867
type of \texttt{default\_random\_engine}, 1502
type of \texttt{deque::const\_iterator}, 948
type of \texttt{deque::difference\_type}, 947
type of \texttt{deque::iterator}, 948
type of \texttt{deque::size\_type}, 947
type of \texttt{flat\_map::const\_iterator}, 1038
type of \texttt{flat\_map::iterator}, 1038
type of \texttt{flat\_multimap::const\_iterator}, 1050
type of \texttt{flat\_multimap::iterator}, 1050
type of \texttt{flat\_multiset::const\_iterator}, 1064
type of \texttt{flat\_multiset::iterator}, 1064
type of \texttt{flat\_set::const\_iterator}, 1057
type of \texttt{flat\_set::iterator}, 1057
type of \texttt{forward\_list::const\_iterator}, 952
type of \texttt{forward\_list::difference\_type}, 952
type of \texttt{forward\_list::iterator}, 952
type of \texttt{forward\_list::size\_type}, 952
type of \texttt{inplace\_vector::const\_iterator}, 973
type of \texttt{inplace\_vector::iterator}, 973
type of \texttt{list::const\_iterator}, 959
type of \texttt{list::difference\_type}, 959
type of \texttt{list::iterator}, 959
type of \texttt{list::size\_type}, 959
type of \texttt{map::const\_iterator}, 980
type of \texttt{map::difference\_type}, 980
type of \texttt{map::iterator}, 980
type of \texttt{map::size\_type}, 980
type of \texttt{match\_results::const\_iterator}, 1914
type of \texttt{multimap::const\_iterator}, 987
type of \texttt{multimap::difference\_type}, 987
Index of implementation-defined behavior

- type of `unordered_set::const_iterator`, 987
- type of `unordered_set::difference_type`, 1014
- type of `unordered_set::iterator`, 1014
- type of `unordered_set::size_type`, 1014
- type of `vector::const_iterator`, 985
- type of `vector::difference_type`, 965
- type of `vector::iterator`, 965
- type of `vector::size_type`, 965
- type of `vector<bool>::const_iterator`, 970
- type of `vector<bool>::const_pointer`, 970
- type of `vector<bool>::difference_type`, 970
- type of `vector<bool>::iterator`, 970
- type of `vector<bool>::pointer`, 969
- type of `vector<bool>::size_type`, 969
- type of `unordered_multiset::const_iterator`, 995
- type of `unordered_multiset::const_local_iterator`, 1009
- type of `unordered_multiset::local_iterator`, 1009
- type of `unordered_multiset::iterator`, 1009
- type of `unordered_multiset::size_type`, 1009
- type of `unordered_multiset::const_local_iterator`, 1009
- type of `unordered_multiset::local_iterator`, 1009
- type of `unordered_multiset::size_type`, 1009
- type of `unordered_multiset::const_iterator`, 1009
- type of `unordered_multiset::local_iterator`, 1009
- type of `unordered_multiset::size_type`, 1009
- type of `unordered_multiset::const_iterator`, 1009
- type of `unordered_multiset::local_iterator`, 1009
- type of `unordered_multiset::size_type`, 1009
- type of `vector::const_iterator`, 1001
- type of `vector::difference_type`, 1001
- type of `vector::iterator`, 1001
- type of `vector::size_type`, 1001
- type of `unordered_map::const_iterator`, 1001
- type of `unordered_map::const_local_iterator`, 1001
- type of `unordered_map::local_iterator`, 1001
- type of `unordered_map::iterator`, 1001
- type of `unordered_map::size_type`, 1001
- type of `unordered_multimap::const_iterator`, 1009
- type of `unordered_multimap::const_local_iterator`, 1009
- type of `unordered_multimap::local_iterator`, 1009
- type of `unordered_multimap::size_type`, 1009
- type of `unordered_multimap::const_iterator`, 1009
- type of `unordered_multimap::local_iterator`, 1009
- type of `unordered_multimap::size_type`, 1009
- type of `unordered_set::const_iterator`, 1001
- type of `unordered_set::const_local_iterator`, 1001
- type of `unordered_set::difference_type`, 1014
- type of `unordered_set::iterator`, 1014
- type of `unordered_set::size_type`, 1014
- type of `vector::const_iterator`, 985
- type of `vector::difference_type`, 965
- type of `vector::iterator`, 965
- type of `vector::size_type`, 965
- type of `vector<bool>::const_iterator`, 970
- type of `vector<bool>::const_pointer`, 970
- type of `vector<bool>::difference_type`, 970
- type of `vector<bool>::iterator`, 970
- type of `vector<bool>::pointer`, 969
- type of `vector<bool>::size_type`, 969
- underlying type for enumeration, 243
- underlying type of bool, 80
- underlying type of char, 79
- underlying type of wchar_t, 79
- unit suffix when `Period::type` is micro, 1632
- value of bit-field that cannot represent assigned value, 157
- initializer, 220
- value of `conditional-escape-sequence`, 25
- value of `ctype<char>::table_size`, 1713
- value of `future_errc::broken_promise`, 2012
- value of `future_errc::future_already_retrieved`, 2012
- value of `future_errc::no_state`, 2012
- value of `future_errc::promise_already_satisfied`, 2012
- value of `has-attribute-expression` for non-standard attributes, 476
- value of `has-attribute-expression` for standard attributes, 476
- value of `non-encodable character literal or multicharacter literal`, 25
- value of `pow(0,0)`, 1482
- value of result of inexact integer to floating-point conversion, 104
- value representation of pointer types, 82
- values of a trivially copyable type, 77
- values of various `ATOMIC_..._LOCK_FREE` macros, 1953
- whether `<cfenv>` functions can be used to manage floating-point status, 1476
- whether a freestanding deleted function is a deleted function, 498
- whether a given `atomic_ref` type’s operations are always lock free, 1955, 1958–1960
whether a parameter is destroyed when the function exits or at the end of the enclosing full-expression, 127
whether `basic_spanbuf`'s move source is empty after a move, 1823
whether freestanding default replaceable global allocation functions satisfy required behavior, 542
whether functions from Annex K of the C standard library are declared when C++ headers are included, 501
whether locale object is global or per-thread, 1704
whether pragma `FENV_ACCESS` is supported, 1476
whether `rand` may introduce a data race, 1526
whether sequence pointers are copied by `basic_filebuf` move constructor, 1831
whether sequence pointers are copied by `basic_stringbuf` move constructor, 1808
whether sequence pointers are initialized to null pointers, 1807
whether source file inclusion of importable header is replaced with `import` directive, 478
whether source of translation units must be available to locate template definitions, 14
whether stack is unwound before invoking the function `std::terminate` when a `noexcept` specification is violated, 472
whether the implementation is hosted or freestanding, 502
whether the sources for module units and header units on which the current translation unit has an interface dependency are required to be available during translation, 14
whether the thread that executes `main` and the threads created by `std::thread` or `std::jthread` provide concurrent forward progress guarantees, 91
whether `time_get::do_get_year` accepts two-digit year numbers, 1731
whether values are rounded or truncated to the required precision when converting between `time_t` values and `time_point` objects, 1636
which functions in the C++ standard library may be recursively reentered, 520
which non-standard-layout objects containing no data are considered empty, 64
which scalar types have unique object representations, 684
width of integral type, 79