Working Draft, Standard for Programming Language C++

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

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1 Scope

This document specifies requirements for implementations of the C++ programming language. The first such requirement is that they implement 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 Programming languages — C (hereinafter referred to as the C standard). 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 8601:2004, Data elements and interchange formats — Information interchange — Representation of dates and times
1.3 ISO/IEC 9899:2018, Programming languages — C
1.5 ISO/IEC/IEEE 9945:2009/Cor 1:2013, Information Technology — Portable Operating System Interface (POSIX), Technical Corrigendum 1
1.7 ISO/IEC 10646, Information technology — Universal Coded Character Set (UCS)
1.8 ISO/IEC 10646:2003, Information technology — Universal Multiple-Octet Coded Character Set (UCS)
1.9 ISO 80000-2:2009, Quantities and units — Part 2: Mathematical signs and symbols to be used in the natural sciences and technology

The library described in ISO/IEC 9899:2018, Clause 7, is hereinafter called the C standard library.\(^2\)

The operating system interface described in ISO/IEC 9945:2009 is hereinafter called POSIX.

The ECMAScript Language Specification described in Standard Ecma-262 is hereinafter called ECMA-262.

[Note 1: References to ISO/IEC 10646:2003 are used only to support deprecated features (D.22). — end note]

\(^{1}\) POSIX® is a registered trademark of the Institute of Electrical and Electronic Engineers, 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.


\(^{3}\) ECMAScript® is a registered trademark of Ecma International. 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.

\(^{4}\) With the qualifications noted in Clause 17 through Clause 33 and in C.7, the C standard library is a subset of the C++ standard library.
3 Terms and definitions

1 For the purposes of this document, the terms and definitions given in ISO/IEC 2382, the terms, definitions, and symbols given in ISO 80000-2:2009, 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 http://www.electropedia.org

3 Terms that are used only in a small portion of this document are defined where they are used and italicized where they are defined.

3.1 access
〈execution-time action〉 read or modify the value of an object

[Note 1 to entry: Only gvalues 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 arbitrary-positional stream
〈library〉 stream that can seek to any integral position within the length of the stream

[Note 1 to entry: Every arbitrary-positional stream is also a repositionable stream (3.49). — end note]

3.3 argument
〈function call expression〉 expression in the comma-separated list bounded by the parentheses

3.4 argument
〈function-like macro〉 sequence of preprocessing tokens in the comma-separated list bounded by the parentheses

3.5 argument
〈throw expression〉 operand of throw

3.6 argument
〈template instantiation〉 constant-expression, type-id, or id-expression in the comma-separated list bounded by the angle brackets

3.7 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

3.8 block
〈statement〉 compound statement

3.9 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 character container type
(library) class or a type used to represent a character

[Note 1 to entry: It is used for one of the template parameters of the string, iostream, and regular expression class templates. — end note]

3.11 collating element
sequence of one or more characters within the current locale that collate as if they were a single character

3.12 component
(library) group of library entities directly related as members, parameters, or return types

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

3.13 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 constant subexpression
expression whose evaluation as subexpression of a conditional-expression CE would not prevent CE from being a core constant expression

3.15 deadlock
(library) situation wherein one or more threads are unable to continue execution because each is blocked waiting for one or more of the others to satisfy some condition

3.16 default behavior
(library implementation) specific behavior provided by the implementation, within the scope of the required behavior

3.17 diagnostic message
message belonging to an implementation-defined subset of the implementation’s output messages

3.18 direct-non-list-initialization
direct-initialization that is not list-initialization

3.19 dynamic type
(glvalue) type of the most derived object to which the glvalue refers

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

3.20 dynamic type
(prvalue) static type of the prvalue expression
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 or are all not constant subexpressions

[Example 1: For a value \( x \) of type \( \text{int} \) 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, and which permits efficient matches against the regular expression to be obtained

3.23 format specifier
(regular expression) sequence of one or more characters that is to be replaced with some part of a regular expression 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 (Clause 17). — end note]

3.25 ill-formed program
program that is not well-formed (3.68)

3.26 implementation-defined behavior
behavior, for a well-formed program 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 \(<\), \(>\), \(\le\), \(\ge\), and \(\le>\)

3.28 implementation limits
restrictions imposed upon programs by the implementation

3.29 iostream class templates
(library) templates that are declared in header \(<\text{iosfwd}\)> and take two template arguments

[Note 1 to entry: The arguments are named \( \text{charT} \) and \( \text{traits} \). The argument \( \text{charT} \) is a character container class, and the argument \( \text{traits} \) is a class which defines additional characteristics and functions of the character type represented by \( \text{charT} \) necessary to implement the iostream class templates. — end note]

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

3.31 matched
(regular expression) condition when a sequence of zero or more characters correspond to a sequence of characters defined by the pattern
3.32 [defns.modifier]
modifier function
(library) class member function other than a constructor, assignment operator, or destructor that alters the state of an object of the class

3.33 [defns.move.assign]
move assignment
(library) assignment of an rvalue of some object type to a modifiable lvalue of the same type

3.34 [defns.move.constr]
move construction
(library) direct-initialization of an object of some type with an rvalue of the same type

3.35 [defns.multibyte]
multibyte character
sequence of one or more bytes representing the code unit sequence for an encoded character of the execution character set

3.36 [defns.nonconst.libcall]
on-constant library call
invocation of a library function that, as part of evaluating any expression \( E \), prevents \( E \) from being a core constant expression

3.37 [defns.ntcts]
NTCTS
(library) sequence of values that have character type that precede the terminating null character type value `charT()`

3.38 [defns.observer]
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]

3.39 [defns.parameter]
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

3.40 [defns.parameter.macro]
parameter
(function-like macro) identifier from the comma-separated list bounded by the parentheses immediately following the macro name

3.41 [defns.parameter.templ]
parameter
(template) member of a `template-parameter-list`

3.42 [defns.regex.primary.equivalence.class]
primary equivalence class
(regular expression) set of one or more characters 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 tailoring

3.43 [defns.prog.def.spec]
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
3.44 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

[Note 1 to entry: Types defined by the implementation include extensions (4.1) and internal types used by the library. — end note]

3.45 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:

```text
{{0, "baz"}, {1, "bar"}, {2, "foo"}}
```

—end example]

3.46 referenceable type

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]

3.47 regular expression

pattern that selects specific strings from a set of character strings

3.48 replacement function

(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]

3.49 repositional stream

(library) stream that can seek to a position that was previously encountered

3.50 required behavior

(library) description of replacement function and handler function 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]

3.51 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]

3.52 signature

(function) name, parameter-type-list, and enclosing namespace

[Note 1 to entry: Signatures are used as a basis for name mangling and linking. — end note]
3.53 signature
(non-template friend function with trailing requires-clause) name, parameter-type-list, enclosing class, and trailing requires-clause

3.54 signature
(function template) name, parameter-type-list, enclosing namespace, return type, template-head, and trailing requires-clause (if any)

3.55 signature
(friend function template with constraint involving enclosing template parameters) name, parameter-type-list, return type, enclosing class, template-head, and trailing requires-clause (if any)

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

3.57 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)

3.58 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), template-head, and trailing requires-clause (if any)

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

3.60 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]

3.61 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]

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

3.63 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

3.64 unblock
satisfy a condition that one or more blocked threads of execution are waiting for

§ 3.64
3.65 \textbf{undefined behavior}

behavior for which this document imposes no requirements

\textit{Note 1 to entry:} Undefined behavior may be expected when this document omits any explicit definition of behavior or when a program uses an erroneous construct or erroneous 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), to terminating a translation or execution (with the issuance of a diagnostic message). Many erroneous 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. \textit{— end note}

3.66 \textbf{unspecified behavior}

behavior, for a well-formed program construct and correct data, that depends on the implementation

\textit{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. \textit{— end note}

3.67 \textbf{valid but unspecified state}

\langle library\rangle 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

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

3.68 \textbf{well-formed program}

C++ program constructed according to the syntax and semantic rules
4 General principles

4.1 Implementation compliance

4.1.1 General

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”.

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:

1. If a program contains no violations of the rules in Clause 5 through Clause 33 and Annex D, a conforming implementation shall, within its resource limits as described in Annex B, accept and correctly execute that program.

2. If a program contains a violation of any diagnosable rule or 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.

3. 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.

[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]

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.

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

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).

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).

Two kinds of implementations are defined: a hosted implementation and a freestanding implementation. For a hosted implementation, this document defines the set of available libraries. A freestanding implementation is one in which execution may take place without the benefit of an operating system, and has an implementation-defined set of libraries that includes certain language-support libraries (16.4.2.4).

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.

“Correct execution” can include undefined behavior, depending on the data being processed; see Clause 3 and 6.9.1.

This documentation also defines implementation-defined behavior; see 4.1.2.

This provision is sometimes called the “as-if” rule, because an implementation is free to disregard any requirement of this document as long as the result is as if the requirement had been obeyed, as far as can be determined from the observable...
Certain aspects and operations of the abstract machine are described in this document as implementation-defined (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. Such documentation shall define the instance of the abstract machine that corresponds to that implementation (referred to as the “corresponding instance” below).

Certain other aspects and operations of the abstract machine are described in this document as unspecified (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 (for example, the effect of attempting to modify a const object).

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).

The least requirements on a conforming implementation are:

1. Accesses through volatile glvalues are evaluated strictly according to the rules of the abstract machine.
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.
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.

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 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.

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

(2.1) — *X-name* is a use of an identifier in a context that determines its meaning (e.g., *class-name*, *typedef-name*).

(2.2) — *X-id* is an identifier with no context-dependent meaning (e.g., *qualified-id*).

(2.3) — *X-seq* is one or more *X*’s without intervening delimiters (e.g., *declaration-seq* is a sequence of declarations).

(2.4) — *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, is called a translation unit.

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

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.

1. Physical source file characters are mapped, in an implementation-defined manner, to the translation character set (5.3) (introducing new-line characters for end-of-line indicators). The set of physical source file characters accepted is implementation-defined.

2. 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. Except for splices reverted in a raw string literal, if a splice results in a character sequence that matches the syntax of a universal-character-name, the behavior is undefined. A source file that is not empty and that does not end in a new-line character, or that ends in a splice, 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. 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 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. — 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 are syntactically and semantically analyzed and translated as a translation unit.
[Note 1: 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 2: 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 3: 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 4: 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 5: 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 6: 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

(1.1) — each character named by ISO/IEC 10646, as identified by its unique UCS scalar value, and

(1.2) — a distinct character for each UCS scalar value where no named character is assigned.

[Note 1: ISO/IEC 10646 code points are integers in the range [0, 10FFFF] (hexadecimal). A surrogate code point is a value in the range [D800, DFFF] (hexadecimal). A UCS 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 96 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.

\[
\begin{align*}
\text{hex-quad} & : \\
\text{hexadecimal-digit hexadecimal-digit hexadecimal-digit hexadecimal-digit}
\end{align*}
\]

\[
\begin{align*}
\text{universal-character-name} & : \\
\text{\textbackslash u} & \text{ hex-quad} \\
\text{\textbackslash u} & \text{ hex-quad hex-quad}
\end{align*}
\]

A universal-character-name designates the character in the translation character set whose UCS 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 UCS 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.

[Note 3: A sequence of characters resembling a universal-character-name in an r-char-sequence (5.13.5) does not form a universal-character-name. — end note]

4 The basic literal character set consists of all characters of the basic character set, plus the control characters specified in Table 2.

[Note 4: The alias BELL for U+0007 shown in ISO 10646 is ambiguous with U+1F514 BELL. — end note]
Table 1: Basic character set  [tab:lex.charset.basic]

<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+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 PARENTHESES</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-THAN SIGN</td>
</tr>
<tr>
<td>U+003F</td>
<td>QUESTION MARK</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+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>

Table 2: Additional control characters in the basic literal character set  [tab:lex.charset.literal]

<table>
<thead>
<tr>
<th>character</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+0000</td>
</tr>
<tr>
<td>U+0007</td>
</tr>
<tr>
<td>U+0008</td>
</tr>
<tr>
<td>U+000D</td>
</tr>
</tbody>
</table>

§ 5.3
5 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.

6 A literal encoding or a locale-specific encoding of one of the execution character sets (16.3.3.3.5) 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.

[Note 5: A character not in the basic literal character set can be encoded with more than one code unit; the value of such a code unit can be the same as that of a code unit for an element of the basic literal character set. — end note]

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 UCS scalar value corresponding to each character of the translation character set is encoded as specified in ISO/IEC 10646 for the respective UCS encoding form.

### 5.4 Preprocessing tokens

 preemptive-tokens:
 header-name
 import-keyword
 module-keyword
 export-keyword
 identifier
 pre-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

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 behavior is undefined. 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), 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

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

(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 <::.

§ 5.4 16
— 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 after the include or import preprocessing token in an #include (15.3) or import (15.5) directive, or within a has-include-expression.

Example 1:
```
#define R "x"
const char* s = R"y";  // ill-formed raw string, not "x" "y"
```

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.11

In all respects of the language, each alternative token behaves the same, respectively, as its primary token, except for its spelling.12 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>{</td>
<td>and</td>
<td>&amp;&amp;</td>
<td>and_eq</td>
<td>&amp;=</td>
</tr>
<tr>
<td>%&gt;</td>
<td>}</td>
<td>bitor</td>
<td></td>
<td></td>
<td>or_eq</td>
</tr>
<tr>
<td>&lt;:</td>
<td>[</td>
<td>or</td>
<td></td>
<td></td>
<td>xor_eq</td>
</tr>
<tr>
<td>;&gt;</td>
<td>]</td>
<td>xor</td>
<td></td>
<td></td>
<td>not</td>
</tr>
<tr>
<td>%: #</td>
<td></td>
<td>compl</td>
<td></td>
<td></td>
<td>not_eq</td>
</tr>
<tr>
<td>%: %:</td>
<td></td>
<td>bitand</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.6 Tokens

The set of tokens is defined in Table 3 according to the following categories:
- identifier
- keyword
- literal
- operator-or-punctuator

There are five kinds of tokens: identifiers, keywords, literals, 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: Some whitespace is required to separate otherwise adjacent identifiers, keywords, numeric literals, and alternative tokens containing alphabetic characters. — end note

11) 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”.

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

13) Literals include strings and character and numeric literals.
5.7 Comments

1 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]

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-THEAN 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

[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.14

5.9 Preprocessing numbers

pp-number:
  digit
  . digit
  pp-number identifier-continue
  pp-number digit
  pp-number nondigit
  pp-number sign
  pp-number number
  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

14) 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.
Any identifier that contains a double underscore `__` or begins with an underscore followed by an uppercase letter is reserved to the implementation for any use.

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

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).

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

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:
Table 5: Keywords  

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

Table 6: Alternative representations  

<table>
<thead>
<tr>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>and</td>
</tr>
<tr>
<td>and_eq</td>
</tr>
<tr>
<td>bitand</td>
</tr>
<tr>
<td>bitor</td>
</tr>
<tr>
<td>compl</td>
</tr>
<tr>
<td>not</td>
</tr>
<tr>
<td>not_eq</td>
</tr>
<tr>
<td>or</td>
</tr>
<tr>
<td>or_eq</td>
</tr>
<tr>
<td>xor</td>
</tr>
<tr>
<td>xor_eq</td>
</tr>
</tbody>
</table>

preprocessing-op-or-punc:  
preprocessing-operator  
operator-or-punctuator  

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

5.13 Literals  

5.13.1 Kinds of literals  

There are several kinds of literals.  

<table>
<thead>
<tr>
<th>Kind</th>
</tr>
</thead>
<tbody>
<tr>
<td>integer-literal</td>
</tr>
<tr>
<td>character-literal</td>
</tr>
<tr>
<td>floating-point-literal</td>
</tr>
<tr>
<td>string-literal</td>
</tr>
<tr>
<td>boolean-literal</td>
</tr>
<tr>
<td>pointer-literal</td>
</tr>
<tr>
<td>user-defined-literal</td>
</tr>
</tbody>
</table>

---

16) The term “literal” generally designates, in this document, those tokens that are called “constants” in ISO C.
5.13.2 Integer literals

integer-literal:
  binary-literal integer-suffix\textsubscript{opt}
  octal-literal integer-suffix\textsubscript{opt}
  decimal-literal integer-suffix\textsubscript{opt}
  hexadecimal-literal integer-suffix\textsubscript{opt}

binary-literal:
  0b binary-digit
  0B binary-digit
  binary-literal \textquotesingle\textsubscript{opt} binary-digit

octal-literal:
  0
  octal-literal \textquotesingle\textsubscript{opt} octal-digit

decimal-literal:
  nonzero-digit
decimal-literal \textquotesingle\textsubscript{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 \textquotesingle\textsubscript{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\textsubscript{opt}
  unsigned-suffix long-long-suffix\textsubscript{opt}
  unsigned-suffix size-suffix\textsubscript{opt}
  long-suffix unsigned-suffix\textsubscript{opt}
  long-long-suffix unsigned-suffix\textsubscript{opt}
  size-suffix unsigned-suffix\textsubscript{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

\footnote{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]}

\footnote{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]}

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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>

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. An integer-literal is a prvalue.

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>unsigned long long int</td>
</tr>
<tr>
<td>u or U</td>
<td>unsigned int</td>
<td>unsigned int</td>
</tr>
<tr>
<td></td>
<td>unsigned long int</td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td>unsigned long long int</td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>1 or L</td>
<td>long int</td>
<td>long int</td>
</tr>
<tr>
<td></td>
<td>long long int</td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>Both u or U and 1 or L</td>
<td>unsigned long int</td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>ll or LL</td>
<td>long long int</td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>Both u or U and ll or LL</td>
<td>unsigned long long int</td>
<td>unsigned 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>

If 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 shall be signed. If all of the types in the list for the integer-literal are unsigned, the extended integer type shall be unsigned. If the list contains both signed and unsigned types, the extended integer type may be signed or unsigned. A program is ill-formed if one of its translation units contains an integer-literal that cannot be represented by any of the allowed types.

5.13.3 Character literals

character-literal:
  encoding-prefixopt ' 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

octal-escape-sequence:
  \ octal-digit
  \ octal-digit octal-digit
  \ octal-digit octal-digit octal-digit

hexadecimal-escape-sequence:
  \x hexadecimal-digit
  hexadecimal-escape-sequence hexadecimal-digit

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 u, U, or x

1 A **non-encodable character literal** is a character-literal whose c-char-sequence consists of a single c-char that is not a numeric-escape-sequence and that specifies a character that either lacks representation in the literal’s associated character encoding or that cannot be encoded as a single code unit. A **multicharacter literal** is a character-literal whose c-char-sequence consists of more than one c-char. The encoding-prefix of a non-encodable character literal or a multicharacter literal shall be absent or L. Such character-literals are conditionally-supported.

2 The kind of a character-literal, its type, and its associated character encoding are determined by its encoding-prefix and its c-char-sequence as defined by Table 9. The special cases for non-encodable character literals and multicharacter literals take precedence over their respective base kinds.

[Note 1: The associated character encoding for ordinary and wide character literals determines encodability, but does not determine the value of non-encodable ordinary or wide character literals or ordinary or wide multicharacter literals. The examples in Table 9 for non-encodable ordinary and wide character literals assume that the specified character lacks representation in the ordinary literal encoding or wide literal encoding, respectively, or that encoding the character would require more than one code unit. — end note]

3 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 non-encodable character literal or 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.

[Note 2: 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 literal is a non-encodable character literal. — end note]

(3.2) A character-literal with a c-char-sequence consisting of a single numeric-escape-sequence that specifies an integer value \( v \) has a value as follows:
ISO/IEC N4910

Table 9: Character literals

<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</td>
<td>'v'</td>
</tr>
<tr>
<td></td>
<td>non-encodable ordinary character literal</td>
<td>int</td>
<td>literal</td>
<td>'\U0001F525'</td>
</tr>
<tr>
<td></td>
<td>ordinary multicharacter literal</td>
<td>int</td>
<td>encoding</td>
<td>'abcd'</td>
</tr>
<tr>
<td>L</td>
<td>wide character literal</td>
<td>wchar_t</td>
<td>wide</td>
<td>L'w'</td>
</tr>
<tr>
<td></td>
<td>non-encodable wide character literal</td>
<td>wchar_t</td>
<td>literal</td>
<td>L'\U0001F32A'</td>
</tr>
<tr>
<td></td>
<td>wide multicharacter literal</td>
<td>wchar_t</td>
<td>encoding</td>
<td>L'abed'</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>

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

(3.2.2) — 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 $T$.

(3.2.3) — Otherwise, the character-literal 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 3: Using an escape sequence for a question mark is supported for compatibility with ISO C++ 2014 and ISO C. — end note]

Table 10: Simple escape sequences

<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>APOSTROPHHE</td>
</tr>
<tr>
<td>U+0022</td>
<td>QUOTATION MARK</td>
</tr>
</tbody>
</table>

5.13.4 Floating-point literals

flooring-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

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fractional-constant:
  digit-sequence_opt . digit-sequence
digit-sequence.

hexadecimal-fractional-constant:
  hexadecimal-digit-sequence_opt . hexadecimal-digit-sequence
  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 l F L

1 The type of a floating-point-literal is determined by its floating-point-suffix as specified in Table 11.

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>
</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 1: 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 1.602176565e-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

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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 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 [tablex.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</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></td>
<td></td>
<td>array of n</td>
<td>wide literal</td>
<td>L&quot;wide 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;w(wide raw string)w&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>array of n</td>
<td>UTF-8</td>
<td>u8&quot;UTF-8 string&quot;</td>
</tr>
<tr>
<td>u</td>
<td>UTF-16 string literal</td>
<td>const char8_t</td>
<td>UTF-16</td>
<td>u&quot;UTF-16 string&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>array of n</td>
<td>UTF-32</td>
<td>u&quot;UTF-32 string&quot;</td>
</tr>
<tr>
<td>U</td>
<td>UTF-32 string literal</td>
<td>const char32_t</td>
<td>UTF-32</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 ')' are permitted 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:

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

5 [Example 1: The raw string

    R"a("
    )
    a"

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

\texttt{R"(x = "y")"}

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

6 Ordinary string literals and UTF-8 string literals are also referred to as narrow string literals.

7 The common encoding-prefix for a sequence of adjacent string-literals is determined pairwise as follows: If two string-literals have the same encoding-prefix, the common encoding-prefix is that encoding-prefix. If one string-literal has no encoding-prefix, the common encoding-prefix is that of the other string-literal. Any other combinations are ill-formed.

[Note 3: A string-literal’s rawness has no effect on the determination of the common encoding-prefix. —end note]

8 In translation phase 6 (5.2), adjacent string-literals are concatenated. The lexical structure and grouping of the contents of the individual string-literals is retained.

[Example 2:

\texttt{"\xA" "B"}

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

\texttt{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>
<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>&quot;b&quot;</td>
</tr>
<tr>
<td>&quot;a&quot;</td>
<td>u&quot;b&quot;</td>
</tr>
</tbody>
</table>

9 Evaluating a string-literal results in a string literal object with static storage duration (6.7.5). Whether all string-literals are distinct (that is, are stored in nonoverlapping objects) and whether successive evaluations of a string-literal yield the same or a different object is unspecified.

[Note 4: The effect of attempting to modify a string literal object is undefined. —end note]

10 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:

(10.1) — 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 string-literal is conditionally-supported and an implementation-defined code unit sequence is encoded.

[Note 5: No character lacks representation in any of the UCS encoding forms. —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 6: The encoded code unit sequence can differ from the sequence of code units that would be obtained by encoding each character independently. —end note]

(10.2) — Each numeric-escape-sequence (5.13.3) that specifies an integer value \(v\) contributes a single code unit with a value as follows:

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

(10.2.2) — Otherwise, if the string-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 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 $T$.

(10.2.3) — Otherwise, the string-literal is ill-formed.

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

(10.3) — 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 Boolean literals

boolean-literal:
false
true

The Boolean literals are the keywords false and true. Such literals are prvalues and have type bool.

5.13.7 Pointer literals

pointer-literal:
nullptr

The pointer literal is the keyword nullptr. It is a prvalue of type std::nullptr_t.

[Note 1: 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]

5.13.8 User-defined literals

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

1 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.

2 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.

3 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
operator "" $X$(nULL)
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

$$\text{operator } "X(\mathit{n})"$$

Otherwise ($S$ contains a numeric literal operator template), $L$ is treated as a call of the form

$$\text{operator } "X(c_1', c_2', \ldots, c_k')"()$$

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

[Note 1: The sequence \(c_1c_2\ldots c_k\) 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

$$\text{operator } "X(fL)"$$

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

$$\text{operator } "X(\mathit{f})"$$

Otherwise (\(S\) contains a numeric literal operator template), \(L\) is treated as a call of the form

$$\text{operator } "X(f\mathit{c}_1', \mathit{c}_2', \ldots, \mathit{c}_k')"()$$

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

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

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

$$\text{operator } "X(\mathit{str})"$$

Otherwise, the literal $L$ is treated as a call of the form

$$\text{operator } "X(\text{str}, \text{len})"$$

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

$$\text{operator } "X(\mathit{ch})"$$

[Example 2:]

```
long double operator ""_w(long double);
std::string operator ""_w(const char16_t*, std::size_t);
unsigned operator ""_w(const char*);
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
}
```

— end example]

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:]

```
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

— declaration, block-declaration, or member-declaration (9.1, 11.4),
— init-declarator (9.3),
— identifier in a structured binding declaration (9.6),
— init-capture (7.5.5.3),
— condition with a declarator (8.1),
— member-declarator (11.4),
— using-declarator (9.9),
— parameter-declaration (9.3.4.6),
— type-parameter (13.2),
— elaborated-type-specifier that introduces a name (9.2.9.4),
— class-specifier (11.1),
— enum-specifier or enumerator-definition (9.7.1),
— exception-declaration (14.1), or
— 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 (7.5.2).

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

— they are identifiers composed of the same character sequence, or
— they are operator-function-ids formed with the same operator, or
— they are conversion-function-ids formed with equivalent (13.7.7.2) types, or
— 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

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` (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 (this usage is deprecated; see D.6),
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;
extern const int c = 1;  // defines a
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
```
that shall not be an incomplete type (6.8.1), an abstract class type (11.7.4), or a (possibly multi-dimensional) array thereof.

### 6.3 One-definition rule

Each of the following is termed a *definable item*:

1. a class type (Clause 11),
2. an enumeration type (9.7.1),
3. a function (9.3.4.6),
4. a variable (6.1),
5. a templated entity (13.1),
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 (7.5.4), 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 $E_1 . \mathsf{template}_{opt} E_2$ 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 $E_1 .* E_2$, 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.

```cpp
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-expression (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—

- A deallocation function for a class is named by a new-expression if it is the single matching deallocation function for the allocation function selected by overload resolution, as specified in 7.6.2.8.

- A deallocation function for a class is named by a delete-expression if it is the selected usual deallocation function as specified in 7.6.2.9 and 11.4.11.

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5 A variable is named by an expression if the expression is an id-expression that denotes it. A variable $x$ whose name appears as 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
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.

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

*this is odr-used if this appears as a potentially-evaluated expression (including as the result of the implicit transformation in the body of a non-static member function (11.4.3)).

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).

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).

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

(10.1) 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

(10.2) 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:

(10.2.1) the intervening scope is a block scope, or

(10.2.2) the intervening scope is the function parameter 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.

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

[Example 2:

```cpp
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]

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 3:

```cpp
auto f() {
    struct A {};
    return A();
}
dec-type(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]

18) An implementation is not required to call allocation and deallocation functions from constructors or destructors; however, this is a permissible implementation technique.
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 4: The following complete translation unit is well-formed, even though it never defines X:

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

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-value 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

- 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,
- 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.

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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, 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).

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 5:

```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()

// 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]
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 discontiguous. 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 \( P \).

Two non-static member functions have corresponding object parameters if:

— 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

— their object parameters have the same type.

Two non-static member function templates have corresponding object parameters if:

— 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

— the types of their object parameters are equivalent.
Two declarations correspond if they (re)introduce the same name, both declare constructors, or both declare destructors, unless

1. either is a using-declarator, or
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
3. each declares a function or function template, except when
   1. both declare functions with the same non-object-parameter-type-list, 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
   2. both declare function templates with equivalent non-object-parameter-type-lists, return types (if any), template-heads, and trailing requires-clauses (if any), and, if both are non-static members, they have corresponding object parameters.

[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 };
void f(int); // #1
void f(Int) {} // defines #1
void f(E) {} // OK, another overload

struct X {
    static void f();
    void f() const; // error: redeclaration
    void g();
    void g() const; // OK
    void g() &; // error: redeclaration
    void h(this X&, int);
    void h(int) &;& // OK, another overload
    void j(this const X&);
    void j() const &; // error: redeclaration
    void k();
    void k(this X&); // error: redeclaration
};
```

—end example]

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 that potentially conflict and one precedes the other (6.5).

[Note 3: 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;
namespace B = A; // OK, no effect
namespace B = B; // OK, no effect
namespace A = B; // OK, no effect
namespace B {} // error: different entity for B

--- end example

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
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 [basic.scope.pdecl]

1 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

2 [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[i]; }
```
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 or opaque-enum-declaration is immediately after the **identifier** (if any) in 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

6 [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

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```
struct X {
    enum E { z = 16 }
    int b[X::z]; // OK
};

The locus of an elaborated-type-specifier that is a declaration (9.2.9.4) 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]

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]
2 If a declaration whose target scope is 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:

```cpp
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) no.ptr-declarator of the form declarator-id attribute-specifier-seq \( \text{opt} \), 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 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:

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

6.4.6 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:

```cpp
...
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]

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

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

2 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
1 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.

2 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

1. \(P\) follows a module-import-declaration or module-declaration that imports \(D\) (directly or indirectly), and
2. \(X\) appears after the module-declaration in \(D\) (if any) and before the private-module-fragment in \(D\) (if any), and
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:
```c
export module Q;
export int sq(int i) { return i*i; }
```
Translation unit #2:
export module R;
export import Q;

Translation unit #3:
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 (7.5.4.2) 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

A search in a scope X for a name N from a program point P is a single search in X for N 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 N is a conversion-function-id or if the single search would find nothing. — end note]

The lookup set for N in 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:

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 object set contains C itself, and calculation is complete.

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, and merge each such lookup set S(N,B) in turn into S(N,C).

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

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

(5.1) — If each of the subobject members of S(N,B) is a base class subobject of at least one of the subobject members of S(N,C), or if S(N,B) 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), or if S(N,C) is empty, the new S(N,C) is a copy of S(N,B).

(5.2) — Otherwise, if the declaration sets of S(N,B) 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.

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

The result of the search is the declaration set of S(N,T). If it is an invalid set, the program is ill-formed. If it differs from the result of a search in T for N from immediately after the class-specifier of T, the program is ill-formed, no diagnostic required.

[Example 1:

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 } }

Example 1:

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 } }

Example 1:
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)

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 N 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 N (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 as 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(); }

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.

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()
}

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An explicit or implicit conversion from a pointer to 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:

```c
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:

```c
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 \( P \).

[Note 1: A using-directive is exported if and only if it appears in a header unit. — end note]

An unqualified search in a scope \( S \) from a program point \( P \) includes the results of searches from \( P \) in

(2.1) \( S \), and

(2.2) 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 2: 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 (7.5.4.2) 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:

```cpp
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]

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:

```cpp
using I = int;  
using D = double;  
namespace A {
    inline namespace N {using C = char; }
    using F = float;  
    void f(I);
```
6.5.4 Argument-dependent name lookup

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:]

```cpp
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
}
```

[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,

```cpp
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 template arguments). 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:

1. If \( T \) is a fundamental type, its associated set of entities is empty.
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 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. If \( T \) is an enumeration type, its associated entities are \( T \) and, if it is a class member, the member’s class.
4. If \( T \) is a pointer to \( U \) or an array of \( U \), its associated entities are those associated with \( U \).
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.
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 \( X \).
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

1. are found by a search of any associated namespace, or
2. are declared as a friend (11.8.4) of any class with a reachable definition in the set of associated entities, or
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: § 6.5.4 48]
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:

```cpp
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:

```cpp
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 N 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:

```cpp
namespace NS {
    class T {
        void f(T);
        void g(T, int);
    }

    NS::T parm;
    void g(NS::T, float);

    int main() {
        f(parm);  // OK, calls NS::f
        extern void g(NS::T, float); // OK, calls NS::f
        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 decltype-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;
};

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

2 A member-qualified name is the (unique) component name (7.5.4.2), 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 (7.5.4.3).

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]

3 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 (7.5.4.2) 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

4 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]:
struct C {
    typedef int I;
};
typedef int I1, I2;
extern int* p;
extern int* q;
void f() {
    p->template C<0>::~I(); // I is looked up in the scope of C
    q->template I1>::~I2(); // I2 is found by unqualified lookup
}
struct A {
    ~A();
};
typedef A AB;
int main() {
    AB* p;
    p->template AB>::~AB(); // explicitly calls the destructor for A
}
—end example]

6.5.5.2 Class members
[1] In a lookup for a qualified name N whose lookup context is a class C in which function names are not ignored,20

(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]:

20) Lookups in which function names are ignored include names appearing in a nested-name-specifier, an elaborated-type-specifier, or a base-specifier.
struct A { A(); };
struct B: public A { B(); };

A::A() { }
B::B() { }

B::A ba; // object of type A
A::A a;  // error: A::A is not a type name
struct A::A a2; // object of type A

— end example

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(); // if declared directly in AB, therefore S is {AB::g()} and AB::g() is chosen
    AB::f(1); // if 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++; // if 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 namespace A;
}

namespace BD {
  using namespace B;
  using namespace D;
}

void g()
{
  BD::a++;  // OK, S is {A::a, A::a}
}

— end example
— end note

3 [Example 3: Because each referenced namespace is searched at most once, the following is well-defined:]

namespace B {
  int b;
}

namespace A {
  using namespace B;
  int a;
}

namespace B {
  using namespace A;
}
void f()
{
    A::a++; // OK, a declared directly in A, S is {A::a}
    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:
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

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]

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.

Example 1:

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 (9.2.9.4)
    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, redefines Data at global scope
struct ::Data; // error: cannot introduce a qualified type (9.2.9.4)
struct Base::Data; // error: cannot introduce a qualified type (9.2.9.4)
struct Base::Datum; // error: Datum undefined
struct Base::Data* pBase; // OK, refers to nested Data
— end example]

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.

transl-unit: decl-seq opt
global-module-fragment opt module-declaration decl-seq opt private-module-fragment opt

dcl

A name is said to have linkage when it can denote the same object, reference, function, type, template, namespace or value as a name introduced by a declaration in another scope:

(2.1) — When a name has external linkage, the entity it denotes can be referred to by names from scopes of other translation units or from other scopes of the same translation unit.

(2.2) — When a name has module linkage, the entity it denotes can be referred to by names from other scopes of the same module unit (10.1) or from scopes of other module units of that same module.

(2.3) — When a name has internal linkage, the entity it denotes can be referred to by names from other scopes in the same translation unit.

(2.4) — When a name has no linkage, the entity it denotes cannot be referred to by names from other scopes.

The name of an entity that belongs to a namespace scope (6.4.5) has internal linkage if it is the name of

(3.1) — a variable, variable template, function, or function template that is explicitly declared static; or

(3.2) — a non-template variable of non-volatile const-qualified type, unless

(3.2.1) — it is explicitly declared extern, or

(3.2.2) — it is inline or exported, or

(3.2.3) — it was previously declared and the prior declaration did not have internal linkage; or

(3.3) — a data member of an anonymous union.

[Note 1: 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

(4.1) — a variable; or

(4.2) — a function; or

(4.3) — 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

(4.4) — 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

(4.5) — an unnamed enumeration that has an enumerator as a name for linkage purposes (9.7.1); or

(4.6) — a template

has its linkage determined as follows:

(4.7) — if the enclosing namespace has internal linkage, the name has internal linkage;

(4.8) — 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;

(4.9) — 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:

```c
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
    extern void h(); // C language linkage
    int i; // #2: i has no linkage
    {
        extern 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, and either

1. they appear in the same translation unit, or
2. they both declare names with module linkage and are attached to the same module, or
3. they both declare names with external linkage.

[Note 2: 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 3: 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:

```c
"decls.h":
int f(); // #1, attached to the global module
int g(); // #2, attached to the global module

Module interface of M:
module;
#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.

§ 6.6
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 (9.2.9.4).
- 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 4: 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
```

—end example]

[Note 5: 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-nameSpecifier, 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 6: 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 (9.2.9.6)),
- 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 7: An inline function template can be an exposure even though explicit specializations of it might 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 8: A specialization can be produced by implicit or explicit instantiation. — end note]

16 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.

17 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.7).

18 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:

```cpp
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 a specialization might be an exposure
```

Translation unit #2:

```cpp
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
    constexpr auto ptr = fr; // error: fr is not usable in constant expressions here
}
```
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.

[Note 1: The representation of types is described in 6.8.1. — end note]

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.

[Note 2: Various features of the language, such as references and virtual functions, might involve additional memory locations that are not accessible to programs but are managed by the implementation. — end note]

Two or more threads of execution (6.9.2) can access separate memory locations without interfering with each other.

[Note 3: Thus a bit-field and an adjacent non-bit-field are in separate memory locations, and therefore can be concurrently updated by two threads of execution without interference. The same applies to two bit-fields, if one is declared inside a nested struct declaration and the other is not, or if the two are separated by a zero-length bit-field declaration, or if they are separated by a non-bit-field declaration. It is not safe to concurrently update two bit-fields in the same struct if all fields between them are also bit-fields of nonzero width. — end note]

Example 1: A class declared as

```
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. — end note]

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. — end note]

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:

---

21) 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.

22) The number of bits in a byte is reported by the macro `CHAR_BIT` in the header `<climits>` (17.3.6).

§ 6.7.2
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
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
}
```

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

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 (9.12.10).

An object has nonzero size if it

- is not a potentially-overlapping subobject, or

- is not of class type, or

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

- has subobjects of nonzero size or unnamed bit-fields of nonzero length.

§ 6.7.2
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 implementation-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.

9 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, or if at least one is a subobject of zero size and they are of different types; otherwise, they have distinct addresses and occupy disjoint bytes of storage. 

[Example 2: ]

```c
static const char test1 = 'x';
static const char test2 = 'x';
const bool b = &test1 != &test2; // always true
```

—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.

10 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.

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

11 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.

12 [Example 3: ]

```c
#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 (6.8.3) with it),
    // in order to give the subclass member access operations
    // defined behavior.
    X *p = (X*)std::malloc(sizeof(struct X));
    p->a = 1;
    p->b = 2;
    return p;
}
```

—end example]

13 An operation that begins the lifetime of an array of char, 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]

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 (20.2.8.3, 20.2.11, 23.5.3, 22.15.3). — end note]

—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 and, if it is of class type or a (possibly multi-dimensional) array thereof, that class type has a trivial default constructor. 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 and 11.4.5.3, and except as described in 20.2.9.2. 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).

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 and any program that depends on the side effects produced by the destructor has undefined behavior.

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:

1. the object will be or was of a class type with a non-trivial destructor and the pointer is used as the operand of a delete-expression,
2. the pointer is used to access a non-static data member or call a non-static member function of the object, or
3. the pointer is implicitly converted (7.3.12) to a pointer to a virtual base class, or
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
5. the pointer is used as the operand of a dynamic_cast (7.6.1.7).

**Example 1**:

```c
#include <cstdlib>

struct B {
    virtual void f();
    void mutate();
};
```

24) For example, before the dynamic initialization of an object with static storage duration (6.9.3.3).
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
(7.4) — the glvalue is used as the operand of a dynamic_cast (7.6.1.7) or as the operand of typeid.

If, after the lifetime of an object has ended and before the storage which the object occupied is reused or
released, a new object is created at the storage location which the original object occupied, 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, if the original object is transparently replaceable (see below) by the new
object. An object \( o_1 \) is transparently replaceable by an object \( o_2 \) if:

(8.1) — the storage that \( o_2 \) occupies exactly overlays the storage that \( o_1 \) occupied, and
(8.2) — \( o_1 \) and \( o_2 \) are of the same type (ignoring the top-level cv-qualifiers), and
(8.3) — \( o_1 \) is not a complete const object, and
(8.4) — neither \( o_1 \) nor \( o_2 \) is a potentially-overlapping subobject (6.7.2), and
(8.5) — 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 \( p_2 \).

[Example 2:

struct C {
    int i;
    void f();
    const C& operator=(const C&);    // lifetime of *this ends
};

const C& C::operator=(const C& other) {
    if (this != &other) {
        this->~C();    // new object of type C created
        new (this) C(other);
        f();           // well-defined
    }
}
return *this;
}

C c1;
C c2;
c1 = c2; // well-defined
cl.f(); // well-defined; c1 refers to a new object of type C
—end example]

[Note 4: 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::lauder (17.6.5). —end note]

9 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 3:
class T { }; 
struct B {
    -B();
};

void h() {
    B b;
    new (&b) T;
} // undefined behavior at block exit
—end example]

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 4:
struct B {
    B0();
    -B();
};

const B b;

void h() {
    b.-B();
    new (const_cast<B*>(&b)) const B; // undefined behavior
} —end example]

11 In this subclause, “before” and “after” refer to the “happens before” relation (6.9.2).

[Note 5: 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 values [basic.indet]

1 When storage for an object with automatic or dynamic storage duration is obtained, the object has an
indeterminate value, and if no initialization is performed for the object, that object retains an indeterminate
value until that value is replaced (7.6.19).

[Note 1: Objects with static or thread storage duration are zero-initialized, see 6.9.3.2. —end note]

2 If an indeterminate value is produced by an evaluation, the behavior is undefined except in the following cases:

25 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.
(2.1) — If an indeterminate value of unsigned ordinary character type (6.8.2) or std::byte type (17.2.1) is
produced by the evaluation of:

(2.1.1) — the second or third operand of a conditional expression (7.6.16),
(2.1.2) — the right operand of a comma expression (7.6.20),
(2.1.3) — 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
(2.1.4) — a discarded-value expression (7.2.3),
then the result of the operation is an indeterminate value.

(2.2) — If an indeterminate 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 replaces the value of
the object referred to by the left operand.

(2.3) — If an indeterminate 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.

(2.4) — 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.

[Example 1:]
int f(bool b) {
    unsigned char c;
    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
}

6.7.5 Storage duration

6.7.5.1 General

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

Static, thread, and automatic storage durations are associated with objects introduced by declarations (6.2)
and implicitly created by the implementation (6.7.7). The dynamic storage duration is associated with
objects created by a new-expression (7.6.2.8).

The storage duration categories apply to references as well.

When the end of the duration of a region of storage is reached, the values of all pointers representing the
address of any part of that region of storage become invalid pointer values (6.8.3). Indirection through an
invalid pointer value and passing an invalid pointer value to a deallocation function have undefined behavior.
Any other use of an invalid pointer value has implementation-defined behavior. 26

6.7.5.2 Static storage duration

All variables which

(1.1) — do not have thread storage duration and
(1.2) — belong to a namespace scope (6.4.5) or are first declared with the static or extern keywords (9.2.2)

26) Some implementations might define that copying an invalid pointer value causes a system-generated runtime fault.
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 [basic.stc.thread]

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 [basic.stc.auto]

1 Variables that belong to a block or parameter scope and are not explicitly declared `static`, `thread_local`, or `extern` have *automatic storage duration*. The storage for these entities lasts until the block in which they are created exits.

2 [Note 1: These variables are initialized and destroyed as described in 8.8. — end note]

3 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 [basic.stc.dynamic]

#### 6.7.5.5.1 General [basic.stc.dynamic.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). 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;
    ```

    ```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;
    ```

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::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) is well-formed. However,
referred to std or std::size_t or std::align_val_t is ill-formed unless the name has been declared by importing or including the appropriate header. — end note]

Allocation and/or deallocation functions may also be declared and defined for any class (11.4.11).

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.

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 null pointer value returned by a replaceable allocation function is a non-null pointer value (6.8.3) 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.27

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.

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 address of 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). The order, contiguity, and initial value of storage that is returned can be unspecified. Even if the size of the space requested is zero, the request can fail. If the request succeeds, the address returned is a non-null pointer value. Any other allocation function never returns a null pointer value and indicates failure only by returning a null pointer value. Any other allocation function never returns a null pointer value and indicates failure only by

A global allocation function is only called as the result of a new expression (7.6.2.8), or for an exception object (14.2).

[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]

6.7.5.5.3Deallocation functions [basic.stc.dynamic.deallocation]

A deallocation function that is not a class member function shall belong to the global scope and not have a name with internal linkage.

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]

---

27) 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.
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

1. optionally, a parameter of type `std::destroying_delete_t`, then
2. optionally, a parameter of type `std::size_t`, then
3. 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.

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.

If the argument given to a deallocation function in the standard library is a pointer that is not the null pointer value (6.8.3), 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

The storage duration of subobjects and reference members is that of their complete object (6.7.2).

### 6.7.6 Alignment

Object types have **alignment requirements** (6.8.2, 6.8.3) 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).

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.

---

28) The global `operator delete(void*, std::size_t)` precludes use of an allocation function `void operator new(std::size_t, std::size_t)` as a placement allocation function (C.4.3).
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; the aligned-storage templates in the library (21.3.8.7) can be used to obtain aligned storage. — 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 [class.temporary]

Temporary objects are created

1. when a prvalue is converted to an xvalue (7.3.5),
2. when needed by the implementation to pass or return an object of trivially copyable type (see below), and
3. when throwing an exception (14.2).

[Note 1: The lifetime of exception objects is described in 14.2. — end note]

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 2: 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` (9.2.9.5), 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 3: 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 member access on a class prvalue (7.6.1.5, 7.6.4),
3. when performing an array-to-pointer conversion or subscripting on an array prvalue (7.3.3, 7.6.1.2),
4. when initializing an object of type `std::initializer_list<T>` from a `braced-init-list` (9.4.5),
5. for certain unevaluated operands (7.6.1.8, 7.6.2.5), and
6. 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:

```cpp
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 function, 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 4: This latitude is granted to allow objects of class type to be passed to or returned from functions in registers. — end note]

4 When an implementation introduces a temporary object of a class that has a non-trivial constructor (11.4.5.2, 11.4.5.3), it shall ensure that a constructor is called for the temporary object. Similarly, the destructor shall be called for a temporary with a non-trivial destructor (11.4.7). 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 three 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 (7.5.5.3, 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,
(6.5) 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,
(6.6) a

(6.6.1) const_cast (7.6.1.11),
(6.6.2) static_cast (7.6.1.9),
(6.6.3) dynamic_cast (7.6.1.7), or
(6.6.4) reinterpret_cast (7.6.1.10)

converting, without a user-defined conversion, a gvalue operand that is one of these expressions to a gvalue that refers to the object designated by the operand, or to its complete object or a subobject thereof.

29) The same rules apply to initialization of an initializer_list object (9.4.5) with its underlying temporary array.

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— a conditional expression (7.6.16) that is a glvalue where the second or third operand is one of these expressions, or

— a comma expression (7.6.20) that is a glvalue where the right operand is one of these expressions.

[Example 2:

```cpp
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 example]

[Note 5: An explicit type conversion (7.6.1.4, 7.6.3) is interpreted as a sequence of elementary casts, covered above.

[Example 3:

```cpp
const int& x = (const int&)1; // temporary for value 1 has same lifetime as x
```

— end example]

— end note]

[Note 6: If a temporary object has a reference member initialized by another temporary object, lifetime extension applies recursively to such a member’s initializer.

[Example 4:

```cpp
struct S {
    const int& m;
};
const S& s = S{1}; // both S and int temporaries have lifetime of s
```

— end example]

— end note]

The exceptions to this lifetime rule are:

— 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.

— 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.

— The lifetime of a temporary bound to the returned value in a function return statement (8.7.4) is not extended; the temporary is destroyed at the end of the full-expression in the return statement.

— 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.

[Note 7: This might introduce a dangling reference. — end note]

[Example 5:

```cpp
struct S { int mi; const std::pair<int, int>& mp; }
S a { 1, {2,3} }; // creates dangling reference
```

— end example]

7 The destruction of a temporary whose lifetime is not extended by being bound to a reference is sequenced before the destruction of every temporary which is constructed earlier in the same full-expression. If the lifetime of two or more temporaries to which references are bound 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 temporaries bound to references 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 `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 `obj1` is destroyed; if `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 `obj2` is destroyed.

8 [Example 6:}
struct 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 \( T_1 \) to hold the result of the expression S(16), a second temporary \( T_2 \) to hold the result of the expression S(23), and a third temporary \( T_3 \) to hold the result of the addition of these two expressions. The temporary \( T_3 \) is then bound to the reference \( cr \). It is unspecified whether \( T_1 \) or \( T_2 \) is created first. On an implementation where \( T_1 \) is created before \( T_2 \), \( T_2 \) shall be destroyed before \( T_1 \). The temporaries \( T_1 \) and \( T_2 \) are bound to the reference parameters of \( \text{operator+} \); these temporaries are destroyed at the end of the full-expression containing the call to \( \text{operator+} \). The temporary \( T_3 \) 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 \( T_3 \) is destroyed takes into account the destruction order of other objects with static storage duration. That is, because \( \text{obj1} \) is constructed before \( \text{T3} \), \( \text{T3} \) is constructed before \( \text{obj2} \), \( \text{obj2} \) shall be destroyed before \( \text{T3} \), and \( \text{T3} \) shall be destroyed before \( \text{obj1} \).

—end example

6.8 Types [basic.types]

6.8.1 General [basic.types.general]

[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]

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 \text{char}, \text{unsigned char}, or \text{std::byte} (17.2.1).\(^{30}\) If the content of that array is copied back into the object, the object shall subsequently hold its original value.

[Example 1:

```c
constexpr std::size_t N = sizeof(T);
char buf[N];
T obj;
std::memcpy(buf, &obj, N); // object initialized to its original value
std::memcpy(&obj, buf, N); // at this point, each subobject of obj of scalar type holds its original value
```
—end example]

For two distinct objects \( \text{obj1} \) and \( \text{obj2} \) of trivially copyable type \( T \), where neither \( \text{obj1} \) nor \( \text{obj2} \) is a potentially-overlapping subobject, if the underlying bytes (6.7.1) making up \( \text{obj1} \) are copied into \( \text{obj2} \),\(^{31}\) \( \text{obj2} \) shall subsequently hold the same value as \( \text{obj1} \).

[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 an object of type \( T \) is the sequence of \( N \) \text{unsigned char} objects taken up by the object of type \( T \), where \( N \) equals \text{sizeof(T)}. The value representation of an object of type \( T \) is the set of bits that participate in representing a value of type \( T \). Bits in the object representation 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.\(^{32}\)

---

30) By using, for example, the library functions (16.4.2.3) \text{std::memcpy} or \text{std::memmove}.

31) By using, for example, the library functions (16.4.2.3) \text{std::memcpy} or \text{std::memmove}.

32) The intent is that the memory model of C++ is compatible with that of ISO/IEC 9899 Programming Language C.
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 incomplete object type. Incompletely-defined object types and cv void are incomplete types.

[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. The type of a pointer to array of unknown bound, or of a type defined by a typedef declaration to be an array of unknown bound, cannot be completed.

[Example 3:

```cpp
class X; // X is an incomplete type
extern X* xp; // xp is a pointer to an incomplete type
extern 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;
```

```cpp
void foo() {
    xp++; // error: X is incomplete
    arrp++; // error: incomplete type
    arrpp++; // OK, sizeof UNKA* is known
}
```

```cpp
struct X { int i; }; // now X is a complete type
int arr[10]; // now the type of arr is complete
X x;
```

```cpp
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: UNKA can’t be completed
}
```

— end example —

[Note 3: 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 (6.8.3), std::nullptr_t, and cv-qualified (6.8.4) 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

(33) The size and layout of an instance of an incompletely-defined object type is unknown.
— a possibly cv-qualified class type (Clause 11) that has all of the following properties:

— it has a constexpr destructor (9.2.6),
— it is either a closure type (7.5.5.2), an aggregate type (9.4.2), 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,
— if it is a union, at least one of its non-static data members is of non-volatile literal type, and
— if it is not a union, all of its non-static data members and base classes are of non-volatile literal types.

[Note 4: 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

1 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]

2 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”, 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]

3 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.\(^{34}\)

[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>
<thead>
<tr>
<th>Type</th>
<th>Minimum width</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>

4 The width of each 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 C 6.2.6.2. — end note]
The types integral and floating-point types are collectively termed

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.

Type wchar_t is a distinct type that has an implementation-defined signed or unsigned integer type as its underlying type. The values of type wchar_t can represent distinct codes for all members of the largest extended character set specified among the supported locales (30.3.1).

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 <cstddef> (17.4.2).

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.

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 (6.8.4) thereof, are collectively termed integral types. A synonym for integral type is integer type.

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 (6.8.4) thereof, are collectively termed floating-point types. The value representation of floating-point types is implementation-defined.

Integral and floating-point types are collectively termed arithmetic types.

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.
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 11: 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 Compound types

Compound types can be constructed in the following ways:

(1.1) — arrays of objects of a given type, 9.3.4.5;

(1.2) — functions, which have parameters of given types and return `void` or references or objects of a given type, 9.3.4.6;

(1.3) — pointers to `cv void` or objects or functions (including static members of classes) of a given type, 9.3.4.2;

(1.4) — 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

(1.5) — 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);

(1.6) — unions, which are classes capable of containing objects of different types at different times, 11.5;

(1.7) — enumerations, which comprise a set of named constant values. Each distinct enumeration constitutes a different enumerated type, 9.7.1;

(1.8) — pointers to non-static class members, 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.

These methods of constructing types can be applied recursively; restrictions are mentioned in 9.3.4. Constructing 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.

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 (6.7.6). Every value of pointer type is one of the following:

(3.1) — a pointer to an object or function (the pointer is said to point to the object or function), or

(3.2) — a pointer past the end of an object (7.6.6), or

(3.3) — the null pointer value for that type, or

(3.4) — 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 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. A pointer value becomes invalid when the storage it denotes reaches the end of its storage duration; see 6.7.5. — end note]

35) Static class members are objects or functions, and pointers to them are ordinary pointers to objects or functions.

36) For an object that is not within its lifetime, this is the first byte in memory that it will occupy or used to occupy.
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]

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).

[Note 4: An array object and its first element are not pointer-interconvertible, even though they have the same address. — end note]

A pointer to \( cv\text{ }void \) 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 \( cv\text{ }void \)” shall have the same representation and alignment requirements as an object of type “pointer to \( cv\text{ }char \)”.

### 6.8.4 CV-qualifiers

Each type other than a function or reference type is part of a group of four distinct, but related, types: a \( cv\text{-unqualified} \) version, a \( const\text{-qualified} \) version, a \( volatile\text{-qualified} \) version, and a \( const\text{-volatile-qualified} \) version. The types in each such group shall have the same representation and alignment requirements (6.7.6). A function or reference type is always \( cv\text{-unqualified} \).

1. A \( const \) object is an object of type \( const\text{ }T \) or a non-mutable subobject of a \( const \) object.
2. A \( volatile \) object is an object of type \( volatile\text{ }T \) or a subobject of a \( volatile \) object.
3. A \( const\text{ }volatile \) object is an object of type \( const\text{ }volatile\text{ }T \), a non-mutable subobject of a \( const\text{ }volatile \) object, a \( const\text{ }subobject \) 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 \( cv\text{-qualifiers} \) 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]

Except for array types, a compound type (6.8.3) is not \( cv\text{-qualified} \) by the \( cv\text{-qualifiers} \) (if any) of the types from which it is compounded.

An array type whose elements are \( cv\text{-qualified} \) is also considered to have the same \( cv\text{-qualifications} \) as its elements.

[Note 2: \( Cv\text{-qualifiers} \) applied to an array type attach to the underlying element type, so the notation “\( cv\text{ }T \)” where \( T \) is an array type, refers to an array whose elements are so-qualified (9.3.4.5). — end note]

[Example 1:
```c
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 \( const\text{ }char \)”, and the array type is considered to be \( const\text{-qualified} \). — end example]

[Note 3: See 9.3.4.6 and 12.2.2 regarding function types that have \( cv\text{-qualifiers} \). — end note]

There is a partial ordering on \( cv\text{-qualifiers} \), so that a type can be said to be more \( cv\text{-qualified} \) than another. Table 15 shows the relations that constitute this ordering.

---

(37) 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.
Table 15: Relations on \texttt{const} and \texttt{volatile} \[tab:basic.type.qualifier.rel\]

<table>
<thead>
<tr>
<th>no cv-qualifier</th>
<th>\texttt{const}</th>
</tr>
</thead>
<tbody>
<tr>
<td>no cv-qualifier</td>
<td>\texttt{volatile}</td>
</tr>
<tr>
<td>no cv-qualifier</td>
<td>\texttt{const volatile}</td>
</tr>
<tr>
<td>\texttt{const}</td>
<td>\texttt{const volatile}</td>
</tr>
<tr>
<td>\texttt{volatile}</td>
<td>\texttt{const volatile}</td>
</tr>
</tbody>
</table>

6 In this document, the notation \texttt{cv} (or \texttt{cv1}, \texttt{cv2}, etc.), used in the description of types, represents an arbitrary set of cv-qualifiers, i.e., one of \{	exttt{const}\}, \{	exttt{volatile}\}, \{	exttt{const, volatile}\}, or the empty set. For a type \texttt{cv T}, the \textit{top-level cv-qualifiers} of that type are those denoted by \texttt{cv}.

[Example 2: The type corresponding to the \textit{type-id} \texttt{const int\&} has no top-level cv-qualifiers. The type corresponding to the \textit{type-id} \texttt{volatile int * const} has the top-level cv-qualifier \texttt{const}. For a class type \texttt{C}, the type corresponding to the \textit{type-id} \texttt{void (C::\* volatile)(int) const} has the top-level cv-qualifier \texttt{volatile}. — end example]

6.8.5 Integer conversion rank \[conv.rank\]

1 Every integer type has an \textit{integer conversion rank} defined as follows:

(1.1) — No two signed integer types other than \texttt{char} and \texttt{signed char} (if \texttt{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 \texttt{long long int} is greater than the rank of \texttt{long int}, which is greater than the rank of \texttt{int}, which is greater than the rank of \texttt{short int}, which is greater than the rank of \texttt{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 \texttt{char} equals the rank of \texttt{signed char} and \texttt{unsigned char}.

(1.7) — The rank of \texttt{bool} is less than the rank of all standard integer types.

(1.8) — The ranks of \texttt{char8\_t}, \texttt{char16\_t}, \texttt{char32\_t}, and \texttt{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 \texttt{T1}, \texttt{T2}, and \texttt{T3}, if \texttt{T1} has greater rank than \texttt{T2} and \texttt{T2} has greater rank than \texttt{T3}, then \texttt{T1} has greater rank than \texttt{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]

6.9 Program execution \[basic.exec\]

6.9.1 Sequential execution \[intro.execution\]

1 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).

2 A \textit{constituent expression} is defined as follows:

(2.1) — The constituent expression of an expression is that expression.

(2.2) — The constituent expressions of a \textit{braced-init-list} or of a (possibly parenthesized) \textit{expression-list} are the constituent expressions of the elements of the respective list.

(2.3) — The constituent expressions of a \textit{brace-or-equal-initializer} of the form = \textit{initializer-clause} are the constituent expressions of the \textit{initializer-clause}.

[Example 1:

\begin{verbatim}
struct A { int x; }
\end{verbatim}
The constituent expressions of the initializer used for the initialization of b are 5 and 1+1. — end example]

3 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 (7.5.5), 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.

4 A subexpression of an expression E is an immediate subexpression of E or a subexpression of an immediate subexpression of E.

[Note 1: Expressions appearing in the compound-statement of a lambda-expression are not subexpressions of the lambda-expression. — end note]

5 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) 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) { }
    int& v() { return I; }
    ~S() noexcept(false) { }
private:
    int I;
};

S s1(1); // full-expression is initialization of I
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()); // 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
```
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.

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 $Y$.

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.  

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.

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
}
```

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 $F$. 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.
occur within $F$; 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.

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. 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 of 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.

[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]

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.

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]

39) In other words, function executions do not interleave with each other.

40) 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 (6.8.3).
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 $B$.

[Note 7: The relation “is dependency-ordered before” is analogous to “synchronizes with”, but uses release/consume in place of release/acquire. — end note]

9 An evaluation $A$ inter-thread happens before an evaluation $B$ if

(9.1) — $A$ synchronizes with $B$, or

(9.2) — $A$ is dependency-ordered before $B$, or

(9.3) — for some evaluation $X$

(9.3.1) — $A$ synchronizes with $X$ and $X$ is sequenced before $B$, or

(9.3.2) — $A$ is sequenced before $X$ and $X$ inter-thread happens before $B$, or

(9.3.3) — $A$ inter-thread happens before $X$ and $X$ inter-thread happens before $B$.

[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 is not permitted to end 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 is not permitted to
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 $A$ happens before an evaluation $B$ (or, equivalently, $B$ happens after $A$) if:

1. $A$ is sequenced before $B$, or
2. $A$ inter-thread happens before $B$.

The implementation shall ensure that no program execution demonstrates a cycle in the “happens before” relation.

[Note 9: This cycle would otherwise be possible only through the use of consume operations. — end note]

An evaluation $A$ simply happens before an evaluation $B$ if either

1. $A$ is sequenced before $B$, or
2. $A$ synchronizes with $B$, or
3. $A$ simply happens before $X$ and $X$ simply happens before $B$.

[Note 10: In the absence of consume operations, the happens before and simply happens before relations are identical.
— end note]

An evaluation $A$ strongly happens before an evaluation $D$ if, either

1. $A$ is sequenced before $D$, or
2. $A$ synchronizes with $D$, and both $A$ and $D$ are sequentially consistent atomic operations (33.5.4), or
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
4. there is an evaluation $B$ such that $A$ strongly happens before $B$, and $B$ strongly happens before $D$.

[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 visible side effect $A$ on a scalar object or bit-field $M$ with respect to a value computation $B$ of $M$ satisfies
the conditions:

1. $A$ happens before $B$ and
2. there is no other side effect $X$ to $M$ such that $A$ happens before $X$ and $X$ happens before $B$.

The value of a non-atomic scalar object or bit-field $M$, as determined by evaluation $B$, shall be the value
stored by the visible side effect $A$.

[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]

[Note 13: This states that operations on ordinary objects are not visibly reordered. This is not actually detectable
without data races, but it is necessary to ensure that data races, as defined below, and with suitable restrictions on
the use of atomics, correspond to data races in a simple interleaved (sequentially consistent) execution. — end note]

The value of an atomic object $M$, as determined by evaluation $B$, shall be the value stored by some side
effect $A$ that modifies $M$, where $B$ does not happen before $A$.

[Note 14: The set of such side effects is also restricted by the rest of the rules described here, and in particular, by
the coherence requirements below. — end note]

If an operation $A$ that modifies an atomic object $M$ happens before an operation $B$ that modifies $M$, then $A$
shall be earlier than $B$ in the modification order of $M$.

[Note 15: This requirement is known as write-write coherence. — end note]

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 $B$ shall either be 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 $M$.

[Note 16: This requirement is known as read-read coherence. — end note]

If a value computation $A$ of an atomic object $M$ happens before an operation $B$ that modifies $M$, then $A$
shall take its value from a side effect $X$ on $M$, where $X$ precedes $B$ in the modification order of $M$.

[Note 17: This requirement is known as read-write coherence. — end note]
If a side effect \( X \) on an atomic object \( M \) happens before a value computation \( B \) of \( M \), then the evaluation \( B \) shall take its value from \( X \) or from a side effect \( Y \) that follows \( X \) in the modification order of \( M \).

[Note 18: This requirement is known as write-read coherence. — end note]

[Note 19: The four preceding coherence requirements effectively disallow compiler reordering of atomic operations to a single object, even if both operations are relaxed loads. This effectively makes the cache coherence guarantee provided by most hardware available to C++ atomic operations. — end note]

[Note 20: The value observed by a load of an atomic depends on the “happens before” relation, which depends on the values observed by loads of atomics. The intended reading is that there must exist an association of atomic loads with modifications they observe that, together with suitably chosen modification orders and the “happens before” relation derived as described above, satisfy the resulting constraints as imposed here. — end note]

Two actions are potentially concurrent if

(21.1) — they are performed by different threads, or

(21.2) — 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.

[Note 21: It can be shown that programs that correctly use mutexes and memory_order::seq_cst operations to prevent all data races and use no other synchronization operations behave as if the operations executed by their constituent threads were simply interleaved, with each value computation of an object being taken from the last side effect on that object in that interleaving. This is normally referred to as “sequential consistency”. However, this applies only to data-race-free programs, and data-race-free programs cannot observe most program transformations that do not change single-threaded program semantics. In fact, most single-threaded program transformations continue to be allowed, since any program that behaves differently as a result has undefined behavior. — end note]

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 \( B \).

[Note 22: 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. — end note]

[Note 23: 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

[ intro.progress]

The implementation may assume that any thread will eventually do one of the following:

(1.1) — terminate,

(1.2) — make a call to a library I/O function,

(1.3) — perform an access through a volatile glvalue, or

(1.4) — perform a synchronization operation or an atomic operation.

[Note 1: This is intended to allow compiler transformations such as removal of empty loops, even when termination cannot be proven. — 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.

(2.1) — If there is only one thread that is not blocked (3.7) in a standard library function, a lock-free execution in that thread shall complete.
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 (3.7) 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.

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.

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.

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 is required regardless of whether or not other threads of executions (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.

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.

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.

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.

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

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

(2.1) — a function of () returning int and
(2.2) — 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 argc and the second function parameter is called argv, where argc shall be the number of arguments passed to the program from the environment in which the program is run. If argv 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) (16.3.3.5.3) and argv[0] shall be the pointer to the initial character of a 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.

The function main shall not be used within a program. 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 a variable main that belongs to the global scope, or that declares a function main that belongs to the global scope and is attached to a named module, or that declares 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

1 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:  
                 // either statically initialized to 0.0 or
                 // dynamically initialized to 0.0 if d1 is
                 // dynamically initialized, or 1.0 otherwise

double d1 = fd();  // either initialized statically or dynamically to 1.0
```

— end note]

### 6.9.3.3 Dynamic initialization of non-block variables

1 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]

2 A declaration `D` is appearance-ordered before a declaration `E` if

(2.1) — `D` appears in the same translation unit as `E`, or

(2.2) — the translation unit containing `E` has an interface dependency on the translation unit containing `D`, in either case prior to `E`.

3 Dynamic initialization of non-block variables `V` and `W` with static storage duration are ordered as follows:

(3.1) — 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

(3.1.1) — 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`;

(3.1.2) — otherwise, the initialization of `V` strongly happens before the initialization of `W`. 

§ 6.9.3.3
— 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.

— Otherwise, the initializations of $V$ and $W$ are indeterminately sequenced.

[Note 2: This definition permits initialization of a sequence of ordered variables concurrently with another sequence. — end note]

4 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.

5 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
// - File 1 -
#include "a.h"
#include "b.h"
B b;
A::A() {
  b.Use();
}

// - File 2 -
#include "a.h"
A a;

// - File 3 -
#include "a.h"
#include "b.h"
extern A a;
extern B b;
int main() {
  a.Use();
  b.Use();
}
```

It is implementation-defined whether either $a$ or $b$ is initialized before main is entered or whether the initializations are delayed until $a$ is first odr-used in main. In particular, if $a$ is initialized before main is entered, it is not guaranteed that $b$ will be initialized before it is odr-used by the initialization of $a$, that is, before $A::A$ is called. If, however, $a$ is initialized at some point after the first statement of main, $b$ will be initialized prior to its use in $A::A$. — end example]

6 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 that variable. It is implementation-defined in which threads and at which points in the program such deferred dynamic initialization occurs.

7 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 $t$ is sequenced before the first non-initialization odr-use by $t$ 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.

8 If the initialization of a non-block variable with static or thread storage duration exits via an exception, the function std::terminate is called (14.6.2).

41) 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).
6.9.3.4 Termination

1. Constructed objects (9.4) with static storage duration are destroyed and functions registered with `std::atexit` are called as part of a call to `std::exit` (17.5). The call to `std::exit` is sequenced before the destructions and the registered functions.

   [Note 1: Returning from `main` invokes `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 `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 `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 `std::atexit` (see `<cstdlib>`, 17.5), the call to the function passed to `std::atexit` is sequenced before the call to the destructor for the object. If a call to `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 `std::atexit`. If a call to `std::atexit` strongly happens before 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 subclause 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

```c
int a, b;
/* ... */
a = a + 32760 + b + 5;
```

the expression statement behaves exactly the same as

```c
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 int is [-32768, +32767], the implementation cannot rewrite this expression as

```c
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

```c
a = ((a + 32765) + b);
```
or

```c
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.]

42) The precedence of operators is not directly specified, but it can be derived from the syntax.
43) Overloaded operators are never assumed to be associative or commutative.
44) 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

<table>
<thead>
<tr>
<th>expression</th>
<th>glvalue</th>
<th>rvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lvalue</td>
<td>xvalue</td>
</tr>
</tbody>
</table>

— A glvalue is an expression whose evaluation determines the identity of an object or function.

— 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.

— An xvalue is a glvalue that denotes an object whose resources can be reused (usually because it is near the end of its lifetime).

— An lvalue is a glvalue that is not an xvalue.

— An rvalue is a prvalue or an xvalue.

Every expression belongs to exactly one of the fundamental classifications 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]

2

[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 classify expressions, not values. — end note]

3

[Note 3: An expression is an xvalue if it is:

— 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:

```cpp
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 \texttt{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 expects a prvalue for that operand, the lvalue-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 \texttt{const int} can, for example, be used where a prvalue of type \texttt{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.

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.

Unless otherwise indicated (9.2.9.5), a prvalue shall always have complete type or the \( void \) type; if it has a class type or (possibly multi-dimensional) array of class type, that class shall not be an abstract class (11.7.4). A glvalue shall not have type \( cv \ void \).

[Note 8: 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 9: A program that attempts to modify an object through a non-modifiable lvalue or through an rvalue is ill-formed (7.6.19, 7.6.1.6, 7.6.2.3). — end note]

If a program attempts to access (3.1) the stored value of an object through a glvalue whose type is not similar (7.3.6) to one of the following types the behavior is undefined:45

\begin{itemize}
  \item the dynamic type of the object,
  \item a type that is the signed or unsigned type corresponding to the dynamic type of the object, or
  \item \texttt{char}, \texttt{unsigned char}, or \texttt{std::byte} type.
\end{itemize}

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 10: 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.

3 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 \texttt{std::nullptr_t}, is:

\begin{itemize}
  \item if both \( p1 \) and \( p2 \) are null pointer constants, \texttt{std::nullptr_t};
\end{itemize}

45) The intent of this list is to specify those circumstances in which an object can or cannot be aliased.
(3.2) — if either \texttt{p1} or \texttt{p2} is a null pointer constant, \texttt{T2} or \texttt{T1}, respectively;

(3.3) — if \texttt{T1} or \texttt{T2} is “pointer to cv1 void” and the other type is “pointer to cv2 T”, where \texttt{T} is an object type or \texttt{void}, “pointer to cv12 void”, where \texttt{cv12} is the union of \texttt{cv1} and \texttt{cv2};

(3.4) — if \texttt{T1} or \texttt{T2} is “pointer to noexcept function” and the other type is “pointer to function”, where the function types are otherwise the same, “pointer to function”;

(3.5) — if \texttt{T1} or \texttt{T2} is “pointer to cv1 C1” and \texttt{T2} is “pointer to cv2 C2”, where \texttt{C1} is reference-related to \texttt{C2} or \texttt{C2} is reference-related to \texttt{C1} (9.4.4), the qualification-combined type (7.3.6) of \texttt{T2} and \texttt{T1}, respectively;

(3.6) — if \texttt{T1} or \texttt{T2} is “pointer to member of \texttt{C1} of type function”, the other type is “pointer to member of \texttt{C2} of type noexcept function”, and \texttt{C1} is reference-related to \texttt{C2} or \texttt{C2} is reference-related to \texttt{C1} (9.4.4), the qualification-combined type of \texttt{T2} and \texttt{T1}, or the qualification-combined type of \texttt{T1} and \texttt{T2}, respectively;

(3.7) — if \texttt{T1} is “pointer to member of \texttt{C1} of type cv1 U” and \texttt{T2} is “pointer to member of \texttt{C2} of type cv2 U”, for some non-function type \texttt{U}, where \texttt{C1} is reference-related to \texttt{C2} or \texttt{C2} is reference-related to \texttt{C1} (9.4.4), the qualification-combined type of \texttt{T2} and \texttt{T1}, or the qualification-combined type of \texttt{T1} and \texttt{T2}, respectively;

(3.8) — if \texttt{T1} and \texttt{T2} are similar types (7.3.6), the qualification-combined type of \texttt{T1} and \texttt{T2};

(3.9) — otherwise, a program that necessitates the determination of a composite pointer type is ill-formed.

[Example 1:

```c
typedef void *p;
typedef const int *q;
typedef int **pi;
typedef const int **pci;
```

The composite pointer type of \texttt{p} and \texttt{q} is “pointer to const void”; the composite pointer type of \texttt{pi} and \texttt{pci} is “pointer to const pointer to const int”. — end example]

### 7.2.3 Context dependence

[expr.context]

1 In some contexts, \textit{unevaluated operands} appear (7.5.7, 7.6.2.5, 7.6.2.7, 9.2.9.5, 13.1, 13.7.9). An unevaluated operand is not evaluated.

[\textit{Note 1}: In an unevaluated operand, a non-static class member can be named (7.5.4) 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]

2 In some contexts, an expression only appears for its side effects. Such an expression is called a \textit{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:

- (expression ), where \textit{expression} is one of these expressions,
- id-expression (7.5.4),
- subscripting (7.6.1.2),
- class member access (7.6.1.5),
- indirection (7.6.2.2),
- pointer-to-member operation (7.6.4),
- conditional expression (7.6.16) where both the second and the third operands are one of these expressions, or

- comma expression (7.6.20) where the right operand is one of these expressions.

[\textit{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.

[\textit{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.

\section*{§ 7.2.3}

93
7.3 Standard conversions

7.3.1 General

1 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:

(1.1) — Zero or one conversion from the following set: lvalue-to-rvalue conversion, array-to-pointer conversion, and function-to-pointer conversion.

(1.2) — 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.

(1.3) — Zero or one function pointer conversion.

(1.4) — 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 a required destination type.

2 [Note 2: Expressions with a given type will be implicitly converted to other types in several contexts:

(2.1) — When used as operands of operators. The operator’s requirements for its operands dictate the destination type (7.6).

(2.2) — When used in the condition of an if statement (8.5.2) or iteration statement (8.6). The destination type is bool.

(2.3) — When used in the expression of a switch statement (8.5.3). The destination type is integral.

(2.4) — 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]

3 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).

4 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 \( \text{bool } t(E) \); is well-formed, for some invented temporary variable \( t \) (9.4).

5 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 \( \text{cv } T \) or reference to \( \text{cv } T \) such that \( T \) is allowed by the context. There shall be exactly one such \( T \).

6 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.

7 [Note 2: 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]

8 [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.\(^{46}\) 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

\(^{46}\) 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.
When an lvalue-to-rvalue conversion is applied to an expression \( E \), and either

(1) \( E \) is not potentially evaluated, or
(2) the evaluation of \( E \) results in the evaluation of a member \( E_x \) of the set of potential results of \( E \), and \( E_x \) names a variable \( x \) that is not odr-used by \( E_x \) (6.3),

the value contained in the referenced object is not accessed.

[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  
```

—end example]

3 The result of the conversion is determined according to the following rules:

(3.1) — If \( T \) is \( cv\) std::nullptr_t, the result is a null pointer constant (7.3.12).

[Note 1: Since the conversion does not access the object to which the glvalue refers, there is no side effect even if \( T \) is volatile-qualified (6.9.1), and the glvalue can refer to an inactive member of a union (11.5). — end note]

(3.2) — Otherwise, if \( T \) has a class type, the conversion copy-initializes the result object from the glvalue.

(3.3) — 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) — Otherwise, the object indicated by the glvalue is read (3.1), and the value contained in the object is the prvalue result.

4 [Note 2: See also 7.2.1. — end note]

7.3.3 Array-to-pointer conversion [conv.array]

1 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.

7.3.4 Function-to-pointer conversion [conv.func]

1 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.48

7.3.5 Temporary materialization conversion [conv.rval]

1 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.

[Note 1: If \( T \) is a class type (or array thereof), it must have an accessible and non-deleted destructor; see 11.4.7. — end note]

[Example 1:

```cpp
struct X { int n; };  
int k = X().n;  // OK, X() prvalue is converted to xvalue  
```

—end example]

47) In C++ class and array prvalues can have cv-qualified types. This differs from ISO C, in which non-lvalues never have cv-qualified types.

48) 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 [conv.qual]

1 A qualification-decomposition of a type $T$ is a sequence of $cv_i$ and $P_i$ such that $T$ is

\[
\text{“} cv_0 P_0 cv_1 P_1 \cdots cv_{n-1} P_{n-1} cv_n \text{”}
\]

for $n \geq 0$,

where each $cv_i$ is a set of cv-qualifiers (6.8.4), 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 $N_i$,” 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 const int ** has three qualification-decompositions, taking $U$ as “int”, as “pointer to const int”, and as “pointer to pointer to const 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 $T$.

2 Two types $T1$ and $T2$ are similar if they have qualification-decompositions with the same $n$ such that 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 $U$ are the same.

3 The qualification-combined type of two types $T1$ and $T2$ is the type $T3$ similar to $T1$ whose qualification-decomposition is such that:

(3.1) for every $i > 0$, $cv^i_j$ is the union of $cv^1_i$ and $cv^2_i$.

(3.2) if either $P^1_i$ or $P^2_i$ is “array of unknown bound of”, $P^3_i$ is “array of unknown bound of”, otherwise it is $P^1_i$, and

(3.3) if the resulting $cv^3_i$ is different from $cv^1_i$ or $cv^2_i$, or the resulting $P^3_i$ is different from $P^1_i$ or $P^2_i$, then const is added to every $cv^k_j$ for $0 < k < i$,

where $cv^i_j$ and $P^i_j$ are the components of the qualification-decomposition of $T_j$. A prvalue of type $T1$ can be converted to type $T2$ if the qualification-combined type of $T1$ and $T2$ is $T2$.

[Note 1: If a program could assign a pointer of type $T**$ to a pointer of type 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,

```c
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 note]

[Note 2: Given similar types $T1$ and $T2$, this construction ensures that both can be converted to the qualification-combined type of $T1$ and $T2$. —end note]

4 [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]

5 [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 [conv.prom]

1 A prvalue of an integer type other than bool, char8_t, char16_t, char32_t, or wchar_t whose integer conversion rank (6.8.5) is less than the rank of int can be converted to a prvalue of type int if int can represent all the values of the source type; otherwise, the source prvalue can be converted to a prvalue of type unsigned int.

2 A prvalue of type char8_t, char16_t, char32_t, or wchar_t (6.8.2) 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, or unsigned long long int. If none of the types in that list can represent all the values of its underlying type, a prvalue of type char8_t, char16_t, char32_t, or wchar_t can be converted to a prvalue of its underlying type.

3 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): int, unsigned int, long int, unsigned long int, long long int, or unsigned long long int. If none of the types in

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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 (6.8.5) 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.

4 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.

5 A prvalue for an integral bit-field (11.4.10) 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. If the bit-field is larger yet, no integral promotion applies to it. If the bit-field has an enumerated type, it is treated as any other value of that type for promotion purposes.

6 A prvalue of type `bool` can be converted to a prvalue of type `int`, with `false` becoming zero and `true` becoming one.

7 These conversions are called integral promotions.

7.3.8 Floating-point promotion

1 A prvalue of type `float` can be converted to a prvalue of type `double`. The value is unchanged.

2 This conversion is called floating-point promotion.

7.3.9 Integral conversions

1 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.

2 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.

3 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.

4 The conversions allowed as integral promotions are excluded from the set of integral conversions.

7.3.10 Floating-point conversions

1 A prvalue of floating-point type can be converted to a prvalue of another 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.

2 The conversions allowed as floating-point promotions are excluded from the set of floating-point conversions.

7.3.11 Floating-integral conversions

1 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]

2 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]

If the value being converted is outside the range of values that can be represented, the behavior is undefined. If the source type is `bool`, the value `false` is converted to zero and the value `true` is converted to one.

7.3.12 Pointer conversions

1 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 (6.8.3) and is distinguishable from every other value of object pointer or function pointer type. Such a conversion

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is called a **null pointer conversion**. Two null pointer values of the same type shall compare equal. 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

2 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 (6.8.3) is unchanged by this conversion.

3 A prvalue 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. The result of the conversion is a pointer to the base class subobject of the derived class object. The null pointer value is converted to the null pointer value of the destination type.

### 7.3.13 Pointer-to-member conversions

1 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**. Two null member pointer values of the same type shall compare equal. 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).

2 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. 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.

### 7.3.14 Function pointer conversions

1 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.

```cpp
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
```

### 7.3.15 Boolean conversions

1 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

1 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:

---

49) 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*`.

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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.

If either operand is of type `long double`, the other shall be converted to `long double`.

Otherwise, if either operand is `double`, the other shall be converted to `double`.

Otherwise, if either operand is `float`, the other shall be converted to `float`.

Otherwise, the integral promotions (7.3.7) shall be performed on both operands. Then the following rules shall be applied to the promoted operands:

- If both operands have the same type, no further conversion is needed.
- Otherwise, if both operands have signed integer types or both have unsigned integer types, the operand with the type of lesser integer conversion rank shall be converted to the type of the operand with greater rank.
- Otherwise, if the type of the operand with signed integer type can represent all of the values of the type of the operand with unsigned integer type, the operand with unsigned integer type shall be converted to the type of the operand with signed integer type.
- Otherwise, both operands shall be converted to the unsigned integer type corresponding to the type of the operand with signed integer type.

If one operand is of enumeration type and the other operand is of a different enumeration type or a floating-point type, this behavior is deprecated (D.2).

### 7.5 Primary expressions

#### 7.5.1 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 5.13.8, and any other `literal` is a prvalue.

#### 7.5.2 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.

2 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 either a static member function or an 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]

50 As a consequence, operands of type `bool`, `char8_t`, `char16_t`, `char32_t`, `wchar_t`, or an enumerated type are converted to some integral type.
[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(); }
};
template auto A::f(int t) -> decltype(t + g());
```
—end example]
—end note

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]

### 7.5.3 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.

### 7.5.4 Names

#### 7.5.4.1 General

An id-expression is a restricted form of a primary-expression.

[Note 1: An id-expression can appear after . and -> operators (7.6.1.5). — end note]

2 If an id-expression E denotes a member M of an anonymous union (11.5.2) U:

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 transformation to a class member access expression (11.4.3)).

   [Example 1: o.x is interpreted as o.u.x, where u names the anonymous union member. — end example]

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.

   [Note 2: Under this interpretation, E no longer denotes a non-static data member. — end note]

   [Example 2: N::x is interpreted as N::u.x, where u names the anonymous union variable. — end example]

3 An id-expression that denotes a non-static data member or non-static member function of a class can only be used:
— as part of a class member access (7.6.1.5) in which the object expression refers to the member’s class or a class derived from that class, or

— to form a pointer to member (7.6.2.2), or

— if that id-expression denotes a non-static data member and it appears in an unevaluated operand.

[Example 3:

```c
struct S {
    int m;
};
int i = sizeof(S::m);        // OK
int j = sizeof(S::m + 42);   // OK
```
— end example]

4 A potentially-evaluated id-expression that denotes an immediate function (9.2.6) shall appear only

— as a subexpression of an immediate invocation, or

— in an immediate function context (7.7).

5 For an id-expression that denotes an overload set, overload resolution is performed to select a unique function (12.2, 12.3).

[Note 3: 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.

[Example 4:

```c
template<typename T> struct A {
    static void f(int) requires false;
};
void g() {
    A<int>::f(0);                   // error: cannot call f
    void (*p1)(int) = A<int>::f;    // error: cannot take the address of f
    decltype(A<int>::f)* p2 = nullptr;          // error: the type decltype(A<int>::f) is invalid
}
```
In each case, the constraints of f are not satisfied. In the declaration of p2, those constraints are required to be satisfied even though f is an unevaluated operand (7.2.3). — end example]

— end note]

### 7.5.4.2 Unqualified names

**unqualified-id:**

- identifier
- operator-function-id
- conversion-function-id
- literal-operator-id
- ~ type-name
- ~ decltype-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 decltype-specifier prefixed by ~ denotes the destructor of the type so named; see 7.5.4.4. Within the definition of a non-static member function, an identifier that names a non-static member is transformed to a class member access expression (11.4.3). — 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 (7.5.4.3, 9.2.9.3, 9.2.9.4, 9.3.4.4, 9.9, 13.2, 13.3, 13.8). — end note]

51) This also applies when the object expression is an implicit (*this) (11.4.3).
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 (7.5.5.3), 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, and:

\[
(3.1) \quad \text{— If } P \text{ is in } E \text{’s function parameter scope but not its parameter-declaration-clause, then the type of the expression is the type of a class member access expression (7.6.1.5) naming the non-static data member that would be declared for such a capture in the object parameter (9.3.4.6) of the function call operator of } E. \\
\text{[Note 3: If } E \text{ is not declared mutable, the type of such an identifier will typically be const qualified. — end note]}
\]

\[
(3.2) \quad \text{— Otherwise (if } P \text{ either precedes } E \text{’s function parameter scope or is in } E \text{’s parameter-declaration-clause), the program is ill-formed.}
\]

Otherwise, the type of the expression is the type of the result.

\[
\text{[Note 4: If the entity is a template parameter object for a template parameter of type } T \text{ (13.2), the type of the expression is const } T. \quad \text{— end note]}
\]

\[
\text{[Note 5: The type will be adjusted as described in 7.2.2 if it is cv-qualified or is a reference type. — end note]}
\]

The expression is an 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.

\[
\text{[Example 1:}
\]

```cpp
void f() {
  float x, &r = x;
  [=]() -> decltype((x)) { // lambda returns float const & because this lambda is not mutable and
    return x; // 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 const
  decltype((r)) r2 = y2; // r2 has type float const
}
```

\[
\text{[expr.prim.id.qual]}
\]

7.5.4.3 Qualified names

qualified-id:

\[
\text{nested-name-specifier template}_{\text{opt}} \text{ unqualified-id}
\]

nested-name-specifier:

\[
::
\text{type-name ::}
\text{namespace-name ::}
\text{decltype-specifier ::}
\text{nested-name-specifier identifier ::}
\text{nested-name-specifier template}_{\text{opt}} \text{ simple-template-id ::}
\]

§ 7.5.4.3
1 The component names of a qualified-id are those of its nested-name-specifier and unqualified-id. The component names of a nested-name-specifier are its identifier (if any) and those of its type-name, namespace-name, simple-template-id, and/or nested-name-specifier.

2 A nested-name-specifier 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-name-specifier.

   A declarative nested-name-specifier shall not have a decltype-specifier. A declaration that uses a declarative nested-name-specifier shall be a friend declaration or inhabit a scope that contains the entity being redeclared or specialized.

3 The nested-name-specifier :: nominates the global namespace. A nested-name-specifier with a decltype-specifier nominates the type denoted by the decltype-specifier, which shall be a class or enumeration type. If a nested-name-specifier 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 nominates the primary template of T; H shall be equivalent to the template-head of T (13.7.7.2).
   (3.2) Otherwise, N nominates 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-name-specifier nominates the entity denoted by its type-name, namespace-name, identifier, or simple-template-id. If the nested-name-specifier is not declarative, the entity shall not be a template.

4 A qualified-id shall not be of the form nested-name-specifier template opt ~ decltype-specifier nor of the form decltype-specifier :: ~ type-name.

5 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
   (5.1) a function other than a non-static member function,
   (5.2) a non-static member function if Q is the operand of a unary & operator,
   (5.3) a variable,
   (5.4) a structured binding (9.6), or
   (5.5) a data member,

   and a prvalue otherwise.

7.5.4.4 Destruction

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).

[Note 1: Such a call ends the lifetime of the object (7.6.1.3, 6.7.3). — end note]

3 [Example 1:]
   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 (5.13.8)
   }
   — end example]
7.5.5 Lambda expressions

7.5.5.1 General

A lambda-expression provides a concise way to create a simple function object.

Example 1:
```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); });
}
```

Example 2:
```cpp
auto x1 = [](int i) { return i; }; // OK, return type is int
auto x2 = [](int i, int j) { return i + j; }; // error: deducing return type from braced-init-list
auto x3 = []() -> int { return j; }; // OK, return type is int
```

Example 3:
```cpp
int i = [](int i, auto a) { return i; }(3, 4); // OK, a generic lambda
int j = [](class T t, int i) { return i; }(3, 4); // OK, a generic lambda
```
7.5.5.2 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.

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]

The closure type is not an aggregate type (9.4.2). 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. the size and/or alignment of the closure type,
2. whether the closure type is trivially copyable (11.2), or
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.

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) whose parameters and return type are described by 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:]

```c++
auto glambda = [](auto a, auto&& b) { return a < b; }; // OK
bool b = glambda(3, 3.14);

auto vglambda = [](auto printer) {
    return [=](auto&& ... ts) {
        printer(std::forward<decltype(ts)>(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]

4. 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:

1. the closure type,
2. a class type derived from the closure type, or
3. a reference to a possibly cv-qualified such type.

[Example 2:]

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struct C {
  template <typename T>
  C(T);
};

void func(int i) {
  int x = [=](this auto&z) { return i; }(); // OK
  int y = [=](this C) { return i; }(); // error
  int z = [] (this C) { return 42; }(); // OK
}

—end example

The function call operator or operator template 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 satisfies the requirements for a constexpr function (9.2.6). It is an immediate function (9.2.6) if the corresponding lambda-expression’s parameter-declaration-clause is followed by constexpr.

Example 3:

```cpp
auto ID = [](auto a) { return a; }
static_assert(ID(3) == 3); // OK
struct NonLiteral {
  NonLiteral(int n) : n(n) { }
  int n;
};
static_assert(ID(NonLiteral{3}).n == 3); // error
—end example
```

Example 4:

```cpp
auto monoid = [](auto v) { return [=] { return v; }; };
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
—end example
```

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:
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] 8

The closure type for a non-generic lambda-expression with no lambda-capture 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. 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.

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For a generic lambda with no lambda-capture, 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
    // the same return type deduced
    /* ... */
  }
  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 (*)(char)) { } // #2
void g(int (*)(int)) { }  // #3
void g(char (*)(char)) { } // #4
void h(int (*)(int)) { }  // #4
auto glambda = [](auto a) { return a; };
f1(glambda); // OK
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 are required to match the return type and parameter types of the pointer to function.]

—end note

[Example 7:]

```cpp
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

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:]

```cpp
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
```

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:]

```cpp
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.

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 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).
7.5.5.3 Captures

1 The body of a lambda-expression may refer to local entities of enclosing block scopes by capturing those entities, as described below.

2 If a lambda-capture includes a capture-default that is &, no identifier in a simple-capture of that lambda-capture shall be preceded by &. If a lambda-capture includes a capture-default that is =, each simple-capture of that lambda-capture shall be of the form “& identifier . . . opt”, “this”, or “* this”.

[Note 1: The form [&,this] is redundant but accepted for compatibility with ISO C++ 2014. — end note]

Ignoring appearances in initializers of init-captures, an identifier or this shall not appear more than once in a lambda-capture.

[Example 1:

```c
struct S2 { void f(int i); }; void S2::f(int i) {
    [&, i]{ }; // OK
    [&, this, i]{ }; // OK, equivalent to [&, i]
    [&, &i]{ }; // error: i preceded by & when & is the default
    [=, *this]{ }; // OK
    [=, this]{ }; // OK, equivalent to [=]
    [i, i]{ }; // error: i repeated
    [this, *this]{ }; // error: this appears twice
}  
@end example]

3 A lambda-expression shall not have a capture-default or simple-capture in its 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 (6.4.6).

4 The identifier in a simple-capture shall denote a local entity (6.5.3, 6.1). The simple-captures this and *this denote the local entity *this. An entity that is designated by a simple-capture is said to be explicitly captured.

5 If an identifier in a simple-capture appears as the declarator-id of a parameter of the lambda-declarator’s parameter-declaration-clause, the program is ill-formed.

[Example 2:

```c
void f() {
    int x = 0;
    auto g = [x](int x) { return 0; }; // error: parameter and simple-capture have the same name
}

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An `init-capture` inhabits the function parameter scope of the `lambda-expression`'s `parameter-declaration-clause`. An `init-capture` without ellipsis behaves as if it declares and explicitly captures a variable of the form "`auto init-capture;`", except that:

(6.1) — 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

(6.2) — if the capture is by reference, the variable’s lifetime ends when the closure object’s lifetime ends.

[Note 2: This enables an `init-capture` like “`x = std::move(x)`”; the second “x” must bind to a declaration in the surrounding context. — end note]

Example 3:

```cpp
int x = 4;
auto y = [\&r = x, x = x+1]() \rightarrow int {
  r += 2;
  return x+2;
}(); // Updates ::x to 6, and initializes y to 7.

auto z = [a = 42](int a) { return 1; }; // error: parameter and local variable have the same name
auto counter = [i=0]() mutable \rightarrow decltype(i) {
  return i++;
};
```

—end example]

For the purposes of lambda capture, an expression potentially references local entities as follows:

(7.1) — 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]

(7.2) — A `this` expression potentially references `*this`.

(7.3) — 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, 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.3.

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:

```
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:

```
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 = [&,j] {
                    int x = m;
                    x += m; // OK, m implicitly captured by m4 and explicitly captured by m3
                    x += i; // error: i is odr-used but not odr-usable
                    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
        }
    }
```

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—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]{ return i; })()); // error
        void g2(int = ([i]{ return 0; })()); // error
        void g3(int = ([*i]{ return i; })()); // error
        void g4(int = ([*i]{ return 0; })()); // OK
        void g5(int = ([]{ return sizeof i; })()); // OK
        void g6(int = ([x=i]{ return x; })()); // OK
        void g7(int = ([x=i]{ return x; })()); // error
    }

—end example]

10 An entity is captured by copy if

(10.1) — 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 value 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;
        [x] { [x=1] } [ ]
        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.

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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();
};

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 destructions 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 = [&a, args...] { return g(args...); };
    lm();

    auto lm2 = [...xs=std::move(args)] { return g(xs...); };
    lm2();
}
```

—end example]
7.5.6 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:

- `+`, `-`, `*`, `/`, `%`, `^`, `&`, `|`, `<<`, `>>`  
- `+=`, `-=`, `*=``, `/=`, `%=``, `^=``, `&=``, `|=``, `<<=``, `>>=``
- `==`, `!=`, `<`, `>`, `<=`, `>=`, `&&`, `||`, `*, .`, `->`*

1 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).

2 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:

```cpp
// 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
}
```

7.5.7 Requires expressions

7.5.7.1 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<op> requirement-body

#### requirement-parameter-list

- (parameter-declaration-clause)

#### requirement-body

- { requirement-seq }

#### requirement-seq

- requirement

#### requirement

- simple-requirement
- type-requirement
- compound-requirement
- nested-requirement

2 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).

3 [Example 1: A common use of requires-expressions is to define requirements in concepts such as the one below:

```cpp
// Example 1:

template<typename T>
concept R = requires (T t) {
    typename T::type;
    {*t} -> 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 (9.3.4.6). A local parameter of a requires-expression shall not have a default argument. 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.

[Example 2:

```cpp
template<typename T> concept C = requires(T t, ...) {
    // error: terminates with an ellipsis
t;
};
```
—end example]

The substitution of template arguments into a requires-expression may result in the formation of invalid types or expressions in its requirements 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.

[Example 3:

```cpp
template<typename T> concept C =
requires {
    new int[-(int)sizeof(T)];  // ill-formed, no diagnostic required
};
```
—end example]

7.5.7.2 Simple requirements

simple-requirement: expression ;

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]

[Example 1:

```cpp
template<typename T> concept C =
requires (T a, T b) {
    a + b;  // C<T> is true if a + b is a valid expression
};
```
—end example]

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]

7.5.7.3 Type requirements

type-requirement: typename nested-name-specifier_opt type-name ;

A type-requirement asserts the validity of a type.

[Note 1: The enclosing requires-expression will evaluate to false if substitution of template arguments fails. — end note]
Example 1:

```cpp
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
};
```

A type-requirement that names a class template specialization does not require that type to be complete (6.8.1).

7.5.7.4 Compound requirements

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. Substitution of template arguments (if any) into the expression is performed.
2. If the noexcept specifier is present, $E$ shall not be a potentially-throwing expression (14.5).
3. If the return-type-requirement is present, then:
   1. Substitution of template arguments (if any) into the return-type-requirement is performed.
   2. The immediately-declared constraint (13.2) of the type-constraint for $\text{decltype}((E))$ shall be satisfied.

Example 1: Given concepts $C$ and $D$,

```cpp
requires {
    { E1 } -> C;
    { E2 } -> D<A_1, \cdots, A_n>;
};
```

is equivalent to

```cpp
requires {
    E1; requires C<\text{decltype}((E1))>;
    E2; requires D<\text{decltype}((E2)), A_1, \cdots, A_n>;
};
```

(including in the case where $n$ is zero). — end example

Example 2:

```cpp
template<typename T> concept C1 = requires(T x) {
    {x++};
};
```

The compound-requirement in $C1$ requires that $x++$ is a valid expression. It is equivalent to the simple-requirement $x++$:

```cpp
template<typename T> concept C2 = requires(T x) {
    {*x} -> std::same_as<typename T::inner>;
};
```

The compound-requirement in $C2$ requires that $*x$ is a valid expression, that $\text{typename T::inner}$ is a valid type, and that $\text{std::same_as<\text{decltype}(*x)}, \text{typename T::inner}>$ is satisfied.

```cpp
template<typename T> concept C3 =
    requires(T x) {
    {g(x)} noexcept;
};
```

The compound-requirement in $C3$ requires that $g(x)$ is a valid expression and that $g(x)$ is non-throwing. — end example
7.5.7.5 Nested requirements

A nested-requirement can be used to specify additional constraints in terms of local parameters. The constraint-expression shall be satisfied (13.5.3) by the substituted template arguments, if any. Substitution of template arguments into a nested-requirement does not result in substitution into the constraint-expression other than as specified in 13.5.2.

[Example 1:

```cpp
template<typename U> concept C = sizeof(U) == 1;

template<typename T> concept D = requires (T t) {
    requires sizeof(dectype (+t));
};

D<T> is satisfied if sizeof(dectype (+t)) == 1 (13.5.2.3). — end example]
```

2 A local parameter shall only appear as an unevaluated operand (7.2.3) within the constraint-expression.

[Example 2:

```cpp
template<typename T> concept C = requires (T a) {
    requires sizeof(a) == 4; // OK
    requires a == 0; // error: evaluation of a constraint variable
};

— end example]
```

7.6 Compound expressions

7.6.1 Postfix expressions

7.6.1.1 General

1 Postfix expressions group left-to-right.

```
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
```

2 [Note 1: The > token following the type-id in a dynamic_cast, static_cast, reinterpret_cast, or const_cast can be the product of replacing a >> token by two consecutive > tokens (13.3). — end note]

7.6.1.2 Subscripting

1 A subscript expression is a postfix expression followed by square brackets containing a possibly empty, comma-separated list of initializer-clauses which constitute the arguments to the subscript operator. The postfix-expression is sequenced before each expression in the expression-list.

2 With the built-in subscript operator, an expression-list shall be present, consisting of a single 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

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A function call is a postfix expression followed by parentheses containing a possibly empty, comma-separated list of arguments.

1. A function call is a postfix expression followed by parentheses containing a possibly empty, comma-separated list of *initializer-clauses* which constitute the arguments to the function.

2. For a call to a non-static member function, the postfix expression shall be an implicit (11.4.3) or explicit class member access (7.6.1.5) whose *id-expression* is a function member name, or a pointer-to-member id-expression (7.6.4) selecting a function member; the call is as a member of the class object referred to by the object expression. In the case of an implicit class member access, the implied object is the one pointed to by *this*.

3. If the selected function is non-virtual, or if the *id-expression* in the class member access expression is a *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 *virtual function call*.

4. If the postfix-expression names a destructor or pseudo-destructor (7.5.4.4), the type of the function call expression is *void*; otherwise, the type of the function call expression is the return type of the statically chosen function (i.e., ignoring the *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).

5. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

6. 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.

7. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

8. 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.

9. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

10. 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.

11. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

12. 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.

13. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

14. 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.

15. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

16. 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.

17. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

18. 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.

19. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

20. 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.

21. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

22. 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.

23. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

24. 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.

25. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

26. 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.

27. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

28. 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.

29. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

30. 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.

31. Calling a function through an expression whose function type *E* is different from the function type *F* of the called function’s definition results in undefined behavior unless the type “pointer to *F*” can be converted to the type “pointer to *E*” via a function pointer conversion (7.3.14).

32. 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.
When a function is called, the type of any parameter shall not be a class type that is either incomplete or abstract.

[Note 7: 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 the lifetime of a parameter ends when the function in which it is defined returns or at the end of the enclosing full-expression. The initialization and destruction of each parameter occurs within the context of the calling function.

[Example 2: The access of the constructor, conversion functions or destructor is checked at the point of call in the calling function. If a constructor or destructor for a function parameter throws an exception, the search for a handler starts in the calling function; in particular, if the function called has a function-try-block (14.1) with a handler that can handle the exception, this handler is not considered. — end example]

8 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 8: All side effects of argument evaluations are sequenced before the function is entered (see 6.9.1). — end note]

[Example 3:

```cpp
do 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 9: 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]

9 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 10: 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 is required 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]

11 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 11: This implies that, except where the ellipsis (...) or a function parameter pack is used, a parameter is available for each argument. — end note]

12 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 12: 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 or of a class type (Clause 11) having an eligible non-trivial copy constructor, an eligible non-trivial move constructor, or a non-trivial destructor (11.4.4), 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 a 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 (9.2.9.6.2).

[Example 1:

```c
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 `{}` (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. The postfix expression before the dot or arrow is evaluated; the result of that evaluation, together with the `id-expression`, determines the result of the entire 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) the first expression shall be a glvalue. For the second option (arrow) the first expression shall be a prvalue having pointer type. The expression `E1->E2` is converted to the equivalent form `(*E1).E2`; the remainder of 7.6.1.5 will address only the first option (dot).

Abbreviating postfix-expression `id-expression` as `E1.E2`, `E1` is called the object expression. If the object expression is of scalar type, `E2` shall name the pseudo-destructor of that same type (ignoring cv-qualifications) and `E1.E2` is an lvalue of type “function of () returning void”.

[Note 2: This value can only be used for a notional function call (7.5.4.4). — end note]

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.

[Note 3: The program is ill-formed if the result differs from that when the class is complete (6.5.2). — end note]

---

53) If the class member access expression is evaluated, the subexpression evaluation happens even if the result is unnecessary to determine the value of the entire postfix expression, for example if the `id-expression` denotes a static member.

54) Note that `(*E1)` is an lvalue.
5 If E2 is a bit-field, E1.E2 is a bit-field. The type and value category of E1.E2 are determined as follows. In the remainder of 7.6.1.5, \( cv \) represents either const or the absence of const and \( vq \) represents either volatile or the absence of volatile. \( cv \) represents an arbitrary set of cv-qualifiers, as defined in 6.8.4.

6 If E2 is declared to have type “reference to T”, then E1.E2 is an lvalue; the type of E1.E2 is T. Otherwise, one of the following rules applies.

(6.1) — If E2 is a static data member and the type of E2 is T, then E1.E2 is an lvalue; the expression designates the named member of the class. The type of E1.E2 is T.

(6.2) — If E2 is a non-static data member and the type of E1 is “cq1 vq1 X”, and the type of E2 is “cq2 vq2 T”, the expression designates the corresponding member subobject of the object designated by the first expression. If E1 is an lvalue, then E1.E2 is an lvalue; otherwise E1.E2 is an xvalue. Let the notation vq12 stand for the “union” of vq1 and vq2; that is, if vq1 or vq2 is volatile, then vq12 is volatile. Similarly, let the notation cq12 stand for the “union” of cq1 and cq2; that is, if cq1 or cq2 is const, then cq12 is const. If E2 is declared to be a mutable member, then the type of E1.E2 is “vq12 T”. If E2 is not declared to be a mutable member, then the type of E1.E2 is “cq12 vq12 T”.

(6.3) — If E2 is an overload set, function overload resolution (12.2) is used to select the function to which E2 refers. The type of E1.E2 is the type of E2 and E1.E2 refers to the function referred to by E2.

(6.3.1) — If E2 refers to a static member function, E1.E2 is an lvalue.

(6.3.2) — Otherwise (when E2 refers to a non-static member function), E1.E2 is a prvalue. The expression can be used only as the left-hand operand of a member function call (11.4.2).

[Note 5: Any redundant set of parentheses surrounding the expression is ignored (7.5.3). — end note]

(6.4) — If E2 is a nested type, the expression E1.E2 is ill-formed.

(6.5) — If E2 is a member enumerator and the type of E2 is T, the expression E1.E2 is a prvalue. The type of E1.E2 is T.

7 If E2 is a non-static data member or a non-static member function, the program is ill-formed if the class of which E2 is directly a member is an ambiguous base (6.5.2) of the naming class (11.8.3) of E2.

[Note 6: The program is also ill-formed if the naming class is an ambiguous base of the class type of the object expression; see 11.8.3. — end note]

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.5. The value of the operand object is modified (3.1) by adding 1 to it. 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. If the operand is a bit-field that cannot represent the incremented value, the resulting value of the bit-field is implementation-defined. See also 7.6.6 and 7.6.19.

2 The operand of postfix -- is decremented analogously to the postfix ++ operator.

[Note 3: For postfix 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...
value 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. 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;
}
```]

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 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.

8 Let C be the class type to which T points or refers. The runtime check logically executes as follows:

   (8.1) — 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.

   (8.2) — 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.

   (8.3) — Otherwise, the runtime check fails.

9 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 std::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 = (E*)ap;  // error: cast from virtual base
}

55) 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.
E* ep1 = dynamic_cast<E*>(ap);  // succeeds

—end example]

[Note 1: Subclause 11.9.5 describes the behavior of a dynamic_cast applied to an object under construction or destruction. —end note]

7.6.1.8 Type identification

1 The result of a typeid expression is an lvalue of static type const std::type_info (17.7.3) and dynamic type const std::type_info or const name where name is an implementation-defined class publicly derived from std::type_info which preserves the behavior described in 17.7.3. The lifetime of the object referred to by the lvalue extends to the end of the program. Whether or not the destructor is called for the std::type_info object at the end of the program is unspecified.

2 If the type of the expression or 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.

3 When typeid is applied to a glvalue whose type is a polymorphic class type (11.7.3), the result refers to a 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. If the glvalue is obtained by applying the unary * operator to a pointer and the pointer is a null pointer value (6.8.3), the typeid expression throws an exception (14.2) of a type that would match a handler of type std::bad_typeid exception (17.7.5).

4 When typeid is applied to an expression other than a glvalue of a polymorphic class type, the result refers to a std::type_info object representing the static type of the expression. Lvalue-to-rvalue (7.3.2), 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).

5 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 1: The type-id cannot denote a function type with a cv-qualifier-seq or a ref-qualifier (9.3.4.6). —end note]

6 If the type of 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

—end example]
```

7 If the header <typeinfo> (17.7.2) is not imported or included prior to a use of typeid, the program is ill-formed.

8 [Note 2: 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

1 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).

2 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 class derived (11.7) from B, if cv2 is the same cv-qualification as, or greater cv-qualification than, cv1. If

56) The recommended name for such a class is extended_type_info.

57) If p is an expression of pointer type, then *p, (**p), (*p), (*(*p)), *(*(p)), and so on all meet this requirement.
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:
    ```
    struct B { }
    struct D : public B { }
    D d;
    B &br = d;
    static_cast<D&>(br); // produces lvalue denoting the original d object
    ```
  — end example]

3 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.

4 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 1: The conversion is ill-formed when attempting to convert an expression of class type to an inaccessible or ambiguous base class. — end note]

[Note 2: If T is “array of unknown bound of U”, this direct-initialization defines the type of the expression as U[1]. — end note]

5 Otherwise, the static_cast shall perform one of the conversions listed below. No other conversion shall be performed explicitly using a static_cast.

6 Any expression can be explicitly converted to type cv void, in which case the operand is a discarded-value expression (7.2).

[Note 3: Such a static_cast has no result as it is a prvalue of type void; see 7.2.1. — end note]

[Note 4: 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]

7 The inverse of any 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:
    ```
    struct B { }
    struct D : private B { }
    void f() {
      static_cast<D*>(B*)0; // error: B is a private base of D
      static_cast<int B::*>(int D::*)0; // error: B is a private base of D
    }
    ```
  — end example]

8 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:

9 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 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 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 (6.8.3) 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.

[Note 5: Function types (including those used in pointer-to-member-function types) are never cv-qualified (9.3.4.6). —end note]

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 or derived class of the class containing the original member, the resulting pointer points to member points to the original member. Otherwise, the behavior is undefined.

[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]

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 is unspecified. Otherwise, if the original pointer value points to an object a, and there is an object b of type T (ignoring cv-qualification) that is pointer-interconvertible (6.8.3) with a, the result is a pointer to b. Otherwise, the pointer value is unchanged by the conversion.

[Example 3:

```c
T* p1 = new T;
const T* p2 = static_cast<const T*>(static_cast<void*>(p1));
bool b = p1 == p2; // b will have the value true.
```

—end example]

7.6.1.10 Reinterpret cast [expr.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.

The reinterpret_cast operator shall not cast away constness (7.6.1.11). An expression of integral, enumeration, pointer, or pointer-to-member type can be explicitly converted to its own type; such a cast yields the value of its operand.

[Note 1: The mapping performed by reinterpret_cast might, or might not, produce a representation different from the original value. —end note]

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 type `std::nullptr_t` can be converted to an integral type; the conversion has the same meaning and validity as a conversion of `(void*)0` to the integral type.

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; 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.

An object pointer can be explicitly converted to an object pointer of a different type. When a prvalue `v` of object pointer type is converted to the object pointer type “pointer to cv `T`”, the result is `static_cast<cv T_DLL>(static_cast<cv void> x(v))`.

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-qualifications, shall yield the original pointer value.

The null pointer value (6.8.3) is converted to the null pointer value of the destination type.

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. 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.

A glvalue of type `T1`, designating an object `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 `reinterpret_cast`. The result is that of `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.

The result of the expression `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) conversions are unspecified.

58) The types can have different cv-qualifiers, subject to the overall restriction that a `reinterpret_cast` cannot cast away constness.

59) `T1` and `T2` can have different cv-qualifiers, subject to the overall restriction that a `reinterpret_cast` cannot cast away constness.

60) This is sometimes referred to as a type pun when the result refers to the same object as the source glvalue.
standard conversions are performed on the expression \( v \). Conversions that can be performed explicitly using `const_cast` are listed below. No other conversion shall be performed explicitly using `const_cast`.

2 [Note 1: Subject to the restrictions in this subclause, an expression can be cast to its own type using a `const_cast` operator. — end note]

3 For two similar types \( T_1 \) and \( T_2 \) (7.3.6), a prvalue of type \( T_1 \) may be explicitly converted to the type \( T_2 \) using a `const_cast` if, considering the qualification-decompositions of both types, each \( P_{1i} \) is the same as \( P_{2i} \) for all \( i \). The result of a `const_cast` refers to the original entity.

4 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:

- (4.1) an lvalue of type \( T_1 \) can be explicitly converted to an lvalue of type \( T_2 \) using the cast `const_cast<T2&>`;
- (4.2) a glvalue of type \( T_1 \) can be explicitly converted to an xvalue of type \( T_2 \) using the cast `const_cast<T2&&>`; and
- (4.3) 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.

5 A null pointer value (6.8.3) 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.

6 [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\(^{61} \) can produce undefined behavior (9.2.9.2). — end note]

7 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

\[
eqv_0 P_0^2 ev_1 P_1^2 \cdots ev_n P_n^2 u_2v_2,\]

and there is no qualification conversion that converts \( T_1 \) to

\[
eqv_0 P_0^2 ev_1 P_1^2 \cdots ev_{n-1} P_{n-1}^2 ev_n^2 u_1v_1.\]

8 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.

9 [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*: the expression to which it is applied shall be a pointer to an object type, or a pointer to a function type and the result is an lvalue referring to the object or function to which the expression points. If the type of the expression is “pointer to T”, the type of the result is “T”.

[Note 1: Indirection through a pointer to an incomplete type (other than cv void) is valid. The lvalue thus obtained can be used in limited ways (to initialize a reference, for example); this lvalue must not be converted to a prvalue, see 7.3.2. —end note]

The result of each of the following unary operators is a prvalue.

1. The operand of the unary & operator shall be an lvalue of some type T. The result is a prvalue.

(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 (6.8.3). 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
```

—end example]

[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

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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 have 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 have 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.

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 - shall have integral or unscoped enumeration type; the result is the ones’ complement of its operand. Integral promotions are performed. The type of the result is the type of the promoted operand. There is an ambiguity in the grammar when - is followed by a type-name or decltype-specifier. The ambiguity is resolved by treating - as the unary complement operator rather than as the start of an unqualified-id naming a destructor.

[Note 6: Because the grammar does not permit an operator to follow the .., ->, or :: tokens, a ~ followed by a type-name or decltype-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 ++ is modified (3.1) by adding 1. 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 completely-defined object type. An operand with volatile-qualified type is deprecated; see D.5. The result is the updated operand; it is an lvalue, and it is a bit-field if the operand is a bit-field. The expression ++x is equivalent to x=x+1.

[Note 1: See the discussions of addition (7.6.6) and assignment operators (7.6.19) for information on conversions. — end note]

2 The operand of prefix -- is modified (3.1) by subtracting 1. The requirements on the operand of prefix -- and the properties of its result are otherwise the same as those of prefix ++.

[Note 2: For postfix increment and decrement, see 7.6.16. — 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.

`await-expression:
    co_await cast-expression`

2 An await-expression shall appear only in a potentially-evaluated expression within the compound-statement of a function-body 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:

1. p is an lvalue naming the promise object (9.5.4) of the enclosing coroutine and p is the type of that object.
2. Unless the await-expression was implicitly produced by a yield-expression (7.6.17), an initial suspend point, or a final suspend point (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.await_transform(cast-expression); otherwise, a is the cast-expression.
3. 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<*>` referring to the enclosing coroutine.

— `await-ready` is the expression $e.\text{await\_ready}()$, contextually converted to `bool`.

— `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`.

— `await-resume` is the expression $e.\text{await\_resume}()$.

The `await-expression` has the same type and value category as the `await-resume` expression.

The `await-expression` evaluates the (possibly-converted) $o$ expression and the `await-ready` expression, then:

1. If the result of `await-ready` is `false`, the coroutine is considered suspended. Then:
   1.1. If the type of `await-suspend` is `std::coroutine_handle<Z>`, `await-suspend.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]
   
   1.2. Otherwise, if the type of `await-suspend` is `bool`, `await-suspend` is evaluated, and the coroutine is resumed if the result is `false`.
   
   1.3. 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).

2. 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 go to sleep...
";  
    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]

2 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. 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.

3 The lvalue-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.

4 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:

```cpp
template<class... Types>
struct count {
    static const std::size_t value = sizeof...(Types);
};
--- end example]
```

5 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 `<cstddef>` (17.2.1, 17.2.4). — end note]

7.6.2.6 Alignof [expr.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 `<cassert>` (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 [expr.unary.noexcept]

1 The `noexcept` operator determines whether the evaluation of its operand, which is an unevaluated operand (7.2.3), can throw an exception (14.2).

```cpp
noexcept-expression:
    noexcept ( expression )
```

2 The result of the `noexcept` operator is a prvalue of type `bool`.

[Note 1: A `noexcept-expression` is an integral constant expression (7.7). — end note]

3 The result of the `noexcept` operator is `true` unless the `expression` is potentially-throwing (14.5).

---

62) `sizeof(bool)` is not required to be 1.

63) 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.

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7.6.2.8 New [expr.new]

The `new-expression` attempts to create an object of the `type-id` (9.3.2) or `new-type-id` 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]

\[
\text{new-expression:} \\
\quad ::= \text{opt new new-placement}_{\text{opt new-type-id new-initializer}_{\text{opt new-placement}}}
\]

\[
\text{new-placement:} \\
\quad ::= \text{opt new new-placement}_{\text{opt new-placement}} (\text{type-id}) \text{ new-initializer}_{\text{opt new-placement}}
\]

\[
\text{new-type-id:} \\
\quad ::= \text{type-specifier-seq new-declarator}_{\text{opt new-declarator}}
\]

\[
\text{new-declarator:} \\
\quad ::= \text{ptr-operator new-declarator}_{\text{opt new-declarator}}
\]

\[
\text{noptr-new-declarator:} \\
\quad ::= [\text{expression}_{\text{opt new-character-specifier-seq}_{\text{opt new-character-specifier-seq}}}
\]

\[
\text{new-initializer:} \\
\quad ::= \text{expression-list}_{\text{opt braced-init-list}}
\]

If a placeholder type (9.2.9.6) 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 (9.2.9.6):

\[
T x \text{ init ;}
\]

[Example 1:

```c
new auto(1); // allocated type is int
auto x = new auto('a'); // allocated type is char, x is of type char*
```

`template<class T> struct A { A(T, T); };`

```c
auto y = new A{1, 2}; // allocated type is A<int>
```

— end example]

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]

[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 (6.8.3):

```c
new (int (*[10])());
```

allocates an array of 10 pointers to functions (taking no argument and returning `int`). — end example]

— end note]

The `attribute-specifier-seq` in a `noptr-new-declarator` appertains to the associated array type.
Every constant-expression in a `nopt-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 `nopt-new-declarator`), but `new float[5][n]` is ill-formed (because `n` is not a constant expression). —end example]  

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).  

If the expression in a `nopt-new-declarator` is present, it is implicitly converted to `std::size_t`. The expression is erroneous if:

1. the expression is of non-class type and its value before converting to `std::size_t` is less than zero;  
2. the expression is of class type and its value before application of the second standard conversion (12.2.4.2.3) is less than zero;  
3. its value is such that the size of the allocated object would exceed the implementation-defined limit (Annex B); or  
4. the new-initializer is a braced-init-list and the number of array elements for which initializers are provided (including the terminating `\0` in a string-literal (5.13.5)) exceeds the number of elements to initialize.

If the expression is erroneous after converting to `std::size_t`:

1. if the expression is a core constant expression, the program is ill-formed;  
2. otherwise, an allocation function is not called; instead  
   1. if the allocation function that would have been called has a non-throwing exception specification (14.5), the value of the new-expression is the null pointer value of the required result type;  
   2. otherwise, the new-expression terminates by throwing an exception of a type that would match a handler (14.4) of type `std::bad_array_new_length` (17.6.4.2).

When the value of the expression is zero, the allocation function is called to allocate an array with no elements.  

[Note 5: 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 T” (that is, the `nopt-new-declarator` syntax is used or the new-type-id or type-id denotes an array type), the new-expression yields a prvalue of type “pointer to T” that points to the initial element (if any) of the array. Otherwise, let `T` be the allocated type; the new-expression is a prvalue of type “pointer to T” that points to the object created.  

[Note 6: Both `new int` and `new int[10]` have type `int*` and the type of `new int[i][10]` is `int (*)[10]`. —end note]  

A new-expression may obtain storage for the object by calling an allocation function (6.7.5.5.2). If the 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 `operator new` and the deallocation function’s name is `operator delete`. If the allocated type is an array type, the allocation function’s name is `operator new[]` and the deallocation function’s name is `operator delete[]`.  

[Note 7: An implementation is required 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 new-expression can include functions that do not perform allocation or deallocation; for example, see 17.6.3.4. —end note]  

If the new-expression does not begin with a unary `::` operator and the allocated type is a class type `T` or array thereof, a search is performed for the allocation function’s name in the scope of `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 new-expression.  

During an evaluation of a constant expression, a call to an allocation function is always omitted.

---

64) If the conversion function returns a signed integer type, the second standard conversion converts to the unsigned type `std::size_t` and thus thwarts any attempt to detect a negative value afterwards.
The implementation may extend the allocation of a new-expression \( e_1 \) to provide storage for a new-expression \( e_2 \) if the following would be true were the allocation not extended:

1. The evaluation of \( e_1 \) is sequenced before the evaluation of \( e_2 \), and
2. \( e_2 \) is evaluated whenever \( e_1 \) obtains storage, and
3. both \( e_1 \) and \( e_2 \) invoke the same replaceable global allocation function, and
4. if the allocation function invoked by \( e_1 \) and \( e_2 \) is throwing, any exceptions thrown in the evaluation of either \( e_1 \) or \( e_2 \) would be first caught in the same handler, and
5. the pointer values produced by \( e_1 \) and \( e_2 \) are operands to evaluated delete-expressions, and
6. the evaluation of \( e_2 \) is sequenced before the evaluation of the delete-expression whose operand is the pointer value produced by \( e_1 \).

\[\text{Example 5:}\]
```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;
    }
}
```

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 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:

— new T results in one of the following calls:
  
  operator new(sizeof(T))
  
  operator new(sizeof(T), std::align_val_t(alignof(T)))

— 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)

— 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)))

— 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 (6.7.5.5.2, 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 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:

— 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]

— 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 object or an array of objects of class type, access and ambiguity control are done for the allocation function, the deallocation function (6.7.5.5.3), and the constructor (11.4.5) selected for the initialization (if any). 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.

65) This can include evaluating a new-initializer and/or calling a constructor.
[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]

27 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).

[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]

28 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]

1 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. The operand shall be of pointer to object type or of class type. If of class type, the operand is contextually implicitly converted (7.3) to a pointer to object type. 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. 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]

66 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.

67 This implies that an object cannot be deleted using a pointer of type void* because void is not an object type.

68 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.
3 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.

4 The cast-expression in a delete-expression shall be evaluated exactly once.

5 If the object being deleted has incomplete class type at the point of deletion and the complete class has a non-trivial destructor or a deallocation function, the behavior is undefined.

6 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, the delete-expression will invoke the destructor (if any) for the object or the elements of the array being deleted. In the case of an array, the elements will be destroyed in order of decreasing address (that is, in reverse order of the completion of their constructor; see 11.9.3).

7 If the value of the operand of the delete-expression is not a null pointer value, then:

   7.1 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.

   7.2 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.

7.3 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.

8 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]

9 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:

   9.1 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).

   9.2 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]

10 If more than one deallocation function is found, the function to be called is selected as follows:

   10.1 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.

   10.2 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.

   10.3 If exactly one function remains, that function is selected and the selection process terminates.

   10.4 If the deallocation functions belong to a class scope, the one without a parameter of type std::size_t is selected.
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 multi-dimensional) array thereof, the function with a parameter of type `std::size_t` is selected.

Otherwise, it is unspecified whether a deallocation function with a parameter of type `std::size_t` is selected.

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.

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 of 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.

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.

Access and ambiguity control are done for both the deallocation function and the destructor (11.4.7, 11.4.11).

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.

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

1. a `const_cast` (7.6.1.11),
2. a `static_cast` (7.6.1.9),
3. a `static_cast` followed by a `const_cast`,
4. a `reinterpret_cast` (7.6.1.10), or
5. a `reinterpret_cast` followed by a `const_cast`,

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:

- 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;
- 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;
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.

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 conversion can be
interpreted in more than one way as a static_cast followed by a const_cast, the conversion is ill-formed.

Example 1:

```cpp
struct A { }
struct I1 : A { }
struct I2 : A { }
struct D : I1, I2 { }
A* foo( D* p ) {
    return (A*)( p );
} // ill-formed static_cast interpretation
```

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 would be permitted
to interpret a cast between pointers to the classes as if the class types were complete at the point of the cast.

7.6.4 Pointer-to-member operators

The pointer-to-member operators →* and .* group left-to-right.

```cpp
pm-expression:
    cast-expression
pm-expression .* cast-expression
pm-expression ->* cast-expression
```

The binary operator .* binds its second operand, which shall be 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 →* binds its second operand, which shall be 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→*E2 is converted into the equivalent form (*(E1)).*E2.

Abbreviating pm-expression .*cast-expression as E1.*E2, E1 is called the object expression. If the dynamic type
of E1 does not contain the member to which E2 refers, the behavior is undefined. Otherwise, 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.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,

```cpp
struct S {
    S() : i(0) { }
    mutable int i;
};
void f()
{
    const S cs;
    int S::* pm = &S::i; // pm refers to mutable member S::i
    cs.*pm = 88; // error: cs is a const object
}
```

—end note]
If the result of .\* or \*\* is a function, then that result can be used only as the operand for the function call operator ()..

[Example 1]:

\[(\text{ptr}\_\text{to}\_\text{obj}\rightarrow\text{ptr}\_\text{to}\_\text{mfct})(10);\]
calls the member function denoted by \text{ptr}\_\text{to}\_\text{mfct} for the object pointed to by \text{ptr}\_\text{to}\_\text{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 \text{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 member pointer value (7.3.13), the behavior is undefined.

7.6.5 Multiplicative operators [expr.mul]

1 The multiplicative operators * , /, and \% group left-to-right.

\[\text{multiplicative-expression}:\]

\[\begin{align*}
\text{pm-expression} & \\
\text{multiplicative-expression} \times \text{pm-expression} & \\
\text{multiplicative-expression} / \text{pm-expression} & \\
\text{multiplicative-expression} \% \text{pm-expression} &
\end{align*}\]

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;\footnote{This is often called truncation towards zero.} if the quotient \(a/b\) is representable in the type of the result, \((a/b)\times b + a\% b\) is equal to \(a\); otherwise, the behavior of both \(a/b\) and \(a\% b\) is undefined.

7.6.6 Additive operators [expr.add]

1 The additive operators + and - group left-to-right. The usual arithmetic conversions (7.4) are performed for operands of arithmetic or enumeration type.

\[\text{additive-expression}:\]

\[\begin{align*}
\text{multiplicative-expression} & \\
\text{additive-expression} + \text{multiplicative-expression} & \\
\text{additive-expression} - \text{multiplicative-expression} &
\end{align*}\]

For addition, either both operands shall have arithmetic or unscoped enumeration type, or one operand shall be a pointer to a completely-defined object type and the other shall have integral or unscoped enumeration type.

2 For subtraction, one of the following shall hold:

1. both operands have arithmetic or unscoped enumeration type; or
2. both operands are pointers to cv-qualified or cv-unqualified versions of the same completely-defined object type; or
3. the left operand is a pointer to a completely-defined object type and the right operand has integral or unscoped enumeration 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.
Otherwise, if $P$ points to an array element $i$ of an array object $x$ with $n$ elements (9.3.4.5), 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.

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 $i - j$.

Otherwise, the behavior is undefined.

[Note 1: If the value $i - j$ is not in the range of representable values of type `std::ptrdiff_t`, the behavior is undefined. — end note]

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.

[Note 2: In particular, a pointer to a base class cannot be used for pointer arithmetic when the array contains objects of a derived class type. — end note]

### 7.6.7 Shift operators

The shift operators `<<` and `>>` group left-to-right.

```
shift-expression:
  additive-expression
  shift-expression << additive-expression
  shift-expression >> additive-expression
```

The operands shall be 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.

The value of $E1 << E2$ is the unique value congruent to $E1 \times 2^{E2}$ modulo $2^N$, where $N$ is the width of the type of the result.

[Note 1: $E1$ is left-shifted $E2$ bit positions; vacated bits are zero-filled. — end note]

The value of $E1 >> E2$ is $E1/2^{E2}$, rounded down.

[Note 2: $E1$ is right-shifted $E2$ bit positions. Right-shift on signed integral types is an arithmetic right shift, which performs sign-extension. — end note]

The expression $E1$ is sequenced before the expression $E2$.

### 7.6.8 Three-way comparison operator

The three-way comparison operator groups left-to-right.

```
compare-expression:
  shift-expression
  compare-expression <=> shift-expression
```

The expression $p <=> q$ is a prvalue indicating whether $p$ is less than, equal to, greater than, or incomparable with $q$.

If one of the operands is of type `bool` and the other is not, the program is ill-formed.

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:

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.

70) As specified in 6.8.3, 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.
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.

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.

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.

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:

1. If two pointer operands `p` and `q` compare equal (7.6.10), `p <=> q` yields `std::strong_ordering::equal`
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);
3. otherwise, the result is unspecified.

7. Otherwise, the program is ill-formed.

The three comparison category types (17.11.2) (the types `std::strong_ordering`, `std::weak_ordering`, and `std::partial_ordering`) are not predefined; if the header `<compare>` (17.11.1) is not imported or included prior to a use of such a class type – even an implicit use in which the type is not named (e.g., via the auto specifier (9.2.9.6) 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

The relational operators group left-to-right.

Example 1: `a<b<c` means `(a<b)<c` and not `(a<b)&&(b<c)`. — end example

```plaintext
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.4).

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) 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.

4. The result of comparing unequal pointers to objects is defined in terms of a partial order consistent with the following rules:

(1) 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), \( p \leq q \) and \( p \geq q \) both yield true and \( p < q \) and \( p > q \) both yield false. Otherwise, if a pointer to object \( p \) compares greater than a pointer \( q \), \( p \geq q \), \( p > q \), \( q \leq p \), and \( q < p \) all yield true and \( p \leq q \), \( p < q \), \( q \geq p \), and \( q > p \) all yield false. Otherwise, the result of each of the operators is unspecified.

If both operands (after conversions) are of arithmetic or enumeration type, each of the operators shall yield true if the specified relationship is true and false if it is false.

### 7.6.10 Equality operators

\[
equality-expression:
  \text{relational-expression} \\
equality-expression == \text{relational-expression} \\
equality-expression != \text{relational-expression}
\]

1. The == (equal to) and the != (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.4).

2. The converted operands shall have arithmetic, enumeration, pointer, or pointer-to-member type, or type `std::nullptr_t`. The operators == and != both yield true or false, i.e., a result of type `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,\(^{72}\) 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 (6.8.3), 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 \( C_1 \) and the other refers to a member of a different class \( C_2 \), where neither is a base class of the other, the result is unspecified.

\[
\begin{example}
\text{Example 1:}
\begin{verbatim}
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{verbatim}
\end{example}
\]

- If both refer to (possibly different) members of the same union (11.5), they compare equal.

---

\(^{72}\) As specified in 6.8.3, an object that is not an array element is considered to belong to a single-element array for this purpose.
(4.6) — 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:

```cpp
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
```

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

```
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

```
exclusive-or-expression
exclusive-or-expression ^ exclusive-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 either (but not both) of \( x_i \) and \( y_i \) are 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

```
inclusive-or-expression
inclusive-or-expression | 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 \( y_i \) are 1, and 0 otherwise.
7.6.14 Logical AND operator

logical-and-expression:
  inclusive-or-expression
  logical-and-expression && inclusive-or-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

logical-or-expression:
  logical-and-expression
  logical-or-expression || 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 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

conditional-expression:
  logical-or-expression
  logical-or-expression ? expression : assignment-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 E1 of type T1 to a target type related to the type T2 of the operand expression E2 as follows:

   (4.1) — If E2 is an lvalue, the target type is “lvalue reference to T2”, but an implicit conversion sequence can only be formed if the reference would bind directly (9.4.4) to a glvalue.

   (4.2) — If E2 is an xvalue, the target type is “xvalue reference to T2”, but an implicit conversion sequence can only be formed if the reference would bind directly.

   (4.3) — If E2 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:
(4.3.1) if $T_1$ and $T_2$ are the same class type (ignoring cv-qualification) and $T_2$ is at least as cv-qualified as $T_1$, the target type is $T_2$.

(4.3.2) otherwise, if $T_2$ is a base class of $T_1$, the target type is $\text{cv1 } T_2$, where $\text{cv1}$ denotes the cv-qualifiers of $T_1$.

(4.3.3) 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]

5 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.

6 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.

7 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:

(7.1) 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.

(7.2) 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.

(7.3) 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.

(7.4) 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.

(7.5) 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]

yield-expression:
  co_yield assignment-expression
  co_yield braced-init-list

1 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:]

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{};
    }
  }
  co_yield T yield_value(T v) {
    return std::suspend_always{};
  }
```cpp
t};
struct iterator { /* ... */ };
iterator begin();
iterator end();
};

my_generator<pair<int, int>> g1() {
    for (int i = i; i < 10; ++i) co_yield {i, i};
}
my_generator<pair<int, int>> g2() {
    for (int i = i; 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

int main() {
    auto r1 = g1();
    auto r2 = g2();
    assert(std::equal(r1.begin(), r1.end(), r2.begin(), r2.end()));
}
—end example

7.6.18 Throwing an exception

throw-expression:
    throw assignment-expression_opt

1 A throw-expression is of type void.
2 Evaluating a throw-expression with an operand throws an exception (14.2); the type of the exception object is determined by removing any top-level cv-qualifiers from the static type of the operand and adjusting the type from “array of T” or function type T to “pointer to T”.
3 A throw-expression with no operand rethrows the currently handled exception (14.4). 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
}
—end example

4 If no exception is presently being handled, evaluating a throw-expression with no operand calls std::terminate() (14.6.2).

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]
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 assignment-expression:
  conditional-expression
  yield-expression
  throw-expression
  logical-or-expression assignment-operator initializer-clause

 assignment-operator: one of
  = *= /= %= += -= >>= <<= &= ^= |=

 2 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.

 3 If the right operand is an expression, it is implicitly converted (7.3) to the cv-unqualified type of the left operand.

 4 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.

 5 A simple assignment whose left operand is of a volatile-qualified type is deprecated (D.5) unless the (possibly parenthesized) assignment is a discarded-value expression or an unevaluated operand (7.2.3).

 6 The behavior of an expression of the form E1 op = E2 is equivalent to E1 = E1 op E2 except that E1 is evaluated only once. Such expressions are deprecated if E1 has volatile-qualified type; see D.5. For += and -=, E1 shall either have arithmetic type or be a pointer to a possibly cv-qualified completely-defined object type. In all other cases, E1 shall have arithmetic type.

 7 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 2: 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 may appear on the right-hand side of

 (8.1) — an assignment to a scalar, in which case the initializer list shall have at most a single element. The meaning of x = {v}, where T is the scalar type of the expression x, is that of x = T{v}. The meaning of x = {} is x = T{}.

 (8.2) — an assignment to an object of class type, in which case the initializer list is passed as the argument to the assignment operator function selected by overload resolution (12.4.3.2, 12.2).

 [Example 1:
  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  [expr.comma]

 1 The comma operator groups left-to-right.

 expression:
  assignment-expression
  expression , assignment-expression

 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.

 [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

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

A variable or temporary object \( o \) is constant-initialized if

1. either it has an initializer or its default-initialization results in some initialization being performed, and
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, \texttt{std::is_constant_evaluated()} (21.3.11) returns \texttt{true}. — end note]

A variable is potentially-constant if it is constexpr or it has reference or const-qualified integral or enumeration type.

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

1. \( V \) is constexpr,
2. \( V \) is not initialized to a TU-local value, or
3. \( P \) is in the same translation unit as \( D \).

An object or reference is usable in constant expressions if it is

1. a variable that is usable in constant expressions, or
2. a template parameter object (13.2), or
3. a string literal object (5.13.5), or
4. 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
5. a non-mutable subobject or reference member of any of the above.

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:

1. \texttt{this} (7.5.2), except in a constexpr function (9.2.6) that is being evaluated as part of \( E \);
2. a control flow that passes through a declaration of a variable with static (6.7.5.2) or thread (6.7.5.3) storage duration;
3. an invocation of a non-constexpr function;
4. an invocation of an undefined constexpr function;
5. an invocation of an instantiated constexpr function that fails to satisfy the requirements for a constexpr function;
6. an invocation of a virtual function (11.7.3) for an object unless
   1. the object is usable in constant expressions or
   2. its lifetime began within the evaluation of \( E \);
7. an expression that would exceed the implementation-defined limits (see Annex B);

\( \)§ 7.7 149

73) Overload resolution (12.2) is applied as usual.
an operation that would have undefined behavior as specified in Clause 4 through Clause 15;\(^74\)

—  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 \(E\);

—  an \textit{id-expression} that refers to a variable or data member of reference type unless the reference has a preceding initialization and either

—  it is usable in constant expressions or

—  its lifetime began within the evaluation of \(E\);

—  in a \textit{lambda-expression}, a reference to \textit{this} or to a variable with automatic storage duration defined outside that \textit{lambda-expression}, where the reference would be an odr-use (6.3, 7.5.5):

\[\text{Example 1:}\]

\begin{verbatim}
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{verbatim}

\[\text{— end example}\]

\[\text{Note 3: If the odr-use occurs in an invocation of a function call operator of a closure type, it no longer refers to \textit{this} or to an enclosing automatic variable due to the transformation (7.5.5.3) of the \textit{id-expression} into an access of the corresponding data member.}\]

\[\text{Example 2:}\]

\begin{verbatim}
auto monad = [](auto v) { return [=] { return v; };};
auto bind = [](auto m) { return [=](auto fvm) { return fvm(m()); };};
\end{verbatim}

\[// OK to capture objects with automatic storage duration created during constant expression evaluation.\]

\begin{verbatim}
static_assert(bind(monad(2))(monad)() == monad(2)());
\end{verbatim}

\[\text{— end example}\]

\[\text{— end note}\]

—  a conversion from type \(\textit{cv void*}\) to a pointer-to-object type;

—  a \texttt{reinterpret\_cast} (7.6.1.10);

—  a modification of an object (7.6.19, 7.6.1.6, 7.6.2.3) unless it is applied to a non-volatile Ivalue 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 \textit{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 \textit{new-expression} (7.6.2.8), unless 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 \(E\);

\[^{74}\text{This includes, for example, signed integer overflow (7.1), certain pointer arithmetic (7.6.6), division by zero (7.6.5), or certain shift operations (7.6.7).}\]
— a 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 (20.2.9.2), unless the allocated storage is deallocated within the evaluation of E;
— a call to an instance of std::allocator<T>::deallocate (20.2.9.2), 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 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 (3.36); or
— a goto statement (8.7.6).

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, or an invocation of the va_start macro (17.13.2), it is unspecified whether E is a core constant expression.

Example 3:

```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
  // because lifetime of k began outside the initializer of x
  return x;
}
constexpr int f2(int k) {
  int x = k; // OK, not required to be a constant expression
  // because x is not constexpr
  return x;
}
constexpr int incr(int &n) {
  return ++n;
}
constexpr int g(int k) {
  constexpr int x = incr(k); // error: incr(k) is not a core constant expression
  // because lifetime of k began outside the expression incr(k)
  return x;
}
constexpr int h(int k) {
  int x = incr(k); // OK, incr(k) is not required to be a core constant expression
  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]
For the purposes of determining whether an expression \( E \) is a core constant expression, the evaluation of a call to a member function of `std::allocator<T>` as defined in 20.2.9.2, where \( T \) is a literal type, does not disqualify \( E \) from being a core constant expression, even if the actual evaluation of such a call would otherwise fail the requirements for a core constant expression. Similarly, the evaluation of a call to `std::construct_at` or `std::ranges::construct_at` (27.11.8) does not disqualify \( E \) from being a core constant expression unless the first argument, of type \( T* \), does not point to storage allocated with `std::allocator<T>` or to an object whose lifetime began within the evaluation of \( E \), or the evaluation of the underlying constructor call disqualifies \( E \) from being a core constant expression.

An object \( a \) is said to have constant destruction if:

1. it is not of class type nor (possibly multi-dimensional) array thereof, or
2. it is of class type or (possibly multi-dimensional) 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 \( E \).

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.

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`.

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

1. user-defined conversions,
2. lvalue-to-rvalue conversions (7.3.2),
3. array-to-pointer conversions (7.3.3),
4. function-to-pointer conversions (7.3.4),
5. qualification conversions (7.3.6),
6. integral promotions (7.3.7),
7. integral conversions (7.3.9) other than narrowing conversions (9.4.5),
8. null pointer conversions (7.3.12) from `std::nullptr_t`,
9. null member pointer conversions (7.3.13) from `std::nullptr_t`, and
10. function pointer conversions (7.3.14),

and where the reference binding (if any) binds directly.

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:

11.1  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,

11.2  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,

11.3  if the value is of pointer-to-member-function type, it does not designate an immediate function, and

11.4  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.

[Example 5:

```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  
```

—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 6: 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 6:

```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]

12 An expression or conversion is in an immediate function context if it is potentially evaluated and either:

13.1  its innermost enclosing non-block scope is a function parameter scope of an immediate function, or

13.2  its enclosing statement is enclosed (8.1) by the compound-statement of a consteval if statement (8.5.2).

An expression or conversion 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 immediate invocation shall be a constant expression.

14 An expression or conversion is manifestly constant-evaluated if it is:

14.1  a constant-expression, or

14.2  the condition of a constexpr if statement (8.5.2), or

14.3  an immediate invocation, or

14.4  the result of substitution into an atomic constraint expression to determine whether it is satisfied (13.5.2.3), or

14.5  the initializer of a variable that is usable in constant expressions or has constant initialization (6.9.3.2).75

[Example 7:

```cpp
template<bool> struct X {};
```

75) Testing this condition can involve a trial evaluation of its initializer as described above.
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
// in constant expressions
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

constexpr 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 7: 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:

15 (15.1) — a manifestly constant-evaluated expression,
(15.2) — a potentially-evaluated expression (6.3),
(15.3) — an immediate subexpression of a braced-init-list,76
(15.4) — an expression of the form & cast-expression that occurs within a templated entity,77 or
(15.5) — a subexpression of one of the above that is not a subexpression of a nested unevaluated operand (7.2.3).

A function or variable is needed for constant evaluation if it is:

15 (15.6) — a constexpr function that is named by an expression (6.3) that is potentially constant evaluated, or
(15.7) — a variable named by a potentially constant evaluated expression that is either a constexpr variable or is of non-volatile const-qualified integral type or of reference type.

76) In some cases, constant evaluation is needed to determine whether a narrowing conversion is performed (9.4.5).
77) 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

Except as indicated, statements are executed in sequence.

```
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
```

The optional `attribute-specifier-seq` appertains to the respective statement.

2 A substatement of a statement is one of the following:

- (2.1) for a `labeled-statement`, its `statement`,
- (2.2) for a `compound-statement`, any `statement` of its `statement-seq`,
- (2.3) for a `selection-statement`, any of its `statements` (but not its `init-statement`), or
- (2.4) 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

- (3.1) S2 is a substatement of S1,
- (3.2) S1 is a `selection-statement` or `iteration-statement` and S2 is the `init-statement` of S1,
- (3.3) S1 is a `try-block` and S2 is its `compound-statement` or any of the `compound-statements` of its `handlers`, or
- (3.4) S1 encloses a statement S3 and S3 encloses S2.

4 The rules for conditions apply both to `selection-statements` and to the `for` and `while` statements (8.6). A condition that is not an expression 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 9.2.9.6.

5 The value of a condition that is an initialized declaration in a statement other than a `switch` statement is the value of the declared 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 initialized declaration in a `switch` statement is the value of the declared variable if it has integral or enumeration type, or of that variable implicitly converted to integral or enumeration type otherwise. 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.

6 If a condition can be syntactically resolved as either an expression or a declaration, it is interpreted as the latter.

7 In the `decl-specifier-seq` of a condition, each `decl-specifier` shall be either a `type-specifier` or `constexpr`.

§ 8.1
8.2 Labeled statement

A statement can be labeled.

\[
\text{labeled-statement:}
\begin{align*}
\text{attribute-specifier-seq} & \text{opt identifier : statement} \\
\text{attribute-specifier-seq} & \text{opt case constant-expression : statement} \\
\text{attribute-specifier-seq} & \text{opt default : statement}
\end{align*}
\]

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 by a labeled-statement.

Case labels and default labels shall occur only in switch statements.

8.3 Expression statement

Expression statements have the form

\[
\text{expression-statement:}
\begin{align*}
\text{expression} & \text{opt} ;
\end{align*}
\]

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 carry a label just before the } of a compound statement and 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.

\[
\text{compound-statement:}
\begin{align*}
\{ & \text{statement-seq opt} \\
\text{statement-seq} & \text{statement}
\end{align*}
\]

[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.

\[
\text{selection-statement:}
\begin{align*}
\text{if constexpr opt ( init-statement opt condition ) statement} \\
\text{if constexpr opt ( init-statement opt condition ) statement else statement} \\
\text{if ! opt constexpr compound-statement} \\
\text{if ! opt constexpr compound-statement else statement} \\
\text{switch ( init-statement opt condition ) statement}
\end{align*}
\]

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 (8.5) 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.78

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.

78) In other words, the else is associated with the nearest un-elsed if.
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.

[Example 1:]
```cpp
class MyClass {
  template<typename T, typename ... Rest> void g(T&& p, Rest&& ...rs) {
    if constexpr (sizeof...(rs) > 0)
      g(rs...); // never instantiated with an empty argument list
  }
  extern int x; // no definition of x required
}
```

[Note 1: Odr-uses (6.3) in a discarded statement do not require an entity to be defined. — end note]

A case or default label appearing within such an if statement shall be associated with a switch statement (8.5.3) within the same if statement. A label (8.2) declared in a substatement of a constexpr if statement shall only be referred to by a statement (8.7.6) in the same substatement.

[Example 2:]
```cpp
int f() {
  if constexpr (true)
    return 0;
  else if (x)
    return x;
  else
    return -x;
}
```

3 An if statement of the form

    if constexpr_opt (init-statement condition) statement

is equivalent to

    { 
      init-statement
      if constexpr_opt (condition) statement
    }

and an if statement of the form

    if constexpr_opt (init-statement condition) statement else statement

is equivalent to

    { 
      init-statement
      if constexpr_opt (condition) statement else statement
    }

except that the init-statement is in the same scope as the condition.

4 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:]
```cpp
class MyClass {
  constexpr void f(bool b) {
    if (true)
      if constexpr { } // error: not a compound-statement; else not associated with outer if
    else ;
  }
}
```
If a consteval 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. A case or default label appearing within such an if statement shall be associated with a switch statement within the same if statement. A label declared in a substatement of a consteval if statement shall only be referred to by a statement in the same substatement.

An if statement of the form

```c
if ! consteval compound-statement
```

is not itself a consteval if statement, but is equivalent to the consteval if statement

```c
if consteval {} else compound-statement
```

An if statement of the form

```c
if ! consteval compound-statement; else statement
```

is not itself a consteval if statement, but is equivalent to the consteval if statement

```c
if consteval statement2 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.

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:

```c
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

```c
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

```c
switch (init-statement condition) statement
```

is equivalent to

```c
{
    init-statement
    switch (condition) statement
}
```

except that the init-statement is in the same scope as the condition.

### 8.6 Iteration statements

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
attribute-specifier-seq[opt] decl-specifier-seq ref-qualifier[opt] [ identifier-list ]

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]

8.6.2 The while statement [stmt.while]

In the while statement the substatement is executed repeatedly until the value of the condition (8.5) becomes false. The test takes place before each execution of the substatement.

A while statement is equivalent to

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:
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 [stmt.do]

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 conditionopt ; expressionopt ) 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 (8.5) 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-statementopt for-range-declaration : for-range-initializer ) statement
```

is equivalent to

```c
{ 
    init-statementopt
    auto &&range = for-range-initializer ;
    auto begin = begin-eexpr ;
    auto end = end-eexpr ;
    for ( ; begin != end ; ++begin ) {
        for-range-declaration = * begin ;
        statement
    }
}
```

where

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`);
2. `range`, `begin`, and `end` are variables defined for exposition only; and
3. `begin-eexpr` and `end-eexpr` are determined as follows:
   1.1. if the `for-range-initializer` is an expression of array type `R`, `begin-eexpr` and `end-eexpr` 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;
   1.2. if the `for-range-initializer` is an expression of 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-eexpr` and `end-eexpr` are `range.begin()` and `range.end()`, respectively;
   1.3. otherwise, `begin-eexpr` and `end-eexpr` 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;
```
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

8.7.1 General

Jump statements unconditionally transfer control.

```pseudo
jump-statement:
  break ;
  continue ;
  return expr-or-braced-init-list_opt ;
  coroutine-return-statement
  goto identifier ;
```

[Note 1: 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. 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]

[Note 2: 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

The break statement shall occur only in an iteration-statement or a switch statement and causes termination of the smallest enclosing iteration-statement or switch statement; control passes to the statement following the terminated statement, if any.

8.7.3 The continue statement

The continue statement shall occur only in an iteration-statement and causes control to pass to the loop-continuation portion of the smallest enclosing iteration-statement, that is, to the end of the loop. More precisely, in each of the statements

```pseudo
while (foo) {
  {
    // ...
  } // ...
}
```

a continue not contained in an enclosed iteration statement is equivalent to goto contin.

8.7.4 The return statement

A function returns to its caller by the return statement.

The expr-or-braced-init-list of a return statement is called its operand. A return statement with no operand shall be used only in a function whose return type is cv void, a constructor (11.4.5), or a destructor (11.4.7). A return statement with an operand of type void shall be used only in a function that has a cv void return type. A return statement with any other operand shall be used only in a function that has a return type other than cv void; the 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.

[Note 1: A constructor or destructor does not have a return type. — end note]

[Note 2: 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]

The destructor for the result object is potentially invoked (11.4.7, 14.3).

[Example 1:]
```pseudo
class A {
  ~A() {}
};
A f() { return A(); }  // error: destructor of A is private (even though it is never invoked)
```
Flowing off the end of a constructor, a destructor, or a non-coroutine function with a `cv void` return type is equivalent to a `return` with no operand. Otherwise, flowing off the end of a function that is neither `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.

### 8.7.5 The `co_return` statement

```
coroutine-return-statement:
  co_return expr-or-braced-init-list_opt ;
```

1. A coroutine returns to its caller or resumer (9.5.4) by the `co_return` statement or when suspended (7.6.2.4). A coroutine shall not enclose a `return` statement (8.7.4).

[Note 1: For this determination, it is irrelevant whether the `return` statement is enclosed by a discarded statement (8.5.2). —end note]

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:

   ```
   { S; goto final-suspend; }
   ```

   where `final-suspend` is the exposition-only label defined in 9.5.4 and `S` is defined as follows:

   - (2.1) If the operand is a `braced-init-list` or an expression of non-void type, `S` is `p.return_value(expr-or-braced-init-list)`. The expression `S` shall be a prvalue of type `void`.

   - (2.2) Otherwise, `S` is the `compound-statement` `{ expression_opt ; p.return_void(); }`. The expression `p.return_void()` shall be a prvalue of type `void`.

3. If `p.return_void()` is a valid expression, 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

```
goto-statement:
  goto label ;
```

1. 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

```
declaration-statement:
  block-declaration
```

1. A declaration statement introduces one or more new names into a block; it has the form

   ```
   block-declaration
   ```

   [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]

2. A variable with automatic storage duration (6.7.5.4) is `active` everywhere in the scope to which it belongs after its `init-declarator`. Upon each transfer of control (including sequential execution of statements) within a function from point `P` to point `Q`, all variables with automatic storage duration that are active at `P` and not at `Q` are destroyed in the reverse order of their construction. Then, all variables with automatic storage duration that are active at `Q` but not at `P` are initialized in declaration order; unless all such variables have vacuous initialization (6.7.3), the transfer of control shall not be a jump.\(^{79}\) 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.

[Example 1:

```
void f() {
  // ...
  goto lx;       // error: jump into scope of a
  // ...
  ly:
  X a = 1;
```

\(^{79}\) The transfer from the condition of a `switch` statement to a `case` label is considered a jump in this respect.

§ 8.8
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.

[Note 2: 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. — end note]

If control re-enters the declaration recursively while the variable is being initialized, the behavior is undefined.

[Example 2:

```cpp
int foo(int i) {
    static int s = foo(2*i);
    // undefined behavior: recursive call
    return i+1;
}
```

—end example]

An object associated with a block variable with static or thread storage duration will be destroyed if and only if it was constructed.

[Note 3: 6.9.3.4 describes the order in which such objects are destroyed. — end note]

8.9 Ambiguity resolution

There is an ambiguity in the grammar involving `expression-statement`s and `declaration`s: 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 a `declaration`.

[Note 1: 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.

[Example 1: Assuming T is a `simple-type-specifier` (9.2.9),

```cpp
T(a)->m = 7;  // expression-statement
T(a)++;       // expression-statement
T(a,5)<<c;    // expression-statement
T(*d)(int);   // declaration
T(e)[5];      // declaration
T(f) = { 1, 2 }; // declaration
T(*g)(double(3)); // declaration
```

In the last example above, g, which is a pointer to T, is initialized to double(3). This is of course ill-formed for semantic reasons, but that does not affect the syntactic analysis. — end example]

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
```
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));
    // T2 will be declared as a variable of type T1, but this will not
    // allow the last part of the declaration to parse properly,
    // since it depends on T2 being a type-name
}
```

— end example [Example 3:]

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9 Declarations

9.1 Preamble

Declarations generally specify how names are to be interpreted. Declarations have the form

```
declarations: declaration
  declarations declaration
declaration: block-declaration
  nodeclspec-function-declaration
  function-definition
  template-declaration
  deduction-guide
  explicit-instantiation
  explicit-specialization
  export-declaration
  linkage-specification
  namespace-definition
  empty-declaration
  attribute-declaration
  module-import-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-seqopt declarator;
alias-declaration:
  using identifier attribute-specifier-seqopt = defining-type-id;
simple-declaration:
  decl-specifier-seq init-declarator-listopt;
  attribute-specifier-seqopt decl-specifier-seq opt init-declarator-list;
  attribute-specifier-seqopt decl-specifier-seq ref-qualifieropt [ identifier-list ] initializer;
static_assert-declaration:
  static_assert ( constant-expression );
  static_assert ( constant-expression , string-literal );
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-defitions 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 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:

```c
[[noreturn]] void f [[noreturn]] () ;  // OK
```

— end example]

4 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.

5 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 reintroduce one or more names into the program.

[Example 2:

```c
enum { } ;  // error
typedef class { } ;  // error
```

— end example]

6 A simple-declaration with an identifier-list is called a structured binding declaration (9.6). If the decl-specifier-seq contains any decl-specifier other than static, thread_local, auto (9.2.9.6), or cv-qualifiers, the program is ill-formed. The initializer shall be of the form “= assignment-expression”, of the form “{ assignment-expression }”, or of the form “( assignment-expression )”, where the assignment-expression is of array or non-union class type.

7 If the decl-specifier-seq contains the typedef specifier, the declaration is called 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]

If the decl-specifier-seq contains no typedef specifier, the declaration is called a function declaration if the type associated with a declarator-id is a function type (9.3.4.6) and an object declaration otherwise.

8 Syntactic components beyond those found in the general form of simple-declaration are added to a function declaration to make a function-definition. An object declaration, however, is also a definition unless it contains the extern specifier and has no initializer (6.2). An object definition causes storage of appropriate size and alignment to be reserved and any appropriate initialization (9.4) to be done.

9 A nodelcspec-function-declaration shall declare a constructor, destructor, or conversion function.

[Note 5: Because a member function cannot be subject to a non-defining declaration outside of a class definition (11.4.2), a nodelcspec-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]

10 In a static_assert-declaration, the constant-expression is contextually converted to bool and the converted expression shall be a constant expression (7.7). If the value of the expression when so converted is true, the declaration has no effect. Otherwise, the program is ill-formed, and the resulting diagnostic message (4.1) should include the text of the string-literal, if one is supplied.

[Example 3:

```c
static_assert(sizeof(int) == sizeof(void*), "wrong pointer size"); static_assert(sizeof(int[2]), "error"); // OK, narrowing allowed
```

— end example]

11 An empty-declaration has no effect.

12 Except where otherwise specified, the meaning of an attribute-declaration is implementation-defined.
9.2 Specifiers  
9.2.1 General

1 The specifiers that can be used in a declaration are

```
decl-specifier:
  storage-class-specifier
  defining-type-specifier
  function-specifier
  friend
  typedef
  constexpr
  consteval
  constinit
  inline

decl-specifier-seq:
  decl-specifier attribute-specifier-seq
  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:]

```c
typedef char* Pc;  // error: name missing
static Pc;
```

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,

```c
void f(const Pc);  // void f(char* const) (not const char*)
void g(const int Pc);  // void g(const int)
```

[Example 2:]

```c
void h(unsigned Pc);  // void h(unsigned int)
void k(unsigned int Pc);  // void k(unsigned int)
```

[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.

```
9.2.2 Storage class specifiers
```

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.

§ 9.2.2
[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: The linkage given by some declarations is affected by previous declarations. Overloads are distinct entities. — end note]

```
static char* f(); // f() has internal linkage
char* f(); // f() still has internal linkage
{ /* ... */ }

char* g(); // g() has external linkage
static char* g(); // error: inconsistent linkage
{ /* ... */ }

void h();
inline void h(); // external linkage

inline void l();
void l(); // external linkage

inline void m();
extern void m(); // external linkage

static void n();
inline void n(); // internal linkage

static int a; // a has internal linkage
int a; // error: two definitions

static int b;
extern int b; // b still has internal linkage

int c;
static int c; // error: inconsistent linkage

extern int d;
static int d; // error: inconsistent linkage
```
The name of a declared but undefined class can be used in an `extern` declaration. Such a declaration can only be used in ways that do not require a complete class type.

[Example 2:

```c
struct S;
extern S a;
extern S f();
extern void g(S);

void h() {
    g(a);           // error: S is incomplete
    f();            // error: S is incomplete
}
```
—end example]

The `mutable` specifier shall appear only in the declaration of a non-static data member (11.4) whose type is neither const-qualified nor a reference type.

[Example 3:

```c
class X {
    mutable const int* p;  // OK
    mutable int* const q;  // error
};
```
—end example]

[Note 5: The `mutable` specifier on a class data member nullifies a `const` specifier applied to the containing class object and permits modification of the mutable class member even though the rest of the object is const (6.8.4, 9.2.9.2).
—end note]

### 9.2.3 Function specifiers [dcl.fct.spec]

A `function-specifier` can be used only in a function declaration.

```
function-specifier:
    virtual
        explicit-specifier
    explicit-specifier:
        explicit ( constant-expression )
    explicit
```

2 The `virtual` specifier shall be used only in the initial declaration of a non-static member function; see 11.7.3.

3 An `explicit-specifier` shall be used only in the declaration of a constructor or conversion function within its class definition; see 11.4.8.2 and 11.4.8.3.

4 In an `explicit-specifier`, the `constant-expression`, if supplied, shall be a contextually converted constant expression of type `bool` (7.7). The `explicit-specifier` `explicit` without a `constant-expression` is equivalent to the `explicit-specifier` `explicit(true)`. If the constant expression evaluates to `true`, the function is explicit. Otherwise, the function is not explicit. A `(` token that follows `explicit` is parsed as part of the `explicit-specifier`.

[Example 1:

```c
struct S {
    explicit(sizeof(char[2])) S(char);  // error: narrowing conversion of value 2 to type bool
    explicit(sizeof(char)) S(bool);    // OK, conversion of value 1 to type bool is non-narrowing
};
```
—end example]

### 9.2.4 The `typedef` specifier [dcl.typedef]

Declarations containing the `decl-specifier` `typedef` declare identifiers that can be used later for naming fundamental (6.8.2) or compound (6.8.3) types. The `typedef` specifier shall not be combined in a `decl-specifier-seq` with any other kind of specifier except a `defining-type-specifier`, and it shall not be used in the `decl-specifier-seq` of a `parameter-declaration` (9.3.4.6) nor in the `decl-specifier-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]

2 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]

3 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.

4 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` (9.2.9.4), 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();
struct T * p;
// error
— end example]

5 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]

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

§ 9.2.4
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

dcl.friend

The friend specifier is used to specify access to class members; see 11.8.4.

9.2.6 The constexpr and consteval specifiers

dcl.constexpr

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 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:

cconstexpr void square(int x); // OK, declaration
cconstexpr int bufsz = 1024;  // OK, definition
cconstexpr struct pixel {
    int x;
    int y;
    constexpr pixel(int);
} ;
cconstexpr pixel::pixel(int a)
    : x(a), y(x) // OK, definition
    { square(x); }
cconstexpr 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;
}
cconstexpr 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 called an immediate function. A destructor, an allocation function, or a deallocation function shall not be declared with the constexpr specifier.

3 The definition of a constexpr function shall satisfy the following requirements:

− its return type (if any) shall be a literal type;
− each of its parameter types shall be a literal type;
− it shall not be a coroutine (9.5.4);
− if the function is a constructor or destructor, its class shall not have any virtual base classes.

[Example 2:
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

4 The definition of a constexpr constructor whose function-body is not = delete shall additionally satisfy the following requirements:

(4.1) — for a non-delegating constructor, every constructor selected to initialize non-static data members and base class subobjects shall be a constexpr constructor;

(4.2) — for a delegating constructor, the target constructor shall be a constexpr constructor.

[Example 3:
 struct Length {
  constexpr explicit Length(int i = 0) : val(i) { }
 private:
  int val;
};
—end example]

5 The definition of a constexpr destructor whose function-body is not = delete shall additionally satisfy the following requirement:

(5.1) — for every subobject of class type or (possibly multi-dimensional) array thereof, that class type shall have a constexpr destructor.

6 For a constexpr function or constexpr constructor that is neither defaulted nor a template, if no argument values exist such that an invocation of the function or constructor could be an evaluated subexpression of a core constant expression (7.7), or, for a constructor, an evaluated subexpression of the initialization full-expression of some constant-initialized object (6.9.3.2), the program is ill-formed, no diagnostic required.

[Example 4:
 constexpr int f(bool b)
{ return b ? throw 0 : 0; }      // OK
constexpr int f() { return f(true); }  // ill-formed, no diagnostic required

struct B {
  constexpr B(int x) : i(0) { }   // x is unused
  int i;
};
int global;

struct D : B {
    constexpr D() : B(global) { } // ill-formed, no diagnostic required
    // value-to-value conversion on non-constant global
};

constexpr int f(int x) {
    static int n = x;
    return n + x;
    // ill-formed, no diagnostic required
    // all calls reach the static variable declaration
}

—end example

7 If the instantiated template specialization of a constexpr function template or member function of a class template would fail to satisfy the requirements for a constexpr function, that specialization is still a constexpr function, even though a call to such a function cannot appear in a constant expression. If no specialization of the template would satisfy the requirements for a constexpr function when considered as a non-template function, the template is ill-formed, no diagnostic required.

8 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

(8.1) — an invocation of a constexpr function can appear in a constant expression (7.7) and
(8.2) — copy elision is not performed in a constant expression (11.9.6).

[Note 3: 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]

9 The constexpr and consteval specifiers have no effect on the type of a constexpr function.

[Example 5:
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]

10 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 shall have constant destruction.

[Example 6:
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 [dcl.constinit]

1 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.

2 If a variable declared with the constexpr specifier has dynamic initialization (6.9.3.3), the program is ill-formed.

[Note 1: The constexpr specifier ensures that the variable is initialized during static initialization (6.9.3.2). — end note]

3 [Example 1:
    const char * g() { return "dynamic initialization"; }

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constexpr const char * f(bool p) { return p ? "constant initializer" : g(); }
constinit const char * c = f(true); // OK
constinit const char * d = f(false); // error
— end example

9.2.8 The inline specifier

1 The inline specifier shall be applied only to the declaration of a variable or function.

2 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]

3 A variable declaration with an inline specifier declares an inline variable.

4 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.

5 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]

6 [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]

7 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

1 The type-specifiers are

```plaintext
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
```

The optional attribute-specifier-seq in a type-specifier-seq or a defining-type-specifier-seq appertains to the type denoted by the preceding type-specifiers or defining-type-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.
As a general rule, at most one defining-type-specifier is allowed in the complete decl-specifier-seq of a declaration or in a defining-type-specifier-seq, and at most one type-specifier is allowed in a type-specifier-seq. The only exceptions to this rule are the following:

1. const can be combined with any type specifier except itself.
2. volatile can be combined with any type specifier except itself.
3. signed or unsigned can be combined with char, long, short, or int.
4. short or long can be combined with int.
5. long can be combined with double.
6. long can be combined with long.

Except in a declaration of a constructor, destructor, or conversion function, at least one defining-type-specifier that is not a cv-qualifier shall appear in a complete type-specifier-seq or a complete decl-specifier-seq.

Example 1:

```c
const int ci = 3; // cv-qualified (initialized as required)
int i = 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,

```c
struct X {
    mutable int i;
    int j;
};
```

There is no special provision for a decl-specifier-seq that lacks a type-specifier or that has a type-specifier that only specifies cv-qualifiers. The "implicit int" rule of C is no longer supported.
struct Y {
    X x;
    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 the value of the object might be changed by means undetectable by an implementation. Furthermore, for some implementations, volatile might indicate that special hardware instructions are required 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

The simple type specifiers are

simple-type-specifier:
    nested-name-specifier_opt type-name
    nested-name-specifier_template simple-template-id
decTypename
    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

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.

A placeholder-type-specifier is a placeholder for a type to be deduced (9.2.9.6). A type-specifier of the form typename_opt nested-name-specifier_opt template-name is a placeholder for a deduced class type (9.2.9.7). 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 \textit{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 16 summarizes the valid combinations of \textit{simple-type-specifiers} and the types they specify.

Table 16: \textit{simple-type-specifiers} and the types they specify \[tab:dcl.type.simple\]

<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 9.2.9.5</td>
</tr>
<tr>
<td>placeholder-type-specifier</td>
<td>the type as defined in 9.2.9.6</td>
</tr>
<tr>
<td>template-name</td>
<td>the type as defined in 9.2.9.7</td>
</tr>
<tr>
<td>char</td>
<td>&quot;char&quot;</td>
</tr>
<tr>
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<tr>
<td>signed char</td>
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</tr>
<tr>
<td>char8_t</td>
<td>&quot;char8_t&quot;</td>
</tr>
<tr>
<td>char16_t</td>
<td>&quot;char16_t&quot;</td>
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<tr>
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<td>&quot;char32_t&quot;</td>
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<tr>
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<td>long double</td>
<td>&quot;long double&quot;</td>
</tr>
<tr>
<td>void</td>
<td>&quot;void&quot;</td>
</tr>
</tbody>
</table>

4 When multiple \textit{simple-type-specifiers} are allowed, they can be freely intermixed with other \textit{decl-specifiers} in any order.

[\textbf{Note 2:} It is implementation-defined whether objects of \texttt{char} type are represented as signed or unsigned quantities. The \texttt{signed} specifier forces \texttt{char} objects to be signed; it is redundant in other contexts. — end note]

\section*{9.2.9.4 Elaborated type specifiers} \[dcl.type.elab\]
elaborated-type-specifier:
  class-key attribute-specifier-seq_{opt} nested-nameSpecifier_{opt} identifier
  class-key simple-template-id
  class-key nested-nameSpecifier template_{opt} simple-template-id
  elaborated-enum-specifier

elaborated-enum-specifier:
  enum nested-nameSpecifier_{opt} identifier

1 The component names of an elaborated-type-specifier are its identifier (if any) and those of its nested-nameSpecifier 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), an explicit instantiation (13.9.3) or it has one of the following forms:
   class-key attribute-specifier-seq_{opt} identifier ;
   class-key attribute-specifier-seq_{opt} simple-template-id ;

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 (13.7)). The attribute-specifier-seq, if any, appertains to the class or template being declared.

3 Otherwise, an elaborated-type-specifier \( E \) shall not have an attribute-specifier-seq. If \( E \) contains an identifier but no nested-nameSpecifier 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.

4 If an elaborated-type-specifier appears with the friend specifier as an entire member-declaration, the member-declaration shall have one of the following forms:
   friend class-key nested-nameSpecifier_{opt} identifier ;
   friend class-key simple-template-id ;
   friend class-key nested-nameSpecifier template_{opt} simple-template-id ;

Any unqualified lookup for the identifier (in the first case) does not consider scopes that contain the target 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. 6.5.6 describes how name lookup proceeds in an elaborated-type-specifier. — end note]

5 [Note 2: 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 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

friend class \( T \);

is ill-formed. However, the similar declaration friend \( T \); is allowed (11.8.4). — end note]

6 The class-key or enum keyword present in the 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:

```cpp
enum class E { a, b };
enum E x = E::a;  // OK
struct S { } s;
class S* p = &s;  // OK
```
—end example]

9.2.9.5 Decltype specifiers

dcl.type.decltype

dcl.type.decltype:
  decltype ( expression )
For an expression \( E \), the type denoted by \( \text{decltype}(E) \) is defined as follows:

1. if \( E \) is an unparenthesized \textit{id-expression} naming a structured binding (9.6), \( \text{decltype}(E) \) is the referenced type as given in the specification of the structured binding declaration;
2. otherwise, if \( E \) is an unparenthesized \textit{id-expression} naming a non-type template-parameter (13.2), \( \text{decltype}(E) \) is the type of the entity named by \( E \). If there is no such entity, the program is ill-formed;
3. otherwise, if \( E \) is an unparenthesized \textit{id-expression} or an unparenthesized class member access (7.6.1.5), \( \text{decltype}(E) \) is the type of the entity named by \( E \). If there is no such entity, the program is ill-formed;
4. otherwise, if \( E \) is an xvalue, \( \text{decltype}(E) \) is \( T&& \), where \( T \) is the type of \( E \);
5. otherwise, if \( E \) is an lvalue, \( \text{decltype}(E) \) is \( T& \), where \( T \) is the type of \( E \);
6. otherwise, \( \text{decltype}(E) \) is the type of \( E \).

The operand of the \texttt{decltype} specifier is an unevaluated operand (7.2.3).

\[\text{Example 1:}\]
\begin{verbatim}
const int&& foo();
int i;
struct A { double x; };
const A* a = new A();
decltype(foo()) x1 = 17; // type is const int&&
default(x) x2; // type is int
default(a-&gt;x) x3; // type is double
default((a-&gt;x)) x4 = x3; // type is const double&
\end{verbatim}

\[\text{Example 2:}\]
\begin{verbatim}
template<class T> struct A { ~A() = delete; };
template<class T> auto h() -> A&lt;T&gt;;
template<class T> auto i(T) -> T; // identity
template<class T> auto i(T) -> decltype(i(h&lt;T&gt;()));
// forces completion of A&lt;T&gt; and implicitly uses A&lt;T&gt;::~A()
// for the temporary introduced by the use of h().
// (A temporary is not introduced as a result of the use of i().)
template&lt;class T&gt; auto i(T) -> void;
auto g() &gt;&gt; void { f(42); // OK, calls #2. (#1 is not a viable candidate: type deduction
// fails (13.10.3) because A&lt;int&gt;::~A() is implicitly used in its
// decltype-specifier)
} template&lt;class T&gt; auto q(T) -> decltype((h&lt;T&gt;())); // does not force completion of A&lt;T&gt;; A&lt;T&gt;::~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
\end{verbatim}

\[\text{Note 1}:\] The rules for determining types involving \texttt{decltype(auto)} are specified in 9.2.9.6. —end note\]

\[\text{Note 2}:\] 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 \texttt{decltype-specifier} is analogous to a use of a \texttt{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\]

\[\text{Note 3}:\] Unlike the preceding rule, parentheses have no special meaning in this context. —end note\]
The specialization \( q(T) \rightarrow \text{decltype}(h<T>()) \) with \( T = \text{int} \);
the return type is \( \text{int} \), so a temporary is introduced and its
destructor is used, so the program is ill-formed.

} —end example]

9.2.9.6 Placeholder type specifiers

9.2.9.6.1 General

A \textit{placeholder-type-specifier} designates a placeholder type that will be replaced later by deduction from an initializer.

A \textit{placeholder-type-specifier} of the form \textit{type-constraint\_opt auto} can be used as a \textit{decl-specifier} of the decl-specifier-seq of a parameter-declaration of a function declaration or lambda-expression and, if it is not the \textit{auto} type-specifier introducing a trailing-return-type (see below), is a \textit{generic parameter type placeholder} of the function declaration or lambda-expression.

\[ \text{Note 1: Having a generic parameter type placeholder signifies that the function is an abbreviated function template (9.3.4.6) or the lambda is a generic lambda (7.5.5).} \quad \text{—end note} \]

A placeholder type can appear with a function declarator in the decl-specifier-seq, type-specifier-seq, conversion-function-id, or trailing-return-type, in any context where such a declarator is valid. If the function declarator includes a trailing-return-type (9.3.4.6), that trailing-return-type specifies the declared return type of the function. Otherwise, the function declarator shall declare a function. If the declared return type of the function contains a placeholder type, the return type of the function is deduced from non-discarded return statements, if any, in the body of the function (8.5.2).

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 and the decl-specifier-seq shall be followed by one or more declarators, each of which shall be followed by a non-empty initializer.

\[ \text{Example 1:} \]
\begin{verbatim}
auto x = 5;          // OK, x has type int
const auto *v = &x, u = 6; // OK, v has type const int*, u has type const 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 h();           // OK, h’s return type will be deduced when it is defined
\end{verbatim}

The \textit{auto} type-specifier can also be used to introduce a structured binding declaration (9.6).

A placeholder 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) and as a decl-specifier of the parameter-declaration’s decl-specifier-seq in a template-parameter (13.2). The \textit{auto} type-specifier can also be used as the simple-type-specifier in an explicit type conversion (functional notation) (7.6.1.4).

A program that uses a placeholder type in a context not explicitly allowed in 9.2.9.6 is ill-formed.

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 (9.2.9.6.2), and if the type that replaces the placeholder type is not the same in each deduction, the program is ill-formed.

\[ \text{Example 2:} \]
\begin{verbatim}
auto x = 5, *y = &x;          // OK, auto is int
auto a = 5, b = { 1, 2 };   // error: different types for auto
\end{verbatim}

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 \texttt{return} statements, the return type is deduced as though from a \texttt{return} statement with no operand at the closing brace of the function body.

\textbf{Example 3:}

\begin{verbatim}
auto f() { }  // OK, return type is \texttt{void}
auto* g() { } // error: cannot deduce \texttt{auto*} from \texttt{void()}
\end{verbatim}

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 \textit{private-module-fragment} (if any).

\textbf{Note 2:} The deduced return type cannot have a name with internal linkage (6.6). 

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 \texttt{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 \texttt{return} statements.

\textbf{Example 4:}

\begin{verbatim}
auto n = n;  // error: \texttt{n}'s initializer refers to \texttt{n}
auto f();
void g() { &f; } // error: \texttt{f}'s return type is unknown
auto sum(int i) {
  if (i == 1)
    return i;
  else
    return sum(i-1)+i;  // OK, \texttt{sum}'s return type has been deduced
}
\end{verbatim}

Return type deduction for a templated entity that is a function or function template with a placeholder in its declared type occurs when the definition is instantiated even if the function body contains a \texttt{return} statement with a non-type-dependent operand.

\textbf{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). 

\textbf{Example 5:}

\begin{verbatim}
template <class T> auto f(T t) { return t; }  // return type deduced at instantiation time
typedef decltype(f(1)) fint_t;  // instantiates \texttt{f<int>} to deduce return type
template<class T> auto f(T* t) { return *t; }  // instantiates both \texttt{f} s to determine return types,
  // chooses second
void g() { int (*p)(int*) = &f; }  // instantiates both \texttt{f} s to determine return types,
  // chooses second
\end{verbatim}

If a function or function template \textit{F} has a declared return type that uses a placeholder type, redeclarations or specializations of \textit{F} shall use that placeholder type, not a deduced type; otherwise, they shall not use a placeholder type.

\textbf{Example 6:}

\begin{verbatim}
auto f();
auto f() { return 42; }  // return type is \texttt{int}
auto f();  // OK
int f();  // error: \texttt{auto} and \texttt{int} don't match
decltype(auto) f();  // error: \texttt{auto} and \texttt{decltype(auto)} don't match

template <typename T> auto g(T t) { return t; }  // \#1
template auto g(int);  // OK, return type is \texttt{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
\end{verbatim}
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; }  // does not instantiate f<int>
extern template auto f(int);  // instantiates f<int> to determine its return type, but an explicit instantiation definition is still required somewhere in the program
— end example]

§ 9.2.9.6.2 Placeholder type deduction  [decl.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:

(2.1) — 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.

(2.1.1) — If the return statement has no operand, then E is void().

(2.1.2) — If the operand is a braced-init-list (9.4.5), the program is ill-formed.

(2.1.3) — 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]

(2.1.4) — Otherwise, E is the operand of the return statement.

If E has type void, T shall be either type-constraint_opt decltype(auto) or cv type-constraint_opt auto.

(2.2) — For a variable declared with a type that contains a placeholder type, T is the declared type of the variable.

(2.2.1) — If the initializer of the variable is a brace-or-equal-initializer of the form = initializer-clause, E is the initializer-clause.

(2.2.2) — If the initializer is a braced-init-list, it shall consist of a single brace-enclosed assignment-expression and E is the assignment-expression.

(2.2.3) — If the initializer is a parenthesized expression-list, the expression-list shall be a single assignment-expression and E is the assignment-expression.

(2.3) — For an explicit type conversion (7.6.1.4), T is the specified type, which shall be auto.

(2.3.1) — If the initializer is a braced-init-list, it shall consist of a single brace-enclosed assignment-expression and E is the assignment-expression.

(2.3.2) — If the initializer is a parenthesized expression-list, the expression-list shall be a single assignment-expression and E is the assignment-expression.

(2.4) — 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. 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\langle U\rangle. Deduce a value for U using the rules of template argument deduction (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:

auto x1 = { 1, 2 }; // decltype(x1) is std::initializer\_list\langle int\rangle
dacltype(x2) is std::initializer\_list\langle int\rangle
auto x3( 1, 2 ); // decltype(x3) is std::initializer\_list\langle int\rangle
auto x4 = { 3 }; // decltype(x4) is std::initializer\_list\langle int\rangle
auto x5( 3 ); // decltype(x5) is int
—end example]

[Example 2:
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:

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 9.2.9.5, as though E had been the operand of the decltype.

[Example 3:

int i;
int&& f();
auto x2a(i); // decltype(x2a) is int
dacltype(auto) x2d(i); // decltype(x2d) is int
auto x3a = i; // decltype(x3a) is int
dacltype(auto) x3d = i; // decltype(x3d) is int
auto x4a = (i); // decltype(x4a) is int
ndacltype(auto) x4d = (i); // decltype(x4d) is int&
auto x5a = f(); // decltype(x5a) is int
ndacltype(auto) x5d = f(); // decltype(x5d) is int&
auto x6a = { 1, 2 }; // decltype(x6a) is std::initializer\_list\langle int\rangle
dacltype(auto) x6d = { 1, 2 }; // error: { 1, 2 } is not an expression
auto *x7a = &i; // decltype(x7a) is int*
dacltype(auto)*x7d = &i; // error: declared type is not plain decltype(auto)
—end example]

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.

9.2.9.7 Deduced class template specialization types

1 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:

template <class ... T> struct A {
    A(T... ) {};
};
a x[29]{}; // error: no declarator operators allowed
const A 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.

2 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.

3 [Example 2:

```cpp
template<class T> struct container {
    container(T t) {}
    template<class Iter> container(Iter beg, Iter end);
};

container<Iter b, Iter e> c = container<typename std::iterator_traits<Iter>::value_type>{};
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]

1 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.

```
init-declarator-list:
  init-declarator
  init-declarator-list , init-declarator
```

2 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 class 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]

3 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,

```
T D1, D2, ... Dn;
```

is usually equivalent to

```
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

```
struct S { /* ... */ ];
S S, T; // declare two instances of struct S
```

which is not equivalent to

```
struct S { /* ... */ ];
S S;
S T; // error
```

Another exception is when T is auto (9.2.9.6), for example:

```
auto i = 1, j = 2.0; // error: deduced types for i and j do not match
```
4 The optional requires-clause (13.1) in an init-declarator or member-declarator shall be present only if the declarator declares a templated function (9.3.4.6). When present after a declarator, the requires-clause is called the trailing requires-clause. The trailing requires-clause introduces the constraint-expression that results from interpreting its constraint-logical-or-expression as a 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
  auto f3(T a) requires true -> bool; // error: 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

```cpp
declarator:  
  ptr-declarator
  noptr-declarator parameters-and-qualifiers trailing-return-type

ptr-declarator:  
  noptr-declarator
  ptr-operator ptr-declarator

nopr-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 [dcl.name]

1 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, which is syntactically a declaration for a variable or function of that type that omits the name of the entity.
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 i // int i
int *pi // int *pi
int (*p3i)[3] // int (*p3i)[3]
int *f() // int *f()
int (*p)(double) // int (*p)(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

2 A type can also be named (often more easily) by using a `typedef` (9.2.4).

### 9.3.3 Ambiguity resolution

1 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 a function declaration with a redundant set of parentheses around a parameter name and an object declaration with a function-style cast as the initializer. Just as for the ambiguities mentioned in 8.9, the resolution is to consider any construct that could possibly be a declaration a declaration.

**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);  
};

void foo(double a) {  
    S w(int(a));  // function declaration  
    S x(int());   // function declaration  
    S y((int(a))); // object declaration  
    S y((int)a);  // object declaration  
    S z = int(a); // object declaration  
}
```
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.

Example 2:

```cpp
template <class T> struct X {};
template <int N> struct Y {};
X<int()> a; // type-id
X<int()> b; // expression (ill-formed)
Y<int()> c; // type-id (ill-formed)
Y<int()> 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)
}
```

Example 3:

```cpp
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,

```cpp
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

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.

If the declaration is a friend declaration:

1. The declarator does not bind a name.
2. If the id-expression E in the declarator-id of the declarator is a qualified-id or a template-id:
3. 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.
(2.2.3) — 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:
   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*);  // #2, more specialized than #1
      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 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:

```c
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 X::r() {/* ... */} // error: r cannot be declared by qualified-id
```

Example 4: In the declaration `int unsigned i;` the type specifiers `int unsigned` determine the type "unsigned int" (9.2.9.3). —end example]  

Thus, (for each declarator) a declaration has the form

```
T D
```

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.

First, the `decl-specifier-seq` determines a type. In a declaration

```
T D
```

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]

In a declaration `attribute-specifier-seq_opt T D` where $D$ is an unadorned name, the type of the declared entity is "$T$".

In a declaration `T D` where $D$ has the form

```
(D1)
```

the type of the contained declarator-id is the same as that of the contained declarator-id in the declaration

```
T D1
```

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

```
* 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

```
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 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:

\[
\begin{align*}
i &= ci; \\
\*cp &= ci; \\
pc++;
\end{align*}
\]

Examples of ill-formed operations are:

\[
\begin{align*}
\text{ci} &= 1; \\
\text{ci}++;
\end{align*}
\]

Examples of ill-formed operations are:

\[
\begin{align*}
\text{ci} &= 1; \\
\text{ci}++;
\end{align*}
\]

Examples of ill-formed operations are:

\[
\begin{align*}
\text{ci} &= 1; \\
\text{ci}++;
\end{align*}
\]

Each is unacceptable because it would either change the value of an object declared \texttt{const} or allow it to be changed through a cv-unqualified pointer later, for example:

\[
\begin{align*}
\*ppc &= \&ci; &\text{// OK, but would make } p \text{ point to } ci \text{ because of previous error} \\
\*p &= 5; &\text{// clobber } ci
\end{align*}
\]

See also § 7.6.19 and 9.4.

[Note 1: Forming a pointer to reference type is ill-formed; see 9.3.4.3. Forming a function pointer type is ill-formed if the function type has \texttt{cv-qualifiers} or a \texttt{ref-qualifier}; see 9.3.4.6. Since the address of a bit-field (11.4.10) cannot be taken, a pointer can never point to a bit-field. — end note]

9.3.4.3 References

1 In a declaration \( T \ D \) where \( D \) has either of the forms

\[
&\text{attribute-specifier-seq}_{\text{opt}}\ D1 \\
&\&\text{attribute-specifier-seq}_{\text{opt}}\ D1
\]

and the type of the contained \texttt{declarator-id} in the declaration \( T \ D1 \) is “\texttt{derived-declarator-type-list} \( T \)”, the type of the \texttt{declarator-id} in \( D \) is “\texttt{derived-declarator-type-list} \texttt{reference to} \( T \)”. The optional \texttt{attribute-specifier-seq} appertains to the reference type. Cv-qualified references are ill-formed except when the cv-qualifiers are introduced through the use of a \texttt{typedef-name} (9.2.4, 13.2) or \texttt{decltype-specifier} (9.2.9.5), in which case the cv-qualifiers are ignored.

[Example 1:

\[
\text{typedef int} & A; \\
\text{const A a}ref = 3; \quad \text{// error: lvalue reference to non-const initialized with rvalue}
\]

The type of \texttt{a}ref is “lvalue reference to \texttt{int}”, not “lvalue reference to \texttt{const int}”. — end example]

[Note 1: A reference can be thought of as a name of an object. — end note]

A declarator that specifies the type “reference to \texttt{cv void}” is ill-formed.

2 A reference type that is declared using \& is called an \texttt{lvalue reference}, and a reference type that is declared using \&\& is called an \texttt{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:

\[
\text{void f(double} & a \) \{ \ a += 3.14; \} \\
// ...
\]

\[
\text{double } d = 0; \\
\text{f(d);}
\]

declares \( a \) to be a reference parameter of \( f \) so the call \( f(d) \) will add 3.14 to \( d \).

\[
\text{int } v[20]; \\
// ...
\]

\[
\text{int} & g(int i) \{ \text{return } v[i]; \} \\
// ...
\]

\[
g(3) = 7;
\]

§ 9.3.4.3
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,

\[
\text{struct link } \\
\text{ link* next; } \\
\}
\]

\[
\text{link* first; }
\]

\[
\text{void } h(\text{link* }& p) \{ \\
\text{ } \text{// } p \text{ is a reference to pointer } \\
\text{ } p->\text{next } = \text{ first; } \\
\text{ } \text{first } = \text{ p; } \\
\text{ } p = 0; \\
\}
\]

\[
\text{void } k() \\
\text{ } \text{link* } q \text{ = new link; } \\
\text{ } h(q); \\
\}
\]
deacls \( p \) to be a reference to a pointer to \( \text{link} \) so \( h(q) \) will leave \( q \) with the value zero. See also 9.4.4. — end example]

4 It is unspecified whether or not a reference requires storage (6.7.5).

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 \texttt{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. A reference shall be initialized to refer to a valid object or function.

[Note 2: In particular, a null reference cannot exist in a well-defined program, because the only way to create such a reference would be to bind it to the “object” obtained by indirection through a null pointer, which causes undefined behavior. As described in 11.4.10, a reference cannot be bound directly to a bit-field. — end note]

6 If a \texttt{typedef-name} (9.2.4, 13.2) or a \texttt{decltype-specifier} (9.2.9.5) denotes a type \( \text{TR} \) that is a reference to a type \( T \), an attempt to create the type “lvalue reference to \texttt{cv TR}” creates the type “lvalue reference to \( T \)”, while an attempt to create the type “rvalue reference to \texttt{cv TR}” creates the type \( \text{TR} \).

[Note 3: This rule is known as reference collapsing. — end note]

[Example 3:

\[
\text{int } i; \\
\text{typedef } \text{int} & \text{LRI;} \\
\text{typedef } \text{int} && \text{RRI;} \\
\]

\[
\text{LRI} & \text{r1 } = \text{i;} \quad \text{// } \text{r1 } \text{has the type } \text{int} & \\
\text{const LRI} & \text{r2 } = \text{i;} \quad \text{// } \text{r2 } \text{has the type } \text{int} & \\
\text{const LRI} && \text{r3 } = \text{i;} \quad \text{// } \text{r3 } \text{has the type } \text{int} && \\
\]

\[
\text{RRI} & \text{r4 } = \text{i;} \quad \text{// } \text{r4 } \text{has the type } \text{int} & \\
\text{RRI} && \text{r5 } = \text{5;} \quad \text{// } \text{r5 } \text{has the type } \text{int} && \\
\text{decltype(r2)} & \text{r6 } = \text{i;} \quad \text{// } \text{r6 } \text{has the type } \text{int} & \\
\text{decltype(r2)} && \text{r7 } = \text{i;} \quad \text{// } \text{r7 } \text{has the type } \text{int} && \\
\]

— end example]

7 [Note 4: Forming a reference to function type is ill-formed if the function type has \texttt{cv-qualifiers} or a \texttt{ref-qualifier}; see 9.3.4.6. — end note]

9.3.4.4 Pointers to members [dcl.mpnt]

1 The component names of a \texttt{ptr-operator} are those of its \texttt{nested-name-specifier}, if any.

2 In a declaration \( T \ D \) where \( D \) has the form

\[
\text{nested-name-specifier } * \text{ attribute-specifier-seqopt } \text{cv-qualifier-seqopt } D1
\]

and the \texttt{nested-name-specifier} denotes a class, and the type of the contained \texttt{declarator-id} in the declaration \( T \ D1 \) is “\texttt{derived-declarator-type-list} \( T' \)”, the type of the \texttt{declarator-id} in \( D \) is “\texttt{derived-declarator-type-list} \texttt{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.

3 [Example 1:

```c
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:

```c
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]

4 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”.

5 [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 [dcl.array]

1 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.

2 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.

3 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.

4 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:

```c
float fa[17], *afp[17];
```

declares an array of float numbers and an array of pointers to float numbers. — end example]

5 Any type of the form “cv-qualifier-seq array of N U” is adjusted to “array of N cv-qualifier-seq U”, and similarly for “array of unknown bound of U”.

[Example 2:

```c
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-qualifier-seq U” has cv-qualified type; see 6.8.4. —end note]

6 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.

7 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”.

8 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 } —end example]

9 [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 × 5 × 7. Any of the expressions x3d, 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 × 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 sizeof(int) × 5 × 7. The result of the addition and indirection is an lvalue denoting the i\textsuperscript{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\textsuperscript{th} array element of the i\textsuperscript{th} array element of x3d (an array of seven integers), and x3d[i][j][k] is an lvalue denoting the k\textsuperscript{th} array element of the j\textsuperscript{th} array element of the i\textsuperscript{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]

10 [Note 4: Conversions affecting expressions of array type are described in 7.3.3. —end note]

11 [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 [decl.fct]

1 In a declaration T D where D has the form

\[
D1 \ ( parameter-declaration-clause ) \ cv-qualifier-seq_opt \nref-qualifier_opt \noexcept-specifier_opt \attribute-specifier-seq_opt
\]

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 noexcept_opt function of parameter-type-list cv-qualifier-seq_opt ref-qualifier_opt returning T”, where

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— the parameter-type-list is derived from the parameter-declaration-clause as described below and
— the optional noexcept is present if and only if the exception specification (14.5) is non-throwing.

The optional attribute-specifier-seq appertains to the function type.

2 In a declaration $T$ $D$ where $D$ has the form

\[
D1 \ ( \text{parameter-declaration-clause} \ ) \ cv-qualifier-seq_opt
\]

\[
\text{ref-qualifier_opt\ noexcept-specifier_opt\ attribute-specifier-seq_opt}\ \text{trailing-return-type}
\]

and the type of the contained declarator-id in the declaration $T$ $D$ is "derived-declarator-type-list $T$", $T$ shall be the single type-specifier auto. The type of the declarator-id in $D$ is "derived-declarator-type-list noexcept_opt function of parameter-type-list cv-qualifier-seq_opt ref-qualifier_opt returning U", where

— the parameter-type-list is derived from the parameter-declaration-clause as described below,
— $U$ is the type specified by the trailing-return-type, and
— the optional noexcept is present if and only if the exception specification is non-throwing.

The optional attribute-specifier-seq appertains to the function type.

A type of either form is a function type.\(^{81}\)

\[
\text{parameter-declaration-clause:}
\]

\[
\text{parameter-declaration-list_opt \ ..._opt}
\]

\[
\text{parameter-declaration-list} , \ \text{parameter-declaration}
\]

\[
\text{parameter-declaration:}
\]

\[
\text{attribute-specifier-seq_opt\ this_opt\ decl-specifier-seq\ declarator}
\]

\[
\text{attribute-specifier-seq_opt\ this_opt\ decl-specifier-seq\ declarator=initializer-clause}
\]

\[
\text{attribute-specifier-seq_opt\ this_opt\ decl-specifier-seq\ abstract-declarator_opt}
\]

\[
\text{attribute-specifier-seq_opt\ this_opt\ decl-specifier-seq\ abstract-declarator_opt=initializer-clause}
\]

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.5. 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

\[
\text{int printf(const char*, ...);}\]

declares a function that can be called with varying numbers and types of arguments.

\[
\text{printf("hello world");}
\]

\[
\text{printf("a=%d b=%d", a, b);}\]

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

\(^{81}\) As indicated by syntax, cv-qualifiers are a significant component in function return types.

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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*); // #1
void f(char[]) {}; // defines #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]

6 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 either:

(6.1) — a member-declarator that declares a member function (11.4), or

(6.2) — a lambda-declarator (7.5.5).

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:

```c
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]

7 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.

8 The object parameter of a non-static member function is either the explicit object parameter or the implicit object parameter (12.2.2).

9 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]

10 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:

(10.1) — the function type for a non-static member function,

(10.2) — the function type to which a pointer to member refers,

(10.3) — the top-level function type of a function typedef declaration or alias-declaration,
— the \textit{type-id} in the default argument of a \textit{type-parameter} (13.2), or
— the \textit{type-id} of a \textit{template-argument} for a \textit{type-parameter} (13.4.2).

[Example 4:
  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]

11 The effect of a \textit{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 \textit{cv-qualifier-seq} is not a cv-qualified type; there are no cv-qualified function types. — end note]

[Example 5:
  typedef void F();
  struct S {
    const F f; // OK, equivalent to: void f();
  };
— end example]

12 The return type, the parameter-type-list, the \textit{ref-qualifier}, the \textit{cv-qualifier-seq}, and the exception specification, but not the default arguments (9.3.4.7) or the trailing \textit{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
  
  int fseek(FILE*, long, int);
  
  declares a function taking three arguments of the specified types, and returning \texttt{int} (9.2.9). — end example]

14 [Note 7: A single name can be used for several different functions in a single scope; this is function overloading (Clause 12). — end note]

15 The return type shall be a non-array object type, a reference type, or \textit{cv void}.

[Note 8: An array of placeholder type is considered an array type. — end note]

16 A volatile-qualified return type is deprecated; see D.5.

17 Types shall not be defined in return or parameter types.

18 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:
  typedef void F();
  F fv; // OK, equivalent to void fv();
  F fv {} // error
  void fv() {} // OK, definition of fv
— end example]

19 An identifier can optionally be provided as a parameter name; if present in a function definition (9.5), it names a parameter.

[Note 9: In particular, parameter names are also optional in function definitions and names used for a parameter in different declarations and the definition of a function need not be the same. — end note]

[Example 8: The declaration
  
  int i,
  *pi,
  f(),
  *fpi(int),
  (*pif)(const char*, const char*),
  (*fpif(int))(int);

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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 fpi, 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]

typedef int IFUNC(int);
IFUNC* fpif(int);

or

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:

-template <class T, class U> auto add(T t, U u) -> decltype(t + u);

rather than

-template <class T, class U> decltype((*(T*)0) + (*(U*)0)) add(T t, U u);

—end note

21 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]

22 An abbreviated function template is a function declaration that has one or more generic parameter type placeholders (9.2.9.6). 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:]

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:

-template<C1 T, C2 U> void g1(const C1 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.

-template<
void g1<int>(const int*, const double&); // OK, specialization of g1<int, const double>
—end example

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:]

-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.

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

A function declaration at block scope shall not declare an abbreviated function template.

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:
    template<typename... T> void f(T (*...t)(int, int));
    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.\(^2\)

9.3.4.7 Default arguments

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]

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]

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); in the latter case, the initializer-clause shall be an assignment-expression. 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.\(^3\)

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.

---

82) One can explicitly disambiguate the parse either by introducing a comma (so the ellipsis will be parsed as part of the parameter-declaration-clause) or by introducing a name for the parameter (so the ellipsis will be parsed as part of the declarator-id).

83) This means that default arguments cannot appear, for example, in declarations of pointers to functions, references to functions, or typedef declarations.
[Note 2: A default argument cannot be redefined by a later declaration (not even to the same value) (6.3). — end note]

[Example 2:]
```c
void g(int = 0, ...); // OK, ellipsis is not a parameter so it can follow
void f(int, int);
void f(int, int = 7);
void h() {
  f(3); // OK, calls f(3, 7)
  void f(int = 1, int);
    // error: does not use default from surrounding scope
}
void m() {
  void f(int, int); // has no defaults
  f(4); // error: wrong number of arguments
  void f(int, int = 5); // OK
  f(4); // OK, calls f(4, 5);
  void f(int, int = 5); // error: cannot redefine, even to same value
}
void n() {
  f(6); // OK, calls f(6, 7)
}
```

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.

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. Name lookup and checking of semantic constraints for default arguments of templated functions are performed as described in 13.9.2.

[Example 3: In the following code, \( g \) will be called with the value \( f(2) \):
```c
int a = 1;
int f(int);
int g(int x = f(a)); // default argument: \( f(\cdot) \)

void h() {
  a = 2;
  { // g(\( f(\cdot) \))
    int a = 3;
    g();
  }
}
```

—end example]

[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]

Except for member functions of class templates, 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 class template shall be specified on the initial declaration of the member function within the class template.

[Example 4:]

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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 = 88, int j) {} // in this translation unit, C::g can be called with no argument
— end example]

7 [Note 4: A local variable cannot be odr-used (6.3) in a default argument. — end note]

[Example 5]:
void f() {
    int i;
    extern void g(int x = i);  // error
    extern void h(int x = sizeof(i));  // OK
    // ...
}
— end example]

8 [Note 5: The keyword this cannot appear in a default argument of a member function; see 7.5.2.]

[Example 6]:
class A {
    void f(A* p = this) { }  // error
};
— end example]
— end note]

9 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]:
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.

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]:
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()
}
—end example]

9.4 Initializers

9.4.1 General

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:
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);
  — end example]

[Note 2: Default arguments are more restricted; see 9.3.4.7. — end note]

[Note 3: The order of initialization of variables with static storage duration is described in 6.9.3 and 8.8. — end note]

5 A declaration D of a variable with linkage shall not have an initializer if D inhabits a block scope.

6 To zero-initialize an object or reference of type T means:

(6.1) — 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.

(6.2) — 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;

(6.3) — 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;

(6.4) — if T is an array type, each element is zero-initialized;

(6.5) — if T is a reference type, no initialization is performed.

7 To default-initialize an object of type T means:

(7.1) — 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 () is chosen through overload resolution (12.2). The constructor thus selected is called, with an empty argument list, to initialize the object.

(7.2) — If T is an array type, each element is default-initialized.

(7.3) — 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

(8.1) — 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,

(8.2) — if T is a union with at least one non-static data member, exactly one variant member has a default member initializer,

(8.3) — 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

(8.4) — 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:

(9.1) — if T is a (possibly cv-qualified) class type (Clause 11), then

84) 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 \( T \) has either no default constructor (11.4.5.2) or a default constructor that is user-provided or deleted, then the object is default-initialized;

— otherwise, the object is zero-initialized and the semantic constraints for default-initialization are checked, and if \( T \) has a non-trivial default constructor, the object is default-initialized;

— if \( T \) is an array type, then each element is value-initialized;

— otherwise, the object is zero-initialized.

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]

If no initializer is specified for an object, the object is default-initialized.

If the entity being initialized does not have class type, the \textit{expression-list} in a parenthesized initializer shall be a single expression.

The initialization that occurs in the \( = \) form of a \textit{brace-or-equal-initializer} or \textit{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 (9.4.2), is called \textit{copy-initialization}.

[Note 5: Copy-initialization can invoke a move (11.4.5.3). — end note]

The initialization that occurs

— for an \textit{initializer} that is a parenthesized \textit{expression-list} or a \textit{braced-init-list},

— for a \textit{new-initializer} (7.6.2.8),

— in a \textit{static_cast} expression (7.6.1.9),

— in a functional notation type conversion (7.6.1.4), and

— 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 type of the object or reference being initialized and the \textit{source type} is the type of the \textit{initializer} expression. If the \textit{initializer} is not a single (possibly parenthesized) \textit{expression}, the \textit{source type} is not defined.

— If the \textit{initializer} is a (non-parenthesized) \textit{braced-init-list} or is \( = \) \textit{braced-init-list}, the object or reference is \textit{list-initialized} (9.4.5).

— If the \textit{destination type} is a reference type, see 9.4.4.

— If the \textit{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 \textit{initializer} is a \textit{string-literal}, see 9.4.3.

— If the \textit{initializer} is (\texttt{}), the object is value-initialized.

[Note 6: Since (\texttt{}) is not permitted by the syntax for \textit{initializer}, \( \texttt{X a;} \)

is not the declaration of an object of class \( \texttt{X} \), but the declaration of a function taking no argument and returning an \( \texttt{X} \). The form (\texttt{}) is permitted in certain other initialization contexts (7.6.2.8, 7.6.1.4, 11.9.3). — end note]

— Otherwise, if the \textit{destination type} is an array, the \textit{object} is initialized as follows. Let \( x_1, \ldots, x_k \) be the elements of the \textit{expression-list}. If the \textit{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 \textit{destination type} is a (possibly \texttt{cv-qualified}) class type:

— If the \textit{initializer expression} is a prvalue and the \texttt{cv-unqualified} version of the \textit{source type} is the same class as the class of the \textit{destination}, the \textit{initializer expression} is used to initialize the \textit{destination object}.

[Example 2: \( \texttt{T x = T(T(T()));} \) calls the \( \texttt{T} \) default constructor to initialize \( x \). — end example]
Otherwise, if the initialization is direct-initialization, or if it is copy-initialization where the cv-unqualified version of the source type is the same class as, or a derived class of, the class of the destination, 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 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 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 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) are permitted, 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.

Example 3:
```c++
struct A {
    int a;
    int&& r;
};

int f();
int n = 10;
A a1{1, f()};
   // OK, lifetime is extended
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. 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) will be used, if necessary, to convert the initializer expression to the cv-unqualified version 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`.]

§ 9.4.1
An *initializer-clause* followed by an ellipsis is a pack expansion (13.7.4).

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

**1** An *aggregate* is an array or a class (Clause 11) with

- no user-declared or inherited constructors (11.4.5),
- no private or protected direct non-static data members (11.8),
- no virtual functions (11.7.3), and
- no virtual, private, or protected base classes (11.7.2).

[Note 1: Aggregate initialization does not allow accessing protected and private base class’ members or constructors. — end note]

**2** The *elements* of an aggregate are:

- for an array, the array elements in increasing subscript order, or
- 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.

**3** 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:

- 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.
- If the initializer list is a brace-enclosed initializer-list, the explicitly initialized elements of the aggregate are the first \( n \) elements of the aggregate, where \( n \) is the number of elements in the initializer list.
- Otherwise, the initializer list must be \( \{ \} \), and there are no explicitly initialized elements.

**4** For each explicitly initialized element:

- 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 designated-initializer-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:

```
struct C {
  union {
    int a;
```]
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N4910

const char* p;
};

int x;
} c = { .a = 1, .x = 3 };
initializes c.a with 1 and c.x with 3. — end example

— Otherwise, the element is copy-initialized from the corresponding initializer-clause or is initialized with the brace-or-equal-initializer of the corresponding designated-initializer-clause. If that initializer is of the form assignment-expression or = assignment-expression and a narrowing conversion (9.4.5) is required to convert the expression, the program is ill-formed.

[Note 2: 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:

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, a.b.j with 3.

struct base1 { int b1, b2 = 42; };
struct base2 {
    base2() {
        b3 = 42;
    }
    int b3;
};
struct derived : base1, base2 {
    int d;
};

derived d1{{1, 2}, {}, 4};
derived 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, d2.d with 4. — end example]

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.

[Example 3:

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'), and in

struct X { int i, j, k = 42; };
X a[1] = { 1, 2, 3, 4, 5, 6 };
X b[2] = { { 1, 2, 3 }, { 4, 5, 6 } };

a and b have the same value

§ 9.4.2
struct A {
    string a;
    int b = 42;
    int c = -1;
};

A{.c=21} has the following steps:

(6.1) — Initialize a with {}
(6.2) — Initialize b with = 42
(6.3) — 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.

9 The destructor for each element of class type is potentially invoked (11.4.7) from the context where the
aggregate initialization occurs.

[Note 3: This provision ensures that destructors can be called for fully-constructed subobjects in case an exception is
thrown (14.3). — end note]

10 An array of unknown bound initialized with a brace-enclosed *initializer-list* containing *n* *initializer-clauses* is
defined as having *n* elements (9.3.4.5).

[Example 4:

```c
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]

An array of unknown bound shall not be initialized with an empty *braced-init-list* {}.

[Note 4: 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 5:

```c
struct S {
    int y[] = { 0 };
};
```

// error: non-static data member of incomplete type
— end example]

— end note]

11 [Note 5: Static data members, non-static data members of anonymous union members, and unnamed bit-fields are
not considered elements of the aggregate.

[Example 6:

```c
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]

12 An *initializer-list* is ill-formed if the number of *initializer-clauses* exceeds the number of elements of the
aggregate.

[Example 7:

85 The syntax provides for empty *braced-init-lists*, but nonetheless C++ does not have zero length arrays.
char cv[4] = { 'a', 's', 'd', 'f', 0 }; // error
is ill-formed. —end example]

13 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:

```cpp
struct A;
extern A a;
struct A {
  const A& a1 { A{a,a} }; // OK
  const A& a2 { A{} }; // error
};
A a(a,a); // OK

struct B {
  int n = B{}.n; // error
};
```
—end example]

14 If an aggregate class C contains a subaggregate element e with no elements, the initializer-clause for e shall not be omitted from an initializer-list for an object of type C unless the initializer-clauses for all elements of C following e are also omitted.

[Example 9:

```cpp
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]

15 When initializing a multi-dimensional array, the initializer-clauses initialize the elements with the last (rightmost) index of the array varying the fastest (9.3.4.5).

[Example 10:

```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,
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]

16 Braces can be elided in an initializer-list as follows. If the initializer-list begins with a left brace, then the succeeding comma-separated list of initializer-clauses initializes the elements of a subaggregate; it is erroneous for there to be more initializer-clauses than elements. If, however, the initializer-list for a subaggregate does not begin with a left brace, then only enough initializer-clauses from the list are taken to initialize the elements of the subaggregate; any remaining initializer-clauses are left to initialize the next element of the aggregate of which the current subaggregate is an element.

[Example 11:

```cpp
float y[4][3] = {
  { 1, 3, 5 },
  { 2, 4, 6 },
};
```
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 \( \text{float}() \), 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

17 All implicit type conversions (7.3) are considered when initializing the element with an assignment-expression. If the assignment-expression can initialize an element, the element is initialized. Otherwise, if the element is itself a subaggregate, brace elision is assumed and the assignment-expression is considered for the initialization of the first element of the subaggregate.

[Note 6: As specified above, brace elision cannot apply to subaggregates with no elements; an initializer-clause for the entire subobject is required. —end note]

[Example 12:

```c
struct A {
    int i;
    operator int();
};
struct B {
    A a1, a2;
    int z;
};
A a;
B b = { 4, a, a };
```

Braces are elided around the initializer-clause for \( b.a1.i \). \( b.a1.i \) is initialized with 4, \( b.a2 \) is initialized with \( a \), \( b.z \) is initialized with whatever \( a.\text{operator int}() \) returns. —end example]

18 [Note 7: 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]

19 [Note 8: 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]

20 When a union is initialized with an initializer list, there shall not be more than one explicitly initialized element.

[Example 13:

```c
union u { int a; const char* b; };;
 u a = { 1 };
 u b = a;
 u c = 1;
 u d = { 0, "asdf" };   // error
 u e = { "asdf" };     // error
 u f = { .b = "asdf" }; // error
 u g = { .a = 1, .b = "asdf" }; // error
```

—end example]

21 [Note 9: 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 can 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). Successive characters of the value of the string-literal initialize the elements of the array.

[Example 1:
There shall not be more initializers than there are array elements.

[Example 2:
```c
char cv[4] = "asdf";  // error
```
ill-formed since there is no space for the implied trailing ‘\0’. — end example]

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:
```c
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;
  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(i);
  // calls function g
  int a[3];
  int (&ra)[3] = a;  // ra refers to the array a
  ra[1] = i;  // modifies a[1]
}
```
— end example]

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.

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:
```c
int& r1;  // error: initializer missing
extern int& r2;  // OK
```
— end example]

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 cv1 T1” 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.

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
(5.1.1) is a lvalue (but is not a bit-field), and “cv1 T1” is reference-compatible with “cv2 T2”, or
(5.1.2) 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”\(^{86}\) (this conversion is selected by enumerating the applicable conversion functions (12.2.2.7) and choosing the best one through overload resolution (12.2)),

---

\(^{86}\) This requires a conversion function (11.4.8.3) returning a reference type.
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
cost 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
cost A& rca = b; // rca refers to A subobject in b
int& ir = B(); // ir refers to the result of B::operator int&
—end example]

(5.2) — 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]

(5.3) — Otherwise, if the initializer expression

(5.3.1) — is an rvalue (but not a bit-field) or function lvalue and “cv1 T1” is reference-compatible with “cv2 T2”, or

(5.3.2) — 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 or function lvalue of 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, its type T4 is adjusted to type “cv1 T4” (7.3.6) and the temporary materialization conversion (7.3.5) is applied. 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();
cost A& rca2 = f(); // binds to the A subobject of the B rvalue.
A& ra = f(); // same as above
struct X {
operator B();
operator int&();
} x;
cost A& r = 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
—end example]

(5.4) — Otherwise:

(5.4.1) — If T1 or T2 is a class type and T1 is not reference-related to T2, user-defined conversions are considered using the rules for copy-initialization of an object of type “cv1 T1” 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 “T1”. The temporary materialization conversion is applied, considering the type of the prvalue to be “cv1 T1”, and the reference is bound to the result.

If T1 is reference-related to T2:

— cv1 shall be the same cv-qualification as, or greater cv-qualification than, cv2; and

— if the reference is an rvalue reference, the initializer expression shall not be an lvalue.

[Example 6:

```c
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
}
```

```c
const double& rcd2 = 2; // rcd2 refers to temporary with 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 & { 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 related type
struct X { operator int&(); }
int& rri2 = X(); // error: result of conversion function is lvalue of 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.

[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.

[Note 1: List-initialization can be used

1. as the initializer in a variable definition (9.4)
2. as the initializer in a new-expression (7.6.2.8)
3. in a return statement (8.7.4)
4. as a for-range-initializer (8.6)
5. as a function argument (7.6.1.3)
6. as a subscript (7.6.1.2)
7. as an argument to a constructor invocation (9.4, 7.6.1.4)
8. as an initializer for a non-static data member (11.4)
9. in a mem-initializer (11.9.3)
A constructor is an **initializer-list constructor** if its first parameter is of type `std::initializer_list<E>` or reference to `cv std::initializer_list<E>` for some type E, and either there are no other parameters or else all other parameters have default arguments (9.3.4.7).

**Note 2:** Initializer-list constructors are favored over other constructors in list-initialization (12.2.2.8). Passing an initializer list as the argument to the constructor template `template<class T> C(T)` of a class `C` does not create an initializer-list constructor, because an initializer list argument causes the corresponding parameter to be a non-deduced context (13.10.3.2). **— end note**

The template `std::initializer_list` is not predefined; if the header `<initializer_list>` is not imported or included prior to a use of `std::initializer_list` — even an implicit use in which the type is not named (9.2.9.6) — the program is ill-formed.

List-initialization of an object or reference of type `T` is defined as follows:

1. If the braced-init-list contains a designated-initializer-list, `T` shall be an aggregate class. The ordered identifiers in the designators of the designated-initializer-list shall form a subsequence of the ordered identifiers in the direct non-static data members of `T`. Aggregate initialization is performed (9.4.2).

   **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
   ```
   **— end example**

2. If `T` is an aggregate class and the initializer list has a single element of type `cv U`, where `U` is `T` or a class derived from `T`, the object is initialized from that element (by copy-initialization for copy-list-initialization, or by direct-initialization for direct-list-initialization).

3. Otherwise, if `T` is a character array and the initializer list has a single element that is an appropriately-typed string-literal (9.4.3), initialization is performed as described in that subclause.

4. Otherwise, if `T` is an aggregate, aggregate initialization is performed (9.4.2).

   **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**

5. Otherwise, if the initializer list has no elements and `T` is a class type with a default constructor, the object is value-initialized.

6. Otherwise, if `T` is a specialization of `std::initializer_list<E>`, the object is constructed as described below.

§ 9.4.5
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:**

```cpp
struct S {
    S(std::initializer_list<double>);  // #1
    S(std::initializer_list<int>);     // #2
    S();                             // #3
    // ...
};
S s1 = { 1.0, 2.0, 3.0 };         // invoke #1
S s2 = { 1, 2, 3 };               // invoke #2
S s3 = {};                        // invoke #3
```

**Example 5:**

```cpp
struct Map {
    Map(std::initializer_list<std::pair<std::string,int>>);
};
Map ship = {{"Sophie",14}, {"Surprise",28}};
```

**Example 6:**

```cpp
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
```

Otherwise, if \( T \) is an enumeration with a fixed underlying type (9.7.1) \( U \), the initializer-list has a single element \( v \), \( v \) 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:**

```cpp
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
```

```cpp
struct A { byte b; }; 
A a1 = { 42 };                  // error
A a2 = { byte{ 42 } };          // OK
```

```cpp
void f(byte);
f({ 42 });                     // error
```

```cpp
enum class Handle : uint32_t { Invalid = 0 }; 
Handle h { 42 };                // OK
```

**Example 8:**

Otherwise, if the initializer list 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:**
int x1 {2}; // OK
int x2 {2.0}; // error: narrowing

— end example

— Otherwise, if T is a reference type, a prvalue is generated. The prvalue initializes its result object by copy-list-initialization. The prvalue is then used to direct-initialize the reference. The type of the temporary is the type referenced by T, unless T is “reference to array of unknown bound of U”, in which case the type of the temporary 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]:

```cpp
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 lvalue
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

— Otherwise, if the initializer list has no elements, the object is value-initialized.

[Example 10]:

```cpp
int** pp {};// initialized to null pointer
```

— end example

— Otherwise, the program is ill-formed.

[Example 11]:

```cpp
struct A { int i; int j; };
A a1 { 1, 2 }; // aggregate initialization
A a2 { 1.2 }; // error: narrowing
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]
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. Each element of that 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 is required 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.

[Example 12:

```cpp
struct X {
    X(std::initializer_list<double> v);
};
X x{ 1, 2, 3 };  
```

The initialization will be implemented in a way roughly equivalent to this:

```cpp
const double __a[3] = {double{1}, double{2}, double{3}};
X x(std::initializer_list<double>(__a, __a+3));
```

assuming that the implementation can construct an `initializer_list` object with a pair of pointers. — end example]

The 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 13:

```cpp
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]

[Note 6: The implementation is free to allocate the array in read-only memory if an explicit array with the same initializer can be so allocated. — end note]

A narrowing conversion is an implicit conversion

(7.1) — from a floating-point type to an integer type, or
(7.2) — from long double to double or float, or from double to float, except where the source is a constant expression and the actual value after conversion is within the range of values that can be represented (even if it cannot be represented exactly), 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 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;  // OK, though it potentially narrows (in this case, it does narrow)
char c1 = x;        // error: potentially narrows
char c2{y};         // error: narrows (assuming char is 8 bits)
char c3{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 In general [dcl.fct.def.general]

Function definitions have the form

```
function-definition:
    attribute-specifier-seq
    decl-specifier-seq
    virt-specifier-seq
    declarator
    function-body
```

```
function-body:
    ctor-initializer
    compound-statement
    function-try-block
    = default;
    = delete;
```

Any informal reference to the body of a function should be interpreted as a reference to the non-terminal `function-body`. The optional `attribute-specifier-seq` in a `function-definition` appertains to the function. A `virt-specifier-seq` can be part of a `function-definition` only if it is a `member-declaration` (11.4).

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]

```
int max(int a, int b, int c) {
    int m = (a > b) ? a : b;
    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 7.5.2. — end note]

[Note 2: Unused parameters need not be named. For example,

```
void print(int a, int) {
    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

```
static const char __func__[] = "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.\(^\text{87}\)

**Example 2:**

```c
struct S {
    S() : s(__func__) { } // OK
    const char* s;
};
void f(const char* s = __func__); // error: __func__ is undeclared
```

---

### § 9.5.2 Explicitly-defaulted functions [dcl.fct.def.default]

1. A function definition whose function-body is of the form \texttt{= default;} is called an explicitly-defaulted definition. A function that is explicitly defaulted shall

1.1 — be a special member function or a comparison operator function (12.4.3), and

1.2 — not have default arguments.

2. The type \( T_1 \) of an explicitly defaulted special member function \( F \) is allowed to differ from the type \( T_2 \) it would have had if it were implicitly declared, as follows:

2.1 — \( T_1 \) and \( T_2 \) may have differing ref-qualifiers;

2.2 — \( T_1 \) and \( T_2 \) may have differing exception specifications; and

2.3 — if \( T_2 \) has a parameter of type \( \text{const } C \& \), the corresponding parameter of \( T_1 \) may be of type \( C \& \).

If \( T_1 \) differs from \( T_2 \) in any other way, then:

2.4 — if \( F \) is an assignment operator, and the return type of \( T_1 \) differs from the return type of \( T_2 \) or \( T_1 \)'s parameter type is not a reference, the program is ill-formed;

2.5 — otherwise, if \( F \) is explicitly defaulted on its first declaration, it is defined as deleted;

2.6 — otherwise, the program is ill-formed.

3. An explicitly-defaulted function that is not defined as deleted may be declared \texttt{constexpr} or \texttt{consteval} only if it is constexpr-compatible (11.4.4, 11.10.1). 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-compatible.

4. **Example 1:**

```c
struct S {
    constexpr S() = default; // error: implicit S() is not constexpr
    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
```

```c
struct T {
    T();
    T(T&&) noexcept(false);
};
struct U {
    T t;
    U U();
    U(U&&) noexcept = default;
};
U u1;
U u2 = static_cast<U&&>(u1); // OK, calls std::terminate if T::T(T&&) throws
```

---

\(^{87}\) 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.
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), 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 defined at the point where it is explicitly defaulted; if such a function is implicitly defined as deleted, the program is ill-formed.

[Note 1: 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]

6 [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
```

9.5.3 Deleted definitions

A *deleted definition* of a function is a function definition whose *function-body* is of the form `= delete`; 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.

2 A program that refers to a deleted function implicitly or explicitly, other than to declare it, is ill-formed.

[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. —end note]

3 [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);
};
```

[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
—end example

A deleted function is implicitly an inline function (9.2.8).

[Note 2: The one-definition rule (6.3) applies to deleted definitions. — end note]

A deleted definition of a function shall be the first declaration of the function or, for an explicit specialization of a function template, the first declaration of that specialization. An implicitly declared allocation or deallocation function (6.7.5.5) shall not be defined as deleted.

[Example 4:

```c++
struct sometype {
    sometype();
};

sometype::sometype() = delete; // error: not first declaration
—end example]

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:

```c++
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;
}
—end example]

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 are 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 Pᵢ, where p₁ denotes the object parameter and pᵢ₊₁ denotes the i_th non-object function parameter for a non-static member function, and pᵢ denotes the i_th function parameter otherwise. For a non-static member function, qᵢ is an lvalue that denotes *this; any other qᵢ is an lvalue that denotes the parameter copy corresponding to pᵢ, as described below.

A coroutine behaves as if its function-body were replaced by:
{ 
    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

— the await-expression containing the call to initial_suspend is the initial suspend point, and
— the await-expression containing the call to final_suspend is the final suspend point, and
— 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 suspend point, and
— promise-type denotes the promise type, and
— the object denoted by the exposition-only name promise is the promise object of the coroutine, and
— the label denoted by the name final-suspend is defined for exposition only (8.7.5), and
— promise-constructor-arguments is determined as follows: overload resolution is performed on a promise constructor call created by assembling an argument list \( q_1 \ldots q_n \). If a viable constructor is found (12.2.3), then promise-constructor-arguments is \( (q_1, \ldots, q_n) \), otherwise promise-constructor-arguments is empty.

6 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]

7 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.

8 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 function 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.

9 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.

9.1 If any declarations are found, 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. The values \( p_1 \ldots p_n \) are the succeeding arguments.

9.2 Otherwise, a search is performed in the global scope.

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 an argument of type std::size_t.

10 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 returns 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;
  using handle = std::coroutine_handle<promise_type>;
  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;
}
```

11 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.

12 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.

13 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 (6.8.4). — 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.unhandled_exception()` exits via an exception, the coroutine is considered suspended at the final suspend point.

The expression `co_await promise.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 identifier-list as names of structured bindings. Let \( cv \) denote the cv-qualifiers in the decl-specifier-seq as names of the decl-specifier-seq (if any). A \( cv \) that includes `volatile` is deprecated; see D.5. First, a variable with a unique name \( e \) is introduced. If the assignment-expression in the initializer has array type \( cv T \) and no ref-qualifier is present, \( e \) is defined by

\[
\text{attribute-specifier-seq} \ S \ cv \ k \ e ;
\]

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

\[
\text{attribute-specifier-seq} \opt \decl-specifier-seq \ref-qualifier \opt \ e \ initializer ;
\]

where the declaration is never interpreted as a function declaration and the parts of the declaration other than the declarator-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 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 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:

```cpp
auto f() -> int[2];
auto [ x, y ] = f(); // x and y refer to elements in a copy of the array return value
auto& [ xr, yr ] = f(); // 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 `std::tuple_size<E>::value` shall be a well-formed integral constant expression and the number of elements in the 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.get<i>()`. Otherwise, the initializer is `get<i>(e)`, where `get` undergoes argument-dependent lookup (6.5.4). In either case, `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 \( U_j \) designated by either \( T_i& \) or \( T_i&\& \), where \( U_j \) is an lvalue reference if the initializer is an lvalue and an rvalue reference otherwise, variables are introduced with unique names \( r_i \) 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 \( T_i \).

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 \( e.name \) in the context of the structured binding. \( E \) shall not have an anonymous union member, and the number of elements in the 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 \( e.m_i \) (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 \( e.m_i \) otherwise. The lvalue is a bit-field if that member is a bit-field.

[Example 2:

```cpp
struct S { mutable int x1 : 2; volatile double y1; };
```
S f();
    const auto [ x, y ] = f();
The type of the id-expression x is “int”, the type of the id-expression y is “const volatile double”. — end example]

9.7 Enumerations

9.7.1 Enumeration declarations

An enumeration is a distinct type (6.8.3) with named constants. Its name becomes an enum-name within its scope.

    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

The optional attribute-specifier-seq in the enum-head and the opaque-enum-declaration appertains to the enumeration; the attributes in that attribute-specifier-seq are thereafter considered attributes of the enumeration whenever it is named. A : following “enum nested-name-specifier_opt identifier” within the decl-specifier-seq of a member-declaration is parsed as part of an 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:
    struct S {
        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).

The enumeration type declared with an enum-key of only enum is an unscoped enumeration, and its enumerators are unscoped enumerators. The enum-keys enum class and enum struct are semantically equivalent; an enumeration type declared with one of these is a scoped enumeration, and its enumerators are scoped enumerators. The optional enum-head-name shall not be omitted in the declaration of a scoped enumeration. The type-specifier-seq of an enum-base shall name an integral type; any cv-qualification is ignored. An

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opaque-enum-declaration declaring an unscoped enumeration shall not omit the enum-base. The identifiers in an enumerator-list are declared as constants, and can appear wherever constants are required. An enumerator-definition with = gives the associated enumerator the value indicated by the constant-expression. If the first enumerator has no initializer, the value of the corresponding constant is zero. An enumerator-definition without an initializer gives the enumerator the value obtained by increasing the value of the previous enumerator by one.

[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.

\[3\] An opaque-enum-declaration is either a redeclaration of an enumeration in the current scope or a declaration of a new enumeration.

[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.

\[4\] 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:

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.
2. If no initializer is specified for the first enumerator, its type is an unspecified signed integral type.
3. 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.\(^{88}\)

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).

**[Example 3]**

```c
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`.

```c
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:

```c
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
```

---

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Example 1:

```cpp
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]

Example 2:

```cpp
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
}
```

—end example] —end note]

4 [Note 2: Two using-enum-declarations that introduce two enumerators of the same name conflict.

9.8 Namespaces [basic.namespace]

9.8.1 General [basic.namespace.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
export 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 6.4.5. 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 [namespace.def]

9.8.2.1 General [namespace.def.general]

```
namespace-name:
    identifier
namespace-alias

namespace-definition:
    named-namespace-definition
    unnamed-namespace-definition
    nested-namespace-definition

named-namespace-definition:
    inline_opt namespace attribute-specifier-seq_opt identifier { namespace-body }

unnamed-namespace-definition:
    inline_opt namespace attribute-specifier-seq_opt { namespace-body }
```
nested-namespace-definition:
  namespace enclosing-namespace-specifier :: inlineopt identifier { namespace-body }

enclosing-namespace-specifier:
  identifier
  enclosing-namespace-specifier :: inlineopt identifier

namespace-body:
  declaration-seqopt

1 Every namespace-definition shall inhabit a namespace scope (6.4.5).

2 In a named-namespace-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 definitions 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

```cpp
namespace E { inlineopt namespace I { B } }
```

where the optional inline is present if and only if the identifier $I$ is preceded by inline.

[Example 2:

```cpp
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:

```c
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:
    identifier

namespace-alias-definition:
    namespace identifier = qualified-name
```

qualified-name:

```
nested-name-specifier_opt namespace-name
```

The identifier in a namespace-alias-definition becomes a namespace-alias and denotes the namespace denoted by the qualified-name.

[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]
The optional attribute-specifier-seq appertains to the using-directive.

2 [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]

3 [Note 3: A using-directive does not introduce any names. — end note]

[Example 1:

```c
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?
    }
    void f3() {
        i = 5;  // uses A::i
    }
    void f4() {
        i = 5;  // error: neither i is visible
    }
} // end example]

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:

```c
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,

```c
namespace A {
    int i;
}
namespace B {
    int i;
    int j;
namespace C {
    namespace D {
        using namespace A;
```
```cpp
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
}
— end example]

[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]

[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,

```cpp
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:

```cpp
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

1 The component names of a using-declarator are those of its nested-name-specifier and unqualified-id. Each using-declarator in a using-declaration\[90\] 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.

2 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]

3 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 (7.5.2).

[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; }
    };

\[90\] A using-declaration with more than one using-declarator is equivalent to a corresponding sequence of using-declarations with one using-declarator each.
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<B, C> x; // OK, B::f and C::f named

—end example—

4 [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 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:]
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:]
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.

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 5:]

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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 potentially conflicts with it (6.4.1), and either is reachable from the other, the program is ill-formed. 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 6:
namespace A {
    int x;
    int f(int);
    int g;
    void h();
}

namespace B {
    int i;
    struct g { }; // OK, hides struct g
    struct x { }; void f(int); void f(double); void g(char);
}

void func() {
    int i;
    using B::i; // error: conflicts
    void f(char);
    using B::f; // OK, each f is a function
    using A::f; // OK, but interferes with B::f(int)
    f(1); // error: ambiguous
    static_cast<int(*)(int)>(f)(1); // OK, calls A::f
    f(3.5); // calls B::f(double)
    using B::g;
    g('a'); // calls B::g(char)
    struct g g1; // g1 has class type B::g
    using A::g; // error: conflicts with B::g
    void h();
    using A::h;
    using B::x;
    using A::x; // OK, hides struct B::x
    x = 99; // assigns to A::x
    struct x x1; // x1 has class type B::x
}

— end example]
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 7:**

```cpp
struct B {
    virtual void f(int);
    virtual void f(char);
    void g(int);
    void h(int);
};

struct 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)
}

struct B1 {
    B1(int);
};

struct B2 {
    B2(int);
};

struct D1 : B1, B2 {
    using B1::B1;
    using B2::B2;
};

D1 d1(0);         // error: ambiguous

struct 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 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]

14 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 8:

```c
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]

15 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 9:

```c
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-seq_opt asm ( string-literal ) ;
```

The asm declaration is conditionally-supported; its meaning is 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

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:

```plaintext
linkage-specification:
  extern string-literal { declaration-seq,.. } extern string-literal declaration
```

The string-literal indicates the required language linkage. This document specifies the semantics for the string-literals "C" and "C++". Use of a string-literal other than "C" or "C++" is conditionally-supported, with implementation-defined semantics.

[Note 2: Therefore, a linkage-specification with a string-literal that is unknown to the implementation requires a diagnostic. —end note]

Recommended practice: The spelling of the string-literal 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:
```plaintext
complex sqrt(complex); // C++ language linkage by default
extern "C" { double sqrt(double); // C language linkage }
—end example]
```

4 A module-import-declaration shall not be directly contained in a linkage-specification. 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 3: 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.

[Example 2:
```plaintext
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(); // obtained from previous declaration.
}

extern void f4(); // OK, name linkage (internal) and function type linkage (C language linkage)
     // obtained from previous declaration.

void f6() {
  extern void f4(); // OK, name linkage (internal) and function type linkage (C language linkage)
```
A C language linkage is ignored in determining the language linkage of class members, friend functions with a trailing \texttt{requires-clause}, and the function type of class member functions.

\textbf{Example 3:}

\begin{verbatim}
extern "C" typedef void FUNC_c();

class C {
  void mf1(FUNC_c*);
  // the function \texttt{mf1} and its type have C++ language linkage;
  // the parameter has type “pointer to C function"
  FUNC_c mf2;
  // the function \texttt{mf2} and its type have C++ language linkage
  static FUNC_c* q;
  // the data member \texttt{q} has C++ language linkage;
  // its type is “pointer to C function"
};

extern "C" {
  class X {
  void mf();
    // the function \texttt{mf} and its type have C++ language linkage
  void mf2(void(*)());
    // the function \texttt{mf2} has C++ language linkage;
    // the parameter has type “pointer to C function"
  }
};
\end{verbatim}

If two declarations of an entity give it different language linkages, the program is ill-formed; no diagnostic is required if neither declaration is reachable from the other. A redeclaration of an entity without a linkage specification inherits the language linkage of the entity and (if applicable) its type.

Two declarations declare the same entity if they (re)introduce the same name, one declares a function or variable with C language linkage, and the other declares such an entity or declares a variable that belongs to the global scope.

\textbf{Example 4:}

\begin{verbatim}
int x;
namespace A {
  extern "C" int f();
  extern "C" int g() { return 1; }
  extern "C" int h();
  extern "C" int x();
    // error: same name as global-space object \texttt{x}
}

namespace B {
  extern "C" int f();
    // \texttt{A::f} and \texttt{B::f} refer to the same function
  extern "C" int g() { return 1; }
    // error: the function \texttt{g} with C language linkage has two definitions
}

int A::f() { return 98; }
extern "C" int h() { return 97; }
    // \texttt{A::h} and \texttt{::h} refer to the same function
\end{verbatim}

A declaration directly contained in a \texttt{linkage-specification} is treated as if it contains the \texttt{extern} specifier \hspace{1em}(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 specify a storage class.

\textbf{Example 5:}

\begin{verbatim}
extern "C" double f();
static double f();
    // error
extern "C" int i;
    // declaration
\end{verbatim}
extern "C" {
    int i; // definition
}
extern "C" static void g(); // error
—end example]

[Note 4: Because the language linkage is part of a function type, when indirecting 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 [dcl.attr]

9.12.1 Attribute syntax and semantics [dcl.attr.grammar]

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-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

2 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 N::, where N is the attribute-namespace specified in the attribute-using-prefix.

[Note 1: This rule imposes no constraints on how an attribute-using-prefix affects the tokens in an attribute-argument-clause. — end note]

[Example 1:
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 (9.2.9.4) 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).

Example 2:

```c
int p[10];
void f() {
    int x = 42, y[5];
    int(p[x] { return x; }());  // error: invalid attribute on a nested declarator-id and
    int(y[] { return 2; }()) = 2;  // error even though attributes are not allowed in this context.
    int i {[[vendor::attr([])]]};  // well-formed implementation-defined attribute.
}
```

—end example

Note 3: An attribute-specifier-seq cannot appertain to an explicit instantiation (13.9.3). —end note

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.

[Note 4: 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]

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4 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.

5 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:

```c
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]

6 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:

```c
// Translation unit #1:
struct S { 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]

7 [Example 3: An aligned buffer with an alignment requirement of A and holding N elements of type T can be declared as:

```c
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]

8 [Example 4:

```c
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 Carries dependency attribute [dcl.attr.depend]

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 (6.9.2) 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.

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.

[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]

[Example 1:
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

9.12.4 Deprecated attribute

The attribute-token deprecated can be used to mark names and entities whose use is still allowed, but is discouraged for some reason.

[Note 1: In particular, deprecated is appropriate for names and entities that are deemed obsolescent or unsafe. —end note]

An attribute-argument-clause may be present and, if present, it shall have the form:

```
(string-literal)
```

[Note 2: The string-literal in the attribute-argument-clause can be used to explain the rationale for deprecation and/or to suggest a replacing entity. —end note]

The attribute may be applied to the declaration of a class, a typedef-name, a variable, a non-static data member, a function, a namespace, an enumeration, an enumerator, or a template specialization.

An entity declared without the deprecated attribute can later be redeclared with the attribute and vice-versa.

[Note 3: Thus, an entity initially declared without the attribute can be marked as deprecated by a subsequent redeclaration. However, after an entity is marked as deprecated, later redeclarations do not un-deprecate 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.

Recommended practice: Implementations should use the deprecated attribute to produce a diagnostic message in case the program refers to a name or entity other than to declare it, after a declaration that specifies the attribute. The diagnostic message should include the text provided within the attribute-argument-clause of any deprecated attribute applied to the name or entity.
9.12.5 Fallthrough attribute

The attribute-token fallthrough may be applied to a null statement (8.3); such a statement is a fallthrough statement. No attribute-argument-clause shall be present. A fallthrough statement may only appear within an enclosing switch statement (8.5.3). The next statement that would be executed after a fallthrough statement shall be a labeled statement whose label is a case label or default label for the same switch statement and, if the fallthrough statement is contained in an iteration statement, the next statement shall be part of the same execution of the substatement of the innermost enclosing iteration statement. The program is ill-formed if there is no such statement.

Recommended practice: The use of a fallthrough statement should suppress a warning that an implementation might otherwise issue for a case or default label that is reachable from another case or default label along some path of execution. Implementations should issue a warning if a fallthrough statement is not dynamically reachable.

Example 1:

```c
void f(int n) {
    void g(), h(), i();
    switch (n) {
    case 1:
    case 2:
        g();
        [[fallthrough]];
    case 3:  // warning on fallthrough discouraged
        do {
            [[fallthrough]];
            // error: next statement is not part of the same substatement execution
        } while (false);
    case 6:
        do {
            [[fallthrough]];
            // error: next statement is not part of the same substatement execution
        } while (n--);
    case 7:
        while (false) {
            [[fallthrough]];
            // error: next statement is not part of the same substatement execution
        }
    case 5:
        h();
    case 4:  // implementation may warn on fallthrough
        i();
        [[fallthrough]];  // error
    }
}
```

—end example

9.12.6 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.

Recommended practice: 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. A path of execution includes a label if and only if it contains a jump to that label.

Note 1: Excessive usage of either of these attributes is liable to result in performance degradation. —end note

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]];

        // n == 2 is considered to be arbitrarily more likely than any other value of n
        case 2:
            g(2);
            break;
    }
    return 3;
}
—end example]

9.12.7 Maybe unused attribute [dcl.attr.unused]

1 The attribute-token maybe_unused indicates that a name 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, a typedef-name, a variable (including a structured binding declaration), a non-static data member, a function, an enumeration, or an enumerator.

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.

5 [Example 1]:

    [[maybe_unused]] void f([[maybe_unused]] bool thing1,
                        [[maybe_unused]] bool thing2) {
    [[maybe_unused]] bool b = thing1 && thing2;
    assert(b);
    }

    Implementations should not warn that b is unused, whether or not NDEBUG is defined. —end example]

9.12.8 Nodiscard attribute [dcl.attr.nodiscard]

1 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:

    ( string-literal )

2 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.

3 A nodiscard type is a (possibly cv-qualified) class or enumeration type marked nodiscard in a reachable declaration. A nodiscard call is either

(3.1) 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

(3.2) 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.

4 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.

[Note 2: This is typically because discarding the return value of a nodiscard call has surprising consequences. —end note]
The string-literal 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.

5 [Example 1]:

```cpp
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(); } // the (reference) return type nor the function is declared nodiscard
```

—end example]

### 9.12.9 Noreturn attribute

1 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 may terminate by throwing an exception. —end note]

3 Recommended practice: Implementations should issue a warning if a function marked `[[noreturn]]` might return.

4 [Example 1]:

```cpp
[[ noreturn ]] void f() {  
    throw "error"; // OK  
}
```

```cpp
[[ noreturn ]] void q(int i) { // behavior is undefined if called with an argument <= 0  
    if (i > 0)  
        throw "positive";  
}
```

—end example]

### 9.12.10 No unique address attribute

1 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]

[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.

Module A contains four translation units:

- a primary module interface unit,
- a module partition A:Foo, which is a module interface unit forming part of the interface of module A,
- a module partition A:Internals, which does not contribute to the external interface of module A, and
— a module implementation unit providing a definition of bar and baz, which cannot be imported because it does not have a partition name.

— end example

5 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.

6 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]

7 A module is either a named module or the global module. A declaration is attached to a module as follows:

(7.1) — 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).

(7.2) — Otherwise, if the declaration

(7.2.1) — is a replaceable global allocation or deallocation function (17.6.3.2, 17.6.3.3), or

(7.2.2) — is a namespace-definition with external linkage, or

(7.2.3) — appears within a linkage-specification,

it is attached to the global module.

(7.3) — Otherwise, the declaration is attached to the module in whose purview it appears.

8 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:

    module B:Y;
    int y();

    // does not implicitly import B

Translation unit #2:

    export module B;
    import :Y;
    int n = y();

    // OK, does not create interface dependency cycle

Translation unit #3:

    module B:X1;
    int &a = n;

    // error: n not visible here

Translation unit #4:

    module B:X2;
    import B;
    int &b = n;

    // OK

Translation unit #5:

    module B;
    int &c = n;

    // implicitly imports B

    // OK

— end example]

10.2 Export declaration

export-declaration:

export declaration
export { declaration-seqopt }

export-keyword module-import-declaration

1 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 declaration, declaration-seq (if any), or module-import-declaration. The declaration or 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

(2.1) — a namespace-definition that contains an exported declaration, or

(2.2) — a declaration within a header unit (10.3) that introduces at least one name.

An exported declaration that is not a module-import-declaration shall declare at least one name. If the declaration is not within a header unit, it shall not declare a name with internal linkage.

[Example 1:

Source file "a.h":

```c
export int x;
```

Translation unit #1:

```c
module;
#include "a.h"  // error: declaration of x is not in the
// preview of a module interface unit
export module M;
export namespace {}
export namespace {
  int a1;
}  // error: export of name with 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;  // error: does not declare a name
```

— 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":

```c
int f();
```

Importable header "c.h":

```c
int g();
```

Translation unit #1:

```c
export module X;
export int h();
```

Translation unit #2:

```c
module;
#include "b.h"
export module M;
import "c.h";
import X;
export using ::f, ::g, ::h;  // OK
struct S;
export using ::S;
namespace N {  // error: S has module linkage
  export int h();
  static int h(int);  // #1
}  // #1
export using N::h;  // error: #1 has internal linkage
```
—end example]

[Note 2: These constraints do not apply to type names introduced by `typedef` declarations and `alias-declarations`.

[Example 3:
```
export module M;
struct S;
export using T = S;            // OK, exports name T denoting type S
—end example]
—end note]

6 A redeclaration of an entity X is implicitly exported if X was introduced by an exported declaration; otherwise it shall not be exported.

[Example 4:
```
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
—end example]

7 [Note 3: Names introduced by exported declarations have either external linkage or no linkage; see 6.6. Namespacerope 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. —end note]

[Example 5:
Interface unit of M:
```
export module M;
export struct X {
    static void f();
    struct Y { }
};

namespace {
    struct S { }
}
export void f(S);    // OK
struct T { };        // OK
export T id(T);      // OK
export struct 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
```

Implementation unit of M:
```
module M;
struct A {
    int value;
};

Main program:
```
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;
export namespace N {
    int x;  // OK
    static_assert(1 == 1);  // error: does not declare a name
}
```

— end example]

10.3 Import declaration

module-import-declaration:
import-keyword module-name attribute-specifier-seqopt ;
import-keyword module-partition attribute-specifier-seqopt ;
import-keyword header-name attribute-specifier-seqopt ;

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.

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]

A module-import-declaration that specifies a module-name M imports all module interface units of M.

A module-import-declaration that specifies a module-partition shall only appear after the module-declaration in a module unit of some module M. Such a declaration imports the so-named module partition of M.

A module-import-declaration that specifies a header-name 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 H, which shall not contain a module-declaration.

[Note 2: 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). 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]

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.

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 M imports another module unit U of M,
it also imports all translation units imported by non-exported `module-import-declarations` in the module unit purview of \( U \).\footnote{This is consistent with the lookup rules for imported names (6.5).} These rules can in turn lead to the importation of yet more translation units.

8 A module implementation unit shall not be exported.

\[\text{Example 1:}\]

Translation unit #1:
```
module M:Part;
```
Translation unit #2:
```
export module M;
export import :Part;  // error: exported partition :Part is an implementation unit
```

9 A module implementation unit of a module \( M \) that is not a module partition shall not contain a `module-import-declaration` nominating \( M \).

\[\text{Example 2:}\]
```
module M;
import M;               // error: cannot import M in its own unit
```

10 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.

\[\text{Example 3:}\]
```
Interface unit of \( M_1 \):
export module M1;
import M2;

Interface unit of \( M_2 \):
export module M2;
import M3;

Interface unit of \( M_3 \):
export module M3;
import M1;               // error: cyclic interface dependency \( M_3 \rightarrow M_1 \rightarrow M_2 \rightarrow M_3 \)
```

10.4 Global module fragment \[\text{module.global.frag}\]

\begin{verbatim}
global-module-fragment: module-keyword ; declaration-seq opt
\end{verbatim}

1 \[\text{Note 1: Prior to phase 4 of translation, only preprocessing directives can appear in the declaration-seq (15.1).} \text{— end note}\]

2 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.

3 A declaration \( D \) is decl-reachable from a declaration \( S \) in the same translation unit if:

\begin{enumerate}
\item \( D \) 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
\item \( D \) declares a function or function template that is named by an expression (6.3) appearing in \( S \), or
\item \( S \) contains a dependent call \( E \) (13.8.3) and \( D \) is found by name lookup for the dependent name in 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
\item \( S \) 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
\end{enumerate}
there exists a declaration \( M \) that is not a namespace-definition for which \( M \) is decl-reachable from \( S \) and either

- \( D \) is decl-reachable from \( M \), or
- \( D \) redeclares the entity declared by \( M \) or \( M \) redeclares the entity declared by \( D \), and \( D \) neither is a friend declaration nor inhabits a block scope, or
- \( D \) declares a namespace \( N \) and \( M \) is a member of \( N \), or
- one of \( M \) and \( D \) declares a class or class template \( C \) and the other declares a member or friend of \( C \), or
- one of \( D \) and \( M \) declares an enumeration \( E \) and the other declares an enumerator of \( E \), or
- \( D \) declares a function or variable and \( M \) is declared in \( D \), or
- \( D \) declares a template and the other declares a partial or explicit specialization or an implicit or explicit instantiation of that template, or
- one of \( M \) and \( D \) 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

- 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,
- 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,
- whether a decltype-specifier that does not denote a dependent type is replaced by its denoted type prior to this determination, and
- whether a non-value-dependent constant expression is replaced by the result of constant evaluation prior to this determination.

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 2: 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]

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.

**Example 1:**

```
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
```

```
template<int N>
void h() noexcept(g(N) == N); // g and :: are decl-reachable from h
```

— end example

5 **Example 2:**

Source file "foo.h":

```
namespace N {
    struct X {};
    int d();
    int e();
    inline int f(X, int = d()) { return e(); }
```

92) A declaration can appear within a lambda-expression in the initializer of a variable.
int g(X);
int h(X);
}

Module M interface:
module;
#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 [module.private.frag]

private-module-fragment:
  module-keyword : private ; declaration-seqopt

1 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.

2 [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 exported inline function is required (9.2.8),
(2.2) — the point by which the definition of an exported function with a placeholder return type is required (9.2.9.6),
(2.3) — whether a declaration is required not to be an exposure (6.6),
(2.4) — where definitions for inline functions and templates must appear (6.3, 9.2.8, 13.1),
(2.5) — the instantiation contexts of templates instantiated before it (10.6), and
(2.6) — the reachability of declarations within it (10.7).
— end note]

3 [Example 1:
    export module A;
    export inline void fn_e(); // error: exported inline function fn_e not defined
    // before private module fragment
    inline void fn_m(); // OK, module-linkage inline function

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static void fn_s();
export struct X;
export void g(X *x) {
    fn_s(); // OK, call to static function in same translation unit
    fn_m(); // OK, call to module-linkage inline function
}
export X *factory(); // OK
module :private;
struct X {};
// definition not reachable from importers of A
X *factory() {
    return new X();
}
void fn_e() {}
void fn_m() {}
void fn_s() {}
—end example

10.6 Instantiation context [module.context]

1 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.

2 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.

3 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).

4 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.

5 During the instantiation of any other template specialization, the instantiation context comprises the point of instantiation of the template.

6 In any other case, the instantiation context at a point within the program comprises that point.

[Example 1:]
Translation unit #1:
export module stuff;
export template<typename T, typename U> void foo(T, U u) { auto v = u; }
export template<typename T> void bar(T, U u) { auto v = *u; }

Translation unit #2:
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:

```c
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

1. The point at the end of translation unit #1,
2. The point at the end of translation unit #2, and
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

1. The point at the end of translation unit #1,
2. The point at the end of translation unit #3, and
3. 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

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).

1. **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

2. 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.93

3. **Note 2**: It is advisable to avoid depending on the reachability of any additional translation units in programs intending to be portable. —end note

4. A declaration `D` is reachable from a point `P` if
   1. `D` appears prior to `P` in the same translation unit, or
   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).

4. **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.

4. **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:

```c
export module M:A;
export struct B;
```

Translation unit #2:

```c
module M:B;
```

93) Implementations are therefore not required to prevent the semantic effects of additional translation units involved in the compilation from being observed.

§ 10.7
struct B {
    operator int();
};

Translation unit #3:
module M:C;
import :A;
B b1;  // error: no reachable definition of struct B

Translation unit #4:
export module M;
export import :A;
import :B;
B b2;
export void f(B b = B());

Translation unit #5:
module X;
import M;
B b3;  // error: no reachable definition of struct B
void g() { f(); }  // error: no reachable definition of struct B

— end example]

— end note]

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:
export module A;
struct X {};
export using Y = X;

Translation unit #2:
module B;
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 (11.3) within its scope.

\[
\text{class-name:} \\
\text{identifier} \\
\text{simple-template-id}
\]

A class-specifier or an elaborated-type-specifier (9.2.9.4) is used to make a class-name. An object of a class consists of a (possibly empty) sequence of members and base class objects.

\[
\text{class-specifier:} \\
\text{class-head \{ member-specification\opt \}}
\]

\[
\text{class-head:} \\
\text{class-key attribute-specifier-seq\opt class-head-name class-virt-specifier\opt base-clause\opt} \\
\text{class-key attribute-specifier-seq\opt base-clause\opt}
\]

\[
\text{class-head-name:} \\
\text{nested-name-specifier\opt class-name}
\]

\[
\text{class-virt-specifier:} \\
\text{final}
\]

\[
\text{class-key:} \\
\text{class} \\
\text{struct} \\
\text{union}
\]

A class declaration where the class-name in the class-head-name is a simple-template-id shall be an explicit specialization (13.9.4) or a partial specialization (13.7.6). 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.

2 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.

3 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:]

```cpp
namespace N {
    template<class>
    struct A {
        struct B;
    };
}

using N::A;
template<class T> struct A<T>::B {}; // OK
template<> struct A<void> {} ; // OK
```

[Note 2: The class-key determines whether the class is a union (11.5) and whether access is public or private by default (11.8). 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:

```cpp
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 (9.12.10) 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]

1 A *trivially copyable class* is a class:

(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),

(1.2) — where each eligible copy constructor, move constructor, copy assignment operator, and move assignment operator is trivial, and

(1.3) — that has a trivial, non-deleted destructor (11.4.7).

2 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]

3 A class $S$ is a *standard-layout class* if it:

(3.1) — has no non-static data members of type non-standard-layout class (or array of such types) or reference,

(3.2) — has no virtual functions (11.7.3) and no virtual base classes (11.7.2),

(3.3) — has the same access control (11.8) for all non-static data members,

(3.4) — has no non-standard-layout base classes,

(3.5) — has at most one base class subobject of any given type,

(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

(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.$^94$

[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]

(3.7.1) — If $X$ is a non-union class type with no non-static data members, the set $M(X)$ is empty.

(3.7.2) — If $X$ is a non-union class type with a non-static data member of type $X_0$ that is either of zero size or is the first non-static data member of $X$ (where said member may be an anonymous union), the set $M(X)$ consists of $X_0$ and the elements of $M(X_0)$.

(3.7.3) — If $X$ is a union type, the set $M(X)$ is the union of all $M(U_i)$ and the set containing all $U_i$, where each $U_i$ is the type of the $i$th non-static data member of $X$.

94 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).
— If \( X \) is an array type with element type \( X_e \), the set \( M(X) \) consists of \( X_e \) and the elements of \( M(X_e) \).

— If \( X \) is a non-class, non-array type, the set \( M(X) \) is empty.

4 [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]

5 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.

6 [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]

7 [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]

8 [Note 4: Aggregates of class type are described in 9.4.2. — end note]

9 A class \( S \) is an implicit-lifetime class if it is an aggregate or 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
a1 = a3; // error: int assigned to X
```
are type mismatches, and that

```c
int f(X);
int f(Y);
```
declare overloads (Clause 12) named f and not simply a single function f twice. For the same reason,

```c
struct S { int a; };  // error: double definition
struct S { int a; };  // error: double definition
```
is ill-formed because it defines S twice. —end example]

2 [Note 1: It can be necessary to use an 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:

```c
struct stat {
    // ...
};

stat gstat;  // use plain stat to define variable
int stat(struct stat*);  // stat now also names a function

void f() {
    struct stat* ps;  // struct prefix needed to name struct stat
    stat(ps);  // call stat function
}
```
—end example]

An elaborated-type-specifier can also be used to declare an identifier as a class-name.

Example 3:

```c
struct s { int a; }

void g() {
    struct s;  // hide global struct s with a block-scope declaration
    s* p;  // refer to local struct s
    struct s { char* p; };  // define local struct s
    struct s;  // redeclaration, has no effect
}
```
—end example]

Such declarations allow definition of classes that refer to each other.

Example 4:

```c
class Vector;

class Matrix {
    // ...
    friend Vector operator*(const Matrix&, const Vector&);
};
class Vector {
    // ...
    friend Vector operator*(const Matrix&, const Vector&);
};
```

Declaration of friends is described in 11.8.4, operator functions in 12.4. —end example]

—end note]

3 [Note 2: An elaborated-type-specifier (9.2.9.4) can also be used as a 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:

```c
struct s { int a; }

void g(int s) {
    struct s* p = new struct s;  // global s
```
4. The declaration of a class name takes effect immediately after the identifier is seen in the class definition or elaborated-type-specifier. For example,

```cpp
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 note

5. A simple-template-id is only a class-name if its template-name names a class template.

11.4 Class members [class.mem]  
11.4.1 General [class.mem.general]

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 1: 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]

2. A member-declaration does not declare new members of the class if it is

- a friend declaration (11.8.4),
- a deduction-guide (13.7.2.3),
- a template-declaration whose declaration is one of the above,
(2.4)  — a static_assert-declaration,
(2.5)  — a using-declaration (9.9), or
(2.6)  — 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.

3 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.

4 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 2: A non-static data member of non-reference type is a member subobject of a class object (6.7.2). — end note]

5 A member shall not be declared twice in the member-specification, except that

(5.1)  — a nested class or member class template can be declared and then later defined, and
(5.2)  — an enumeration can be introduced with an opaque-enum-declaration and later redeclared with an enum-specifier.

[Note 3: A single name can denote several member functions provided their types are sufficiently different (6.4.1). — end note]

6 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.

7 A complete-class context of a class (template) is a

(7.1)  — function body (9.5.1),
(7.2)  — default argument (9.3.4.7),
(7.3)  — default template argument (13.2),
(7.4)  — noexcept-specifier (14.5), or
(7.5)  — default member initializer

within the member-specification of the class or class template.

[Note 4: 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]

8 A class is considered a completely-defined object type (6.8.1) (or complete type) at the closing } of the class-specifier. The class is regarded as complete within its complete-class contexts; otherwise it is regarded as incomplete within its own class member-specification.

9 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]:

```cpp
struct S {
    using T = void();
    T * p = 0;  // OK, brace-or-equal-initializer
    virtual T f = 0;  // OK, pure-specifier
};
```

—end example

10 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]:

```cpp
int a;
const int b = 0;
```
```cpp
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
    int z : 1 || new int { 0 }; // OK, brace-or-equal-initializer is absent
};
```

--- end example

11 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.

12 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*.

13 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.

14 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.

15 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).

16 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 multi-dimensional) array thereof.

[Note 5: 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]

17 [Note 6: See 7.5.4 for restrictions on the use of non-static data members and non-static member functions. — end note]

18 [Note 7: 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

20 [Note 8: 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]

21 If T is the name of a class, then each of the following shall have a name different from T:

(21.1) — every static data member of class T;

(21.2) — every member function of class T;

[Note 9: This restriction does not apply to constructors, which do not have names (11.4.5) — end note]

§ 11.4.1 264
(21.3) every member of class T that is itself a type;
(21.4) every member template of class T;
(21.5) every enumerator of every member of class T that is an unscoped enumerated type; and
(21.6) every member of every anonymous union that is a member of class T.

22 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.

23 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), either both entities are declared with the no_unique_address attribute (9.12.10) or neither is, and either both entities are bit-fields with the same width or neither is a bit-field.

[Example 4:

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]

24 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).

25 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).

26 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:

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 10: Reading a volatile object through a glvalue of non-volatile type has undefined behavior (9.2.9.2). — end note]

27 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 11: 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 12: The object and its first subobject are pointer-interconvertible (6.8.3, 7.6.1.9). — end note]

11.4.2 Member functions

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 inl ine, constexpr, or constexpr. — end note]

2 [Example 1:

struct X {
    typedef int T;
    static T count;

§ 11.4.2
The definition of the member function \texttt{f} of class \texttt{X} inhabits the global scope; the notation \texttt{X::f} indicates that the function \texttt{f} is a member of class \texttt{X} and in the scope of class \texttt{X}. In the function definition, the parameter type \texttt{T} refers to the typedef member \texttt{T} declared in class \texttt{X} and the default argument \texttt{count} refers to the static data member \texttt{count} declared in class \texttt{X}. —end example

3 Member functions of a local class shall be defined inline in their class definition, if they are defined at all.

4 [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. For example,]

\begin{verbatim}
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{verbatim}

Also see 13.4. —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.

2 If a non-static member function of a class \texttt{X} is called for an object that is not of type \texttt{X}, or of a type derived from \texttt{X}, the behavior is undefined.

3 When an \textit{id-expression} (7.5.4) that is not part of a class member access syntax (7.6.1.5) and not used to form a pointer to member (7.6.2.2) is used where the current class is \texttt{X} (7.5.2), if name lookup (6.5) resolves the name in the \textit{id-expression} to a non-static non-type member of some class \texttt{C}, and if either the \textit{id-expression} is potentially evaluated or \texttt{C} is \texttt{X} or a base class of \texttt{X}, the \textit{id-expression} is transformed into a class member access expression (7.6.1.5) using (*\texttt{this}) as the \texttt{postfix-expression} to the left of the \texttt{operator}.

[Note 1: If \texttt{C} is not \texttt{X} or a base class of \texttt{X}, the class member access expression is ill-formed. —end note]

This transformation does not apply in the template definition context (13.8.3.2).

[Example 1:]

\begin{verbatim}
struct tnode {
  char tword[20];
  int count;
  tnode* left;
  tnode* right;
  void set(const char*, tnode* l, tnode* r);
};

void tnode::set(const char* w, tnode* l, tnode* r) {
  count = strlen(w)+1;
  if (sizeof(tword)<=count)
    perror("tnode string too long");
  strcpy(tword,w);
  left = l;
  right = r;
}

void f(tnode n1, tnode n2) {
  n1.set("abc",&n2,0);
}\end{verbatim}
In the body of the member function `tnode::set`, the member names `tword`, `count`, `left`, and `right` refer to members of the object for which the function is called. Thus, in the call `n1.set("abc", &n2, 0)`, `tword` refers to `n1.tword`, and in the call `n2.set("def", 0, 0)`, it refers to `n2.tword`. The functions `strlen`, `perror`, and `strcpy` are not members of the class `tnode` and should be declared elsewhere.\footnote{Note 2: An implicit object member function can be declared with `cv-qualifiers`, which affect the type of the `this` pointer (7.5.2), 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 [special]

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 if they are odr-used (6.3) or needed for constant evaluation (7.7). — 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.

```cpp
struct A { }; // implicitly declared A::operator=
struct B : A {
    B & operator=(const B &); 
};
B & B::operator=(const B & a) {
    this->A::operator=(a); // well-formed
    return *this;
}
— end example
```

**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:

- they are both default constructors,
- they are both copy or move constructors with the same first parameter type, or
- 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:

- the function is not deleted,
- the associated constraints (13.5), if any, are satisfied, and
- no special member function of the same kind 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**.

A defaulted special member function is **constexpr-compatible** if the corresponding implicitly-declared special member function would be a constexpr function.

---

\footnote{95) See, for example, `<cstring>` (23.5.3).}
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

\[\text{ptr-declarator ( parameter-declaration-clause ) noexcept-specifier opt attribute-specifier-seq opt}\]

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:]

```cpp
class S { 
    S(); // declares the constructor
    
    S :: S() {} // defines the constructor
    
    — end example
```}

2 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:]

```cpp
complex zz = complex(1,2.3);  
cprint( complex(7.8,1.2) );  

— end example
```}

[Note 2: For initialization of objects of class type see 11.9. — end note]

3 An object created in this way is unnamed.

[Note 3: 6.7.7 describes the lifetime of temporary objects. — end note]

[Note 4: Explicit constructor calls do not yield lvalues, see 7.2.1. — end note]

4 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.

5 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.

11.4.5.2 Default constructors

1 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 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. \(X\) is a union that has a variant member with a non-trivial default constructor and no variant member of \(X\) has a default member initializer,
2. \(X\) is a non-union class that has a variant member \(M\) with a non-trivial default constructor and no variant member of the anonymous union containing \(M\) has a default member initializer,
— any non-static data member with no default member initializer (11.4) is of reference type,

— any non-variant non-static data member of const-qualified type (or array thereof) with no brace-or-equal-initializer is not const-default-constructible (9.4),

— X is a union and all of its variant members are of const-qualified type (or array thereof),

— X is a non-union class and all members of any anonymous union member are of const-qualified type (or array thereof),

— any potentially constructed subobject, except for a non-static data member with a brace-or-equal-initializer, has class type M (or array thereof) and either M has no default constructor or overload resolution (12.2) as applied to find M’s corresponding constructor results in an ambiguity or in a function that is deleted or inaccessible from the defaulted default constructor, or

— any potentially constructed subobject has a type with a destructor that is deleted or inaccessible from the defaulted default constructor.

3 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.

4 A default constructor that is defaulted and not defined as deleted is implicitly defined when it is odr-used (6.3) to initialize an object of its class type (6.7.2), when it is needed for constant evaluation (7.7), or when it is explicitly defaulted after its first declaration. The implicitly-defined 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 satisfy the requirements of a constexpr constructor (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]

5 [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 is required to be accessible (11.8). — end note]

6 [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]
struct Y {
    Y(const Y&);  
    Y(Y&&);  
};
    
extern Y f(int);
Y d(f(1));  // calls Y(Y&&)
Y e = d;  // calls Y(const Y&)
—end example]

3 [Note 1: All forms of copy/move constructor can be declared for a class.

[Example 3:]
struct X {
    X(const X&);  
    X(X&);  // OK
    X(X&&);  // OK, but possibly not sensible
};  
—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:]
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:]
struct S {
    template<typename T> S(T);
    S();
};
S g;

void h() {
    S a(g);  // does not instantiate the member template to produce S::S<S>(S);
    // 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.8).

7 The implicitly-declared copy constructor for a class X will have the form
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&. Otherwise, the implicitly-declared copy constructor

96) This implies that the reference parameter of the implicitly-declared copy constructor cannot bind to a volatile lvalue; see C.6.7.
will have the form
\[ X::X(X&) \]

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

1. \( X \) does not have a user-declared copy constructor,
2. \( X \) does not have a user-declared copy assignment operator,
3. \( X \) does not have a user-declared move assignment operator, and
4. \( X \) 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:

1. a potentially constructed subobject type \( M \) (or array thereof) that cannot be copied/moved because overload resolution (12.2), as applied to find \( M \)'s corresponding constructor, results in an ambiguity or a function that is deleted or inaccessible from the defaulted constructor,
2. a variant member whose corresponding constructor as selected by overload resolution is non-trivial,
3. any potentially constructed subobject of a type with a destructor that is deleted or inaccessible from the defaulted constructor, or,
4. 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:

1. \( X \) has no virtual functions (11.7.3) and no virtual base classes (11.7.2), and
2. the constructor selected to copy/move each direct base class subobject is trivial, and
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.

A copy/move constructor that is defaulted and not defined as deleted is implicitly defined when it is odr-used (6.3), when it is needed for constant evaluation (7.7), or when it is explicitly defaulted after its first declaration.

[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 the implicitly-defined constructor would satisfy the requirements of a constexpr constructor (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. See also the example in 11.9.3. — 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:

1. if the member is an array, each element is direct-initialized with the corresponding subobject of \( x \);
— if a member \( m \) has rvalue reference type \( T&& \), it is direct-initialized with \( \text{static
cast}<T&&>(x.m) \);
— 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 \( X::\text{operator=} \) is a non-static non-template member function of class \( X \) with exactly one parameter of type \( X, X\&, \text{const } X\&, \text{volatile } X\&, \text{or } \text{const volatile } X\& \).

[Note 1: An overloaded assignment operator must be declared to have only one parameter; see 12.4.3.2. — end note]

[Note 2: More than one form of copy assignment operator can be declared for a class. — end note]

[Note 3: If a class \( X \) only has a copy assignment operator with a 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&);
};
const X cx;
X x;
void f() {
    x = cx;    // error: X::operator=(X&) cannot assign cx into x
}
```

— end example]
— end note]

2 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.8). The implicitly-declared copy assignment operator for a class \( X \) will have the form

\( X\& X::\text{operator}=(\text{const } X\&) \)

if

(2.1) each direct base class \( B \) of \( X \) has a copy assignment operator whose parameter is of type \( \text{const } B\&, \text{const volatile } B\&, \text{or } B, \text{and} \)

(2.2) for all the non-static data members of \( X \) that are of a class type \( M \) (or array thereof), each such class type has a copy assignment operator whose parameter is of type \( \text{const } M\&, \text{const volatile } M\&, \text{or } M \).

Otherwise, the implicitly-declared copy assignment operator will have the form

\( X\& X::\text{operator}=(X\&) \)

A user-declared move assignment operator \( X::\text{operator=} \) is a non-static non-template member function of class \( X \) with exactly one parameter of type \( X&&, \text{const } X&&, \text{volatile } X&&, \text{or } \text{const volatile } X&& \).

[Note 4: An overloaded assignment operator must be declared to have only one parameter; see 12.4.3.2. — end note]

[Note 5: More than one form of move assignment operator can be declared for a class. — end note]
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

1. $X$ does not have a user-declared copy constructor,
2. $X$ does not have a user-declared move constructor,
3. $X$ does not have a user-declared copy assignment operator, and
4. $X$ does not have a user-declared destructor.

[Example 2: The class definition

```cpp
struct S {
  int a;
  S& operator=(const S&) = default;
};
```

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.

```cpp
struct S {
  int a;
  S& operator=(const S&) = default;
  S& operator=(S&&) = default;
};
```

—end example]

The implicitly-declared move assignment operator for a class $X$ will have the form

$\texttt{X}& \texttt{X::operator=(X&&)}$

The implicitly-declared copy/move assignment operator for class $X$ has the return type $\texttt{X}&$. An implicitly-declared copy/move assignment operator is an inline public member of its class.

A defaulted copy/move assignment operator for class $X$ is defined as deleted if $X$ has:

1. a variant member with a non-trivial corresponding assignment operator and $X$ is a union-like class, or
2. a non-static data member of const non-class type (or array thereof), or
3. a non-static data member of reference type, or
4. a direct non-static data member of class type $M$ (or 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, results in an ambiguity or a function that is deleted or inaccessible from the defaulted assignment operator.

[Note 6: A defaulted move assignment operator that is defined as deleted is ignored by overload resolution (12.2, 12.3). — end note]

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 7: A 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 declared as a member of $C$. — end note]

A copy/move assignment operator for class $X$ is trivial if it is not user-provided and if:

1. $X$ has no virtual functions (11.7.3) and no virtual base classes (11.7.2), and
2. the assignment operator selected to copy/move each direct base class subobject is trivial, and
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 non-trivial.

A copy/move assignment operator for a class $X$ that is defaulted and not defined as deleted is implicitly defined when it is odr-used (6.3) (e.g., when it is selected by overload resolution to assign to an object of its class type), when it is needed for constant evaluation (7.7), or when it is explicitly defaulted after its first declaration. The implicitly-defined copy/move assignment operator is constexpr if

[10.1] $X$ is a literal type, and
The assignment operator selected to copy/move each direct base class subobject is a constexpr function, and

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 a constexpr function.

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 8: An implicitly-declared copy/move assignment operator has an implied exception specification (14.5). — end note]

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 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:

— if the subobject is of class type, as if by a call to 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);

— if the subobject is an array, each element is assigned, in the manner appropriate to the element type;

— 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 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 of the form

\[\text{ptr-declarator ( parameter-declaration-clause ) noexcept-specifier\_opt attribute-specifier-seq\_opt}\]

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. Each decl-specifier of the decl-specifier-seq of a prospective destructor declaration (if any) shall be friend, inline, virtual, constexpr, or consteval.

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
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:

7.1 — \( X \) is a union-like class that has a variant member with a non-trivial destructor,

7.2 — any potentially constructed subobject has class type \( M \) (or array thereof) and \( M \) has a deleted destructor or a destructor that is inaccessible from the defaulted destructor,

7.3 — 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 satisfies the requirements for a constexpr destructor (9.2.6).

A destructor that is defaulted and not defined as deleted is implicitly defined when it is odr-used (6.3) or when it is explicitly defaulted after its first declaration.

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, 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

15.1 — for a constructed object with static storage duration (6.7.5.2) at program termination (6.9.3.4),

15.2 — for a constructed object with thread storage duration (6.7.5.3) at thread exit,

15.3 — for a constructed object with automatic storage duration (6.7.5.4) when the block in which an object is created exits (8.8),

15.4 — 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.

16 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]

17 In an explicit destructor call, the destructor is specified by a `~` followed by a `type-name` or `decltype-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:]
```c++
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 D’s destructor
    B_ptr->B_alias::~B_alias();  // 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` (7.5.4.3); in particular, the `unary-expression ~X()` in a member function is not an explicit destructor call (7.6.2.2). — end note]

18 [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. For example,

```c++
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
}
```

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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 2: 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

Note 10: The notation for explicit call of a destructor can be used for any scalar type name (7.5.4.4). Allowing this
makes it possible to write code without having to know if a destructor exists for a given type. For example:

```c
typedef int I;
I* p;
p->I::~I();
—end note
```

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).

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).

Note 1: See 12.2 for a discussion of the use of conversions in function calls as well as examples below. —end note

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

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))
}
```
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:

```cpp
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(1); // 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
```

— end example

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

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

```
ptr-declarator ( parameter-declaration-clause ) cv-qualifier-seq_opt ref-qualifier-seq_opt 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. (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;

2. (1.2) — otherwise, the id-expression is a qualified-id whose unqualified-id is a conversion-function-id.

A conversion function shall have no non-object parameters and shall be a non-static member function of a class or class template X; 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.

The type of the conversion function is “`noexcept_opt` function taking no parameter `cv-qualifier-seq_opt ref-qualifier_opt` returning `conversion-type-id`”.

A conversion function is never used to convert a (possibly cv-qualified) object to the (possibly cv-qualified) same object type (or a reference to it), to a (possibly cv-qualified) base class of that type (or a reference to it), or to `cv void`.99

99) These conversions are considered as standard conversions for the purposes of overload resolution (12.2.4.2, 12.2.4.2.5) and therefore initialization (9.4) and explicit casts (7.6.1.9). A conversion to `void` does not invoke any conversion function (7.6.1.9). Even though never directly called to perform a conversion, such conversion functions can be declared and can potentially be
Example 1:

```cpp
struct X {
    operator int();
    operator auto() -> short;  // error: trailing return type
};
```

```cpp
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

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:

```cpp
class Y { }
struct Z {
    explicit operator Y() const;
};
```

```cpp
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
}
```

Example 3:

```cpp
&ac.operator int*i;  // 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:

```cpp
operator int [[noreturn]] () ;  // error: noreturn attribute applied to a type
```

—end example

—end note

Note 2: 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: reached through a call to a virtual conversion function in a base class.
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
}

8 Conversion functions can be virtual.

9 A conversion function template shall not have a deduced return type (9.2.9.6).

[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

11.4.9.1 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:

    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]

[Note 2: A static member function does not have a this pointer (7.5.2). A static member function cannot be qualified with const, volatile, or virtual (9.3.4.6). — end note]

11.4.9.3 Static data members

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 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 (6.4.6). — end note]

[Example 1:]
```cpp
class process {
    static process* run_chain;
    static process* running;
};
```

```cpp
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.6). 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]

[Note 4: Static data members of a class in namespace scope have the linkage of the name of the class (6.6). — end note]

### 11.4.10 Bit-fields

A `member-declarator` of the form

```cpp
identifier_opt attribute-specifier-seq_opt : 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 \texttt{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]

4 If a value of integral type (other than \texttt{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 \texttt{true} or \texttt{false} is stored into a bit-field of type \texttt{bool} of any size (including a one bit bit-field), the original \texttt{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:

\begin{verbatim}
enum BOOL { FALSE=0, TRUE=1 };
struct A {
  BOOL b:1;
};
A a;
void f() {
  a.b = TRUE;
  if (a.b == TRUE)    // yields true
    { /* ... */ }
}
\end{verbatim}

—end example]

11.4.11 Allocation and deallocation functions

[class.free]

1 Any allocation function for a class \(T\) is a static member (even if not explicitly declared \texttt{static}).

2 [Example 1:

\begin{verbatim}
class Arena;
struct B {
  void* operator new(std::size_t, Arena*);
};
struct D1 : B {
};

Arena* ap;
void foo(int i) {
  new (ap) D1;    // calls \texttt{::operator new(std::size_t, Arena*)}
  new D1[i];     // calls \texttt{::operator new[](std::size_t)}
  new D1;        // error: \texttt{::operator new(std::size_t)} hidden
}
\end{verbatim}

—end example]

3 Any deallocation function for a class \(X\) is a static member (even if not explicitly declared \texttt{static}).

[Example 2:

\begin{verbatim}
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{verbatim}

—end example]

4 Since member allocation and deallocation functions are \texttt{static} they cannot be virtual.

[Note 1: However, when the \texttt{cast-expression} of a \texttt{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. For example,
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 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. For example,

    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
    }

    —end note]

Access to the deallocation function is checked statically, even if a different one is actually executed.
[Example 3: 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 7.5.4 for restrictions on the use of non-static data members and non-static member functions. —end note]

[Example 1:]

    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:

struct enclose {
    struct inner {
        static int x;
        void f(int i);
    }
};

int enclose::inner::x = 1;

void enclose::inner::f(int i) { /* ... */ }

class E {
    class I1; // forward declaration of nested class
    class I2; // definition of nested class
};

class E::I2 { }; // definition of nested class

—end example]

—end note]

3 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.

2 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, it is permitted to inspect the common initial sequence of any of the standard-layout struct members; see 11.4. — end note]

3 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 (6.8.3, 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. — end note

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

Example 2:

```cpp
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;
  // creates objects to hold union members 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

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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

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

Anonymous unions declared in the scope of a namespace with external linkage shall be declared static. Anonymous unions declared at block scope shall be declared with any storage class allowed for a block variable, or with no storage class. A storage class is not allowed in a declaration of an anonymous union in a class scope.

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

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;
  }
```

§ 11.5.2
11.6 Local class declarations

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 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
```

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 ...opt
base-specifier-list , base-specifier ...opt

base-specifier:
    attribute-specifier-seqopt class-or-decltype
    attribute-specifier-seqopt virtual access-specifieropt class-or-decltype
    attribute-specifier-seqopt access-specifier virtualopt class-or-decltype

class-or-decltype:
    nested-name-specifieropt type-name
    nested-name-specifier template simple-template-id
dectype-specifier
```
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 :: (7.5.4.3) 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:

```
struct Base {
    int a, b, c;
};
struct Derived : Base {
    int b;
};
struct Derived2 : Derived {
    int c;
};
```

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]

A base-specifier followed by an ellipsis is a pack expansion (13.7.4).

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)

[Note 4: Initialization of objects representing base classes can be specified in constructors; see 11.9.3. — end note]

[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

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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

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]

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]

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 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

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:

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]

5 [Note 5: In contrast, consider the case with a virtual base class:
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.

---

Note 6: A class can have both virtual and non-virtual base classes of a given type.

---

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).

---

Note 1: Virtual functions support dynamic binding and object-oriented programming. — end note

---

A class with a virtual member function is called a polymorphic class.

---

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 \( F \). 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

---

100) The use of the virtual specifier in the declaration of an overriding function is valid but redundant (has empty semantics).

101) 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.

102) 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.
class, if a virtual member function of a base class subobject has more than one final overrider the program is ill-formed.

Example 1:

```cpp
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 example

Example 2:

```cpp
struct A { virtual void f();
};
struct B : A { void f(); }
struct C : A { void f(); }
struct D : B, C { }    // OK, A::f and C::f are the final overriders
                        // for the B and C subobjects, respectively
```

—end example

3 [Note 2: A virtual member function does not have to be visible to be overridden, for example,

```cpp
struct B {
    virtual void f() const;
};
struct D : B {
    void f(int);
};
struct D2 : D {
    void f();
};
```

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]

If a virtual function `f` in some class `B` is marked with the `virt-specifier 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
};
```

—end example

5 If a virtual function is marked with the `virt-specifier 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
    virtual void f(int) override;  // OK
};

— end example]

A virtual function shall not have a trailing requires-clause (9.3).

[Example 5:
    template<typename T>
    struct A {
        virtual void f() requires true;  // error: virtual function cannot be constrained (13.5.3)
    };
    — end example]

7 The 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 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:
    class B { }
    class D : private B { friend class Derived; }
    struct Base {
        virtual void vf1();
        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:

103) Multi-level pointers to classes or references to multi-level pointers to classes are not allowed.
// 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:

```cpp
struct A {
    virtual void f();
};

struct B1 : A { // note non-virtual derivation
    void f();
};

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:

```cpp
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 (7.5.4.3) 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]

1 [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]

2 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 (7.5.4.3).

Example 1:

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:
  struct C {
    virtual void f() = 0; // error
  };
—end example]

3 [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]

4 A class is abstract if it has at least one pure virtual function for which the final overrider is pure virtual.

[Example 3:
  class ab_circle : public shape {
    int radius;
    public:
      void rotate(int) { } //ab_circle::draw() is a pure virtual
      void 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,
  class circle : public shape {
    int radius;
    public:
      void rotate(int) { } // a definition is required somewhere
      void draw(); // a definition is required somewhere
  };
would make class circle non-abstract and a definition of circle::draw() must be provided. —end example]

5 [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]

6 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 [class.access]
11.8.1 General [class.access.general]

1 A member of a class can be
   (1.1) — private, that is, it can be named only by members and friends of the class in which it is declared;
   (1.2) — 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
   (1.3) — 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]

2 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.104

3 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:
  class X {
    int a; //X::a is private by default
  };
  struct S {
    int a; // S::a is public by default
  };

104) Access permissions are thus transitive and cumulative to nested and local classes.
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).]

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.

[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. For example,

```cpp
class A {
    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 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 2:

```cpp
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 3:]
```cpp
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
```

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:]
```cpp
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:]
```cpp
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]

[Note 1: The effect of access control on the order of allocation of data members is specified in 7.6.9. — end note]

4 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:]
```cpp
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 2: 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:

```cpp
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]

1 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.\(^\text{105}\)

2 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:

```cpp
class B { /* ... */ }
class D1 : private B { /* ... */ }
class D2 : public B { /* ... */ }
class D3 : B { /* ... */ }
struct D4 : public B { /* ... */ }
struct D5 : private B { /* ... */ }
struct D6 : B { /* ... */ }
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. For example,

```cpp
class B {
    public:
        int mi; // non-static member
        static int si; // static member
    }
    class D : private B {
    }
    class DD : public B {
        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* bpi = this;
        ::B* bp2 = (::B*)this;
        bp2->mi = 3; // OK, access through a pointer to B.
    }
```

\(^\text{105}\) 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.
4 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 2:

```c++
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 \( p->T::i \)), 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) — \( m \) as a member of \( N \) is public, or

(5.2) — \( m \) as a member of \( N \) is private, and \( R \) occurs in a direct member or friend of class \( N \), or

(5.3) — \( m \) 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) — 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 3:

```c++
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
}
```
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

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, B accessible to friend
  friend class X;
};

struct X : A::B { // OK, X accessible to friend
  A::B mx;
  friend class Y; // OK, Y accessible to member of friend
};

struct Y : A::B { // OK, Y accessible to nested member of friend
  A::B my;
};
—end example]

[Example 3:
class X {
  enum { a=100 }; // OK, a 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 have one of the following forms:
friend elaborated-type-specifier ;
friend simple-type-specifier ;
friend typename-specifier ;

[Note 1: A friend declaration can be the declaration in a template-declaration (13.1, 13.7.5). — end note]

If the type specifier in a friend declaration designates a (possibly cv-qualified) class type, that class is declared as a friend; otherwise, the friend declaration is ignored.

[Example 4:

```cpp
class C;
typedef C Ct;

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 T> class R {
    friend T;
};

R<C> rc;       // class C is a friend of R<C>
R<int> Ri;     // OK, "friend int;" is ignored
```
—end example]

4 A function first declared in a friend declaration has the linkage of the namespace of which it is a member (6.6). Otherwise, the function retains its previous linkage (9.2.2).

5 [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:
```cpp
class Y {
    friend char* X::foo(int);
    friend X::X(char);
    friend X::~X();        // constructors can be friends
    friend X::X();         // destructors can be friends
};
```
—end example]
—end note]

6 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:
```cpp
class M {
    friend void f() {}       // definition of global f, a friend of M,
                            // not the definition of a member function
};
```
—end example]

7 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]

8 No storage-class-specifier shall appear in the decl-specifier-seq of a friend declaration.

9 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.

10 Friendship is neither inherited nor transitive.
[Example 7:

class A {
    friend class B;
    int a;
};

class B {
    friend class C;
};

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, 9.2.9.4). — 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
    };
    }

    // 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
}
—end example

11.8.5 Protected member access [class.protected]

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:

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 a D2, even though naming class is B)
   int B::* pm_B = &B::i;
   int B::* pm_B2 = &D2::i; // OK (type of &D2::i is int B::* )
   B::j = 5; // error: not a friend of naming class B
   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;
   int B::* pm_B = &B::i;
   int B::* pm_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
}

106) This additional check does not apply to other members, e.g., static data members or enumerator member constants.
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.

**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
}
```

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

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

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
    }
```
11.9 Initialization

11.9.1 General

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.

An object of class type (or array thereof) can be explicitly initialized; see 11.9.2 and 11.9.3.

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

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:

```c
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]

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:

```c
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 v[2], v[4], and v[5]. For another example,

```c
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 \textit{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 \textit{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 \textit{class.base.init}

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 \textit{ctor-initializer}, which has the form

\[
\text{ctor-initializer:} \\
\quad: \text{mem-initializer-list}
\]

\[
\text{mem-initializer-list:} \\
\quad\text{mem-initializer} \ldots_{\text{opt}} \\
\quad\text{mem-initializer-list} , \text{mem-initializer} \ldots_{\text{opt}}
\]

\[
\text{mem-initializer:} \\
\quad\text{mem-initializer-id} ( \text{expression-list}_{\text{opt}} ) \\
\quad\text{mem-initializer-id} \text{ braced-init-list}
\]

\[
\text{mem-initializer-id:} \\
\quad\text{class-or-decltype} \text{ identifier}
\]

2 Lookup for an unqualified name in a \textit{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 \textit{mem-initializer-id} naming the member or base class and composed of a single identifier refers to the class member. A \textit{mem-initializer-id} for the hidden base class can be specified using a qualified name. —end note]

Unless the \textit{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 \textit{mem-initializer} is ill-formed.

3 A \textit{mem-initializer-list} can initialize a base class using any \textit{class-or-decltype} that denotes that base class type.

[Example 1:]

```c
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]

4 If a \textit{mem-initializer-id} is ambiguous because it designates both a direct non-virtual base class and an indirect virtual base class, the \textit{mem-initializer} is ill-formed.

[Example 2:]

```c
struct A { A(); }; struct B: public virtual A { };struct C: public A, public B { C(); };
C::C(): A() { } // error: which A?
```

—end example]

5 A \textit{ctor-initializer} may initialize a variant member of the constructor’s class. If a \textit{ctor-initializer} specifies more than one \textit{mem-initializer} for the same member or for the same base class, the \textit{ctor-initializer} is ill-formed.

6 A \textit{mem-initializer-list} can delegate to another constructor of the constructor’s class using any \textit{class-or-decltype} that denotes the constructor’s class itself. If a \textit{mem-initializer-id} designates the constructor’s class, it shall be the only \textit{mem-initializer}; the constructor is a \textit{delegating constructor}, and the constructor selected by the \textit{mem-initializer} is the \textit{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:]

```c
struct C { C( int ) { } // #1: non-delegating constructor
```

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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.

Example 5:

```cpp
struct A {  
    A() : v(42) { } // error  
    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 value. —end note

Example 6:
```cpp
struct A {
    A();
};

struct B {
    B(int);
};

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 value
    int j = 5; // OK, j has the value 5
};
```

—end example

10 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]

11 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]

12 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]

13 In a non-delegating constructor, initialization proceeds in the following order:

13.1 — 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.

13.2 — 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).

13.3 — 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).

13.4 — 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]

14 [Example 9:

```cpp
struct V {
    V();
};
```

§ 11.9.3
struct A : virtual V {
    A();
    A(int);
};

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]

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;
public:
    D() : C(f()), // undefined behavior: calls member function but base C not yet initialized
        i(f()) { } // well-defined: bases are all initialized
};

—end example

17 [Note 8: 11.9.5 describes the result 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]

18 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:

template<class... Mixins>
class X : public Mixins... {
public:
    X(const Mixins&... mixins) : Mixins(mixins)... { }
};
—end example]

11.9.4 Initialization by inherited constructor [class.inhctor.init]

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 invocation of the inherited constructor. The complete initialization is considered to be a single function call; in particular, the initialization of the inherited constructor’s parameters is sequenced before the initialization of any part of the D object.

[Example 1:

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 d(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 a deleted default constructor
}

struct D2 : B2 {
    using B2::B2;
    B1 b;
};

§ 11.9.4
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

If the constructor was inherited from multiple base class subobjects of type B, the program is ill-formed.

[Example 2:

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 p0();      // OK, use M(0) to initialize N's base class,
            // use M() 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 [class.cdtor]

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:

struct X { int i; }
struct Y : X { Y(); }
struct A { int a; }
struct B : public A { int j; Y y; } // non-trivial

§ 11.9.5
extern B bobj;
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,
struct W { int j; }
struct X : public virtual W { }
struct Y {
    int* p;
    X x;
    Y() : p(&x.j) { // undefined, x is not yet constructed
    }
};
—end example

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:

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) {}
    int a, b;
};
D d = D(1);                        // value of d.b is unspecified
—end example]

To explicitly or implicitly convert a pointer (a glvalue) referring to an object of class X to a pointer (reference)
to a direct or indirect base class B of X, the construction of X and the construction of all of its direct or
indirect bases that directly or indirectly derive from 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 obj, the construction of 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.

[Example 3:

struct A { }
struct B : virtual A { };

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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* → D* → A*
       // but D is not constructed
     // “D(C*this)” would be defined: E* → C* is defined because E() has started,
     // and C* → A* is defined because C is fully constructed
    X(this) {}  // defined: upon construction of X, C/B/D/A sublattice is fully constructed
  // 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 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 x or one of that object’s base class subobjects but not x or one of its base class subobjects, the behavior is undefined.

[Example 4:
  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
  }
– end example]

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);
    // type_info for B
    typeid(*v);
    // well-defined: *v has type V, a base of B yields type_info for B
    typeid(*a);
    // undefined behavior: type A not a base of B
    dynamic_cast<B*>(v);
    // well-defined: v of type V*, V base of B results in B*
    dynamic_cast<B*>(a);
    // undefined behavior: a has type A*, A not a base of B
}
```

—end example]  

11.9.6 Copy/move elision

[class.copy.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.\(^{107}\) This elision of copy/move operations, called *copy elision*, is permitted in the following circumstances (which may be combined to eliminate multiple copies):

\(^{107}\)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.

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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]

2 [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]

3 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 copy-initialization contexts, a move operation is first considered before attempting a copy operation:

(3.1) — If the expression in a return (8.7.4) or co_return (8.7.5) statement is a (possibly parenthesized) id-expression that names an implicitly movable entity declared in the body or parameter-declaration-clause of the innermost enclosing function or lambda-expression, or

(3.2) — if the operand of a throw-expression (7.6.18) is a (possibly parenthesized) id-expression that names an implicitly movable entity that belongs to a scope that does not contain the compound-statement of the innermost try-block or function-try-block (if any) whose compound-statement or ctor-initializer contains the throw-expression,

overload resolution to select the constructor for the copy or the return_value overload to call is first performed as if the expression or operand were an rvalue. If the first overload resolution fails or was not performed, overload resolution is performed again, considering the expression or operand as an lvalue.
[Note 3: This two-stage overload resolution is performed regardless of whether copy elision will occur. It determines the constructor or the return_value overload to be called if elision is not performed, and the selected constructor or return_value overload must be accessible even if the call is elided. — end note]

4 [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() {
   Weird w;
   return w; // OK, first overload resolution fails, second overload resolution selects Weird(Weird&)
}

— end example]

5 [Example 3:

```cpp```
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
   }
}

— end example]

11.10 Comparisons

11.10.1 Defaulted comparison operator functions

A defaulted comparison operator function (12.4.3) for some class C shall be a non-template function that is

(1.1) a non-static const non-volatile member of C having one parameter of type const C& and either no ref-qualifier or the ref-qualifier &, or

(1.2) a friend of C having either two parameters of type const C& or two parameters of type C.
A comparison operator function for class \( C \) that is defaulted on its first declaration and is not defined as deleted is *implicitly defined* when it is odr-used or needed for constant evaluation. Name lookups in the defaulted definition 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.

A defaulted \( \Rightarrow \) 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 \( a \odot b \) is *usable* if either

1. \( a \) or \( b \) is of class or enumeration type and overload resolution (12.2) as applied to \( a \odot b \) results in a usable candidate, or
2. neither \( a \) nor \( b \) is of class or enumeration type and \( a \odot b \) is a valid expression.

A defaulted comparison function is *constexpr-compatible* if it satisfies the requirements for a constexpr function (9.2.6) and no overload resolution performed when determining whether to delete the function results in a usable candidate that is a non-constexpr function.

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 \( \text{bool} \) and the declarator-id is replaced with operator\(==\).

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.

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 [class.eq]

A defaulted equality operator function (12.4.3) shall have a declared return type \( \text{bool} \).
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).

The return value `V` 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 `bool`, yields `false`. If no such index exists, `V` is `true`. Otherwise, `V` is `false`.

[Example 1:

```cpp
struct D {
    int i;
    friend bool operator==(const D& x, const D& y) = default;
    // OK, returns x.i == y.i
};
```

—end example]

### 11.10.3 Three-way comparison

The synthesized three-way comparison of type `R` (17.11.2) of glvalues `a` and `b` of the same type is defined as follows:

(1.1) — If `a <=> b` is usable (11.10.1), `static_cast<R>(a <=> b)`.

(1.2) — Otherwise, if overload resolution for `a <=> b` is performed and finds at least one viable candidate, the synthesized three-way comparison is not defined.

(1.3) — 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.

(1.4) — Otherwise, if `R` is `strong_ordering`, then

```cpp
a == b ? strong_ordering::equal :
a < b ? strong_ordering::less :
strong_ordering::greater
```

(1.5) — Otherwise, if `R` is `weak_ordering`, then

```cpp
a == b ? weak_ordering::equivalent :
(a < b ? weak_ordering::less :
weak_ordering::greater)
```

(1.6) — Otherwise (when `R` is `partial_ordering`),

```cpp
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]

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`.

(2.1) — If `R` is `auto`, then let `cv_i R_i` be the type of the expression `x_i <=> 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, ..., R_{n-1}`.

(2.2) — Otherwise, `R` shall not contain a placeholder type. If the synthesized three-way comparison of type `R` between any objects `x` and `x_i` is not defined, the operator function is defined as deleted.

The return value `V` 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 != 0`, contextually converted to `bool`, yields `true`; `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`. If no such index exists, `V` is a copy of `v_i`.

The common comparison type `U` of a possibly-empty list of `n` comparison category types `T_0, T_1, ..., T_{n-1}` is defined as follows:

(4.1) — If at least one `T_i` is `std::partial_ordering`, `U` is `std::partial_ordering (17.11.2.2).`
— Otherwise, if at least one $T_i$ is `std::weak_ordering`, $U$ is `std::weak_ordering` (17.11.2.3).

— Otherwise, $U$ is `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 `bool`.

The operator function with parameters $x$ and $y$ is defined as deleted if

1. overload resolution (12.2), as applied to $x @ y$, does not result in a usable candidate, or
2. the candidate selected by overload resolution is not a rewritten candidate.

Otherwise, the operator function yields $x @ y$. The defaulted operator function is not considered as a candidate in the overload resolution for the `@` operator.

[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:

— invocation of a function named in the function call syntax (12.2.2.2);
— 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);
— invocation of the operator referenced in an expression (12.2.2.3);
— invocation of a constructor for default- or direct-initialization (9.4) of a class object (12.2.2.4);
— invocation of a user-defined conversion for copy-initialization (9.4) of a class object (12.2.2.5);
— 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
— 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:

— 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).
— 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.

The set of candidate functions can contain both member and non-member functions to be resolved against the same argument list. So that argument and parameter lists are comparable within this heterogeneous set, a member function that does not have an explicit object parameter 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. For the purposes of overload resolution, both static and non-static member functions have an object parameter, but constructors do not.

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.

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 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]

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]

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).
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 $cvU$, any $cv2U$, $cv2U&$, or $cv2U&&$ 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 $cv1P$" (including such a constructor instantiated from a template) is excluded from the set of candidate functions when constructing an object of type $cv2D$ if the argument list has exactly one argument and C is reference-related to $P$ and $P$ is reference-related to $D$.

[Example 3:]

```cpp
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
B b3 = C();

[end example]
```

12.2.2.2 Function call syntax [over.match.call]

12.2.2.2.1 General [over.match.call.general]

In a function call (7.6.1.3)

```
postfix-expression ( expression-list_opt )
```

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.

---

108) The process of argument deduction fully determines the parameter types of the function template specializations, i.e., the parameters of function template specializations contain no template parameter types. Therefore, except where specified otherwise, function template specializations and non-template functions (9.3.4.6) are treated equivalently for the remainder of overload resolution.
If the *postfix-expression* is the address of an overload set, overload resolution is applied using that set as described above. If the function selected by overload resolution is a non-static member function, the program is ill-formed.

>Note 1: 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:

```plaintext
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.

In qualified function calls, the function is named by an *id-expression* preceding a `->` 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* is the left operand of the `.` operator has type "cv T" where `T` denotes a class.\(^{109}\) 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 (1) entirely of non-member functions or (2) entirely of member functions of some class `T`. In case (1), the argument list is the same as the *expression-list* in the call. In case (2), 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` (7.5.2) refers to it, then the implied object argument is `(*this)`. Otherwise, a contrived object of type `T` becomes the implied object argument;\(^{110}\) 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 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
    }
}
```

109) Note that cv-qualifiers on the type of objects are significant in overload resolution for both glvalue and class prvalue objects.

110) 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.
12.2.2.2.3 Call to object of class type

1 If the postfix-expression \( E \) in the function call syntax evaluates to a class object of type “\( \text{cv} \ T \)”, 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 \( \text{operator}() \) in the scope of \( T \).

2 In addition, for each non-explicit conversion function declared in \( T \) of the form

\[
\text{operator conversion-type-id ( ) cv-qualifier-seq_{opt} ref-qualifier_{opt} noexcept-specifier_{opt} attribute-specifier-seq_{opt} ;}
\]

where the optional \( \text{cv-qualifier-seq} \) is the same \( \text{cv-qualification} \) as, or a greater \( \text{cv-qualification} \) than, \( \text{cv} \), and where \( conversion-type-id \) denotes the type “pointer to function of \((P_1, \ldots, P_n)\) returning \( R \)”, or the type “reference to pointer to function of \((P_1, \ldots, P_n)\) returning \( R \)”, or the type “reference to function of \((P_1, \ldots, P_n)\) returning \( R \)”, a surrogate call function with the unique name \( \text{call-function} \) and having the form

\[
R \ \text{call-function} \ ( conversion-type-id \ F, P_1 a_1, \ldots, P_n a_n ) \ { \text{return} \ F (a_1, \ldots, a_n); } \}
\]

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.\(^{111}\)

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. The conversion function from which the surrogate call function was derived will be used in the conversion sequence for that parameter since it converts the implied object argument to the appropriate function pointer or reference required by that first parameter. — end note]

[Example 1:

\[
\text{struct String } \{
\text{String (const String&);}
\text{String (const char*);}
\text{operator const char* () ;}
\};
\text{String operator + (const String&, const String&);}
\]

— end example]

12.2.2.3 Operators in expressions

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:

\[
\text{struct String } \{
\text{String (const String&);}
\text{String (const char*);}
\text{operator const char* () ;}
\};
\text{String operator + (const String&, const String&);}
\]

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.
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 17 (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 17: Relationship between operator and function call notation

<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 , or 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
(3.3.3) — accept operand types to which the given operand or operands can be converted according to 12.2.4.2, and
(3.3.4) — do not have the same parameter-type-list as any non-member candidate that is not a function template specialization.

(3.4) — The rewritten candidate set is determined as follows:

(3.4.1) — For the relational (7.6.9) operators, the rewritten candidates include all non-rewritten candidates for the expression x <=> y.
(3.4.2) — 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 <=> x.
(3.4.3) — For the != operator (7.6.10), the rewritten candidates include all non-rewritten candidates for the expression x == y.

§ 12.2.2.3
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 \( y == x \).

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]

For the built-in assignment operators, conversions of the left operand are restricted as follows:

— no temporaries are introduced to hold the left operand, and

— no user-defined conversions are applied to the left operand to achieve a type match with the left-most parameter of a built-in candidate.

For all other operators, no such restrictions apply.

The set of candidate functions for overload resolution for some operator \( \oplus \) is the union of the member candidates, the non-member candidates, the built-in candidates, and the rewritten candidates for that operator \( \oplus \).

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.

**Example 2:**
```cpp
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)
}
```

If a rewritten \( \operatorname{operator\<=>} \) candidate is selected by overload resolution for an operator \( \oplus \), \( x \oplus y \) is interpreted as \( 0 \oplus (y \operatorname{\<=>} x) \) if the selected candidate is a synthesized candidate with reversed order of parameters, or \( (x \operatorname{\<=>} y) \oplus 0 \) otherwise, using the selected rewritten \( \operatorname{operator\<=>} \) candidate. Rewritten candidates for the operator \( \oplus \) are not considered in the context of the resulting expression.

If a rewritten \( \operatorname{operator==} \) candidate is selected by overload resolution for an operator \( \oplus \), its return type shall be \( \text{cv bool} \), and \( x \oplus y \) is interpreted as:

1. If \( \oplus \) is \( \neq \) and the selected candidate is a synthesized candidate with reversed order of parameters, \( !((y == x)) \),
2. otherwise, if \( \oplus \) is \( \neq \), \( !((x == y)) \),
3. otherwise (when \( \oplus \) is \( == \)), \( y == x \),

in each case using the selected rewritten \( \operatorname{operator==} \) 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 3:**
```cpp
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
```

112) If the set of candidate functions is empty, overload resolution is unsuccessful.
The second operand of operator \( \to \) is ignored in selecting an operator\( \to \) function, and is not an argument when the operator\( \to \) function is called. When operator\( \to \) returns, the operator \( \to \) is applied to the value returned, with the original second operand.\(^{113}\)

If the operator is the operator \( , \) the unary operator \&, or the operator \( \to \), and there are no viable functions, then the operator is assumed to be the built-in operator and interpreted according to 7.6.

\[\text{Note 3: The lookup rules for operators in expressions are different than the lookup rules for operator function names in a function call, as shown in the following example:}\]

```c
struct A { }
void operator + (A, A);

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

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 that is not in the context of copy-initialization, the candidate functions are all the constructors of the class of the object being initialized. For copy-initialization (including default initialization in the context of copy-initialization), 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.

### 12.2.2.5 Copy-initialization of class by user-defined conversion

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.

\[\text{Note 1: The conversion performed for indirect binding to a reference to a possibly cv-qualified class type is determined in terms of a corresponding non-reference copy-initialization. —end note}\]

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. The converting constructors (11.4.8.2) of T are candidate functions.
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.

In both cases, the argument list has one argument, which is the initializer expression.

\[\text{Note 2: This argument will be compared against the first parameter of the constructors and against the object parameter of the conversion functions. —end note}\]

---

\(^{113}\) If the value returned by the operator\( \to \) function has class type, this can result in selecting and calling another operator\( \to \) function. The process repeats until an operator\( \to \) function returns a value of non-class type.
12.2.2.6 Initialization by conversion function

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. 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

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. 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. 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.

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 (9.2.9.7) 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. 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 types of the function parameters are those of the constructor.

   1.1.3 The return type is the class template specialization designated by C and template arguments corresponding to the template parameters of C.
If \( C \) is not defined or does not declare any constructors, an additional function template derived as above from a hypothetical constructor \( C() \).

An additional function template derived as above from a hypothetical constructor \( C(C) \), called the copy deduction candidate.

For each deduction-guide, a function or function template with the following properties:

- The template parameters, if any, and function parameters are those of the deduction-guide.
- 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

brace elision is not considered for any aggregate element that has a dependent non-array type or an array type with a value-dependent bound, and each non-trailing aggregate element that is a pack expansion is assumed to correspond to no elements of the initializer list, and 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

- if \( e_i \) is of array type and \( x_i \) is a braced-init-list or string-literal, \( T_i \) is an rvalue reference to the declared type of \( e_i \), and
- 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 \( T_n, \ldots \).

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

\[
\text{typename}_{\text{opt}} \text{ nested-name-specifier}_{\text{opt}} \text{ template}_{\text{opt}} \text{ simple-template-id}
\]

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. 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 \( A \):

- The function type of \( f' \) is the function type of \( g \).
- 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.
- 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.
- If \( f \) is a copy deduction candidate, then \( f' \) is considered to be so as well.
- If \( f \) was generated from a deduction-guide (13.7.2.3), then \( f' \) is considered to be so as well.
- The explicit-specifier of \( f' \) is the explicit-specifier of \( g \) (if any).

The arguments of a template \( A \) are said to be deducible from a type \( T \) if, given a class template

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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.

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:

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.

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.

Example 1:

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 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>

template <typename... T>
struct Types {};           // #1

template <typename... T>
struct F : Types<T...>, T... {}; // #2

struct X {};
struct Y {};
struct Z {};
struct W { operator Y(); };

F f1 = {Types<X, Y, Z>{}, {}, {}};       // OK, F<X, Y, Z> deduced
F f2 = {Types<X, Y, Z>{}, X(), Y()};    // OK, F<X, Y, Z> deduced
F f3 = {Types<X, Y, Z>{}, X(), W()};    // error: conflicting types deduced; operator Y not considered

— end example

Example 2:

template <class T, class U> struct C {
  C(T, U);                // #1
};

template<class T, class U>
C(T, U) -> C<T, std::type_identity_t<U>>;   // #2

template<class V> using A = C<V *, V *>;

int i{};
double d{};
A a1(&i, &i);         // deduces A<int>
A a2(i, 1);           // error: cannot deduce V * from i
A a3(&i, &d);         // error: #1: cannot deduce (V *, V *) from (int *, double *)

// #2: cannot deduce A<V> from C<int *, double *>
B b1(&i, &i);         // deduces B<int>
B b2(&d, &d);         // error: cannot deduce B<w> from C<double *, double *>

Possible exposition-only implementation of the above procedure:

// The following concept ensures a specialization of A is deduced.
template <class> class AA;
template <class V> class AA<A<V>> { };  // #1

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<T, 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 *;
// 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>>> && deduces_B<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.
template <class> class BB;
template <class V> class BB<B<V>> { }; // The guides for B derived from the above f1' and f2' for A are as follows:
template<std::integral W>
    requires deduces_A<C<W *, W *>, std::type_identity_t<T>>
    auto f1_prime_for_B(W *, W *) -> C<W *, W *>; // The guides for B derived from the above f1' and f2' for A are as follows:
template<std::integral W, class U>
    requires deduces_A<C<W *, U>, std::type_identity_t<T>> &&
    deduces_B<C<W *, std::type_identity_t<T>>>
    auto f2_prime_for_B(W *, U) -> C<W *, std::type_identity_t<T>>;

— end example] 

12.2.3 Viable functions [over.match.viable]

1 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.

2 First, to be a viable function, a candidate function shall have enough parameters to agree in number with the arguments in the list.

(2.1) If there are m arguments in the list, all candidate functions having exactly m parameters are viable.

(2.2) 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).

(2.3) A candidate function having more than m parameters is viable only if all parameters following the mth 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.

3 Second, for a function to be viable, if it has associated constraints (13.5.3), those constraints shall be satisfied (13.5.2).

4 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

12.2.4.1 General

Define ICS\(^i\)(F) as follows:

(1.1) If \(F\) is a static member function, ICS\(^i\)(F) is defined such that ICS\(^i\)(F) is neither better nor worse than ICS\(^i\)(G) for any function G, and, symmetrically, ICS\(^i\)(G) is neither better nor worse than ICS\(^i\)(F),\(^\text{114}\) otherwise.

(1.2) let ICS\(^i\)(F) denote 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

(2.1) for some argument \(j\), ICS\(^j\)(F\(_1\)) is a better conversion sequence than ICS\(^j\)(F\(_2\)), or, if not that,

(2.2) 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 return type of \(F_1\) to the destination type (i.e., the type of the entity being initialized) is a better conversion sequence than the standard conversion sequence from the return type of \(F_2\) to the destination type

[Example 1:

```cpp
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:

```cpp
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 with the same parameter-type-lists, and \(F_1\) is more constrained than \(F_2\) according to the partial ordering of constraints described in 13.5.5, or if not that,

(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 3:

If a function is a static member function, this definition means that the first argument, the implied object argument, has no effect in the determination of whether the function is better or worse than any other function.

\(^{114}\) If a function is a static member function, this definition means that the first argument, the implied object argument, has no effect in the determination of whether the function is better or worse than any other function.
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 4:
    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 5:
    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 is generated from a deduction-guide (12.2.2.9) and F2 is not, or, if not that,

(2.11) — F1 is the copy deduction candidate (12.2.2.9) and F2 is not, or, if not that,

(2.12) — F1 is generated from a non-template constructor and F2 is generated from a constructor template.

[Example 6:
    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(U, T, int);    // #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

    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

    // § 12.2.4.1 334
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.\(^{115}\)

[Example 7:

```c
void Fcn(const int*, short);
void Fcn(int*, int);

int i;
short s = 0;

void f() {
    Fcn(&i, s); // is ambiguous because &i \rightarrow int* is better than &i \rightarrow const int*
                   // but s \rightarrow short is also better than s \rightarrow int
    Fcn(&i, 1L); // calls Fcn(int*, int), because &i \rightarrow int* is better than &i \rightarrow const int*
                   // and 1L \rightarrow short and 1L \rightarrow int are indistinguishable
    Fcn(&i, 'c'); // calls Fcn(int*, int), because &i \rightarrow int* is better than &i \rightarrow const int*
                   // and c \rightarrow int is better than c \rightarrow 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 8:

```c
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

1 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).

2 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.

\(^{115}\) 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.
A well-formed implicit conversion sequence is one of the following forms:

- a standard conversion sequence (12.2.4.2.2),
- a user-defined conversion sequence (12.2.4.2.3), or
- an ellipsis conversion sequence (12.2.4.2.4).

However, if the target is
- the first parameter of a constructor or
- the object parameter of a user-defined conversion function
and the constructor or user-defined conversion function is a candidate by
- 12.2.2.4, when the argument is the temporary in the second step of a class copy-initialization,
- 12.2.2.5, 12.2.2.6, or 12.2.2.7 (in all cases), or
- 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:]

```c
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.

[Note 4: There is no such standard conversion; this derived-to-base conversion exists only in the description of implicit conversion sequences. — end note]

A derived-to-base conversion has Conversion rank (12.2.4.2.2).

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 converting to the explicit object parameter, if any, user-defined conversion sequences are allowed. — 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.]

Example 3:

class B;
class A { A (B&); }; 
class B { operator A () ; }; 
class C { C (B&); }; 
void f(A) { } 
void f(C) { } 
B b; 
f(b); // error: ambiguous because there is a conversion b → C (via constructor) 
// and an (ambiguous) conversion b → A (via constructor or conversion function) 
void f(B) { } 
f(b); // OK, unambiguous
—end example
—end note

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 18 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 18 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 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.

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

§ 12.2.4.2.3
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 reference type binds directly (9.4.4) to an argument expression, the implicit conversion sequence is the identity conversion, unless the argument expression has a type that is a derived class of the parameter type, in which case the implicit conversion sequence is a derived-to-base conversion (12.2.4.2).

[Example 1:

```c
struct A {};
struct B : public A {} b;
int f(const 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 either an identity conversion or, if the conversion function returns an entity of a type that is a derived class of the parameter type, a derived-to-base conversion.

2 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.

3 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 other than a function value.
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

1 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.

2 If the initializer list is a designated-initializer-list, 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). — end note]

Example 1:

```cpp
class A { int x, y; }
class 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]

3 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.

4 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.

5 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 worst conversion sequence is the one required to convert 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(std::initializer_list<int>);
f( {} );    // OK, f(initializer_list<int>) identity conversion
f( {1,2,3} ); // OK, f(initializer_list<int>) identity conversion
f( {'a','b'} ); // OK, f(initializer_list<int>) integral promotion
f( {1.0} );   // error: narrowing

struct A {
  A(std::initializer_list<double>);  // #1
  A(std::initializer_list<complex<double>>);  // #2
```

116) Since there are no parameters of array type, this will only occur as the referenced type of a reference parameter.
A(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:
 struct A {
  A(std::initializer_list<int>);
};
void f(A);
f( {'a', 'b'} );                                    // OK, f(A(std::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(std::string);
};
void h(C);
h(“foo”);                                          // OK, h(C(std::string("foo")))

struct D {
  D(A, C);
};
void i(D);
i({ {1,2}, {"bar"} });                               // OK, i(D(A(std::initializer_list<int>{1,2}), C(std::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:

(10.1) — 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]

(10.2) — 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]

1 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
— L1 converts to `std::initializer_list<X>` for some X and L2 does not, or, if not that,
— L1 and L2 convert to arrays of the same element type, and either the number of elements \( n_1 \) initialized by L1 is less than the number of elements \( n_2 \) initialized by L2, or \( n_1 = n_2 \) 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]:**

```cpp
class A {
public:
  A& operator<<(int);
  void p() &;
  void p() &&;
  A& operator<<(A&&, char);
protected:
  A() << 1;  // calls A::operator<<(int)
  A() << 'c';  // calls operator<<(A&&, char)
  A a;
  a << 1;  // calls A::operator<<(int)
a << 'c';  // calls A::operator<<(int)
  A().p();  // calls A::p()&
};
```

**[Example 2]:**

```cpp
void f1(int);
void f1(std::initializer_list<long>);  // #2
void g1() { f1({42}); }  // chooses #2
void f2(std::pair<const char*, const char*>);  // #3
void f2(std::initializer_list<std::string>);  // #4
void g2() { f2("foo","bar"); }  // chooses #4
```

— end example]

**[Example 3]:**

```cpp
int i;
int f1();
int&& f2();
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() << 'c';  // calls operator<<(A&&, char)
A a;
a << 1;  // calls A::operator<<(int)
a << 'c';  // calls A::operator<<(int)
A().p();  // calls A::p()&
```

— end example]

**§ 12.2.4.3**
...
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) 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*.

(4.4) If class B is derived directly or indirectly from class A and class C is derived directly or indirectly from B,

(4.4.1) conversion of C* to B* is better than conversion of C* to A*;

(4.4.2) 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,

(4.4.3) conversion of A::* to B::* is better than conversion of A::* to C::*;

(4.4.4) conversion of C to B is better than conversion of C to A,

(4.4.5) conversion of B* to A* is better than conversion of C* to A*;

(4.4.6) 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,

(4.4.7) conversion of B::* to C::* is better than conversion of A::* to C::* and

(4.4.8) 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.

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 (7.5.3).
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]

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.

Non-member functions, static member functions, and explicit object member functions match targets of function pointer type or reference to function type. Non-static 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]

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 \( F_0 \) is eliminated if the set contains a second non-template function that is more constrained than \( F_0 \) according to the partial ordering rules of 13.5.5. Any given function template specialization \( F_1 \) is eliminated if the set contains a second function template specialization whose function template is more specialized than the function template of \( F_1 \) according to the partial ordering rules of 13.7.7.3. After such eliminations, if any, there shall remain exactly one selected function.

[Example 1:]
```c
int f(double);
int f(int);
int (*pfd)(double) = &f;   // selects f(double)
int (*pfi)(int) = &f;     // selects f(int)
int (*)(...) = &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 (*)(...) = &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
```

[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
```
```c
void g(D*);
void (*p2)(B*) = &g; // error
```

— end note]
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

operator: one of
new delete new[] delete[] co_await () [] -> ->*
~ ! + - * / % ^ &
| = += -= *= /= %= ^= &=
|| << >> <<= >>= ++ -- ,

[Note 1: The operators new[], delete[], (), and [] are formed from more than one token. The latter two operators are function call (7.6.1.3) and subscripting (7.6.1.2). —end note]

2 Both the unary and binary forms of
+ - * &
can be overloaded.

3 [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);
—end example]

5 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.

6 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 be a non-static member function or 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]

10 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.

11 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

```cpp
cast-expression . operator @ ()
```

Otherwise, if a non-member function is selected, the expression is interpreted as

```cpp
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

```cpp
x . operator @ ( y )
```

Otherwise, if a non-member function is selected, the expression is interpreted as

```cpp
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 in `D` does not override `B`’s virtual copy/move assignment operator.

[Example 1:]

```cpp
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
}
```
12.4.4 Function call

A function call operator function is a function named \( \text{operator}() \) that is a non-static member function with an arbitrary number of parameters. It may have default arguments. For an expression of the form

\[
\text{postfix-expression} (\text{expression-list}_{\text{opt}})
\]

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 for a conversion function named operator conversion-type-id is selected, the expression is interpreted as

\[
\text{postfix-expression} . \text{operator conversion-type-id} () (\text{expression-list}_{\text{opt}})
\]

Otherwise, the expression is interpreted as

\[
\text{postfix-expression} . \text{operator} () (\text{expression-list}_{\text{opt}})
\]

12.4.5 Subscripting

A subscripting operator function is a function named \( \text{operator[]} \) that is a non-static member function. For an expression of the form

\[
\text{postfix-expression} [\text{expression-list}_{\text{opt}}]
\]

the operator function is selected by overload resolution (12.2.2.3). If a member function is selected, the expression is interpreted as

\[
\text{postfix-expression} \cdot \text{operator} () (\text{expression-list}_{\text{opt}})
\]

[Example 1:

```cpp
struct X {
  Z operator[](std::initializer_list<int>);
  Z operator[](auto...);
};

X x;
x[{1,2,3}] = 7; // OK, meaning x.operator[](\{1,2,3\})
x[1,2,3] = 7; // OK, meaning x.operator[](1,2,3)
int a[10];
a[{1,2,3}] = 7; // error: built-in subscript operator
a[1,2,3] = 7; // error: built-in subscript operator
```

—end example]

12.4.6 Class member access

A class member access operator function is a function named \( \text{operator}\rightarrow() \) that is a non-static member function taking no non-object parameters. For an expression of the form

\[
\text{postfix-expression} \rightarrow \text{template}_{\text{opt}} \text{id-expression}
\]

the operator function is selected by overload resolution (12.2.2.3), and the expression is interpreted as

\[
(\text{postfix-expression} . \text{operator} \rightarrow () ) \rightarrow \text{template}_{\text{opt}} \text{id-expression}
\]

12.4.7 Increment and decrement

An increment operator function is a function named \( \text{operator}++ \). 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 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 \( \text{int} \)) or a non-member function with two parameters (the second of which shall be of type \( \text{int} \)), 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 \( \text{int} \) argument will have value zero.\(^{117}\)

[Example 1:

Calling \( \text{operator}++ \) explicitly, as in expressions like \( \text{a} \cdot \text{operator}++(2) \), has no special properties: The argument to \( \text{operator}++ \) is 2.
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 */

2 A decrement operator function is a function named operator-- and is handled analogously to an increment operator function.

12.5 Built-in operators [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]

2 In this subclause, the term 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. int and long but excluding e.g. 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]

3 In the remainder of this subclause, vq represents either volatile or no cv-qualifier.

4 For every pair (T, vq), where T is a cv-unqualified arithmetic type other than bool or a cv-unqualified pointer to (possibly cv-qualified) object type, there exist candidate operator functions of the form

    vq T& operator++(vq T&);
    T operator++(vq T&, int);
    vq T& operator--(vq T&);
    T operator--(vq T&, int);

5 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& operator*(T*);

6 For every type T there exist candidate operator functions of the form

    T* operator*(T*);

7 For every cv-unqualified floating-point or promoted integral type T, there exist candidate operator functions of the form

    T operator+(T);
For every promoted integral type \( T \), there exist candidate operator functions of the form
\[
T \text{ operator-}(T);
\]

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
\[
cv12 \ T \text{ operator-}>(cv1 \ C1*, cv2 \ T \ C2::*);
\]
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
\[
LR \text{ operator*}(L, R);
LR \text{ operator/}(L, R);
LR \text{ operator-}(L, R);
bool \text{ operator==}(L, R);
bool \text{ operator!=}(L, R);
bool \text{ operator<(L, R)};
bool \text{ operator>(L, R)};
bool \text{ operator<=(L, R)};
bool \text{ operator>=(L, R)};
\]
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
\[
\text{std::strong_ordering operator<=>}(T, T);
\]

For every pair of floating-point types \( L \) and \( R \), there exists a candidate operator function of the form
\[
\text{std::partial_ordering operator<=>}(L, R);
\]

For every cv-qualified or cv-unqualified object type \( T \) there exist candidate operator functions of the form
\[
T\* \text{ operator+}(T\*, std::ptrdiff_t);
T\* \text{ operator-}(T\*, std::ptrdiff_t);
T\* \text{ operator+}(std::ptrdiff_t, T\*);
T\* \text{ operator-}(std::ptrdiff_t, T*);
\]

For every \( T \), where \( T \) is a pointer to object type, there exist candidate operator functions of the form
\[
\text{std::ptrdiff_t operator-}(T, T);
\]

For every \( T \), where \( T \) is an enumeration type or a pointer type, there exist candidate operator functions of the form
\[
bool \text{ operator==}(T, T);
bool \text{ operator!=}(T, T);
bool \text{ operator<(T, T)};
bool \text{ operator>(T, T)};
bool \text{ operator<=(T, T)};
bool \text{ operator>=(T, T)};
\]
where \( R \) is the result type specified in 7.6.8.

For every \( T \), where \( T \) is a pointer-to-member type or \( \text{std::nullptr_t} \), there exist candidate operator functions of the form
\[
bool \text{ operator==}(T, T);
bool \text{ operator!=}(T, T);
\]

For every pair of promoted integral types \( L \) and \( R \), there exist candidate operator functions of the form
\[
LR \text{ operator%}(L, R);
LR \text{ operator&}(L, R);
LR \text{ operator^}(L, R);
LR \text{ operator|}(L, R);
L \text{ operator}<<(L, R);
\]
L  operator>>(L, R);

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

vq Lk  operator=(vq Lk, R);

vq Lk  operator**=(vq Lk, R);

vq Lk  operator/=(vq Lk, R);

vq Lk  operator+=(vq Lk, R);

vq Lk  operator-=(vq Lk, R);

For every pair (T, vq), where T is any type, there exist candidate operator functions of the form

T*vqk  operator=(T*vqk, T*);

For every pair (T, vq), where T is an enumeration or pointer-to-member type, there exist candidate operator functions of the form

vq Tk  operator=(vq Tk, T);

For every pair (T, vq), where T is a cv-qualified or cv-unqualified object type, there exist candidate operator functions of the form

T*vqk  operator+=(T*vqk, std::ptrdiff_t);

T*vqk  operator-=(T*vqk, std::ptrdiff_t);

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

vq Lk  operator%=(vq Lk, R);

vq Lk  operator<<=(vq Lk, R);

vq Lk  operator>>=(vq Lk, R);

vq Lk  operator&=(vq Lk, R);

vq Lk  operator^=(vq Lk, R);

vq Lk  operator|=(vq Lk, R);

There also exist candidate operator functions of the form

bool  operator!(bool);

bool  operator&&(bool, bool);

bool  operator||(bool, bool);

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  operator?:(bool, L, R);

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

T  operator?:(bool, T, T);

12.6 User-defined literals [over.literal]

literal-operator-id:

operator string-literal identifier

operator user-defined-string-literal

1 The string-literal or user-defined-string-literal in a literal-operator-id shall have no encoding-prefix and shall contain no characters other than the implicit terminating '0'. The ud-suffix of the user-defined-string-literal or the identifier in a literal-operator-id is called a literal suffix identifier. 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.
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`
- `char`
- `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.

A *raw literal operator* is a literal operator with a single parameter whose type is `const char*`.

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.

Literal operators and literal operator templates shall not have C language linkage.

[Note 1: Literal operators and literal operator templates are usually invoked implicitly through user-defined literals (5.13.8). 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]

[Example 1:]

```c
void operator " _km(long double); // OK
string operator " _i18n(const char*, std::size_t); // OK
template <char...> double operator " _\u03C0(); // 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, 5.13.8)
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 " _5X(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

1 A template defines a family of classes, functions, or variables, an alias for a family of types, or a concept.

   template-declaration:
     template-head declaration
     template-head concept-definition

   template-head:
     template < template-parameter-list > requires-clause<opt>

   template-parameter-list:
     template-parameter
     template-parameter-list , template-parameter

   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

[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 deduction-guide, or
   (2.5) — 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.

   [Example 1:
    template<class T>
      constexpr T pi = T(3.1415926535897932385L);
    template<class T>
      T circular_area(T r) {
        return pi<T> * r * r;
      }
    struct matrix_constants {
      template<class T>
        using pauli = hermitian_matrix<T, 2>;
      template<class T>
        constexpr static pauli<T> sigma1 = { { 0, 1 }, { 1, 0 } };
      template<class T>
        constexpr static pauli<T> sigma2 = { { 0, -1i }, { 1i, 0 } };
      template<class T>
        constexpr static pauli<T> sigma3 = { { 1, 0 }, { 0, -1 } };
    };
    — end example]

[Note 2: A template-declaration can appear only as a namespace scope or class scope declaration. — end note]
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]

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.

5 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]

6 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]

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 (7.5.5.2) 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 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:

```cpp
template<int N> requires N == sizeof new unsigned short
int f();        // error: parentheses required around == expression
```

— end example]

— end note]

9 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

The syntax for template-parameters is:

```
template-parameter:
    type-parameter
    parameter-declaration

type-parameter:
    template-head 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
```

§ 13.2
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]

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 { /* ... */ };  
  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 storage class shall not be specified in a template-parameter declaration. Types shall not be defined in a template-parameter declaration.

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 K, class V, template<class T> class C = myarray>
  class Map {
    C<K> key;
    C<V> value;
  };
  —end note]

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<A₁, ⋯, Aₙ>, then let E’ be C<T, A₁, ⋯, Aₙ>. 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).

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;
  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> && ...)

118) 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.
A non-type template-parameter shall have one of the following (possibly cv-qualified) types:

1. a structural type (see below),
2. a type that contains a placeholder type (9.2.9.6), or
3. a placeholder for a deduced class type (9.2.9.7).

The top-level cv-qualifiers on the template-parameter are ignored when determining its type.

A structural type is one of the following:

1. a scalar type, or
2. an lvalue reference type, or
3. a literal class type with the following properties:
   1. all base classes and non-static data members are public and non-mutable and
   2. the types of all bases classes and non-static data members are structural types or (possibly multi-dimensional) array thereof.

An id-expression naming a non-type template-parameter of class type \( T \) denotes a static storage duration object of type \( \text{const } T \), known as a template parameter object, whose value is that of the corresponding template argument after it has been converted to the type of the template-parameter. All such template parameters in the program of the same type with the same value denote the same template parameter object. A template parameter object shall have constant destruction (7.7).

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 \( \text{const } T \) (7.5.4.2).

Example 3:

```cpp
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    // error: change of template-parameter value
    &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
}
```

Note 4: A non-type template-parameter cannot be declared to have type cv void.

Example 4:

```cpp
template<void v> class X; // error
template<void* pv> class Y; // OK
```

Note 4: A non-type template-parameter cannot be declared to have type cv void.

Example 4:

```cpp
template<void v> class X; // error
template<void* pv> class Y; // OK
```

End note

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:

```cpp
template<int* a> struct R { /* ... */ }; // OK
template<int b[5]> struct S { /* ... */ }; // OK due to parameter adjustment
int p;
R<&p> v; // OK
S<&p> x; // OK due to implicit argument conversion
int v[5];
R<&v> y; // OK due to both adjustment and conversion
S<&v> z; // OK due to both adjustment and conversion
```

---

8 A non-type template-parameter shall have one of the following (possibly cv-qualified) types:

1. a structural type (see below),
2. a type that contains a placeholder type (9.2.9.6), or
3. a placeholder for a deduced class type (9.2.9.7).

The top-level cv-qualifiers on the template-parameter are ignored when determining its type.

7 A structural type is one of the following:

1. a scalar type, or
2. an lvalue reference type, or
3. a literal class type with the following properties:
   1. all base classes and non-static data members are public and non-mutable and
   2. the types of all bases classes and non-static data members are structural types or (possibly multi-dimensional) array thereof.

8 An id-expression naming a non-type template-parameter of class type \( T \) denotes a static storage duration object of type \( \text{const } T \), known as a template parameter object, whose value is that of the corresponding template argument after it has been converted to the type of the template-parameter. All such template parameters in the program of the same type with the same value denote the same template parameter object. A template parameter object shall have constant destruction (7.7).

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 \( \text{const } T \) (7.5.4.2). End note

Example 3:

```cpp
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    // error: change of template-parameter value
    &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
}
```

Note 4: A non-type template-parameter cannot be declared to have type cv void.

Example 4:

```cpp
template<void v> class X; // error
template<void* pv> class Y; // OK
```

End note

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:

```cpp
template<int* a> struct R { /* ... */ }; // OK
template<int b[5]> struct S { /* ... */ }; // OK due to parameter adjustment
int p;
R<&p> v; // OK
S<&p> x; // OK due to implicit argument conversion
int v[5];
R<&v> y; // OK due to both adjustment and conversion
S<&v> z; // OK due to both adjustment and conversion
```
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:

```cpp
template<class T1, class T2 = int> class A;
template<class T1 = int, class T2> class A;
```

is equivalent to

```cpp
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:

```cpp
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:

```cpp
template<int i = 3 > 4 >
class X { /* ... */ };

// syntax error
template<int i = (3 > 4) >
class Y { /* ... */ };
```

—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:

```cpp
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:

```cpp
template <class... Types>
    // Types is a template type parameter pack
class Tuple;
    // but not a pack expansion

template <class T, int... Dims>
struct multi_array;
    // but not a pack expansion

template <class... T>
struct value_holder {
    template <T... Values> struct apply { }; // Values is a non-type template parameter pack
    // and a pack expansion
};

template <class... T, T... Values>
struct static_array;
    // error: Values expands template type parameter
    // 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:

```cpp
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 ...
    template-argument-list , template-argument ...

template-argument:
    constant-expression
    type-id
    id-expression
```

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

(3.2) — for which name lookup finds the injected-class-name of a class template or finds any declaration of a template, or

(3.3) — that is an unqualified name for which name lookup either finds one or more functions or finds nothing, or

(3.4) — 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:

```cpp
struct X {
    template<std::size_t> X* alloc();
    template<std::size_t> static X* adjust();
};
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 >\(^{119}\) 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:

```cpp
template<int i> class X { /* ... */ }; // syntax error
X<1>2 > x1;                           // syntax error
X<(1>2)> x2;                          // OK

template<class T> class Y { /* ... */ }; // OK, same as Y<X<1>> > x3;
Y<X<1>> x3;                           // syntax error
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 (7.5.4.3).

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 allowed even when lookup for the name would already find a template. — end note]

[Example 3:

```cpp
template <class T> struct A {
    void f(int);
    template <class U> void f(U);
};

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 { };           // 119 A > that encloses the type-id of a dynamic_cast, static_cast, reinterpret_cast or const_cast, or which encloses the template-arguments of a subsequent template-id, is considered nested for the purpose of this description.
};
// 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
pack (13.7.4),

(7.2) — there is an argument for each non-deducible non-pack parameter that does not have a default template-
argument,

(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
paragraph.

A simple-template-id shall be valid unless it names a function template specialization (13.10.3).

[Example 4:

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<1>; // 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:

template<concept 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<concept T>
struct S2 { Ptr<int> x; }; // ill-formed, no diagnostic required

template<concept 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
};

template<concept T> concept C2 = sizeof(T) == 1;
template struct S<char[2]>; // error: constraints not satisfied
template<> struct S<char[2]> { } // error: constraints not satisfied
—end example]
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:]
```cpp
template<typename T> concept C = true;
static_assert(C<int>); // OK
@end example]
```

13.4 Template arguments [temp.arg]
13.4.1 General [temp.arg.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:]
```cpp
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]
```

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.

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.\(^\text{120}\)

[Example 2:]
```cpp
template<class T> void f();
template<int I> void f();

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]

\(^\text{120}\) 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.
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.

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.

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.

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:

```c
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 [temp.arg.type]

1 A template-argument for a template-parameter which is a type shall be a type-id.

2 [Example 1:

```c
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);    // OK
    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 [temp.arg.nontype]

1 If the type T of a template-parameter (13.2) contains a placeholder type (9.2.9.6) or a placeholder for a deduced class type (9.2.9.7), the type of the parameter is the type deduced for the variable x in the invented declaration

```c
T x = template-argument;
```

If a deduced parameter type is not permitted for a template-parameter declaration (13.2), the program is ill-formed.

2 A template-argument for a non-type template-parameter shall be a converted constant expression (7.7) of the type of the template-parameter.

[Note 1: If the template-argument is an overload set (or the address of such, including forming a pointer-to-member), the matching function is selected from the set (12.3). — end note]

3 For a non-type template-parameter of reference or pointer type, or for each non-static data member of reference or pointer type in a non-type 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 typeid expression (7.6.1.8),
4. a predefined __func__ variable (9.5.1), or
5. a subobject (6.7.2) of one of the above.

[Example 1:

```c
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

— end example

[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]

[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 &r; };
template<Y y> struct C { /* ... */};
C<Y{X{i}.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

A template-argument for a template template-parameter shall be the name of a class template or an alias template, expressed as \textit{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.

\textbf{Example 1:}

\begin{verbatim}
template<class T> class A { // primary template
  int x;
};
template<class T> class A<T*> { // partial specialization
  long x;
};
template<template<class U> class V> class C {  // V<int> within C<A> uses the primary template, so c.y.x has type int
  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{verbatim}

\textbf{Example 2:}

\begin{verbatim}
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{verbatim}

\textbf{Example 3:}

\begin{verbatim}
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;
\end{verbatim}
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<B<int, float>> eB; // OK, matches partial specialization of eval
eval<C<17>> eC;    // error: C does not match T in partial specialization
eval<D<int, 17>> eD; // error: D does not match T in partial specialization
eval<E<int, float>> eE; // error: E does not match T 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 { };
template< C > struct X { };
template< D > struct Y { };
template< typename T > struct Z { };

S< X > s1;        // OK, X and P have equivalent constraints
S< Y > s2;        // error: P is not at least as specialized as Y
S< Z > s3;        // OK, P is at least as specialized as Z

— end example

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 id-expression 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

[Note 1: Subclause 13.5 defines the meaning of constraints on template arguments. The abstract syntax and satisfaction rules are defined in 13.5.2. Constraints are associated with declarations in 13.5.3. Declarations are partially ordered by their associated constraints (13.5.5). — end note]

13.5.2 Constraints

13.5.2.1 General

[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 \( \wedge \) and disjunction is spelled using the symbol \( \vee \). The operands of these operations are called the left and right operands. In the constraint \( A \wedge B \), \( A \) 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.

[Example 1:

```cpp
template<typename T>
constexpr bool get_value() { return T::value; }
```

```cpp
template<typename T>
requires (sizeof(T) > 1) && (get_value<T>())
void f(T);
// has associated constraint sizeof(T) > 1 \&\& get_value<T>()
```

```cpp
void f('a'); // OK, calls f(int)
```

In the satisfaction of the associated constraints (13.5.3) of \( f \), the constraint \( \text{sizeof(char)} > 1 \) is not satisfied; the second operand is not checked for satisfaction. — end example]

[Note 2: A logical negation expression (7.6.2.2) is an atomic constraint; the negation operator is not treated as a logical operation on constraints. As a result, distinct negation constraint-expressions that are equivalent under 13.7.7.2 do not subsume one another under 13.5.5. Furthermore, if substitution to determine whether an atomic constraint is satisfied (13.5.2.3) encounters a substitution failure, the constraint is not satisfied, regardless of the presence of a negation operator.

[Example 2:

```cpp
template <class T> concept sad = false;
```

```cpp
template <class T> int f1(T) requires (!sad<T>);
template <class T> int f1(T) requires (!sad<T>) && true;
int i1 = f1(42); // ambiguous, !sad<T> atomic constraint expressions (13.5.2.3)
// are not formed from the same expression
```

```cpp
template <class T> concept not_sad = !sad<T>;
template <class T> int f2(T) requires not_sad<T>;
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
```

```cpp
template <class T> int f3(T) requires (!sad<T>::type);
int i3 = f3(42); // error: associated constraints not satisfied due to substitution failure
```

```cpp
template <class T> concept sad_nested_type = sad<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, \( \text{requires } (!\text{sad<T>::type}) \) requires that there is a nested \text{type} that is not \text{sad}, whereas \text{requires} \( (!\text{sad_nested_type<T>}) \) requires that there is no \text{sad} \text{nested} \text{type}. — end example]

— end note]

13.5.2.3 Atomic constraints

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).
Two atomic constraints, $e_1$ and $e_2$, 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 $e_1$ is the same (13.6) as a template-id naming $A$ whose template-arguments are the targets of the parameter mapping of $e_2$.

[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:**

```cpp
template <unsigned N> constexpr bool Atomic = true;
template <unsigned N> concept C = Atomic<N>;
template <unsigned N> concept Add1 = C<N + 1>;
template <unsigned N> concept AddOne = C<N + 1>;
template <unsigned N> void f() requires Add1<2 * M>;
template <unsigned N> int f() requires AddOne<2 * M> & & true;

int x = f<0>(); // OK, the atomic constraints from concept C in both fs are Atomic<N>
// with mapping similar to N -> 2 * M + 1

template <unsigned N> struct WrapN;
template <unsigned N> using Add1Ty = WrapN<N + 1>;
template <unsigned N> using AddOneTy = WrapN<N + 1>;
template <unsigned N> void g(Add1Ty<2 * M> *);
template <unsigned N> void g(AddOneTy<2 * M> *);

void h() {
g<0>(nullptr); // OK, there is only one g
}
```

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:**

```cpp
template <unsigned N> void f2() requires Add1<2 * M>;
template <unsigned N> int f2() requires Add1<N * 2> & & true;
void h2() {
f2<0>(); // ill-formed, no diagnostic required:
 // requires determination of subsumption between atomic constraints that are
 // functionally equivalent but not equivalent
}
```

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, the constraint is not satisfied. Otherwise, the lvalue-to-rvalue conversion (7.3.2) is performed if necessary, and $E$ shall be a constant expression of type `bool`. The constraint is satisfied if and only if evaluation of $E$ 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; // requires atomic constraints sizeof(T) == 4 and !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 —

13.5.3 Constrained declarations [temp.constr.decl]

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:

constraint-expression:
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:

1. If there are no introduced constraint-expressions, the declaration has no associated constraints.
2. Otherwise, if there is a single introduced constraint-expression, the associated constraints are the normal form (13.5.4) of that expression.
3. Otherwise, the associated constraints are the normal form of a logical AND expression (7.6.14) whose operands are in the following order:
   1. the constraint-expression introduced by each type-constraint (13.2) in the declaration’s template-parameter-list, in order of appearance, and
   2. the constraint-expression introduced by a requires-clause following a template-parameter-list (13.1), and
   3. the constraint-expression introduced by each type-constraint in the parameter-type-list of a function declaration, and
   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:]

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>.

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 f4 and f5 are C1<T> \land C2<T>.

template<C1 T> requires C2<T> void f6();
template<C2 T> requires C1<T> void f7();

The associated constraints of f6 are C1<T> \land C2<T>, and those of f7 are C2<T> \land C1<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
};

template <> template <class U>
U A<int>::f(U u) requires C<int> { return u; } // OK, specializes #2
```

Substituting \( \text{int} \) for \( T \) in \( C\text{typename T::type} \) 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]

The normal form of an expression \( E \) is a constraint (13.5.2) that is defined as follows:

1. The normal form of an expression \( E \) is the normal form of \( E \).
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 \( E_2 \).
3. The normal form of an expression \( E_1 \land E_2 \) is the conjunction of the normal forms of \( E_1 \) and \( E_2 \).
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*>;
    template<typename V> concept C = B<V&>;
    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 \( \text{sizeof}(T) == 1 \) (with mapping \( T \mapsto U* \)) \( \lor \) 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. 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 (7.5.4). — 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; }

    template<U> void f1(U); // #1
    template<U> void f2(U); // #2
    template<U> void f3(U); // #3
```

The associated constraints of #1 are \( \text{sizeof}(T) == 1 \) (with mapping \( T \mapsto U \)) \( \land \) 1 == 2.
The associated constraints of #2 are \( \text{requires} \{ \text{typename} T::\text{type}; \} \) (with mapping \( T \mapsto U \)).
The associated constraints of #3 are \( \text{requires} \{ T x \} \{ \text{++x}; \} \) (with mapping \( T \mapsto U \)). — 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\(^{121}\) of \( P \), \( P_i \) subsumes every conjunctive clause \( Q_j \) in the conjunctive normal form\(^{122}\) of \( Q \), where

1. a disjunctive clause \( P_i \) subsumes a conjunctive clause \( Q_j \) if and only if there exists an atomic constraint \( P_a \) in \( P_i \) for which there exists an atomic constraint \( Q_b \) in \( Q_j \) such that \( P_a \) subsumes \( Q_b \), and

2. an atomic constraint \( A \) subsumes another atomic constraint \( B \) if and only if there exists an atomic constraint \( P_a \) in \( A \) for which there exists an atomic constraint \( Q_b \) in \( B \) such that \( P_a \) subsumes \( Q_b \), and

\(^{121}\) 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 \( A \wedge (B \vee C) \) is \( (A \wedge B) \vee (A \wedge C) \). Its disjunctive clauses are \((A \wedge B)\) and \((A \wedge C)\).

\(^{122}\) 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 \( A \wedge (B \vee C) \) is in conjunctive normal form. Its conjunctive clauses are \( A \) and \((B \vee C)\).
(2.1) — they are of integral type and their values are the same, or
(2.2) — they are of floating-point type and their values are identical, or
(2.3) — they are of type std::nullptr_t, or
(2.4) — they are of enumeration type and their values are the same, or
(2.5) — they are of pointer type and they have the same pointer value, or
(2.6) — they are of pointer-to-member type and they refer to the same class member or are both the null
member pointer value, or
(2.7) — they are of reference type and they refer to the same object or function, or
(2.8) — they are of array type and their corresponding elements are template-argument-equivalent, or
(2.9) — 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
(2.10) — they are of class type and their corresponding direct subobjects and reference members are template-
argument-equivalent.

3 [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

```cpp
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.

```cpp
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]

4 If an expression e is type-dependent (13.8.3.3), decltype(e) denotes a unique dependent type. Two such
decay-type-specifiers refer to the same type only if their expressions are equivalent (13.7.7.2).

[Note 1: However, such a type might be aliased, e.g., by a typedef-name. — end note]

## 13.7 Template declarations

### 13.7.1 General

The template parameters of a template are specified in the angle bracket enclosed list that immediately
follows the keyword `template`.

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.

For purposes of name lookup and instantiation, default arguments, `type-constraints`, `requires-clauses` (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-clauses`, or `noexcept-specifiers`. For the purpose of instantiation, the substatements of a constexpr if
statement (8.5.2) are considered definitions.

Because an alias-declaration cannot declare a template-id, it is not possible to partially or explicitly specialize
an alias template.

123) The identity of enumerators is not preserved.
124) An array as a `template-parameter` decays to a pointer.
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:

```cpp
template<class T> class Array {
  T* v;
  int sz;
public:
  explicit Array(int);
  T& operator[](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:

```cpp
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

template<class ... Types> void B<Types>::f4() { } // error
```

—end example]

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 (9.2.9.4).
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:

```cpp
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:

```cpp
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:

```cpp
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
void S<T>::g() {} // error: no matching function in S<T>
```

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);
```

```cpp
v1[3] = 7; // Array<int>::operator[]
v2[3] = dcomplex(7,8); // Array<dcomplex>::operator[]
```

—end example]

13.7.2.3  Deduction guides  [temp.deduct.guide]

Deduction guides are used when a template-name appears as a type specifier for a deduced class type (9.2.9.7). 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.

```text
deduction-guide:
  explicit-specifier_opt template-name ( parameter-declaration-clause ) -> 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>
—end example]

The same restrictions apply to the parameter-declaration-clause of a deduction guide as in a function declaration (9.3.4.6). 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
[temp.mem.class]

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,]

```
template<class T> struct A {
    class B;
};
A<int>::B* b1; // OK, requires A to be defined but not A::B
template<class T> class A<T>::B { }
A<int>::B b2; // OK, requires A::B to be defined
—end note]
```

13.7.2.5 Static data members of class templates
[temp.static]

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]:
```
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]
```

[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] = { 1 }; // OK, 1 element
—end example]
```

13.7.2.6 Enumeration members of class templates
[temp.mem.enum]

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;
};
```

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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:

```cpp
// 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) {
}
```

Example 2:

```cpp
// 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
// template C1 T> template<typename U> void S<T>::g(U) { }
// error: no matching function in S<T>
```

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:
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*() { return 0; } // specialization
}

int main() {
    A a;
    int* ip;
    ip = a.operator int*(); // explicit call to template operator A::operator int*()
}
```

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<> error; // error: 0 is not a type
```

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
```

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:
template <typename... Args>
void foo(Args... args) {
    [...]xs=args[...]
    // xs is an init-capture pack
    bar(xs...);
}

foo();  // xs contains zero init-captures
foo(1); // xs contains one init-capture

— end example]}

4 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.

5 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:

(5.1) — In a function parameter pack (9.3.4.6); the pattern is the parameter-declaration without the ellipsis.
(5.2) — In a using-declaration (9.9); the pattern is a using-declarator.
(5.3) — In a template parameter pack that is a pack expansion (13.2):
     (5.3.1) — if the template parameter pack is a parameter-declaration; the pattern is the parameter-declaration without the ellipsis;
     (5.3.2) — if the template parameter pack is a type-parameter; the pattern is the corresponding type-parameter without the ellipsis.
(5.4) — In an initializer-list (9.4); the pattern is an initializer-clause.
(5.5) — In a base-specifier-list (11.7); the pattern is a base-specifier.
(5.6) — 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.
(5.7) — In a template-argument-list (13.4); the pattern is a template-argument.
(5.8) — In an attribute-list (9.12.1); the pattern is an attribute.
(5.9) — In an alignment-specifier (9.12.2); the pattern is the alignment-specifier without the ellipsis.
(5.10) — In a capture-list (7.5.5.3); the pattern is the capture without the ellipsis.
(5.11) — In a sizeof... expression (7.6.2.5); the pattern is an identifier.
(5.12) — In a fold-expression (7.5.6); the pattern is the cast-expression that contains an unexpanded pack.

[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]}

6 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.

7 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.

[Example 5:
    template<typename...> struct Tuple {};
    template<typename T1, typename T2> struct Pair {};

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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)...);

    f(args);
    // error: pack "args" is not expanded
    f(h(args ...) + args ...);
    // OK, first "args" expanded within h,
    // 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:

(8.1) — 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;
(8.2) — 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
(8.3) — 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.

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 $N$.

The instantiation of a fold-expression (7.5.6) produces:

(10.1) — $(E_1 \ op \ E_2 \ op \ \cdots \ op \ E_N)$ for a unary left fold,
(10.2) — $E_1 \ op \ (\cdots \ op \ (E_{N-1} \ op \ E_N))$ for a unary right fold,
(10.3) — $(((E \ op \ E_1) \ op \ E_2) \ op \ \cdots \ op \ E_N)$ for a binary left fold, and
(10.4) — $E_1 \ op \ (\cdots \ op \ (E_{N-1} \ op \ (E_N \ op \ E)))$ for a binary right fold.

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.

[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 $(true && true) && false$, which evaluates to false. —end example]

If $N$ is zero for a unary fold, the value of the expression is shown in Table 19; if the operator is not listed in Table 19, the instantiation is ill-formed.

The instantiation of any other pack expansion produces a list of elements $E_1, E_2, \ldots, E_N$. 

§ 13.7.4
Table 19: 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>

[Note 1: The variety of list varies with the context: expression-list, base-specifier-list, template-argument-list, etc. — end note]

When $N$ is zero, the instantiation of the expansion produces an empty list.

[Example 7:]
```cpp
template<class... T> struct X : T... { };  
template<class... T> void f(T... values) {  
    X<T...> x(values...);  
}

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:]
```cpp
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]

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]

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:]
```cpp
class A {  
    template<class T> friend class B;  // OK
};
```
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:

```cpp
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
```

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 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>::D::h(); // because its return type does not match
    template<class T> friend template<T U> A<T> i(); // grants friendship to A<int>\':\':i() and A<float*>\':\':i()
    friend T A<T>::i(); // grants friendship to instantiations of A<T>::i() and
} // to A<int>::i(), and thereby to all specializations
@end example
```

A friend template shall not be declared in a local class.

A friend declaration shall not declare partial specializations.

Example 5:
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

1 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 (13.7.6.2). 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.

2 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:

```
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]

4 A partial specialization may be constrained (13.5).

[Example 2:

```
template<typename T> concept C = true;

template<typename T> struct X { };    // #1

template<typename 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]

5 The template argument list of a partial specialization is the template-argument-list following the name of the template.

6 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:

```
template<class T> struct A {

    struct C {
        template<class T2> struct B { };  // partial specialization #1
    
        template<class T2> struct B<T2**> { };  // partial specialization #1
    
};

```
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]

[Example 4:

```cpp
namespace N {
    template<class T1, class T2> class A { }; // primary template
}

using N::A; // refers to the primary template

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]

A non-type argument is non-specialized if it is the name of a non-type parameter. All other non-type arguments are specialized.

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:

```cpp
    template <class T, T t> struct C {}
    template <class T> struct C<T, 1>; // error

    template< int X, int (*array_ptr)[X] > class A {}; // error
    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.125

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.

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]

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.

125 There is no context in which they would be used.
If exactly one matching partial specialization is found, the instantiation is generated from that partial specialization.

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.

If no matches are found, the instantiation is generated from the primary template.

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:

```cpp
// #1
template<class T1, class T2, int I> class A { };

// #2
template<class T, int I> class A<T, T*, I> { };

// #3
template<class T2, int I> class A<T1*, T2, I> { };

// #4
template<class T1, class T2, int I> class A<T1, T2*, I> { };

A<int, int, 1> a1; // uses #1
A<int, int*, 1> a2; // uses #2, T is int, I is 1
A<int, char*, 1> 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
```

Example 2:

```cpp
template<typename T> concept C = requires (T t) { t.f(); };

template<typename T> struct S { };

// #2
template<C T> struct S<T> { };

 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
```

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 {}; // error

template <int I> struct A<I,J, I*2> {}; // OK

template <int I> struct A<I, I> {}; // OK

// OK
```

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. Each of the two function templates has the same template parameters and associated constraints (13.5.3) as the corresponding partial specialization.
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:**

```
#include <iostream>

// #1
template<int I, int J, class T> class X { };

// #2
template<int I> class X<I, I, int> { };

// A
template<int I0, int J0> void f(X<I0, J0, int>);  

// B
template<int I0> void f(X<I0, I0, int>);
```

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 \( #3 \).

**Example 2:**

```
#include <iostream>

// #1
template<typename T> class S { };

// #2
template<typename T> class S<T> { };

// A
template<typename T> void f(S<T>);

// B
template<typename T> void f(S<T>);
```

According to the ordering rules for function templates, the function template \( B \) is more specialized than the function template \( A \). Therefore, the partial specialization \( #2 \) is more specialized than \( #1 \) because \( B \) is more specialized than \( A \).

### 13.7.6.4 Members of class template partial specializations

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:**

```
// 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() {
}

int main() {
    A<char,0> a0;
    A<char,2> a2;
    a0.f(); // OK, uses definition of primary template’s member
    a2.g(); // 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
}

Example 2:

```cpp
template<class T> struct A {
    template<class T2> struct B {}; // #1
    template<class T2> struct B<T2*> {}; // #2
};

template<> template<class T2> struct A<short>::B {}; // #3
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.

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:

126) 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.
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.]

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 unit and, conversely, to ensure that function templates that are intended to be distinct are not linked with one another.

[Example 2:]

```
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
```

[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 the first declaration of the function template (13.8.4.2). — end note]

[Example 3:]

```
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()); }
int i = h<int>();  // ... although the lookup here does find g(int)
```

§ 13.7.7.2
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
};
```

— end example]

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.

[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>);
```

— end note]
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 (6.7.5.3, 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.

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.

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 $A$:

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.**
2. **Otherwise, $X(M)$ is “lvalue reference to $cv A$.”**

Using the transformed function template’s function type, perform type deduction against the other template as described in 13.10.3.5.

**Example 1:**
```
struct A { };  
template<class T> struct B {
    template<class R> int operator*(R&);  // #1
};

template<class T, class R> int operator*(T&, R&);  // #2

int main() {
    A a;
    B<A> b;
    b * a;  // calls #1
}
```

**Example 2:**
```
template<class T> struct A { A(); };  
```
```cpp
template<class T> void f(T);
template<class T> void f(T*);
template<class T> void f(const 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 ellipsis parameters).]

[Example 3:

```cpp
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:

```cpp
template<class T, class U> struct A { },

void h() {
    f<int>(42, (A<int, int>*)0); // calls #2
    f<int>(42); // error: ambiguous
    g(42); // error: ambiguous
}
```

— end example]

[Example 5:

```cpp
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() {
    f<int>(42); // OK, calls #2
    g(42); // OK, calls #3
}
```
6 If deduction against the other template succeeds for both transformed templates, constraints can be considered as follows:

- 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.

- Otherwise:
  - If exactly one of the templates was considered by overload resolution via a rewritten candidate with reversed order of parameters:
    - 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 &, auto &) = delete;
template <C Q> void f(Q &, C auto &);

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; // OK, correspondence of [T, U, V] and [U, V, T]
}
```

—end example]
—end note]

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:

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]

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]

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]

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

A concept is a template that defines constraints on its template arguments.

custom-concept-definition:
  concept concept-name = constraint-expression ;
2 A concept-definition declares a concept. Its identifier becomes a concept-name referring to that concept within its scope.

[Example 1:

```cpp
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<typename T>
requires C<T> // C, as a type-constraint, constrains f2(T)
T f2(T x) { return x; }

—end example]

A concept-definition shall inhabit a namespace scope (6.4.5).

4 A concept shall not have associated constraints (13.5.3).

5 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]

6 The constraint-expression of a concept-definition is an unevaluated operand (7.2.3).

7 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

13.8.1 General

1 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(); };  // conversion-function-id is dependent

template<class B, class T>
struct D : B {
    T get() { return operator T(); }
};

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(t);  // dependent
    dd++;  // not dependent; error: declaration for dd not found
}

enum E { e };
void f(E);
```
double dd;
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:
struct A {
  struct B { /* ... */ };  
  int a;
  int Y;
};

int a;

template<class T> struct Y : T {
  struct B { /* ... */ };  // The B defined in Y
  void f(int i) { a = i; } // ::a
  Y* p;                    // Y<T>
};

Y<A> ya;
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.

typename-specifier:
typename nested-name-specifier identifier
typename nested-name-specifier template_opt simple-template-id

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:
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

— a typename-specifier, nested-name-specifier, elaborated-type-specifier, class-or-decltype, or

— a type-specifier of a
— new-type-id,
— defining-type-id,
— conversion-type-id,
— trailing-return-type,
— default argument of a type-parameter, or
— type-id of a static_cast, const_cast, reinterpret_cast, or dynamic_cast, or
— a decl-specifier of the decl-specifier-seq of a
— simple-declaration or a function-definition in namespace scope,
— member-declaration,
— parameter-declaration in a member-declaration,\(^{127}\) unless that parameter-declaration appears in a 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.

\[\text{Example 5:}\]

```cpp
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 P = PtrTraits<T>::Ptr;
    T::R f(T::P p) {  // OK, in a defining-type-id
        return static_cast<T::R>(p);  // OK, type-id of a static_cast
    }
    auto g() -> S<T>::P;  // OK, trailing-return-type
};
template<typename T> void f() {  // variable pf of type void* initialized with T::X
    void (*pf)(T::X);
    void g(T::X);  // error: T::X at block scope does not denote a type
                   // (attempt to declare a void variable)
}
```

\[\text{— end example}\]

\(^{5}\) 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.

\[\text{Example 6:}\]

```cpp
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;
    static int const x = 5;
};

int main() {
    f<Bar>(1);  // OK
    f<Foo>(1);  // error: Foo::x is a type
}
```

\(^{127}\) This includes friend function declarations.

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The validity of a template 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:

1. no valid specialization can be generated for a template or a substatement of a constexpr if statement (8.5.2) within a template and the template is not instantiated, or
2. 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
3. every valid specialization of a variadic template requires an empty template parameter pack, or
4. a hypothetical instantiation of a template immediately following its definition would be ill-formed due to a construct that does not depend on a template parameter, or
5. 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 template.

[Note 4: This can happen in situations including the following:

1. 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
2. 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
3. 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
4. constant expression evaluation (7.7) within the template instantiation uses

   a. the value of a const object of integral or unscoped enumeration type or
   b. the value of a constexpr object or
   c. the value of a reference or
   d. the definition of a constexpr function, and that entity was not defined when the template was defined, or
5. 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]

Otherwise, no diagnostic shall be issued for a template for which a valid specialization can be generated.

[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:

```c
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

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 inject-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 <>.

[Example 1:

template<template<class> class T> class A { }
template<class T> class Y;
template<class Y<int>> {  // meaning Y<int>
    Y* p;
    Y<char>* q;  // meaning Y<char>
    A*<Y*> a;  // meaning A<Y>
    class B {
        template<class Y> friend class Y;  // meaning ::Y
    };
}
—end example]

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 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
};

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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:

```cpp
template<class T> class X {
    X* p;
    X<T>* p2;
    X<int>* p3;
    ::X* p4; // error: missing template argument list
    // ::X does not refer to the injected-class-name
};
```

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
};
```

The name of a template-parameter shall not be bound to any following declaration 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
};
```

The name of a template-parameter shall not be bound to any following declaration 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
};
```

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. —end note

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 [temp.dep]

13.8.3.1 General [temp.dep.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
A dependent call is an expression, possibly formed as a non-member candidate for an operator (12.2.2.3), of the form:

\[
\text{postfix-expression ( expression-list}_{\text{opt} }\)
\]

where the postfix-expression is an unqualified-id and

1. any of the expressions in the expression-list is a pack expansion (13.7.4), or
2. any of the expressions or braced-init-lists in the expression-list is type-dependent (13.8.3.3), or
3. the unqualified-id is a template-id in which any of the template arguments depends on a template parameter.

The component name of an unqualified-id (7.5.4.2) is dependent if

1. it is a conversion-function-id whose conversion-type-id is dependent, or
2. it is operator= and the current class is a templated entity, or
3. the unqualified-id is the postfix-expression in a dependent call.

\[\text{Note 1:}\] 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). \[\text{— end note}\]

\[\text{Example 1:}\]

\[
\text{template<class T> struct X : B<T> {}
\text{typename T::A* pa;}
\text{void f(B<T>* pb) {}
\text{\hspace{1em} static int i = B<T>::i;}
\text{\hspace{1em} pb->j++;}
\text{}}
\]

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. \[\text{— end example}\]

13.8.3.2 Dependent types

A name or template-id refers to the current instantiation if it is

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,
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),
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
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).

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

1. it has the same type as the template parameter (ignoring cv-qualification) and
2. its initializer consists of a single identifier that names the template parameter or, recursively, such a variable.

\[\text{Note 1:}\] Using a parenthesized variable name breaks the equivalence. \[\text{— end note}\]

\[\text{Example 1:}\]

\[
\text{template <class T> class A {}
\text{A* pl; // A is the current instantiation}
\]
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:]

```cpp
template<class T> struct A {
    typedef int M;
    struct B {
        typedef void M;
        struct C;
    };
};
```

> end example

A qualified (6.5.5) or unqualified name is a member of the current instantiation if

1. its lookup context, if it is a qualified name, is the current instantiation, and
2. lookup for it finds any member of a class that is the current instantiation

[Example 3:]

```cpp
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

(5.1) — it is a conversion-function-id whose conversion-type-id is dependent, or
(5.2) — its lookup context is dependent and is not the current instantiation, or
(5.3) — its lookup context is the current instantiation and it is operator=, or
(5.4) — its lookup context is the current instantiation and has at least one dependent base class, and qualified name lookup for the name finds nothing (6.5.5).

[Example 4:
    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]

6 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:
    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 11.4.3
—end example]

7 A type is dependent if it is

(7.1) — a template parameter,
(7.2) — denoted by a dependent (qualified) name,
(7.3) — a nested class or enumeration that is a direct member of a class that is the current instantiation,
(7.4) — a cv-qualified type where the cv-unqualified type is dependent,

128) Every instantiation of a class template declares a different set of assignment operators.

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— a compound type constructed from any dependent type,
— an array type whose element type is dependent or whose bound (if any) is value-dependent,
— a function type whose parameters include one or more function parameter packs,
— a function type whose exception specification is value-dependent,
— 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,\(^\text{129}\) or
— denoted by `decltype(expression)`, where `expression` is type-dependent (13.8.3.3).

\(^{129}\) This includes an injected-class-name (11.1) of a class template used without a `template-argument-list`.

13.8.3.3 Type-dependent expressions  
(7.5) Except as described below, an expression is type-dependent if any subexpression is type-dependent.

(7.6) This is type-dependent if the current class (7.5.2) is dependent (13.8.3.2).
(7.7) An `id-expression` is type-dependent if it is a `template-id` that is not a concept-id and is dependent; or if its terminal name is

(7.8) associated by name lookup with one or more declarations declared with a dependent type,
(7.9) associated by name lookup with a non-type `template-parameter` declared with a type that contains a placeholder type (9.2.9.6),
(7.10) associated by name lookup with a variable declared with a type that contains a placeholder type (9.2.9.6) where the initializer is type-dependent,
(7.11) 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,
(7.12) associated by name lookup with a structured binding declaration (9.6) whose `brace-or-equal-initializer` is type-dependent,
(7.13) associated by name lookup with an entity captured by copy (7.5.5.3) in a `lambda-expression` that has an explicit object parameter whose type is dependent (9.3.4.6),
(7.14) the `identifier __func__` (9.5.1), where any enclosing function is a template, a member of a class template, or a generic lambda,
(7.15) a `conversion-function-id` that specifies a dependent type, or
(7.16) 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 the type specified by the `type-id`, `simple-type-specifier` or `new-type-id` is dependent, even if any subexpression is type-dependent:

- `simple-type-specifier` (expression-list opt)
- `::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)`
- `cast-expression`

Expressions of the following forms are never type-dependent (because the type of the expression cannot be dependent):
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]

A braced-init-list is type-dependent if any element is type-dependent or is a pack expansion.

A fold-expression is type-dependent.

### 13.8.3.4 Value-dependent expressions

1. 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.

2. An id-expression is value-dependent if:

   (2.1) it is a concept-id and any of its arguments are dependent,

(2.2) it is type-dependent,

(2.3) it is the name of a non-type template parameter,

(2.4) it names a static data member that is a dependent member of the current instantiation and is not initialized in a member-declarator,

(2.5) it names a static member function that is a dependent member of the current instantiation, or

(2.6) 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:

- sizeof unary-expression
- 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]

3. 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:

   - simple-type-specifier ( expression-listopt )
   - static_cast < type-id > ( expression )
   - const_cast < type-id > ( expression )
   - reinterpret_cast < type-id > ( expression )
   - ( type-id ) cast-expression

4. Expressions of the following form are value-dependent:

   - sizeof ... ( identifier )
   - fold-expression

5. 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 [temp.dep.temp]
1 A type template-argument is dependent if the type it specifies is dependent.
2 A non-type template-argument is dependent if its type is dependent or the constant expression it specifies is value-dependent.
3 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.
4 A template template-parameter is dependent if it names a template-parameter or its terminal name is dependent.

13.8.4 Dependent name resolution [temp.dep.res]
13.8.4.1 Point of instantiation [temp.point]
1 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.
2 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.
3 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 noexcept-specifier is the point of instantiation of the specialization that requires it. Otherwise, the point of instantiation for such a noexcept-specifier immediately follows the namespace scope declaration or definition that requires the noexcept-specifier.
4 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.
5 If a virtual function is implicitly instantiated, its point of instantiation is immediately following the point of instantiation of its enclosing class template specialization.
6 An explicit instantiation definition is an instantiation point for the specialization or specializations specified by the explicit instantiation.
7 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.

§ 13.8.4.1
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":
namespace Q {
    struct X { }
}

Source file "G.h":
namespace Q {
    void g_impl(X, X);
}

Module interface unit of M1:
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:
module;
#include "X.h"
export module M2;
import M1;
void h(Q::X x) {
    g(x);
    // OK
}

— end example]

[Example 2:

Module interface unit of Std:
export module Std;
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 { /* ... */ }; // #1
void swap(S& s, S& s); // #1

void f(S* p, S* q)
{
    indirect_swap(p, q); // finds #1 via ADL in instantiation context
}

— end example]

[Example 3:

Source file "X.h":
struct X { /* ... */ };
X operator+(X, X);

Module interface unit of F:

```cpp
export module F;
export template<typename T>
void f(T t) {
    t + t;
}
```

Module interface unit of M:

```cpp
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:

```cpp
export module A;
export template<typename T>
void f(T t) {
    cat(t, t); // #1
    dog(t, t); // #2
}
```

Module interface unit of B:

```cpp
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:

```cpp
struct foo {
    friend int cat(foo, foo);
};
int dog(foo, foo);
```

Module interface unit of C1:

```cpp
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:

```cpp
import C1;
void i() {
    h(0); // error: dog not found at #2
}
```

Importable header "bar.h":

```cpp
struct bar {
    friend int cat(bar, bar);
};
int dog(bar, bar);
```
Module interface unit of C2:

```c
module;
#include "bar.h"    // imports header unit "bar.h"
export module C2;
import B;
export template<
type T>
   void j(T t) {
      g(bar{ }, t);
   }
```

Translation unit:

```c
import C2;
void k() {
   j(0);    // OK, dog found in instantiation context:
              // visible at end of module interface unit of C2
}
```

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
   template<> void g(char) { }         // specialize for U == char
   // 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
   // specialize for T == char
   template<class T = int> struct B {
      static int x;
   };
   template<> int B<>::x = 1;          // specialize for T == int
   
   —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 \textit{template-arguments},

\begin{enumerate}
\item[(5.1)] an explicit instantiation definition shall appear at most once in a program,
\item[(5.2)] an explicit specialization shall be defined at most once in a program, as specified in 6.3, and
\item[(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.
\end{enumerate}

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, \textit{base-clause}, \textit{member-specification}, \textit{enumerator-list}, or static data member or variable template initializer.

\textit{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.

\textit{Example 2:}

\begin{verbatim}
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 \textit{s} of type \textit{int} and X<char*> has a static member \textit{s} of type \textit{char*}. —end example
\end{verbatim}

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.

\textit{Example 3:}

\begin{verbatim}
template<class T> struct A {
  static T t;
};
typedef int function();
A<function> a; // error: would declare A<function>::t as a static member function
—end example
\end{verbatim}

\section*{13.9.2 Implicit instantiation \textbf{[temp.inst]}}

A template specialization \(E\) is a \textit{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

\begin{enumerate}
\item[(1.1)] an inline function,
\item[(1.2)] declared with a type deduced from its initializer or return value (9.2.9.6),
\item[(1.3)] a potentially-constant variable (7.7), or
\item[(1.4)] a specialization of a templated class.
\end{enumerate}

\textit{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.

\textit{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

\textit{Example 1:}
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);  // instantiation of D<int> required: call f(B<int>*)
  B<char>* q = pp;  // instantiation of D<char> required: convert D<char> to B<char>*
  delete ppp;  // instantiation of D<double> required
}

—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:]

    template<class T> class X;
    X<char> ch;  // error: incomplete type X<char>

—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, noexcept-specifiers, and non-static data member initializers, if any, but not their type-constraints or 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]

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 noexcept-specifiers of the class member functions.

[Example 3:]

    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
    template<> void C<int>::g() { }  // error: redefinition of C<int>::g

—end example]

However, for the purpose of determining whether an instantiated redeclaration is valid according to 6.3 and 11.4, a declaration that corresponds to a definition in the template is considered to be a definition.

[Example 4:]

    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.

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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)

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.

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]

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:]

```cpp
template<typename T> constexpr int f() { return T::value; }
template< bool B, typename T> void g(decltype(B ? f<T>() : 0));
template< bool B, typename T> void h(decltype(int{B ? f<T>() : 0}));
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
```

§ 13.9.2
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:

```cpp
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
    // 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 shall not cause the template to be implicitly instantiated except that a class template may be instantiated where its complete type is needed to determine the correctness of the default argument. The use of a default argument in a function call causes specializations in the default argument to be implicitly instantiated.

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 an 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

16 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
};
S<char> s1;  // error: no matching constructor
S<char[8]> s2;  // OK, calls #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:
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`.

```cpp
[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

  namespace N {
    template<class T> void f(T&) { }
  }
  template void N::f<int>(int&);
—end example]
```

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.

```cpp
[Note 1: These declarations are required to have matching types as specified in 6.6, except as specified in 14.5.

[Example 2:
  template<typename T> T var = {};  // OK, instantiated variable has type float
  template float var<float>;

  template int var<int[16]>[]; // OK, absence of major array bound is permitted
  template int *var<int>;; // error: instantiated variable has type int

  template<typename T> auto av = T();
  template int av<int>;; // OK, variable with type int can be redeclared with type auto

  template<typename T> auto f () {}
  template void f<int>(); // error: function with deduced return type
  // redeclared with non-deduced return type (9.2.9.6)
—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.
8 A trailing template-argument can be left unspecified in an explicit instantiation of a function template specialization or of a member function template specialization provided it can be deduced (13.10.3.7). If all template arguments can be deduced, the empty template argument list <> may be omitted.

[Example 3:]
```cpp
template<class T> class Array { /* ... */ };
template<class T> void sort(Array<T>& v) { /* ... */ }

// instantiate sort(Array<int>&) – template-argument deduced
template void sort<>(Array<int>&);
```
—end example]

9 [Note 2: An explicit instantiation of a constrained template is required 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 implicit 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 4:]
```cpp
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 [temp.expl.spec]

1 An explicit specialization of any of the following:

(1.1) function template
(1.2) class template
(1.3) variable template
(1.4) member function of a class template
(1.5) static data member of a class template
(1.6) member class of a class template

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— member enumeration of a class template
— member class template of a class or class template
— member function template of a class or class template

can be declared by a declaration introduced by `template<>`; that is:

```
explicit-specialization:
  template <> declaration
```

[Example 1:
  ```
template<class T> class stream;
  template<> class stream<char> { /* ... */ };
  template<class T> class Array { /* ... */ };
  template<class T> void sort(Array<T>& v) { /* ... */ }
  template<> void sort<char*>(Array<char*>&);
```

Given these declarations, `stream<char>` will be used as the definition of streams of `char`; other streams will be handled by class template specializations instantiated from the class template. Similarly, `sort<char*>` will be used as the sort function for arguments of type `Array<char*>`; other `Array` types will be sorted by functions generated from the template. —end example]

2 An explicit specialization shall not use a `storage-class-specifier` (9.2.2) other than `thread_local`.

3 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).

4 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 required. —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:
  ```
template<> class X<int> { /* ... */ };
  template<class T> class X;
  template<> class X<char*> { /* ... */ };
  // OK, X is a template
```

—end example]

5 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.

6 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:
  ```
template<class T> struct A {
    struct B { }
  };
```

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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<> is used when defining a member of an explicitly specialized member class template
// specialized as a class template
template<>
template<class U> struct A<char>::C {
    void f();
};

// template<> not permitted
template<> void A<char>::C<U>::f() { /* ... */ }

// error: template<> required
template<class T> struct A {
    enum E : T;
    enum class S : T;
};

template<> enum A<int>::E : int { eint }; // OK

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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 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 class templates 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.

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).

A trailing `template-argument` can be left unspecified in the `template-id` naming an explicit function template specialization provided it can be deduced (13.10.3.7).

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).

Whether an explicit specialization of a function or variable template is inline, constexpr, or an immediate function is determined by the explicit specialization and is independent of those properties of the template.
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 8:

```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
```cpp
template<> void A<int>::f(int);
```

// out of class member template definition
```cpp
template<class T> template<class X1> void A<T>::g1(T, X1) { }
```

// member template specialization
```cpp
template<class X1> void A<int>::g1(int, X1);
```

// member template specialization
```cpp
template<> template<> class A<int>::B<double>;    // X1 deduced as char
```

```cpp
template<> template<> void A<char>::B<char>::mf();    // X2 specified as char
```

// member specialization even if defined in class definition
```cpp
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 9:

```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.

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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:

- the explicit specialization of a function template;
- the explicit specialization of a member function template;
- 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

13.10.1 General

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.

Each function template specialization instantiated from a template has its own copy of any static variable.

[Example 1:

```
template<class T> void f(T* p) {
  static T s;
};

template<class T> void g(T a, char* b) {
  f(&a); // calls f<int>(int*)
  f(&b); // calls f<char*>(char**)  
}
```

Here \( f<int>(\text{int}*) \) has a static variable \( s \) of type \( \text{int} \) and \( f<\text{char*>(char**)} \) has a static variable \( s \) of type \( \text{char*} \). —end example]

13.10.2 Explicit template argument specification

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:

```
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

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

Template arguments shall not be specified when referring to a specialization of a constructor template (11.4.5, 6.5.5.2).

A template argument list may be specified when referring to a specialization of a function template

— when a function is called,
— 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,
— in an explicit specialization,
— in an explicit instantiation, or
— in a friend declaration.

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, they may all be omitted; in this case, the empty template argument list <> itself may also be omitted.

[Example 2:]

    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>);       // Y for outer f deduced as int (*)(bool)
        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>);       // Y for outer f deduced as int (*)(bool),
                                     // Z deduced as an empty sequence
    }
— end example

[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:

    template <class T> int f(T);  // #1
    int f(int);                   // #2
    int k = f(1);                 // uses #2
    int l = f<>(1);               // 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:]

    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);
    f<int, const char*>("aa", 3.0); // Z deduced as const char*
    f<"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);
```

```cpp
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]

1 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]

2 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)
    f<int,char>(); // f<int,char>(0,0)
}
```
— end example]

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:

template <class T> struct Z {
  typedef typename T::x xx;
};

template <class T> concept C = requires { typename T::A; };

template <class T> typename Z<T>::xx f(void *, T); // #1

template <class T> void f(int, T); // #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 substitution occurs in all types and expressions that are used in the function type and in template parameter declarations. 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:

template <class T> struct A { using X = typename T::X; };

template <class T> typename T::X f(typename A<T>::X);

void f(...) { }

template <class T> auto g(typename A<T>::X) -> typename T::X;

void g(...) { }

template <class T> typename T::X h(typename A<T>::X);

void h(...) { // redeclaration
}

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]
Only invalid types and expressions in the immediate context of the function type, its template parameter types, and its `explicit-specifier` can result in a deduction failure.

[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]

A `lambda-expression` appearing in a function type or a template parameter is not considered part of the immediate context for the purposes of template argument deduction.

[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(...);
  // error: invalid expression not part of the immediate context

template <class T, std::size_t = sizeof([]() { T::invalid; })>
  void g(T);
void g(...);
  // error: invalid expression not part of the immediate context

template <class T>
  auto h(T) -> decltype([]() { [x = T::invalid](); });
void h(...);
  // error: invalid expression not part of the immediate context

template <class T>
  auto i(T) -> decltype([]() -> typename T::invalid { });
void i(...);
  // error: invalid expression not part of the immediate context

template <class T>
  auto j(T t) -> decltype([](auto x) -> decltype(x.invalid) { } (t));
void j(...);
  // deduction fails on #1, calls #2

  // #1

  // #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

  // end example]

[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

  // end example]
```
— Attempting to use a type that is not a class or enumeration type in a qualified name.

\[ \text{Example 10:} \]
```cpp
template <class T> int f(typename T::B*);
int i = f<int>(0);
— end example
```

— Attempting to use a type in a \textit{nested-name-specifier} of a \textit{qualified-id} when that type does not contain the specified member, or

— the specified member is not a type where a type is required, or

— the specified member is not a template where a template is required, or

— the specified member is not a non-type where a non-type is required.

\[ \text{Example 11:} \]
```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;
};
```
```cpp
int main() {
    // Deduction fails in each of these cases:
    f<A>(0); // \textit{A} does not contain a member \textit{Y}
    f<B>(0); // The \textit{Y} member of \textit{B} is not a type
    g<C>(0); // The \textit{N} member of \textit{C} is not a non-type
    h<D>(0); // The \textit{TT} member of \textit{D} is not a template
}
— end example
```

— Attempting to create a pointer to reference type.

— Attempting to create a reference to \textit{void}.

— Attempting to create “pointer to member of \textit{T}” when \textit{T} is not a class type.

\[ \text{Example 12:} \]
```cpp
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.

\[ \text{Example 13:} \]
```cpp
template <class T, T> struct S {}
```
```cpp
template <class T> int f(S<T, T>()*);
```
```cpp
struct X {}
```
```cpp
int i0 = f<X>(0);
— end example
```

— Attempting to perform an invalid conversion in either a template argument expression, or an expression used in the function declaration.

\[ \text{Example 14:} \]
```cpp
template <class T, T*> int f(int);
```
```cpp
int i2 = f<int,1>(0); // can't conv \textit{1} to \textit{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.

— end note

[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 <int> int f(int);
template <signed char> int f(int);
int i1 = f<1000>(0); // OK
int i2 = f<1> (0); // ambiguous; not narrowing

— end example

13.10.3.2 Deducing template arguments from a function call

Template argument deduction is done by comparing each function template parameter type (call it $P$) that contains `template-parameters` 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<P'>` 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<class T> void f(std::initializer_list<T>);  
f({1,2,3}); // T deduced as int
f({1,"asdf"}); // error: T deduced as both int and const char*

template<class T> void g(T);  
g({1,2,3}); // error: no argument deduced for T

template<class T, int N> void h(T const(&)[N]);  
h({1,2,3}); // T deduced as int; N deduced as 3  
j({42}); // T deduced as int; array bound not considered

struct Aggr { int i; int j; };  
template<int 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<int M, int N> void m(T const(&)[M][N]);  
m({{1,2},{3,4}}); // M and N both deduced as 2

template<class T, int N> void n(T const(&)[N], T);  
n({{1},{2},{3}},Aggr()); // OK, T is Aggr, N is 3

template<typename T, int N> void o(T (* const (&)[N])(T)) { }  
int f1(int);
int f4(int);
char f4(char);
o(&f1, &f4 ); // OK, T deduced as int from first element, nothing
// deduced from second element, N deduced as 2
o(&f1, static_cast<char(*)(char)>(char>)(&f4) ); // error: conflicting deductions for T

— end example

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:

- (2.1) 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,
- (2.2) 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,
- (2.3) 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<const int>(const volatile int&)
```
— end example]

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.
    // U&& is a forwarding reference.
    A(T&&, int*); // #2
};

template <class T> A(T&&, int*) -> A<T>; // #3: T&& is a forwarding reference.

int *ip;
A a1{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
```

§ 13.10.3.2
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:

(4.1) — 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 \( A \).

(4.2) — 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).

(4.3) — If \( P \) is a class and \( P \) has the form \textit{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 \textit{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.

\[ \text{Example 5:} \]
```
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<int>, C is X<int>
int z = f(E()); // calls f<int>, not f<> 
\] — end example]

These alternatives are considered only if type deduction would otherwise fail. If they yield more than one possible deduced \( A \), the type deduction fails.

\[ \text{Note 1: If a template-parameter is not used in any of the function parameters of a function template, or is used only in a non-deduced context, its corresponding template-argument cannot be deduced from a function call and the template-argument must be explicitly specified. — end note] \]

When \( P \) is a function type, function pointer type, or pointer-to-member-function type:

(6.1) — If the argument is an overload set containing one or more function templates, the parameter is treated as a non-deduced context.

(6.2) — 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.

\[ \text{Example 6:} \]
```
// Only one function of an overload set matches the call so the function parameter is a deduced context.
template <class T> int f(T (*p)(T));
int g(int);
int g(char);
int i = f(g); // calls f(int (*)(int))
\] — end example]

\[ \text{Example 7:} \]
```
// Ambiguous deduction causes the second function parameter to be a non-deduced context.
template <class T> int f(T, T (*p)(T));
int g(int);
char g(char);
int i = f(1, g); // calls f(int, int (*)(int))
\] — end example]

\[ \text{Example 8:} \]
13.10.3.3 Deducing template arguments taking the address of a function template
[temp.deduct.funcaddr]

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 (9.2.9.6) 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 [temp.deduct.conv]

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 following transformations 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:

1. 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,

2. 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,

3. 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 A. However, certain attributes of A may be ignored:

1. If the original A is a reference type, any cv-qualifiers of 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, its noexcept.

3. Any cv-qualifiers in 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 [temp.deduct.partial]

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:
In the context of a function call, the types used are those function parameter types for which the function call has arguments.\(^\text{130}\)

In the context of a call to a conversion function, the return types of the conversion function templates are used.

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 \(P\) and \(A\).

Before the partial ordering is done, certain transformations are performed on the types used for partial ordering:

If \(P\) is a reference type, \(P\) is replaced by the type referred to.

If \(A\) is a reference type, \(A\) is replaced by the type referred to.

If both \(P\) 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.

Remove any top-level cv-qualifiers:

If \(P\) is a cv-qualified type, \(P\) is replaced by the cv-unqualified version of \(P\).

If \(A\) is a cv-qualified type, \(A\) is replaced by the cv-unqualified version of \(A\).

Using the resulting types \(P\) and \(A\), the deduction is then done as described in 13.10.3.6. If \(P\) is a function parameter pack, the type \(A\) of each remaining parameter type of the argument template is compared with the type \(P\) 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

f(); // calls #1
f(1, 2, 3); // calls #2
f(1, 2); // calls #3; non-variadic template #3 is more specialized // than the variadic templates #1 and #2
```

If, for a given type, the types are identical after the transformations above and both \(P\) and \(A\) were reference types (before being replaced with the type referred to above):

- if the type from the argument template was an lvalue reference and the type from the parameter template was not, the parameter type is not considered to be at least as specialized as the argument type; otherwise,

- if the type from the argument template is more cv-qualified than the type from the parameter template (as described above), the parameter type is not considered to be at least as specialized as the argument type.

Function template \(F\) is 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 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 \(G\).

\(^{130}\) Default arguments are not considered to be arguments in this context; they only become arguments after a function has been selected.
12 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.

[Note 2: A template parameter used in a non-deduced context is considered used. — end note]

[Example 2:

```cpp
template <class T> T f(int);  // #1
template <class T, class U> T f(U);  // #2
void g() {
    f<int>(1);  // calls #1
}
```
—end example]

13 [Note 3: Partial ordering of function templates containing template parameter packs is independent of the number of
deduced arguments for those template parameter packs. — end note]

[Example 3:

```cpp
template<class ...> struct Tuple { };
template<class ... Types> void g(Tuple<Types ...>);  // #1
template<class T1, class ... Types> void g(Tuple<T1, Types ...>);  // #2
template<class T1, class ... Types> void g(Tuple<T1, Types& ...>);  // #3
```

g(Tuple<>());  // calls #1
g(Tuple<int, float>());  // calls #2
g(Tuple<int, float&>());  // calls #3
g(Tuple<int>());  // calls #3
—end example]

13.10.3.6 Deducing template arguments from a type  [temp.deduct.type]

1 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 \( A \).

2 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.

3 A given type \( P \) can be composed from a number of other types, templates, and non-type values:

(3.1) A function type includes the types of each of the function parameters and the return type.

(3.2) A pointer-to-member type includes the type of the class object pointed to and the type of the member
pointed to.

(3.3) A type that is a specialization of a class template (e.g., \( A\langle\text{int}\rangle \)) includes the types, templates, and
non-type values referenced by the template argument list of the specialization.

(3.4) An array type includes the array element type and the value of the array bound.

4 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 \( A \) need not have the same form. — end note]

5 The non-deduced contexts are:
(5.1) The nested-name-specifier of a type that was specified using a qualified-id.

(5.2) The expression of a decltype-specifier.

(5.3) A non-type template argument or an array bound in which a subexpression references a template parameter.

(5.4) 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.

(5.5) A function parameter for which the associated argument is an overload set (12.3), and one or more of the following apply:

(5.5.1) more than one function matches the function parameter type (resulting in an ambiguous deduction),

(5.5.2) no function matches the function parameter type, or

(5.5.3) the overload set supplied as an argument contains one or more function templates.

(5.6) 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).

(5.7) A 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 A<T>::B<T2>, both T and T2 are non-deduced. Likewise, if a type is specified as A<I+J>::X<T>, I, J, and T are non-deduced. If a type is specified as 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:

template<class T> void f(T x, T y) { /* ... */ }
struct A { /* ... */ };
struct B : A { /* ... */ };
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:

template <class T, class U> void f( T (*)( T, U, U ) );

int g1( int, float, float);
char g2( int, float, float);
int g3( int, char, float);

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 a qualification conversion applies between the argument type on the function call and the deduced template argument type:

template<class T> void f(const T*) { }

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:

template <class T> struct B { };
template <class T> struct D : public B<T> { };
struct D2 : public B<int> { };
template <class T> void f(B<T>&) {}
void t() {
    D<int> d;
    D2 d2;
    f(d); // calls f(B<int>&)
    f(d2); // calls f(B<int>&)
}

— end example |

A template type argument T, a template template argument TT or a template non-type argument i can be deduced if P and A have one of the following forms:

T
cv T
T*
T&
T&& T[integer-constant]
template-name<T> (where template-name refers to a class template)
type(T)
T()
T(T)
T type::*
type T::*

T T::*
T (type::*())
type (T::*())
type (type::*)(T)
type (T::*)(T)
T (type::*)(T)
T (T::*)(T)
T (T::*)(T)
type[i]
template-name<i> (where template-name refers to a class template)
TT<T>
TT<i>
TT<>

where (T) represents a parameter-type-list (9.3.4.6) where at least one parameter type contains a T, and () represents a parameter-type-list where no parameter type contains a T. 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:
template<class T1, class... Z> class S; // #1

template<class T1, class... Z> class S<T1, const Z&...> { }; // #2

template<class T1, class T2> class S<T1, const T2&> { }; // #3

S<int, const int&> s; // both #2 and #3 match; #3 is more specialized

template<class T, class... U> struct A { }; // #1

template<class T1, class T2, class... U> struct A<T1, T2*, U...> { }; // #2

template<class T1, class T2> struct A<T1, T2> { }; // #3

template struct A<int, int*>; // selects #2

—end example

10 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 2: 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]:

template <class T> void f(T&&); // #1
template <> void f(int&) { } // #2

template <> void f(int&&) { } // #3

g(int i) {
    f(i); // calls f<int&>(int&), i.e., #1
    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:

(10.1) — if \( P \) does not contain a function parameter type corresponding to \( A_i \) then \( A_i \) is ignored;

(10.2) — otherwise, if \( P_i \) is not a function parameter pack, template argument deduction fails.

[Example 6]:

template<class T, class... U> void f(T*, U...) { } // #1

template<class T> void f(T) { } // #2

void f(int*);

—end example

11 These forms can be used in the same way as \( T \) is for further composition of types.

[Example 7]:

X<int> (*)(char[6])

is of the form

template-name<T> (*)(type[i])

which is a variant of

type (*)(T)

where type is X<int> and \( T \) is 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]:

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template<
    long n>
struct A {};

template<typename T>
struct C;

template<typename T, T n>
struct C<A<n>> {
    using Q = T;
};

using R = long;
using R = C<A<2>>::Q;  // OK; T was deduced as long from the
// template argument value in the type A<2>

— end example]

14 The type of N in the type T[N] is std::size_t.

[Example 9:]

    template<typename T>
    struct S;

    template<typename T, T n>
    struct S<int[n]> {
        using Q = T;
    };

    using V = decltype(sizeof 0);
    using V = S<int[42]>::Q;  // OK; T was deduced as std::size_t from the type int[42]

— end example]

15 [Example 10:]

    template<class T, T i>
    void f(int (&a)[i]);

    int v[10];

    void g() {
        f(v);  // OK, T is std::size_t
    }

— end example]

16 [Note 3: 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:]

    template<int i>
    void f1(int a[10][i]);

    template<int i>
    void f2(int a[i][20]);

    template<int i>
    void f3(int (&a)[i][20]);

    void g() {
        int v[10][20];
        f1(v);  // OK, i deduced as 20
        f1<20>(v);  // OK
        f2(v);  // error: cannot deduce template-argument i
        f2<10>(v);  // OK
        f3(v);  // OK, i deduced as 10
    }

— end note]

17 [Note 4: 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 11:]

    template<int i>
    class A { /* ... */ };

    template<int i>
    void g(A<i+1>);

    template<int i>
    void f(A<i>, A<i+1>);

    void k() {
        A<1> a1;
        A<2> a2;
        g(a1);  // error: deduction fails for expression i+1
        g<0>(a1);  // OK
        f(a1, a2);  // OK
    }

— end example]
Note 5: Template parameters do not participate in template argument deduction if they are used only in non-deduced contexts. For example,

template<int i, typename T>
T deduce(typename A<T>::X x, // T is not deduced here
         T t, // but T is deduced here
typename B<i>::Y y); // i is not deduced here
A<int> a;
B<77> b;

int x = deduce<77>({a.xm, 62, b.ym});
// T deduced as int; a.xm must be convertible to A<int>::X
// i is explicitly specified to be 77; b.ym must be convertible to B<77>::Y

—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 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.\(^\text{131}\)

Example 12:

template<int i> class A { /* ... */};
template<short s> void f(A<s>);
void k1() {
  A<1> a;
  f(a); // error: deduction fails for conversion from int to short
  f<1>(a); // OK
}

template<const short cs> class B { };  
template<short s> void g(B<s>);
void k2() {
  B<1> b;
  g(b); // OK, cv-qualifiers are ignored on template parameter types
}
—end example

A template-argument can be deduced from a function, pointer to function, or pointer-to-member-function type.

Example 13:

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);
void h(char,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 example

A template type-parameter cannot be deduced from the type of a function default argument.

Example 14:

template <class T> void f(T = 5, T = 7);
void g() {
  f(1); // OK, calls f<int>(1,7)
  f(); // error: cannot deduce T

131) Although the template-argument corresponding to a template-parameter of type bool can be deduced from an array bound, the resulting value will always be true because the array bound will be nonzero.
The template-argument corresponding to a template template-parameter is deduced from the type of the template-argument of a class template specialization used in the argument list of a function call.

**Example 15:**

```cpp
template <template <class T> class X> struct A { };
template <template <class T> class X> void f(A<X>) { }
template<class T> struct B { };  
A<int> ab;  
f(ab);  // calls f(A<int>)
```

**Example 16:**

```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<int>;  // use 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
```

### 13.10.3.7 Deducing template arguments from a function declaration

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

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, 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. If, for a given function template, 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:**

```c
template<class T> T max(T a, T b) { return a>b?a:b; }
```

```c
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

```c
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`.  

**Example 2:** Here is an example involving conversions on a function argument involved in template-argument deduction:

```c
template<class T> struct B { /* ... */ };
```

```c
template<class T> struct D : public B<T> { /* ... */ };
```

```c
template<class T> void f(B<T>&);
```

```c
void g(B<int>& bi, D<int>& di) {
    f(bi); // f(bi)
    f(di); // f((B<int>&)di)
}
```

**Example 3:** Here is an example involving conversions on a function argument not involved in template-parameter deduction:

```c
template<class T> void f(T*,int);
// #1
```

```c
template<class T> void f(T,char);
// #2
```

```c
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))
}
```

**Example 4:**

```c
template<class T> void f(T);  // declaration
```

```c
void g() {
    f("Annemarie"); // call of f<const char>*
}
```

The call of `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).  

---

132) The parameters of function template specializations contain no template parameter types. The set of conversions allowed on deduced arguments is limited, because the argument deduction process produces function templates with parameters that either match the call arguments exactly or differ only in ways that can be bridged by the allowed limited conversions. Non-deduced arguments allow the full range of conversions. Note also that 12.2.4 specifies that a non-template function will be given preference over a template specialization if the two functions are otherwise equally good candidates for an overload match.
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.

```plaintext
try-block:
  try compound-statement handler-seq

function-try-block:
  try ctor-initializer\opt\ compound-statement handler-seq

handler-seq:
  handler handler-seq\opt\n
handler:
  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\n```

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 A goto or switch statement shall not be used to transfer control into a try block or into a handler.

[Example 1:

```plaintext
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:

```plaintext
lab: try {
  T1 t1;
  try {
    T2 t2;
    if (condition)
      goto lab;
  } catch(...) { /* handler 2 */ }
} catch(...) { /* handler 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

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:

```c++
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

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` (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:

```c++
throw "Help!";
```
can be caught by a `handler` of `const char*` type:

```c++
try {
  // ...
} catch(const char* p) {
  // handle character string exceptions here
}
```

and

```c++
class Overflow {
public:
  Overflow(char, double, double);
};
void f(double x) {
  throw Overflow('+', x, 3.45e107);
}
```
can be caught by a handler for exceptions of type `Overflow`:

```c++
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 copy-initializes (9.4, 11.4.5.3) a temporary object, called the exception object. If the type of the exception object would be an incomplete type, an abstract class type (11.7.4), or a pointer to an incomplete type other than cv void 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:

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;
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]

When the thrown object is a class object, the constructor selected for the copy-initialization as well as the constructor selected for a copy-initialization considering the thrown object as an lvalue shall be non-deleted and accessible, even if the copy/move operation is elided (11.9.6). The destructor 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) { }
}
```

—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

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 (...) {
    }
    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]

If the initialization or destruction of an object other than by delegating constructor is terminated by an exception, the destructor is invoked for each of the object’s direct subobjects and, for a complete object, virtual base class subobjects, whose initialization has completed (9.4) and whose destructor has not yet begun execution, except that in the case of destruction, the variant members of a union-like class are not destroyed.

[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]

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.

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.

[Note 2: 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

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”.

A handler of type “array of T” or function type T is adjusted to be of type “pointer to T”.

A handler is a match for an exception object of type E if

1. 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
2. the handler is of type cv T or cv T& and T is an unambiguous public base class of E, or
3. 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
   1. a standard pointer conversion (7.3.12) not involving conversions to pointers to private or protected or ambiguous classes
   2. a function pointer conversion (7.3.14)
   3. a qualification conversion (7.3.6), or
4. 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.

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[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:

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]

4 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]

5 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.

6 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.

7 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.

8 The exception with the most recently activated handler that is still active is called the currently handled exception.

9 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).

10 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.

11 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 Tk, 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.

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;
   };

   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]

5 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:
   extern void f(); // potentially-throwing

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The call to \texttt{f} is well-formed even though, when called, \texttt{f} might throw an exception. — end example]

An expression \( E \) is potentially-throwing if

1. \( E \) is a function call (7.6.1.3) whose \textit{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 \textit{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 \textit{throw-expression} (7.6.18), or
4. \( E \) is a \texttt{dynamic_cast} expression that casts to a reference type and requires a runtime check (7.6.1.7), or
5. \( E \) is a \texttt{typeid} expression applied to a (possibly parenthesized) built-in unary \texttt{*} 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 \texttt{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.

The exception specification for an implicitly-declared destructor, or a destructor without a \texttt{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 \texttt{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 \texttt{noexcept-specifier} has a non-throwing exception specification.

The exception specification for a comparison operator function (12.4.3) without a \texttt{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.

\[ \text{Example 4:} \]

```
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:

(13.1) — in an expression, the function is selected by overload resolution (12.2, 12.3);
(13.2) — 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;
(13.3) — the exception specification is compared to that of another declaration (e.g., an explicit specialization or an overriding virtual function);
(13.4) — the function is defined; or
(13.5) — 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
(1.3) — when the search for a handler (14.4) encounters the outermost block of a function with a non-throwing exception specification (14.5), or
(1.4) — when the destruction of an object during stack unwinding (14.3) terminates by throwing an exception, or
(1.5) — when initialization of a non-block variable with static or thread storage duration (6.9.3.3) exits via an exception, or
(1.6) — when destruction of an object with static or thread storage duration exits via an exception (6.9.3.4), or
(1.7) — when execution of a function registered with std::atexit or std::at_quick_exit exits via an exception (17.5), or
(1.8) — when a throw-expression (7.6.18) with no operand attempts to rethrow an exception and no exception is being handled (14.2), or
(1.9) — when the function std::nested_exception::rethrow_nested is called for an object that has captured no exception (17.9.8), or
(1.10) — when execution of the initial function of a thread exits via an exception (33.4.3.3), or
(1.11) — 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

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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.

—end note]

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

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 lparen identifier-list_opt ) replacement-list new-line
  # define identifier lparen 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
  # 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 constant-expression new-line group_opt
  # ifndefdef constant-expression 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.\(^{133}\)

[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
#              // preprocessing directive
module ;       // preprocessing directive
export module leftpad; // 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]

2. 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.

---

\(^{133}\) 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
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.

134) 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, the value of the has-attribute-expression is given by Table 20. 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 20: __has_cpp_attribute values  [tab:cpp.cond.ha]

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<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

```
# if  constant-expression new-line group_opt
# elif constant-expression new-line group_opt
```

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).

[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.

Preprocessing directives of the forms
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.\(^\text{135}\)

**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
```

**Example 2:** This demonstrates a way to use the attribute \([\text{acme::deprecated}]\) only if it is available.

```
#include <optional>
#if __cpp_lib_optional >= 201603
#define have_optional 1
#else
#endif
```

---

### 15.3 Source file inclusion

A preprocessing 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>
```

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"
```

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

```
#include <h-char-sequence>
```

\(^{\text{135}}\) 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.
with the identical contained sequence (including > characters, if any) from the original directive.

4 A preprocessing directive of the form

```
#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

```
import header-name ; new-line
```

[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:

```
#include <stdio.h>
#include <unistd.h>
#include "usefullib.h"
#include "myprog.h"
```

—end note]

8 [Example 1: This illustrates macro-replaced `#include` directives:

```
#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 example]

15.4 Module directive [cpp.module]

```
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 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]

3 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]

136) 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.
15.5 Header unit importation

**pp-import:**
\[\text{export}_{\text{opt}} \text{import} \text{header-name}_{\text{opt}} \text{pp-tokens}_{\text{opt}}; \text{new-line}\]
\[\text{export}_{\text{opt}} \text{import} \text{header-name}_{\text{tokens}} \text{pp-tokens}_{\text{opt}}; \text{new-line}\]
\[\text{export}_{\text{opt}} \text{import} \text{pp-tokens}; \text{new-line}\]

1 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.

2 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.

3 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.

4 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]

5 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 predefined 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":
   
   ```
   #define X 123  // #1
   ```

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#define Y 45 // #2
#define Z a // #3
#undef X // point of undefinition of #1 in "a.h"

Importable header "b.h":
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":
#define Y 45 // #4
#define Z c // #5

Importable header "d.h":
import "c.h"; // point of definition of #4 and #5 in "d.h"

Importable header "e.h":
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

—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.

3 [Example 1: The following sequence is valid:
#define OBJ_LIKE (1-1)
#define OBJ_LIKE /* whitespace */ (1-1) /* other */
#define FUNC_LIKE(a) ( a )
#define FUNC_LIKE( a ) ( /* note the whitespace */ \a /* other stuff on this line */ */ )

But the following redefinitions are invalid:
#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.
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.

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.

A preprocessing directive of the form

```
#define identifier replacement-list new-line
```

defines an *object-like macro* that causes each subsequent instance of the macro name\(^{137}\) to be replaced by the replacement list of preprocessing tokens that constitute the remainder of the directive.\(^{138}\) The replacement list is then rescanned for more macro names as specified below.

[Example 2: The simplest use of this facility is to define a “manifest constant”, as in]

```
#define TABSIZE 100
int table[TABSIZE];
```

—end example—

A preprocessing directive of the form

```
#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
```

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 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,\(^ {139}\) 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.]

```
#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

*va-opt-replacement*:

\[
__VA_OPT__() \ (pp-tokens_{opt})
\]

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, the preprocessing tokens naming the parameter are replaced by a token sequence determined as follows:

(1.1) 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.

---

\(^{137}\) 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.

\(^{138}\) 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.

\(^{139}\) A *conditionally-supported-directive* is a preprocessing directive regardless of whether the implementation supports it.
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;
```

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");  
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");  
puts("The first, second, and third items.");  
((x>y) ? puts("x>y") : printf("x is %d but y is %d", x, y));
```

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:**
```c
#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__ })

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)  
SDEF(foo);  // replaced by S foo;  
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 H5A(...) __VA_OPT__()/**/__VA_OPT__()
#define H5B(X) a ## X ## b
#define H5C(X) H5B(X)
H5C(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.

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.\(^\text{140}\)

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. If the result begins with a sequence matching the syntax of universal-character-name, the behavior is undefined.

[Note 1: This determination does not consider the replacement of universal-character-names in translation phase 3 (5.2). — 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.

\(^{140}\) Placemarker preprocessing tokens do not appear in the syntax because they are temporary entities that exist only within translation phase 4.
```c
#define str(s) # s
#define vxstr(s) str(s)
#define debug(s, t) printf("x" # s "= %d, x" # t "= %s,\n" 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"

debug(1, 2);
fputs(str(strncmp("abc\0d", "abc", '\4')) == 0) str(: @
), s);
#include xstr(INCFILE(2).h)
glue(HIGH, LOW);
xglue(HIGH, LOW)
```

results in

```c
printf("x1= %d, x2= %s", x1, x2);
```

or, after concatenation of the character string literals,

```c
printf("x1= %d, x2= %s", x1, x2);
fputs(str(strncmp("abc\0d", "abc", '\4')) == 0) str(': @
), s);
```

Space around the # and ## tokens in the macro definition is optional. — end example]

5 [Example 2: In the following fragment:

```c
#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:

```c
join(x, y)
in_between(x hash_hash y)
in_between(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]

6 [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(10,11), t(12,13), t(14,15), t(16,17), t(18,19) };
```

results in

```c
int j[] = { 123, 45, 67, 89,
    10, 11, 12, };
```

— end example]

15.6.5 Rescanning and further replacement [cpp.rescan]

1 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.

2 [Example 1: 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(10,11), t(12,13), t(14,15), t(16,17), t(18,19) };
```

results in

```c
int j[] = { 123, 45, 67, 89,
    10, 11, 12, };
```

— end example]
```c
#define x 3
#define f(a) f(x * (a))
#undef x
#define x 2
#define g f
#define m(a) a
#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(z)) % 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() };
```

---

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.

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.

A preprocessing directive of the form

```c
#define f(a) f(x * (a))
```  
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.

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.

A preprocessing directive of the form

```c
#define f(a) f(x * (a))
```  
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.

---

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sets the presumed line number similarly and changes the presumed name of the source file to be the contents of the character string literal.

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 Error directive

A preprocessing directive of the form

```
# error pp-tokens opt new-line
```

causes the implementation to produce a diagnostic message that should include the specified sequence of preprocessing tokens, and renders the program ill-formed.

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

```
#
```

has no effect.

15.11 Predefined macro names

The following macro names shall be defined by the implementation:

```
__cplusplus
The integer literal 202002L.

[Note 1: Future revisions of C++ will replace the value of this macro with a greater value. — end note]
```

The names listed in Table 21 shall be defined to the corresponding integer literal.

```
[Note 2: Future revisions of C++ might replace the values of these macros with greater values. — end note]
```

```
__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.

__FILE__
The presumed name of the current source file (a character string literal).\(^{141}\)

__LINE__
The presumed line number (within the current source file) of the current source line (an integer literal).\(^{142}\)

__STDC_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).

\(^{141}\) The presumed source file name can be changed by the `#line` directive.

\(^{142}\) The presumed line number can be changed by the `#line` directive.
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]

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 21: 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_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>201811L</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>202110L</td>
</tr>
<tr>
<td>__cpp_constexpr_dynamic_alloc</td>
<td>201907L</td>
</tr>
<tr>
<td>__cpp_constexpr_in_decltype</td>
<td>201711L</td>
</tr>
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<td>__cpp_decltype</td>
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<td>__cpp_deduction_guides</td>
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<td>__cpp_delegating_constructors</td>
<td>200604L</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>
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<tr>
<td>__cpp_Generic_Lambdas</td>
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<tr>
<td>__cpp_Guaranteed_Copy_Elision</td>
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<td>__cpp_hex_float</td>
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<td>__cpp_if_consteval</td>
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<td>__cpp_if_constexpr</td>
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<td>__cpp_Impl_Coroutine</td>
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<td>__cpp_Impl_Destroying_Delete</td>
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<td>__cpp_Impl_Three_Way_Comparison</td>
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<td>__cpp_Modules</td>
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<td>__cpp_Multidimensional_Subscript</td>
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</tr>
<tr>
<td>__cpp_Namespace_Attributes</td>
<td>201411L</td>
</tr>
<tr>
<td>__cpp_Noexcept_Function_Type</td>
<td>201510L</td>
</tr>
<tr>
<td>__cpp_Nontype_Template_Args</td>
<td>201911L</td>
</tr>
<tr>
<td>__cpp_Nontype_Template_Parameter_Auto</td>
<td>201606L</td>
</tr>
</tbody>
</table>
Table 21: Feature-test macros (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>__cpp_nsdmi</td>
<td>200809L</td>
</tr>
<tr>
<td>__cpp_range_based_for</td>
<td>201603L</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_sizeof_deallocation</td>
<td>201309L</td>
</tr>
<tr>
<td>__cpp_static_assert</td>
<td>201411L</td>
</tr>
<tr>
<td>__cpp_structured_bindings</td>
<td>201606L</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_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:

```
__STDC__
Whether __STDC__ is predefined and if so, what its value is, are implementation-defined.

__STDC_MB_MIGHT_NEQ_WC__
The integer literal 1, intended to indicate that, in the encoding for wchar_t, a member of the basic
color set need not have a code value equal to its value when used as the lone character in an
ordinary character literal.

__STDC_VERSION__
Whether __STDC_VERSION__ is predefined and if so, what its value is, are implementation-defined.

__STDC_ISO_10646__
An integer literal of the form yyyymmL (for example, 199712L). If this symbol is defined, then every
character in the Unicode required set, when stored in an object of type wchar_t, has the same value
as the code point of that character. The Unicode required set consists of all the characters that are
defined by ISO/IEC 10646, along with all amendments and technical corrigenda as of the specified year
and month.

__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.

15.12 Pragma operator

```
Pragma ( string-literal )
```

1. A unary operator expression of the form:
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.

2 Example 1:

```c
#pragma listing on ".\listing.dir"
```
can also be expressed as:

```c
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:

```c
#define LISTING(x) PRAGMA(listing on #x)
#define PRAGMA(x) _Pragma(#x)
```

```c
LISTING( ..\listing.dir )
```

—end example]
16 Library introduction

16.1 General

1 This Clause describes the contents of the 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 22.

Table 22: Library categories

<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>

4 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).

5 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.

6 The diagnostics library (Clause 19) provides a consistent framework for reporting errors in a C++ program, including predefined exception classes.

7 The memory management library (Clause 20) provides components for memory management, including smart pointers and scoped allocators.

8 The metaprogramming library (Clause 21) describes facilities for use in templates and during constant evaluation, including type traits, integer sequences, and rational arithmetic.

9 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.

10 The strings library (Clause 23) provides support for manipulating text represented as sequences of type char, sequences of type char8_t, sequences of type char16_t, sequences of type char32_t, sequences of type wchar_t, and sequences of any other character-like type.

11 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 thread 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 an ISO C `restrict` qualifier) are the same unless otherwise stated.

A call to a C standard library function is a non-constant library call (3.36) 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 Annex F of the C standard 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:

1. Summary
2. Requirements
3. Detailed specifications
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.

2. The contents of the summary and the detailed specifications include:

---

144) See also ISO/IEC 9899:2018 section 7.6.
143) 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.
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:

1. Template arguments
2. Derived classes
3. 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 34) 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 (18.5.4) 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:

1. Name and brief description
2. Synopsis (class definition or function declaration, as appropriate)
3. Restrictions on template arguments, if any
4. Description of class invariants
5. Description of function semantics

(145) Although in some cases the code given is unambiguously the optimum implementation.
Descriptions of class member functions follow the order (as appropriate):\(^{(2.1)}\)
- constructor(s) and destructor
- copying, moving & assignment functions
- comparison operator functions
- modifier functions
- observer functions
- operators and other non-member functions

Descriptions of function semantics contain the following elements (as appropriate):\(^{(3.1)}\)
- 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 \emph{constraint-expression} \((13.5.3)\). — end example]

- Mandates: the conditions that, if not met, render the program ill-formed.
  
  [Example 2: An implementation can express such a condition via the \emph{constant-expression} in a \emph{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 \emph{constraint-expression} \((13.5.3)\) and also define the function as deleted. — end example]

- Preconditions: the conditions that the function assumes to hold whenever it is called; violation of any preconditions results in undefined behavior.

- Effects: the actions performed by the function.

- Synchronization: the synchronization operations \((6.9.2)\) applicable to the function.

- Postconditions: the conditions (sometimes termed observable results) established by the function.

- Result: for a \emph{typename-specifier}, a description of the named type; for an \emph{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.

- Returns: a description of the value(s) returned by the function.

- Throws: any exceptions thrown by the function, and the conditions that would cause the exception.

- Complexity: the time and/or space complexity of the function.

- Remarks: additional semantic constraints on the function.

- 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 \emph{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-\emph{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 \emph{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.

\(^{(146)}\) 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.

\(^{(147)}\) 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{148}

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 functions

Several function templates defined in Clause 17 through Clause 33 and Annex D are only defined for the purpose of exposition. The declaration of such a function 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:

```cpp
namespace std {
    template<class T> constexpr decay_t<T> decay-copy(T&& v) noexcept(is_nothrow_convertible_v<T, decay_t<T>>) // exposition only
    { 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_way_comparable_with<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&>()));
}

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{149} 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.

Certain types defined in Clause 31 are used to describe implementation-defined types. They are based on other types, but with added constraints.

\textsuperscript{148} This simplifies the presentation of complexity requirements in some cases.

\textsuperscript{149} Examples from 16.4.4 include: \texttt{Cpp17EqualityComparable}, \texttt{Cpp17LessThanComparable}, \texttt{Cpp17CopyConstructible}. Examples from 25.3 include: \texttt{Cpp17InputIterator}, \texttt{Cpp17ForwardIterator}.
16.3.3.3.2 Exposition-only types

Several types defined in Clause 17 through Clause 33 and Annex D are defined for the purpose of exposition. The declaration of such a type is followed by a comment ending in `exposition only`.

[Example 1:
```cpp
namespace std {
    extern "C" using some-handler = int(int, void*, double); // exposition only
}
```
The type placeholder `some-handler` can now be used to specify a function that takes a callback parameter with C language linkage. — end example]

16.3.3.3.3 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.\(^{150}\)

2 The enumerated type `enumerated` can be written:
```cpp
enum enumerated { V0, V1, V2, V3, ... };
inline const enumerated C0(V0);
inline const enumerated C1(V1);
inline const enumerated C2(V2);
inline const enumerated C3(V3);
...
```

Here, the names `C0`, `C1`, etc. represent enumerated elements for this particular enumerated type. All such elements have distinct values.

16.3.3.3.4 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).

2 The bitmask type `bitmask` can be written:
```cpp
// For exposition only.
// int_type is an integral type capable of representing all values of the bitmask type.
enum bitmask : int_type {
    V0 = 1 << 0, V1 = 1 << 1, V2 = 1 << 2, V3 = 1 << 3, ...
};
inline constexpr bitmask C0(V0);
inline constexpr bitmask C1(V1);
inline constexpr bitmask C2(V2);
inline constexpr bitmask C3(V3);
...
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));
}
```

\(^{150}\) 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:

1. To set a value \( Y \) in an object \( X \) is to evaluate the expression \( X \&\& Y \).
2. To clear a value \( Y \) in an object \( X \) is to evaluate the expression \( X \&\& \sim Y \).
3. The value \( Y \) is set in the object \( X \) if the expression \( X \& Y \) is nonzero.

16.3.3.3.5 Character sequences

16.3.3.3.5.1 General

1. The C standard library makes widespread use of characters and character sequences that follow a few uniform conventions:

   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.

   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.

   [Note 1: The encodings of the execution character sets can be unrelated to any literal encoding. — end note]

   3. A letter is any of the 26 lowercase or 26 uppercase letters in the basic character set.

   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.

   5. A character sequence is an array object (9.3.4.5) \( A \) that can be declared as \( T A \), 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.

16.3.3.3.5.2 Byte strings

1. 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.\(^{151}\)

2. The length of an ntbs is the number of elements that precede the terminating null character. An empty ntbs has a length of zero.

3. The value of an ntbs is the sequence of values of the elements up to and including the terminating null character.

4. A static ntbs is an ntbs with static storage duration.\(^{152}\)

\(^{151}\) Many of the objects manipulated by function signatures declared in `<string>` (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.

\(^{152}\) A string literal, such as "abc", is a static ntbs.
16.3.3.5.3 Multibyte strings

A null-terminated multibyte string, or NTMB, is an NTMB that constitutes a sequence of valid multibyte characters, beginning and ending in the initial shift state.\(^{153}\)

A static NTMB is an NTMB with static storage duration.

16.3.3.6 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.

The type of a customization point object, ignoring cv-qualifiers, shall model semiregular (18.6).

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.

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.

For a given customization point object \(o\), let \(p\) be a variable initialized as if by \(\text{auto } p = o;\). Then for any sequence of arguments \(\text{args}...\), the following expressions have effects equivalent to \(o(\text{args}...):\)

\[
\begin{align*}
\text{(5.1)} & \quad p(\text{args}...) \\
\text{(5.2)} & \quad \text{as}_\text{const}(p)(\text{args}...) \\
\text{(5.3)} & \quad \text{std}::\text{move}(p)(\text{args}...) \\
\text{(5.4)} & \quad \text{std}::\text{move}(\text{as}_\text{const}(p))(\text{args}...) 
\end{align*}
\]

Each customization point object constrains its return type to model a particular concept.

[Note 1: Many of the customization point objects in the library evaluate function call expressions with an unqualified name which results in a call to a program-defined function found by argument dependent name lookup (6.5.4). To preclude such an expression resulting in a call to unconstrained functions with the same name in namespace \(\text{std}\), customization point objects specify that lookup for these expressions is performed in a context that includes deleted overloads matching the signatures of overloads defined in namespace \(\text{std}\). When the deleted overloads are viable, program-defined overloads need to be more specialized (13.7.7.3) or more constrained (13.5.5) to be used by a customization point object. — end note]

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.

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 \(\text{exposition only},\) as in:

```
streambuf* sb; // exposition only
```

An implementation may use any technique that provides equivalent observable behavior.

---

\(^{153}\) An NTMB that contains characters only from the basic literal character set is also an NTMB. Each multibyte character then consists of a single byte.
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

16.4.2.2 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. 16.4.2.4 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 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 (24.3.7.6) 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).

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 23. The facilities of the C standard library are provided in the additional headers shown in Table 24. It is intentional that there is no C++ header for any of these C headers: <stdnoreturn.h>, <threads.h>.

154) 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.

155) This gives implementers freedom to use inline namespaces to support multiple configurations of the library.

156) 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).

157) It is intentional that there is no C++ header for any of these C headers: <stdnoreturn.h>, <threads.h>.

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Table 23: C++ library headers  [tab:headers.cpp]

<table>
<thead>
<tr>
<th>Header</th>
<th>Header</th>
<th>Header</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;algorithm&gt;</td>
<td>&lt;format&gt;</td>
<td>&lt;new&gt;</td>
<td>&lt;stdexcept&gt;</td>
</tr>
<tr>
<td>&lt;any&gt;</td>
<td>&lt;forward_list&gt;</td>
<td>&lt;numbers&gt;</td>
<td>&lt;stop_token&gt;</td>
</tr>
<tr>
<td>&lt;array&gt;</td>
<td>&lt;fstream&gt;</td>
<td>&lt;optional&gt;</td>
<td>&lt;string&gt;</td>
</tr>
<tr>
<td>&lt;atomic&gt;</td>
<td>&lt;functional&gt;</td>
<td>&lt;operator&gt;</td>
<td>&lt;string_view&gt;</td>
</tr>
<tr>
<td>&lt;barrier&gt;</td>
<td>&lt;future&gt;</td>
<td>&lt;ostream&gt;</td>
<td>&lt;string_view&gt;</td>
</tr>
<tr>
<td>&lt;bitset&gt;</td>
<td>&lt;initializer_list&gt;</td>
<td>&lt;queue&gt;</td>
<td>&lt;stringstream&gt;</td>
</tr>
<tr>
<td>&lt;bitset&gt;</td>
<td>&lt;iosomanip&gt;</td>
<td>&lt;random&gt;</td>
<td>&lt;sysconfig&gt;</td>
</tr>
<tr>
<td>&lt;chrono&gt;</td>
<td>&lt;iostream&gt;</td>
<td>&lt;ratio&gt;</td>
<td>&lt;thread&gt;</td>
</tr>
<tr>
<td>&lt;codecvt&gt;</td>
<td>&lt;iostream&gt;</td>
<td>&lt;regex&gt;</td>
<td>&lt;tuple&gt;</td>
</tr>
<tr>
<td>&lt;compare&gt;</td>
<td>&lt;iostream&gt;</td>
<td>&lt;scoped_allocator&gt;</td>
<td>&lt;typeinfo&gt;</td>
</tr>
<tr>
<td>&lt;complex&gt;</td>
<td>&lt;iterator&gt;</td>
<td>&lt;semaphore&gt;</td>
<td>&lt;typeinfo&gt;</td>
</tr>
<tr>
<td>&lt;concepts&gt;</td>
<td>&lt;latch&gt;</td>
<td>&lt;set&gt;</td>
<td>&lt;type_traits&gt;</td>
</tr>
<tr>
<td>&lt;condition_variable&gt;</td>
<td>&lt;limits&gt;</td>
<td>&lt;shared_mutex&gt;</td>
<td>&lt;unordered_map&gt;</td>
</tr>
<tr>
<td>&lt;coroutine&gt;</td>
<td>&lt;list&gt;</td>
<td>&lt;source_location&gt;</td>
<td>&lt;unordered_set&gt;</td>
</tr>
<tr>
<td>&lt;deque&gt;</td>
<td>&lt;locale&gt;</td>
<td>&lt;span&gt;</td>
<td>&lt;utility&gt;</td>
</tr>
<tr>
<td>&lt;exception&gt;</td>
<td>&lt;map&gt;</td>
<td>&lt;spanstream&gt;</td>
<td>&lt;valarray&gt;</td>
</tr>
<tr>
<td>&lt;execution&gt;</td>
<td>&lt;memory&gt;</td>
<td>&lt;sstream&gt;</td>
<td>&lt;variant&gt;</td>
</tr>
<tr>
<td>&lt;expected&gt;</td>
<td>&lt;memory_resource&gt;</td>
<td>&lt;stack&gt;</td>
<td>&lt;vector&gt;</td>
</tr>
<tr>
<td>&lt;filesystem&gt;</td>
<td>&lt;mutex&gt;</td>
<td>&lt;stacktrace&gt;</td>
<td>&lt;version&gt;</td>
</tr>
</tbody>
</table>

Table 24: C++ headers for C library facilities  [tab:headers.cpp.c]

<table>
<thead>
<tr>
<th>Header</th>
<th>Header</th>
<th>Header</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;cassert&gt;</td>
<td>&lt;cfenv&gt;</td>
<td>&lt;climits&gt;</td>
<td>&lt;csetjmp&gt;</td>
</tr>
<tr>
<td>&lt;cctype&gt;</td>
<td>&lt;cfloat&gt;</td>
<td>&lt;clocale&gt;</td>
<td>&lt;csignal&gt;</td>
</tr>
<tr>
<td>&lt;cerrno&gt;</td>
<td>&lt;cstdarg&gt;</td>
<td>&lt;cstdio&gt;</td>
<td>&lt;cstring&gt;</td>
</tr>
<tr>
<td>&lt;cfenv&gt;</td>
<td>&lt;cstddef&gt;</td>
<td>&lt;cstdlib&gt;</td>
<td>&lt;ctime&gt;</td>
</tr>
<tr>
<td>&lt;cfloat&gt;</td>
<td>&lt;cstdint&gt;</td>
<td>&lt;cstring&gt;</td>
<td>&lt;cwchar&gt;</td>
</tr>
<tr>
<td>&lt;cinttypes&gt;</td>
<td>&lt;cstring&gt;</td>
<td>&lt;cwctype&gt;</td>
<td></td>
</tr>
</tbody>
</table>

— end example —

5 Except as noted in Clause 16 through Clause 33 and Annex D, the contents of each header `c_name` 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 (6.4.5) 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).

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.¹⁵⁸

8 Identifiers that are keywords or operators in C++ shall not be defined as macros in C++ standard library headers.¹⁵⁹

9 17.14, C standard library headers, describes the effects of using the `name.h` (C header) form in a C++ program.¹⁶⁰

10 Annex K of the C standard 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

¹⁵⁸ 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.

¹⁵⁹ In particular, including the standard header `<iso646.h>` has no effect.

¹⁶⁰ 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.

§ 16.4.2.3
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.)

Table 25 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.

Table 25: C standard Annex K names

<table>
<thead>
<tr>
<th>Name</th>
<th>Function</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>abort_handler_s</td>
<td>mbstowcs_s</td>
<td>strncat_s</td>
</tr>
<tr>
<td>asctime_s</td>
<td>memcpy_s</td>
<td>vswprintf_s</td>
</tr>
<tr>
<td>bsearch_s</td>
<td>memcpy_s</td>
<td>wvprintf_s</td>
</tr>
<tr>
<td>constraint_handler_t</td>
<td>memset_s</td>
<td>wvsprintf_s</td>
</tr>
<tr>
<td>ctime_s</td>
<td>printf_s</td>
<td>wvsprintf_s</td>
</tr>
<tr>
<td>errno_t</td>
<td>qsort_s</td>
<td>wvcscpy_s</td>
</tr>
<tr>
<td>fopen_s</td>
<td>RSIZE_MAX</td>
<td>wctime_s</td>
</tr>
<tr>
<td>fprintf_s</td>
<td>size_t</td>
<td>wcstombs_s</td>
</tr>
<tr>
<td>freopen_s</td>
<td>scanf_s</td>
<td>wcscpy_s</td>
</tr>
<tr>
<td>fscanf_s</td>
<td>set_constraint_handler_s</td>
<td>vfstream_s</td>
</tr>
<tr>
<td>fwchar_s</td>
<td>setlocale_s</td>
<td>wcstok_s</td>
</tr>
<tr>
<td>getenv_s</td>
<td>snprintf_s</td>
<td>wctombs_s</td>
</tr>
<tr>
<td>gets_s</td>
<td>sprintf_s</td>
<td>wcstombs_s</td>
</tr>
<tr>
<td>gmtime_s</td>
<td>strcat_s</td>
<td>wcscat_s</td>
</tr>
<tr>
<td>ignore_handler_s</td>
<td>strcpy_s</td>
<td>wcslen_s</td>
</tr>
<tr>
<td>localtime_s</td>
<td>strerrorlen_s</td>
<td>wcscpy_s</td>
</tr>
<tr>
<td>L_tmpnam_s</td>
<td>strerror_s</td>
<td>wcslen_s</td>
</tr>
<tr>
<td>mbstowcs_s</td>
<td>strlcn_s</td>
<td>wcslen_s</td>
</tr>
<tr>
<td>mbstowcs_s</td>
<td>vswprintf_s</td>
<td>wcslen_s</td>
</tr>
</tbody>
</table>

16.4.2.4 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 26.

Table 26: C++ headers for freestanding implementations

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2</td>
<td>&lt;cstddef&gt;</td>
</tr>
<tr>
<td>17.3</td>
<td>&lt;cfloat&gt;, &lt;climits&gt;, &lt;limits&gt;, &lt;version&gt;</td>
</tr>
<tr>
<td>17.4</td>
<td>&lt;cassert&gt;</td>
</tr>
<tr>
<td>17.5</td>
<td>&lt;cstdlib&gt;</td>
</tr>
<tr>
<td>17.6</td>
<td>&lt;new&gt;</td>
</tr>
<tr>
<td>17.7</td>
<td>&lt;typeinfo&gt;</td>
</tr>
<tr>
<td>17.8</td>
<td>&lt;source_location&gt;</td>
</tr>
<tr>
<td>17.9</td>
<td>&lt;exception&gt;</td>
</tr>
<tr>
<td>17.10</td>
<td>&lt;initializer_list&gt;</td>
</tr>
<tr>
<td>17.11</td>
<td>&lt;compare&gt;</td>
</tr>
<tr>
<td>17.12</td>
<td>&lt;coroutine&gt;</td>
</tr>
<tr>
<td>17.13</td>
<td>&lt;cstdarg&gt;</td>
</tr>
<tr>
<td>Clause 18</td>
<td>&lt;concepts&gt;</td>
</tr>
<tr>
<td>21.3</td>
<td>&lt;type_traits&gt;</td>
</tr>
<tr>
<td>22.15</td>
<td>&lt;bit&gt;</td>
</tr>
<tr>
<td>33.5</td>
<td>&lt;atomic&gt;</td>
</tr>
</tbody>
</table>

3 The supplied version of the header <cstdlib> (17.2.2) shall declare at least the functions abort, atexit, at_quick_exit, exit, and quick_exit (17.5). The supplied version of the header <atomic> (33.5.2) shall meet the same requirements as for a hosted implementation except that support for always lock-free integral
atomic types (33.5.5) is implementation-defined, and whether or not the type aliases atomic_signed_lock_free and atomic_unsigned_lock_free are defined (33.5.3) is implementation-defined. The other headers listed in this table shall meet the same requirements as for a hosted implementation.

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.\[161\]

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.\[162\]

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 27–34. In these tables, T is an object or reference type to be supplied by a C++ program instantiating a template; a, b, and c are values of type (possibly const) T; s and t are modifiable lvalues of type T; u denotes an identifier; rv is an rvalue of type T; and v is an lvalue of type (possibly const) T or an rvalue of type const T.

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).

\[161\) This is the same as the C standard library.\[162\) 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 7.1.4 of the C Standard.
Table 27: Cpp17EqualityComparable requirements  [tab:cpp17.equalitycomparable]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>a == b</td>
<td>convertible to bool</td>
<td>== is an equivalence relation, that is, it has the following properties:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— For all a, a == a.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— If a == b, then b == a.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— If a == b and b == c, then a == c.</td>
</tr>
</tbody>
</table>

Table 28: 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>convertible to bool</td>
<td>&lt; is a strict weak ordering relation (27.8)</td>
</tr>
</tbody>
</table>

Table 29: 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 30: 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>
</tbody>
</table>

rv’s state is unspecified

[Note 1: rv must still meet the requirements of the library component that is using it. The operations listed in those requirements must work as specified whether rv has been moved from or not. — end note]

Table 31: 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 32: 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>
</tbody>
</table>

rv’s state is unspecified.

[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]
16.4.4.3 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 \( U \).

1. An object \( t \) is swappable with an object \( u \) if and only if:
   - the expressions \( \text{swap}(t, u) \) and \( \text{swap}(u, t) \) are valid when evaluated in the context described below, and
   - these expressions have the following effects:
     - the object referred to by \( t \) has the value originally held by \( u \) and
     - the object referred to by \( u \) has the value originally held by \( t \).

2. The context in which \( \text{swap}(t, u) \) and \( \text{swap}(u, t) \) 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:
   - the two \text{swap} function templates defined in <utility> (22.2.1) and
   - the lookup set produced by argument-dependent lookup (6.5.5).

3. An rvalue or lvalue \( t \) is swappable if and only if \( t \) is swappable with any rvalue or lvalue, respectively, of type \( T \).

4. A type \( X \) meeting any of the iterator requirements (25.3) meets the \text{Cpp17ValueSwappable} requirements if, for any dereferenceable object \( x \) of type \( X \), \( *x \) is swappable.

5. 

   [Example 1: User code can ensure that the evaluation of \text{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: lvalues of T are swappable.
   template<class T>
   void lv_swap(T& t1, T& t2) {
     using std::swap;
   }
   ```

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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  [nullablepointer.requirements]

1 A Cpp17NullablePointer type is a pointer-like type that supports null values. A type P meets the Cpp17 NullablePointer requirements if:

1.1 — P meets the Cpp17EqualityComparable, Cpp17DefaultConstructible, Cpp17CopyConstructible, Cpp17CopyAssignable, and Cpp17Destructible requirements,

1.2 — lvalues of type P are swappable (16.4.4.3),

1.3 — the expressions shown in Table 35 are valid and have the indicated semantics, and

1.4 — 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-initialzed object of type P may have an indeterminate value.

[Note 1: Operations involving indeterminate values can cause undefined behavior. — 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 35, 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 35: Cpp17NullablePointer requirements  [tab:cpp17.nullablepointer]

<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></td>
</tr>
<tr>
<td>P(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>contextually convertible to bool</td>
<td>!(a == b)</td>
</tr>
<tr>
<td>a == np</td>
<td>contextually convertible to bool</td>
<td>a == P()</td>
</tr>
<tr>
<td>np == a</td>
<td>contextually convertible to bool</td>
<td>!(a == np)</td>
</tr>
<tr>
<td>np != a</td>
<td>contextually convertible to bool</td>
<td>!(a == np)</td>
</tr>
</tbody>
</table>
16.4.4.5 Cpp17Hash requirements

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 31) and Cpp17Destructible (Table 34) requirements, and

1.3 — the expressions shown in Table 36 are valid and have the indicated semantics.

Given Key is an argument type for function objects of type $H$, in Table 36 $h$ 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 36: Cpp17Hash requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h(k)$</td>
<td>size_t</td>
<td>The value returned shall depend only on the argument $k$ for the duration of the program. $\text{[Note 1: Thus all evaluations of the expression } h(k) \text{ with the same value for } k \text{ yield the same result for a given execution of the program.} - \text{end note]}$ For two different values $t_1$ and $t_2$, the probability that $h(t_1)$ and $h(t_2)$ compare equal should be very small, approaching $1.0 / \text{numeric limits}&lt;\text{size_t}&gt;::\text{max}()$.</td>
</tr>
<tr>
<td>$h(u)$</td>
<td>size_t</td>
<td>Shall not modify $u$.</td>
</tr>
</tbody>
</table>

16.4.4.6 Cpp17Allocator requirements

16.4.4.6.1 General

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), string buffers and string streams (Clause 31), and match_results (Clause 32) are parameterized in terms of allocators.

2 In subclause 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,

2.4 — XX denotes the type allocator_traits$\langle$X$\rangle$,

2.5 — YY denotes the type allocator_traits$\langle$Y$\rangle$,

2.6 — a, a1, a2 denote lvalues of type X,

2.7 — u denotes the name of a variable being declared,

2.8 — b denotes a value of type Y,

2.9 — c denotes a pointer of type C$*$ through which indirection is valid,

2.10 — p denotes a value of type XX$::$pointer obtained by calling a1.allocate, where a1 == a,

2.11 — q denotes a value of type XX$::$const_pointer obtained by conversion from a value p,

2.12 — r denotes a value of type T& obtained by the expression *p,

2.13 — w denotes a value of type XX$::$void_pointer obtained by conversion from a value p,

2.14 — x denotes a value of type XX$::$const_void_pointer obtained by conversion from a value q or a value w,

2.15 — 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,

2.16 — n denotes a value of type XX$::$size_type,

2.17 — Args denotes a template parameter pack, and
args denotes a function parameter pack with the pattern Args&&.

The class template allocator_traits (20.2.8) 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. A user specialization of allocator_traits may provide different defaults and may provide defaults for different requirements than the primary template.

typename X::pointer

Remarks: Default: T*

typename X::const_pointer

Mandates: X::pointer is convertible to X::const_pointer.

Remarks: Default: pointer_traits<X::pointer>::rebind<const T>

typename X::void_pointer
typename Y::void_pointer

Mandates: X::pointer is convertible to X::void_pointer. X::void_pointer and Y::void_pointer are the same type.

Remarks: Default: pointer_traits<X::pointer>::rebind<void>

typename X::const_void_pointer
typename Y::const_void_pointer

Mandates: X::pointer, X::const_pointer, and X::void_pointer are convertible to X::const_void_pointer. X::const_void_pointer and Y::const_void_pointer are the same type.

Remarks: Default: pointer_traits<X::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<X::difference_type>

typename 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<X::pointer>::difference_type

typename X::template rebind<U>::other

Result: Y

Postconditions: For all U (including T), Y::template rebind<T>::other 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 1: 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: Tk
\*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<X::pointer>(w)

 Result: X::pointer

 Postconditions: static\_cast<X::pointer>(w) == p.

 static\_cast<X::const\_pointer>(x)

 Result: X::const\_pointer

 Postconditions: static\_cast<X::const\_pointer>(x) == q.

 pointer\_traits<X::pointer>::pointer\_to(r)

 Result: X::pointer

 Postconditions: Same as p.

 a.allocate(n)

 Result: X::pointer

 Effects: Memory is allocated for an array of n T and such an object is created but array elements are not constructed.

 [Example 1: When reusing storage denoted by some pointer value p, launder(reinterpret\_cast<T*>(new (p) byte[n * sizeof(T)])) can be used to implicitly create a suitable array object and obtain a pointer to it. —end example]

 Throws: allocate may throw an appropriate exception.

 [Note 2: 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: X::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<X::pointer>

 Returns: allocation\_result<X::pointer>{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: An allocator need not support allocate\_at\_least, but no default is provided in allocator\_traits. If an allocator has an allocate\_at\_least member, it shall satisfy the requirements.
\texttt{a.deallocate(p, n)}

\textbf{Result:} (not used)

\textbf{Preconditions:}

\begin{itemize}
\item[(48.1)] If \texttt{p} is memory that was obtained by a call to \texttt{a.allocate\_at\_least}, let \texttt{ret} be the value returned and \texttt{req} be the value passed as the first argument of that call. \texttt{p} is equal to \texttt{ret.ptr} and \texttt{n} is a value such that \texttt{req} \leq \texttt{n} \leq \texttt{ret.count}.
\item[(48.2)] Otherwise, \texttt{p} is a pointer value obtained from \texttt{allocate}. \texttt{n} equals the value passed as the first argument to the invocation of \texttt{allocate} which returned \texttt{p}.
\end{itemize}

\texttt{p} has not been invalidated by an intervening call to \texttt{deallocate}.

\textbf{Throws:} Nothing.

\texttt{a.max\_size()}

\textbf{Result:} \texttt{X::size\_type}

\textbf{Returns:} The largest value that can meaningfully be passed to \texttt{X::allocate()}.

\textbf{Remarks:} Default: \texttt{numeric\_limits<\texttt{size\_type}>::max() / sizeof(value\_type)}

\texttt{a1 == a2}

\textbf{Result:} bool

\textbf{Returns:} \texttt{true} only if storage allocated from each can be deallocated via the other.

\textbf{Throws:} Nothing.

\textbf{Remarks:} \texttt{operator==} shall be reflexive, symmetric, and transitive.

\texttt{a1 != a2}

\textbf{Result:} bool

\textbf{Returns:} \texttt{!(a1 == a2)}.

\texttt{a == b}

\textbf{Result:} bool

\textbf{Returns:} \texttt{a == Y::rebind<T>::other(b)}.

\texttt{a != b}

\textbf{Result:} bool

\textbf{Returns:} \texttt{!(a == b)}.

\texttt{X u(a);
X u = a;}

\textbf{Postconditions:} \texttt{u == a}

\textbf{Throws:} Nothing.

\texttt{X u(b);}

\textbf{Postconditions:} \texttt{Y(u) == b} and \texttt{u == X(b)}.

\textbf{Throws:} Nothing.

\texttt{X u(std::move(a));
X u = std::move(a);}

\textbf{Postconditions:} The value of \texttt{a} is unchanged and is equal to \texttt{u}.

\textbf{Throws:} Nothing.

\texttt{X u(std::move(b));}

\textbf{Postconditions:} \texttt{u} is equal to the prior value of \texttt{X(b)}.

\textbf{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;

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 33) and the copy
           operation shall not throw exceptions.
    Remarks: Default: false_type

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 32) and the move
           operation shall not throw exceptions.
    Remarks: Default: false_type

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, values of type X shall be swappable (16.4.4.3) and the swap operation shall not throw
           exceptions.
    Remarks: Default: false_type

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 31). The X::pointer,  
X::const_pointer, X::void_pointer, and X::const_void_pointer types shall meet the Cpp17Nullable- 
Pointer requirements (Table 35). 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 a and (a + n) are dereferenceable pointer values for some integral value n,  
addressof(*(a + n)) == addressof(*a) + 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 \texttt{x1} and \texttt{x2} can be explicitly converted to the two corresponding objects \texttt{px1} and \texttt{px2} of type \texttt{X::const_pointer}, using a sequence of \texttt{static_cast}s using only these four types, and the expression \texttt{px1 == px2} evaluates to \texttt{true}.

94 Let \texttt{w1} and \texttt{w2} denote objects of type \texttt{X::void_pointer}. Then for the expressions
\begin{verbatim}
  w1 == w2
  w1 != w2
\end{verbatim}
either or both objects may be replaced by an equivalently-valued object of type \texttt{X::const_void_pointer} with no change in semantics.

95 Let \texttt{p1} and \texttt{p2} denote objects of type \texttt{X::pointer}. Then for the expressions
\begin{verbatim}
  p1 == p2
  p1 != p2
  p1 <= p2
  p1 >= p2
  p1 > p2
  p1 - p2
\end{verbatim}
either or both objects may be replaced by an equivalently-valued object of type \texttt{X::const_pointer} with no change in semantics.

96 An allocator may constrain the types on which it can be instantiated and the arguments for which its \texttt{construct} or \texttt{destroy} members may be called. If a type cannot be used with a particular allocator, the allocator class or the call to \texttt{construct} or \texttt{destroy} may fail to instantiate.

97 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.

[\textit{Note 3: Additionally, the member function allocate for that type can fail by throwing an object of type bad_alloc.} ---end note]\n
98 [\textit{Example 2:} The following is an allocator class template supporting the minimal interface that meets the requirements of 16.4.4.6.1:
\begin{verbatim}
  template<class Tp>
  struct SimpleAllocator {
    typedef Tp value_type;
    SimpleAllocator(ctor args);

    template<class T> SimpleAllocator(const SimpleAllocator<T>& other);

    [[nodiscard]] Tp* allocate(std::size_t n);
    void deallocate(Tp* p, std::size_t n);
  };

  template<class T, class U>
  bool operator==(const SimpleAllocator<T>&, const SimpleAllocator<U>&);
  template<class T, class U>
  bool operator!=(const SimpleAllocator<T>&, const SimpleAllocator<U>&);
\end{verbatim}
---end example]

16.4.4.6.2 Allocator completeness requirements [allocator.requirements.completeness]

\begin{enumerate}
\item If \texttt{X} is an allocator class for type \texttt{T}, \texttt{X} additionally meets the allocator completeness requirements if, whether or not \texttt{T} is a complete type:
\begin{enumerate}
\item \texttt{X} is a complete type, and
\item all the member types of \texttt{allocator_traits<\texttt{X}> (20.2.8)} other than \texttt{value_type} are complete types.
\end{enumerate}
\end{enumerate}

16.4.5 Constraints on programs [constraints]

16.4.5.1 Overview [constraints.overview]

\begin{enumerate}
\item 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 headers (16.4.5.4), 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 std

1. Unless otherwise specified, the behavior of a C++ program is undefined if it adds declarations or definitions to namespace std or to a namespace within namespace std.

2. Unless explicitly prohibited, a program may add a template specialization for any standard library class template to namespace std provided that (a) the added declaration depends on at least one program-defined type and (b) the specialization meets the standard library requirements for the original template. 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.

3. The behavior of a C++ program is undefined if it declares an explicit specialization of any member function of a standard library class template, or

   (4.1) an explicit specialization of any member function template of a standard library class or class template, or

   (4.2) an explicit or partial specialization of any member class template of a standard library class or class template, or

   (4.3) a deduction guide for any standard library class template.

4. A program may explicitly instantiate a class template defined in the standard library only if the declaration (a) depends on the name of at least one program-defined type and (b) the instantiation meets the standard library requirements for the original template.

5. 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 addressable function, the behavior of a C++ program is unspecified (possibly ill-formed) if it explicitly or implicitly attempts to form a pointer to $F$.

   [Note 1: Possible means of forming such pointers include application of the unary & operator (7.6.2.2), addressof (20.2.10), or a function-to-pointer standard conversion (7.3.4). — end note]

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.

6. Other than in namespace std or in a namespace within namespace std, a program may provide an overload for any library function template designated as a customization point, provided that (a) the overload’s declaration depends on at least one user-defined type and (b) the overload meets the standard library requirements for the customization point.

   [Note 2: This permits a (qualified or unqualified) call to the customization point to invoke the most appropriate overload for the given arguments. — end note]

7. A translation unit shall not declare namespace std to be an inline namespace (9.8.2).

16.4.5.2.2 Namespace posix

1. 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

1. 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.

   (63) 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.

   (64) Any library customization point must be prepared to work adequately with any user-defined overload that meets the minimum requirements of this document. Therefore an implementation can elect, under the as-if rule (6.9.1), to provide any customization point in the form of an instantiated function object (22.10) even though the customization point’s specification is in the form of a function template. The template parameters of each such function object and the function parameters and return type of the object’s operator() must match those of the corresponding customization point’s specification.
Example 1: The top-level namespace std2 is reserved for use by future revisions of this International Standard.

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 following names are reserved for previous standardization:

1.1 auto_ptr,
1.2 auto_ptr_ref,
1.3 binary_function,
1.4 binary_negate,
1.5 bindist,
1.6 bind2nd,
1.7 binder1st,
1.8 binder2nd,
1.9 const_mem_fun1_ref_t,
1.10 const_mem_fun1_t,
1.11 const_mem_fun_ref_t,
1.12 const_mem_fun_t,
1.13 declare_no_pointers,
1.14 declare_reachable,
1.15 get_pointer_safety,
1.16 get_temporary_buffer,
1.17 get_unexpected,
1.18 gets,
1.19 is_literal_type,
1.20 is_literal_type_v,
1.21 mem_fun1_ref_t,
1.22 mem_fun1_t,
1.23 mem_fun_ref_t,
1.24 mem_fun_ref,
1.25 mem_fun_t,
1.26 mem_fun,
1.27 not1,
1.28 not2,
1.29 pointer_safety,
1.30 pointer_to_binary_function,
1.31 pointer_to_unary_function,
The following names are reserved as members for previous standardization, and may not be used as a name for object-like macros in portable code:

- argument_type,
- first_argument_type,
- io_state,
- open_mode,
- preferred,
- second_argument_type,
- seek_dir, and.
- strict.

3 The name stossc is reserved as a member function for previous standardization, and may not be used as a name for function-like macros in portable code.

4 The header names `<ccomplex>`, `<ciso646>`, `<cstdalign>`, `<cstdbool>`, and `<ctgmath>` are reserved for previous standardization.

16.4.5.3.3 Macro names [macro.names]

1 A translation unit that includes a standard library header shall not `#define` or `#undef` names declared in any standard library header.

2 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 [extern.names]

1 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.

2 Each global function signature declared with external linkage in a header is reserved to the implementation to designate that function signature with external linkage.

3 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.

---

165) The list of such reserved names includes `errno`, declared or defined in `<cerrno>` (19.4.2).

166) 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 `<stdarg>` (17.13.2).
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.

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 (15.3), 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).

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 delete(void*)

operator new(std::size_t, std::align_val_t)
operator delete(void*, std::align_val_t)

operator new(std::size_t, const std::nothrow_t&)
operator delete(void*, const std::nothrow_t&)

operator new(std::size_t, std::align_val_t, const std::nothrow_t&)
operator delete(void*, std::align_val_t, const std::nothrow_t&)

operator new[](std::size_t)
operator delete[](void*)

operator new[](std::size_t, std::align_val_t)
operator delete[](void*, std::align_val_t)

operator new[](std::size_t, const std::nothrow_t&)
operator delete[](void*, const std::nothrow_t&)

operator new[](std::size_t, std::align_val_t, const std::nothrow_t&)
operator delete[](void*, std::align_val_t, const std::nothrow_t&)

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):

(1.1) — 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. 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 effects are 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.

- 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.
- 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.
- 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]

2 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.

2 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.

3 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.

2 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.

2 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).

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.

2 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).

2 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.\(^{168}\)

3 An implementation shall not declare a non-member function signature with additional default arguments.

4 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:

```cpp
*out_stream << value;
if (delim != 0)
  *out_stream << delim;
```

168) 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.
return *this;
—end note]

16.4.6.5 Member functions
[member.functions]

1 It is unspecified whether any member functions in the C++ standard library are defined as inline (9.2.8).

2 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
[hidden.friends]

1 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, an implementation is not allowed to provide an additional declaration 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]

16.4.6.7 Constexpr functions and constructors
[constexpr.functions]

1 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
<algorithm.stable]

1 When the requirements for an algorithm state that it is “stable” without further elaboration, it means:

(1.1) — For the sort algorithms the relative order of equivalent elements is preserved.

(1.2) — For the remove and copy algorithms the relative order of the elements that are not removed is preserved.

(1.3) — 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
[reentrancy]

1 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
[res.on.data.races]

1 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.

2 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.

3 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]

4 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 [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 [derivation]

1 An implementation may derive any class in the C++ standard library from a class with a name reserved to the implementation.

2 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.

3 In any case:

(3.1) — Every base class described as virtual shall be virtual;

(3.2) — Every base class not specified as virtual shall not be virtual;

(3.3) — 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]

4 All types specified in the C++ standard library shall be non-final types unless otherwise specified.

16.4.6.13 Restrictions on exception handling [res.on.exception.handling]

1 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 an exception handler for the base type.

2 Functions from the C standard library shall not throw exceptions (169) except when such a function calls a program-supplied function that throws an exception (170).

3 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.

4 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 (171). Implementations should report errors by throwing exceptions of or derived from the standard exception classes (17.6.4.1, 17.9, 19.2).

5 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 [value.error.codes]

1 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

169) That is, the C 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.

170) The functions qsort() and bsearch() (27.12) meet this condition.

171) 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).

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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.
17 Language support library

17.1 General

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.

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 37.

Table 37: Language support library summary

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17.2 Common definitions

17.2.1 Header <cstddef> synopsis

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;
  template<class IntType>
    constexpr byte& operator|=(byte& l, byte r) noexcept;
  template<class IntType>
    constexpr byte operator|(byte l, byte r) noexcept;
  template<class IntType>
    constexpr byte& operator&=(byte& l, byte r) noexcept;
  template<class IntType>
    constexpr byte operator&(byte l, byte r) noexcept;
  template<class IntType>
    constexpr byte& operator^=(byte& l, byte r) noexcept;
  template<class IntType>
    constexpr byte operator^(byte l, byte r) noexcept;
  constexpr byte operator~(byte b) noexcept;

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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 <cstddef> are the same as the C standard library header <stddef.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 C 7.19

17.2.2 Header <cstdlib> synopsis [cstdlib.syn]

namespace std {
    using size_t = see below;
    using div_t = see below;
    using ldiv_t = see below;
    using lldiv_t = see below;
}

#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();
    extern "C++" using atexit_handler = void();
    extern "C" using c_compare_pred = int(const void*, const void*);
    extern "C++" using compare_pred = int(const void*, const void*);

    // 17.5, start and termination
    [[noreturn]] void abort() noexcept;
    int atexit(c_atexit_handler* func) noexcept;
    int atexit(atexit_handler* func) noexcept;
    int at_quick_exit(c_atexit_handler* func) noexcept;
    int at_quick_exit(atexit_handler* func) noexcept;
    [[noreturn]] void exit(int status);
    [[noreturn]] void _Exit(int status) noexcept;
    [[noreturn]] void quick_exit(int status) noexcept;
    char* getenv(const char* name);
    int system(const char* string);

    // 20.2.11, 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 strtod(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 int strtoll(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 mblen(const char* s, size_t n);
int mbtowc(wchar_t* pwc, const char* s, size_t n);
int wcwidth(char* s, wchar_t wchar);
size_t mbstowcs(wchar_t* pwc, const char* s, size_t n);
size_t wcstombs(char* s, const wchar_t* pwcs, size_t n);

// 27.12, C standard library algorithms
void* bsearch(const void* key, const void* base, size_t nmemb, size_t size,
               c-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,
          c-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 float abs(float j);
constexpr double abs(double j);
constexpr long double abs(long double j);

constexpr long int labs(long int j);
constexpr 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); // see 16.2

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, 20.2.11, 23.5.6, 27.12, 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 C 7.22

17.2.3 Null pointers

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_t’s address cannot be taken, the address of another nullptr_t object that is an lvalue can be taken. — end note]

The macro NULL is an implementation-defined null pointer constant.172

See also: ISO C 7.19

17.2.4 Sizes, alignments, and offsets

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.173

172) Possible definitions include 0 and 0L, but not (void*)0.
173) Note that offsetof is required to work as specified even if unary operator& is overloaded for any of the types involved.
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 data member or a function member is undefined. No operation invoked by the `offsetof` macro shall throw an exception and `nothrow(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).

Recommended practice: An implementation should choose types for `ptrdiff_t` and `size_t` whose integer conversion ranks (6.8.5) 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 C 7.19

17.2.5 byte type operations

```cpp
template<class IntType>
constexpr byte& operator===(byte& b, IntType shift) noexcept;

Constraints: is_integral_v<IntType> is true.
Effects: Equivalent to: return b = b << shift;

template<class IntType>
constexpr byte operator<<(byte b, IntType shift) noexcept;

Constraints: is_integral_v<IntType> is true.
Effects: Equivalent to:
return cast<byte>(cast<unsigned int>(b) << shift);

template<class IntType>
constexpr byte& operator>>(byte& b, IntType shift) noexcept;

Constraints: is_integral_v<IntType> is true.
Effects: Equivalent to:
return cast<byte>(cast<unsigned int>(b) >> shift);

template<class IntType>
constexpr byte operator|(byte l, byte r) noexcept;

Effects: Equivalent to:
return cast<byte>(cast<unsigned int>(l) | cast<unsigned int>(r));

constexpr byte& operator&=(byte& l, byte r) noexcept;

Effects: Equivalent to:
return l = l & r;

constexpr byte operator&=(byte l, byte r) noexcept;

Effects: Equivalent to:
return cast<byte>(cast<unsigned int>(l) & cast<unsigned int>(r));

constexpr byte& operator^=(byte& l, byte r) noexcept;

Effects: Equivalent to:
return l = l ^ r;

constexpr byte operator^=(byte& l, byte r) noexcept;

Effects: Equivalent to:
return cast<byte>(cast<unsigned int>(l) ^ cast<unsigned int>(r));
```

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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;

Constraints: is_integral_v<IntType> is true.

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).

Each of the macros defined in <version> is also defined after inclusion of any member of the set of library headers indicated in the corresponding comment in this synopsis.

[Note 1: Future revisions of C++ might replace the values of these macros with greater values. — end note]

#define __cpp_lib_addressofconstexpr 201603L // also in <memory>
#define __cpp_lib_allocate_at_least 202106L // also in <memory>
#define __cpp_lib_adaptor_iterator_pair_constructor 202106L // also in <memory>, <scoped_allocator>, <string>, <deque>, <forward_list>, <list>, <vector>, <map>, <set>, <unordered_map>, <unordered_set>
#define __cpp_lib_adaptor_iterator_pair_constructor 202106L // also in <map>, <set>, <unordered_map>, <unordered_set>
#define __cpp_lib_addressofconstexpr 201603L // also in <memory>
#define __cpp_lib_allocate_at_least 202106L // also in <memory>
#define __cpp_lib_adaptor_iterator_pair_constructor 202106L // 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_array_constexpr 201811L // also in <iterator>, <array>
#define __cpp_lib_assume_aligned 201811L // also in <memory>
#define __cpp_lib_atomic_flag_test 201907L // also in <atomic>
#define __cpp_lib_atomic_float 201711L // also in <atomic>
#define __cpp_lib_atomic_is_always_lock_free 201603L // also in <atomic>
#define __cpp_lib_atomic_lock_free_type_aliases 201907L // also in <atomic>
#define __cpp_lib_atomic_ref 201806L // also in <atomic>
#define __cpp_lib_atomic_shared_ptr 201711L // also in <atomic>, <memory>
#define __cpp_lib_atomic_value_initialization 201911L // also in <atomic>, <memory>
#define __cpp_lib_atomic_wait 201907L // also in <atomic>
#define __cpp_lib_barrier 201907L // also in <atomic>, <memory>
#define __cpp_lib_bind_back 202202L // also in <functional>
#define __cpp_lib_bind_front 201907L // also in <functional>
#define __cpp_lib_bit_cast 201806L // also in <bit>
#define __cpp_lib_bitops 201907L // also in <bit>
#define __cpp_lib_bool_constant 201505L // also in <type_traits>
#define __cpp_lib_bounded_array_traits 201902L // also in <type_traits>
#define __cpp_lib_boyer_moore_searcher 201603L // also in <functional>
#define __cpp_lib_byte 201603L // also in <cstddef>
#define __cpp_lib_byteswap 202110L // also in <bit>
#define __cpp_lib_char8_t 201907L // also in <atomic>, <filesystem>, <iostream>, <limits>, <locale>, <ostream>, <string>, <string_view>
#define __cpp_lib_chrono 201907L // also in <chrono>
#define __cpp_lib_chrono_udls 201304L // also in <chrono>
#define __cpp_lib_clamp 201603L // also in <algorithm>
#define __cpp_lib_complex_uuds 201309L // also in <complex>
#define __cpp_lib_concepts 202002L // also in <concepts>
#define __cpp_lib_constexpr_algorithms 201806L // also in <algorithm>
#define __cpp_lib_constexpr_cmath 202202L // also in <cmath>, <cstdlib>
#define __cpp_lib_constexpr_complex 201711L // also in <complex>
#define __cpp_lib_constexpr_dynamic_alloc 201907L // also in <memory>
#define __cpp_lib_constexpr_functional 201907L // also in <functional>
#define __cpp_lib_constexpr_iterator 201811L // also in <iterator>
#define __cpp_lib_constexpr_memory 202202L // also in <memory>
#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_tuple 201811L // also in <tuple>
#define __cpp_lib_constexpr_typeinfo 202106L // also in <typeinfo>
#define __cpp_lib_constexpr_utility 201811L // also in <utility>
#define __cpp_lib_list_remove_return_type 201806L // also in <forward_list>, <list>
#define __cpp_lib_launder 201603L // also in <new>
#define __cpp_lib_latch 201907L // also in <latch>
#define __cpp_lib_launder 201603L // also in <new>
#define __cpp_lib_latch 201907L // also in <latch>
#define __cpp_lib_make_from_tuple 201603L // also in <tuple>
17.3.3 Header <limits> synopsis

```
namespace std {
    // 17.3.4, floating-point type properties
    enum float_round_style;
    enum float_denorm_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>;
    template<> class numeric_limits<char32_t>;
    template<> class numeric_limits<wchar_t>;
    template<> class numeric_limits<short>;
    template<> class numeric_limits<int>;
    template<> class numeric_limits<long>;
    template<> class numeric_limits<long long>;
    template<> class numeric_limits<unsigned short>;
    template<> class numeric_limits<unsigned int>;
    template<> class numeric_limits<unsigned long>;
    template<> class numeric_limits<unsigned long long>;
    template<> class numeric_limits<float>;
    template<> class numeric_limits<double>;
    template<> class numeric_limits<long double>;
}
```

17.3.4 Floating-point type properties

17.3.4.1 Type float_round_style

```
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
    };
}
```

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
round_toward_infinity if the rounding style is toward infinity
round_toward_neg_infinity if the rounding style is toward negative infinity

17.3.4.2 Type float_denorm_style

```cpp
namespace std {
  enum float_denorm_style {
    denorm_indeterminate = -1,
    denorm_absent = 0,
    denorm_present = 1
  }
}
```

1 The presence or absence of subnormal numbers (variable number of exponent bits) is characterized by the values:

- denorm_indeterminate if it cannot be determined whether or not the type allows subnormal values
- denorm_absent if the type does not allow subnormal values
- denorm_present if the type does allow subnormal values

17.3.5 Class template numeric_limits

17.3.5.1 General

The `numeric_limits` class template provides a C++ program with information about various properties of the implementation’s representation of the arithmetic types.

```cpp
namespace std {
  template<class T> class numeric_limits {
    public:
      static constexpr bool is_specialized = false;
      static constexpr T min() noexcept { return T(); }
      static constexpr T max() noexcept { return T(); }
      static constexpr T lowest() noexcept { return T(); }
      static constexpr int digits = 0;
      static constexpr int digits10 = 0;
      static constexpr int max_digits10 = 0;
      static constexpr bool is_signed = false;
      static constexpr bool is_integer = false;
      static constexpr bool is_exact = false;
      static constexpr int radix = 0;
      static constexpr T epsilon() noexcept { return T(); }
      static constexpr T round_error() noexcept { return T(); }
      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 float_denorm_style has_denorm = denorm_absent;
      static constexpr bool has_denorm_loss = 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;
  }
}
```
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.

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`.

`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.

Equivalent to `FLT_MIN`, `DBL_MIN`, etc.

Equivalent to `FLT_MANT_DIG`, `DBL_MANT_DIG`, etc.

Equivalent to `FLT_DIG`, `DBL_DIG`, `LDBL_DIG`.

17.3.5.2 `numeric_limits` members

1 Each member function defined in this subclause is signal-safe (17.13.5).

2 Minimum finite value.174

3 For floating-point types with subnormal numbers, returns the minimum positive normalized value.

4 Meaningful for all specializations in which `is_bounded != false`, or `is_bounded == false && is_signed == false`.

5 Maximum finite value.175

6 Meaningful for all specializations in which `is_bounded != false`.

7 A finite value `x` such that there is no other finite value `y` where `y < x`.176

8 Meaningful for all specializations in which `is_bounded != false`.

9 Number of radix digits that can be represented without change.

10 For integer types, the number of non-sign bits in the representation.

11 For floating-point types, the number of radix digits in the mantissa.177

12 Number of base 10 digits that can be represented without change.178

13 Meaningful for all specializations in which `is_bounded != false`.

14 Number of base 10 digits required to ensure that values which differ are always differentiated.

15 Meaningful for all floating-point types.

174) Equivalent to `CHAR_MIN`, `SHRT_MIN`, `FLT_MIN`, `DBL_MIN`, etc.
175) Equivalent to `CHAR_MAX`, `SHRT_MAX`, `FLT_MAX`, `DBL_MAX`, etc.
176) `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.
177) Equivalent to `FLT_MANT_DIG`, `DBL_MANT_DIG`, `LDBL_MANT_DIG`.
178) Equivalent to `FLT_DIG`, `DBL_DIG`, `LDBL_DIG`.
static constexpr bool is_signed;
   true if the type is signed.
Meaningful for all specializations.

static constexpr bool is_integer;
   true if the type is integer.
Meaningful for all specializations.

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.

static constexpr int radix;
   For floating-point types, specifies the base or radix of the exponent representation (often 2).\(^{179}\)
   For integer types, specifies the base of the representation.\(^{180}\)
Meaningful for all specializations.

static constexpr T epsilon() noexcept;
   Machine epsilon: the difference between 1 and the least value greater than 1 that is representable.\(^{181}\)
Meaningful for all floating-point types.

static constexpr T round_error() noexcept;
   Measure of the maximum rounding error.\(^{182}\)

static constexpr int min_exponent;
   Minimum negative integer such that \(\text{radix}\) raised to the power of one less than that integer is a
   normalized floating-point number.\(^{183}\)
Meaningful for all floating-point types.

static constexpr int min_exponent10;
   Minimum negative integer such that 10 raised to that power is in the range of normalized floating-point
   numbers.\(^{184}\)
Meaningful for all floating-point types.

static constexpr int max_exponent;
   Maximum positive integer such that \(\text{radix}\) raised to the power one less than that integer is a representable
   finite floating-point number.\(^{185}\)
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.\(^{186}\)
Meaningful for all floating-point types.

static constexpr bool has_infinity;
   true if the type has a representation for positive infinity.

\(^{179}\) Equivalent to \texttt{FLT\_RADIX}.
\(^{180}\) Distinguishes types with bases other than 2 (e.g. BCD).
\(^{181}\) Equivalent to \texttt{FLT\_EPSILON, DBL\_EPSILON, LDBL\_EPSILON}.
\(^{182}\) Rounding error is described in LIA-1 Section 5.2.4 and Annex C Rationale Section C.5.2.4 — Rounding and rounding
   constants.
\(^{183}\) Equivalent to \texttt{FLT\_MIN\_EXP, DBL\_MIN\_EXP, LDBL\_MIN\_EXP}.
\(^{184}\) Equivalent to \texttt{FLT\_MIN\_10\_EXP, DBL\_MIN\_10\_EXP, LDBL\_MIN\_10\_EXP}.
\(^{185}\) Equivalent to \texttt{FLT\_MAX\_EXP, DBL\_MAX\_EXP, LDBL\_MAX\_EXP}.
\(^{186}\) Equivalent to \texttt{FLT\_MAX\_10\_EXP, DBL\_MAX\_10\_EXP, LDBL\_MAX\_10\_EXP}. 

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Meaningful for all floating-point types.
Shall be `true` for all specializations in which `is_iec559 != false`.

```cpp
static constexpr bool has_quiet_NaN;
```
true if the type has a representation for a quiet (non-signaling) “Not a Number”.
Meaningful for all floating-point types.
Shall be `true` for all specializations in which `is_iec559 != false`.

```cpp
static constexpr bool has_signaling_NaN;
```
true if the type has a representation for a signaling “Not a Number”.
Meaningful for all floating-point types.
Shall be `true` for all specializations in which `is_iec559 != false`.

```cpp
static constexpr float_denorm_style has_denorm;
```
denorm_present if the type allows subnormal values (variable number of exponent bits),
denorm_absent if the type does not allow subnormal values, and
denorm_indeterminate if it is indeterminate at compile time whether the type allows subnormal values.
Meaningful for all floating-point types.

```cpp
static constexpr bool has_denorm_loss;
```
true if loss of accuracy is detected as a denormalization loss, rather than as an inexact result.

```cpp
static constexpr T infinity() noexcept;
```
Representation of positive infinity, if available.
Meaningful for all specializations for which `has_infinity != false`. Required in specializations for which `is_iec559 != false`.

```cpp
static constexpr T quiet_NaN() noexcept;
```
Representation of a quiet “Not a Number”, if available.
Meaningful for all specializations for which `has_quiet_NaN != false`. Required in specializations for which `is_iec559 != false`.

```cpp
static constexpr T signaling_NaN() noexcept;
```
Representation of a signaling “Not a Number”, if available.
Meaningful for all specializations for which `has_signaling_NaN != false`. Required in specializations for which `is_iec559 != false`.

```cpp
static constexpr T denorm_min() noexcept;
```
Minimum positive subnormal value.
Meaningful for all floating-point types.
In specializations for which `has_denorm == false`, returns the minimum positive normalized value.

```cpp
static constexpr bool is_iec559;
```
true if and only if the type adheres to ISO/IEC/IEEE 60559.
Meaningful for all floating-point types.

187) Required by LIA-1.
188) Required by LIA-1.
189) Required by LIA-1.
191) Required by LIA-1.
192) Required by LIA-1.
193) Required by LIA-1.
194) Required by LIA-1.
static constexpr bool is_bounded;

true if the set of values representable by the type is finite.\[196\]

[Note 1: All fundamental types (6.8.2) are bounded. This member would be false for arbitrary precision types. — end note]

Meaningful for all specializations.

static constexpr bool is_modulo;

true if the type is modulo.\[197\] 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]

Meaningful for all specializations.

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.\[198\]

Meaningful for all specializations.

static constexpr bool tinyness_before;

true if tinyness is detected before rounding.\[199\]

Meaningful for all floating-point types.

static constexpr float_round_style round_style;

The rounding style for the type.\[200\]

Meaningful for all floating-point types. Specializations for integer types shall return round_toward_-zero.

### 17.3.5.3 numeric_limits specializations [numeric.special]

All members shall be provided for all specializations. However, many values are only required to be meaningful under certain conditions (for example, \(\text{epsilon}()\) is only meaningful if \(\text{is_integer}\) 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;
            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; }
```}

196) Required by LIA-1.
197) Required by LIA-1.
198) Required by LIA-1.
200) Equivalent to FLT_ROUNDS. Required by LIA-1.
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_denorm_style has_denorm = denorm_absent;
static constexpr bool has_denorm_loss = false;

static constexpr float infinity() noexcept { return value; }
static constexpr float quiet_NaN() noexcept { return value; }
static constexpr float signaling_NaN() noexcept { return value; }
static constexpr float denorm_min() noexcept { return min(); }

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;
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

#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

1 The header <climits> defines all macros the same as the C standard library header <limits.h>.

[Note 1: The types of the constants defined by macros in <climits> are not required to match the types to which the macros refer. — end note]

See also: ISO C 5.2.4.2.1

17.3.7 Header <cfloat> synopsis

#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_MAX_10_EXP see below
#define DBL_MAX_10_EXP see below
#define LDBL_MAX_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 C 5.2.4.2.2

17.4   Integer types

17.4.1   General

1 The header `<cstdint>` (17.4.2) supplies integer types having specified widths, and macros that specify limits of integer types.

17.4.2   Header `<cstdint>` synopsis

```cpp
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; // optional
  using int_fast16_t = signed integer type; // optional
  using int_fast32_t = signed integer type; // optional
  using int_fast64_t = signed integer type; // optional
  using int_least8_t = signed integer type; // optional
  using int_least16_t = signed integer type; // optional
  using int_least32_t = signed integer type; // optional
  using int_least64_t = signed integer type; // optional
  using intmax_t = signed integer type;    // optional
  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_fast8_t = unsigned integer type; // optional
  using uint_fast16_t = unsigned integer type; // optional
  using uint_fast32_t = unsigned integer type; // optional
  using uint_fast64_t = unsigned integer type; // optional
  using uint_least8_t = unsigned integer type; // optional
  using uint_least16_t = unsigned integer type; // optional
  using uint_least32_t = unsigned integer type; // optional
  using uint_least64_t = unsigned integer type; // optional
}
```
17.5 Startup and termination

1 The header defines all types and macros the same as the C standard library header `<stdint.h>.

See also: ISO C 7.20

2 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]
[[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).

```c
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 (6.8.9.2) 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.201 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.

(9.3) 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.203

```c
int at_quick_exit(c-atexit-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 (6.8.9.2) all calls to `quick_exit` will succeed.

**Note 3:** The `at_quick_exit()` functions do not introduce a data race (16.4.6.10). — end note

**Note 4:** The order of registration could be indeterminate if `at_quick_exit` was called from more than one thread. — end note

**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.

[[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).

201) A function is called for every time it is registered.

202) 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`.

203) The macros `EXIT_FAILURE` and `EXIT_SUCCESS` are defined in `<cstdlib>` (17.2.2).

§ 17.5
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 C 7.22.4

17.6 Dynamic memory management

17.6.1 General

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.

17.6.2 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;
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;
}
```

§ 17.6.2
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  [new.delete]

17.6.3.1 General  [new.delete.general]

Exception 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.

17.6.3.2 Single-object forms  [new.delete.single]

`[[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 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 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.

[Example 1]:

```cpp
T* p1 = new T; // throws bad_alloc if it fails
T* p2 = new(nothrow) T; // returns nullptr if it fails
```
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]

Default behavior: If ptr is null, does nothing. Otherwise, reclaims the storage allocated by the earlier call to operator new.

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, calloc, 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 noexcept 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
[<new.delete.array>]
[[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.\(^{204}\)

**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.

**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.

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]

---

204) 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.
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.

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]] 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]] 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

```cpp
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;
    }
}
```

1 The class `bad_alloc` defines the type of objects thrown as exceptions by the implementation to report a failure to allocate storage.

```cpp
const char* what() const noexcept override;
```

Returns: An implementation-defined ntbs.

17.6.4.2 Class bad_array_new_length

```cpp
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;
    }
}
```

1 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

```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:

(2.1) — make more storage available for allocation and then return;

(2.2) — throw an exception of type `bad_alloc` or a class derived from `bad_alloc`;

(2.3) — terminate execution of the program without returning to the caller.

17.6.4.4 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

```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

```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 the result are reachable through \( p \) (see below).

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. A byte of storage \( b \) is reachable through a pointer value that points to an object \( Y \) if there is an object \( Z \), pointer-interconvertible with \( Y \), such that \( b \) is within the storage occupied by \( Z \), or the immediately-enclosing array object if \( Z \) is an array element.

[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

```cpp
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 \( \text{alignof(max_align_t)} \).

[Example 1:

```cpp
struct keep_apart {
    alignas(hardware_destructive_interference_size) atomic<int> cat;
    alignas(hardware_destructive_interference_size) atomic<int> dog;
};
— end example]
```

```cpp
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 \( \text{alignof(max_align_t)} \).

[Example 2:

```cpp
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

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.

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.

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.

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.

const char* name() const noexcept;

Returns: An implementation-defined ntbs.

Remarks: The message may be a null-terminated multibyte string (16.3.3.3.5.3), suitable for conversion and display as a wstring (23.4, 30.4.2.5).

17.7.4 Class bad_cast

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).

const char* what() const noexcept override;

Returns: An implementation-defined ntbs.
17.7.5 Class bad_typeid

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).

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.

namespace std {
    struct source_location;
}

17.8.2 Class source_location

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
    };
}

The type source_location meets the Cpp17DefaultConstructible, Cpp17CopyConstructible, Cpp17Copy-Assignable, and Cpp17Destructible requirements (16.4.4.2). Lvalues of type source_location are swappable (16.4.4.3). All of the following conditions are true:

— is_nothrow_move_constructible_v<source_location>
— is_nothrow_move_assignable_v<source_location>
— 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]

The data members file_name_ and function_name_ always each refer to an ntbs.

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:

— strcmp(lhs.file_name(), rhs_p.file_name()) == 0
17.8.2.2 Creation

static consteval source_location current() noexcept;

Returns:

— 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 38.

Table 38: Value of object returned by current

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>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>column_</td>
<td>An implementation-defined value denoting some offset from the start of the line denoted by 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>file_name_</td>
<td>A presumed name of the current source file (15.11) as an ntbs.</td>
</tr>
<tr>
<td>function_name_</td>
<td>A name of the current function such as in <strong>func</strong> (9.5.1) if any, an empty string otherwise.</td>
</tr>
</tbody>
</table>

— Otherwise, when invoked in some other way, returns a source_location whose data members are initialized with valid but unspecified values.

Remarks: Any call to 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 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 member refer to the location of the calling function (9.3.4.7)
    {}
    s(int blather) :
        other_member(blather)
    {}
    s(double) // values of member refer to this location
    {}
};
void f(source_location a = source_location::current()) {
    source_location b = source_location::current(); // values in b refer to this line
}
void g() {
    f(); // f’s first argument corresponds to this line of code
}```
source_location c = source_location::current();
f(c);
// f’s first argument gets the same values as c, above
}

constexpr source_location() noexcept;

Effects: The data members are initialized with valid but unspecified values.

17.8.2.3 Observers

constexpr uint_least32_t line() const noexcept;

Returns: line_.

constexpr uint_least32_t column() const noexcept;

Returns: column_.

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;
    };
}

§ 17.9.3
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.

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).

```cpp
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.

```cpp
virtual ~exception();
```

**Effects:** Destroys an object of class `exception`.

```cpp
virtual const char* what() const noexcept override;
```

**Returns:** An implementation-defined `ntbs`.

**Remarks:** The message may be a null-terminated multibyte string (16.3.3.5.3), 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`

```cpp
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;
    };
}
```

1 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.

**Returns:** An implementation-defined `ntbs`.

### 17.9.5 Abnormal termination

#### 17.9.5.1 Type `terminate_handler`

```cpp
using terminate_handler = void (*)(void);
```

1 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`

```cpp
terminate_handler set_terminate(terminate_handler f) noexcept;
```

1 **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`.  

§ 17.9.5.2 524
17.9.5.3 get_terminate

```cpp
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

```cpp
[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.

[Note 1: A default terminate_handler is always considered a callable handler in this context. — end note]

Remarks: 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;
```

Returns: The number of uncaught exceptions (14.6.3).

Remarks: When uncaught_exceptions() > 0, throwing an exception can result in a call of the function std::terminate (14.6.2).

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 35).

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]

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.

[Note 4: The copy constructor of the thrown exception can also fail, so the implementation is allowed to substitute a bad_exception object to avoid infinite recursion. — end note]
[[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.

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:

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

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.

[[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.

exception_ptr nested_ptr() const noexcept;

Returns: The stored exception captured by this nested_exception object.

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).
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:

\[
\text{if (auto p = \text{dynamic\_cast<\text{const nested\_exception}*>(addressof(e)))})}
\]
\[
p->\text{rethrow\_nested();}
\]

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

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
    };

    // 17.10.5, initializer list range access
    template<class E> constexpr const E* begin(initializer_list<E> il) noexcept;
    template<class E> constexpr const E* end(initializer_list<E> il) noexcept;
}

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;
    constexpr const E* end() 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 size_t size() const noexcept;
```

Returns: The number of elements in the array.

Complexity: Constant time.
17.10.5  Initializer list range access  

(template<class E> constexpr const E* begin(initializer_list<E> il) noexcept;
1
Returns: il.begin().

template<class E> constexpr const E* end(initializer_list<E> il) noexcept;
2
Returns: il.end().

17.11  Comparisons
17.11.1  Header <compare> synopsis
1
The header <compare> specifies types, objects, and functions for use primarily in connection with the
three-way comparison operator (7.6.8).

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;

    // 17.11.6, comparison algorithms
    inline namespace unspecified {
        inline constexpr unspecified strong_order = unspecified;
        inline constexpr unspecified weak_order = unspecified;
        inline constexpr unspecified partial_order = unspecified;
        inline constexpr unspecified compare_strong_order_fallback = unspecified;
        inline constexpr unspecified compare_weak_order_fallback = unspecified;
        inline constexpr unspecified compare_partial_order_fallback = unspecified;
    }
}
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:

```cpp
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 subclause 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) that (a) admits all of the six two-way comparison operators (7.6.9, 7.6.10), (b) does not imply substitutability, and (c) permits two values to be incomparable.\(^{205}\)

```cpp
namespace std {
    class partial_ordering {
        int value; // exposition only
        bool is_ordered; // exposition only

        // exposition-only constructors
        constexpr explicit partial_ordering(ord v) noexcept : value(int(v)), is_ordered(true) {} // exposition only
        constexpr explicit partial_ordering(ncmp v) noexcept : value(int(v)), is_ordered(false) {} // exposition only

        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, partial_ordering w) noexcept = default;
        friend constexpr bool operator<(partial_ordering v, unspecified) noexcept;
        friend constexpr bool operator<(partial_ordering v, partial_ordering w) noexcept;
        friend constexpr bool operator>(partial_ordering v, unspecified) noexcept;
        friend constexpr bool operator>(partial_ordering v, partial_ordering w) noexcept;
        friend constexpr bool operator<=(partial_ordering v, unspecified) noexcept;
        friend constexpr bool operator<=(partial_ordering v, partial_ordering w) noexcept;
        friend constexpr bool operator>= (partial_ordering v, unspecified) noexcept;
        friend constexpr bool operator>= (partial_ordering v, partial_ordering w) noexcept;
        friend constexpr partial_ordering operator<=>(partial_ordering v, unspecified) noexcept;
        friend constexpr partial_ordering operator<=>(partial_ordering v, partial_ordering w) noexcept;
    }

    // valid values' definitions
    inline constexpr partial_ordering partial_ordering::less(ord::less);
    inline constexpr partial_ordering partial_ordering::equivalent(ord::equivalent);
}
```

\(^{205}\) That is, \( a < b, a == b, \) and \( a > b \) might all be *false.*
inline constexpr partial_ordering partial_ordering::greater(ord::greater);
inline constexpr partial_ordering partial_ordering::unordered(ncmp::unordered);
}

constexpr bool operator==(partial_ordering v, unspecified) noexcept;
constexpr bool operator< (partial_ordering v, unspecified) noexcept;
constexpr bool operator> (partial_ordering v, unspecified) noexcept;
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 < 0 ? partial_ordering::greater : v > 0 ? partial_ordering::less : v.

17.11.2.3 Class weak_ordering [cmp.weakord]

The weak_ordering type is typically used as the result type of a three-way comparison operator (7.6.8) that
(a) admits all of the six two-way comparison operators (7.6.9, 7.6.10), and (b) does 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, unspecified) noexcept;
        friend constexpr bool operator<=(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator>=(weak_ordering v, unspecified) noexcept;
        friend constexpr bool operator<(unspecified, weak_ordering v) noexcept;
        friend constexpr bool operator>(unspecified, weak_ordering v) noexcept;
        friend constexpr bool operator<=(unspecified, weak_ordering v) noexcept;
        friend constexpr bool operator>=(unspecified, weak_ordering v) noexcept;
        friend constexpr weak_ordering operator<=>(weak_ordering v, unspecified) noexcept;
        friend constexpr weak_ordering operator<=>(unspecified, weak_ordering v) 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;

Returns:
value == 0 ? partial_ordering::equivalent :
value < 0 ? partial_ordering::less :
partial_ordering::greater

castexpr bool operator==(weak_ordering v, unspecified) noexcept;
castexpr bool operator< (weak_ordering v, unspecified) noexcept;
castexpr bool operator> (weak_ordering v, unspecified) noexcept;
castexpr bool operator<= (weak_ordering v, unspecified) noexcept;
castexpr bool operator>= (weak_ordering v, unspecified) noexcept;

Returns: v.value @ 0 for operator@.

castexpr weak_ordering operator<=>(weak_ordering v, unspecified) noexcept;

Returns: v.

castexpr 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

The strong_ordering type is typically used as the result type of a three-way comparison operator (7.6.8) that (a) admits all of the six two-way comparison operators (7.6.9, 7.6.10), and (b) 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;
castexpr operator weak_ordering() const noexcept;

    // comparisons
    friend constexpr bool operator==(strong_ordering v, unspecified) noexcept;
castexpr bool operator==(strong_ordering v, strong_ordering w) noexcept = default;
castexpr bool operator< (strong_ordering v, unspecified) noexcept;
castexpr bool operator< (strong_ordering v, strong_ordering w) noexcept = default;
castexpr bool operator> (strong_ordering v, unspecified) noexcept;
castexpr bool operator> (strong_ordering v, strong_ordering w) noexcept = default;
castexpr bool operator<= (strong_ordering v, unspecified) noexcept;
castexpr bool operator<= (strong_ordering v, strong_ordering w) noexcept = default;
castexpr bool operator>= (strong_ordering v, unspecified) noexcept;
castexpr bool operator>= (strong_ordering v, strong_ordering w) noexcept = default;
castexpr strong_ordering operator<=>(strong_ordering v, unspecified) noexcept;
castexpr strong_ordering operator<=>(unspecified, strong_ordering v) noexcept;
};
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 bool operator==(strong_ordering v, unspecified) noexcept;
constexpr bool operator<(strong_ordering v, unspecified) noexcept;
constexpr bool operator>(strong_ordering v, unspecified) noexcept;
constexpr bool operator<=(strong_ordering v, unspecified) noexcept;
constexpr bool 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]

17.11.4 Concept three_way_comparable

template<class T, class Cat>
concept compares_as = // exposition only
  same_as<common_comparison_category_t<T, Cat>, Cat>;
template<class T, class U>
concept partially-ordered-with = // exposition only
    requires(const remove_reference_t<T>& t, const remove_reference_t<U>& u) {
    { t < u } -> boolean-testable;
    { 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;
    };

Let t and u be lvalues of types const remove_reference_t<T> and const remove_reference_t<U>, respectively. T and U model partially-ordered-with<T, U> only if:

1. 
   — t < u, t <= u, t > u, t >= u, u < t, u <= t, u > t, and u >= t have the same domain.

2. 
   — bool(t < u) == bool(u > t) is true,
   — bool(u < t) == bool(t > u) is true,
   — bool(t <= u) == bool(u >= t) is true, and
   — bool(u <= t) == bool(t >= u) is true.

Let a and b be lvalues of type const remove_reference_t<T>. T and Cat model three-way-comparable<T, Cat> only if:

1. 
   — (a <=> b == 0) == bool(a == b) is true,
   — (a <=> b != 0) == bool(a != b) is true,
   — ((a <=> b) <=> 0) and (0 <=> (b <=> a)) are equal,
   — (a <=> b < 0) == bool(a < b) is true,
   — (a <=> b > 0) == bool(a > b) is true,
   — (a <=> b <= 0) == bool(a <= b) is true,
   — (a <=> b >= 0) == bool(a >= b) is true, and
   — if Cat is convertible to strong_ordering, T models totally_ordered (18.5.4).

Let t and u be lvalues of types const remove_reference_t<T> and const remove_reference_t<U>, respectively. Let C be common_reference_t<const remove_reference_t<T> & t, const remove_reference_t<U> & u>. T, U, and Cat model three-way-comparable_with<T, U, Cat> only if:

1. 
   — t <=> u and u <=> t have the same domain,
   — (t <=> u) <=> 0 and (0 <=> (u <=> t)) are equal,
(3.3) \( (t \leftrightarrow u = 0) == \text{bool}(t == u) \) is true,
(3.4) \( (t \leftrightarrow u != 0) == \text{bool}(t != u) \) is true,
(3.5) \( \text{Cat}(t \leftrightarrow u) == \text{Cat}(\text{C}(t) \leftrightarrow \text{C}(u)) \) is true,
(3.6) \( (t \leftrightarrow u < 0) == \text{bool}(t < u) \) is true,
(3.7) \( (t \leftrightarrow u > 0) == \text{bool}(t > u) \) is true,
(3.8) \( (t \leftrightarrow u <= 0) == \text{bool}(t <= u) \) is true,
(3.9) \( (t \leftrightarrow u >= 0) == \text{bool}(t >= u) \) is true, and
(3.10) if \( \text{Cat} \) is convertible to \text{strong\_ordering}, \( T \) and \( U \) model \text{totally\_ordered\_with}\langle T, U \rangle (18.5.4).

17.11.5 Result of three-way comparison

1 For the \text{compare\_three\_way\_result} type trait applied to the types \( T \) and \( U \), let \( t \) and \( u \) denote lvalues of types \text{const \_remove\_reference\_t}\langle T \rangle and \text{const \_remove\_reference\_t}\langle U \rangle, respectively. If the expression \( t \leftrightarrow u \) is well-formed when treated as an unevaluated operand (7.2.3), the member \text{typedef\_name\_type} denotes the type \( \text{decltype}(t \leftrightarrow u) \). Otherwise, there is no member \text{type}.

17.11.6 Comparison algorithms

1 The name \text{strong\_order} denotes a customization point object (16.3.3.3.6). Given subexpressions \( E \) and \( F \), the expression \text{strong\_order}(E, F) is expression-equivalent (3.21) to the following:

(1.1) — If the decayed types of \( E \) and \( F \) differ, \text{strong\_order}(E, F) is ill-formed.
(1.2) — Otherwise, \text{strong\_ordering}(\text{strong\_order}(E, F)) if it is a well-formed expression with overload resolution performed in a context that does not include a declaration of \text{std\_::strong\_order}.
(1.3) — Otherwise, if the decayed type \( T \) of \( E \) is a floating-point type, yields a value of type \text{strong\_ordering} that is consistent with the ordering observed by \( T \)'s comparison operators, and if \text{numeric\_limits\langle T\rangle\_::is\_ieee559} is true, is additionally consistent with the \text{totalOrder} operation as specified in ISO/IEC/IEEE 60559.
(1.4) — Otherwise, \text{strong\_ordering}(\text{compare\_three\_way\_result}(E, F)) if it is a well-formed expression.
(1.5) — Otherwise, \text{strong\_order}(E, F) is ill-formed.

[Note 1: Ill-formed cases above result in substitution failure when \text{strong\_order}(E, F) appears in the immediate context of a template instantiation. — end note]

2 The name \text{weak\_order} denotes a customization point object (16.3.3.3.6). Given subexpressions \( E \) and \( F \), the expression \text{weak\_order}(E, F) is expression-equivalent (3.21) to the following:

(2.1) — If the decayed types of \( E \) and \( F \) differ, \text{weak\_order}(E, F) is ill-formed.
(2.2) — Otherwise, \text{weak\_ordering}(\text{weak\_order}(E, F)) if it is a well-formed expression with overload resolution performed in a context that does not include a declaration of \text{std\_::weak\_order}.
(2.3) — Otherwise, if the decayed type \( T \) of \( E \) is a floating-point type, yields a value of type \text{weak\_ordering} that is consistent with the ordering observed by \( T \)'s comparison operators and \text{strong\_order}, and if \text{numeric\_limits\langle T\rangle\_::is\_ieee559} is true, is additionally consistent with the following equivalence classes, ordered from lesser to greater:

(2.3.1) — together, all negative NaN values;
(2.3.2) — negative infinity;
(2.3.3) — each normal negative value;
(2.3.4) — each subnormal negative value;
(2.3.5) — together, both zero values;
(2.3.6) — each subnormal positive value;
(2.3.7) — each normal positive value;
(2.3.8) — positive infinity;
(2.3.9) — together, all positive NaN values.

§ 17.11.6
Otherwise, weak_ordering(compare_three_way()(E, F)) if it is a well-formed expression.

— Otherwise, weak_ordering(strong_order(E, F)) if it is a well-formed expression.

— Otherwise, weak_order(E, F) is ill-formed.

[Note 2: Ill-formed cases above result in substitution failure when weak_order(E, F) appears in the immediate context of a template instantiation. — end note]

The name partial_order denotes a customization point object (16.3.3.3.6). Given subexpressions E and F, the expression partial_order(E, F) is expression-equivalent (3.21) to the following:

— If the decayed types of E and F differ, partial_order(E, F) is ill-formed.

— Otherwise, partial_ordering(partial_order(E, F)) if it is a well-formed expression with overload resolution performed in a context that does not include a declaration of std::partial_order.

— Otherwise, partial_ordering(compare_three_way()(E, F)) if it is a well-formed expression.

— Otherwise, partial_order(E, F) is ill-formed.

[Note 3: Ill-formed cases above result in substitution failure when partial_order(E, F) appears in the immediate context of a template instantiation. — end note]

The name compare_strong_order_fallback denotes a customization point object (16.3.3.3.6). Given subexpressions E and F, the expression compare_strong_order_fallback(E, F) is expression-equivalent (3.21) to:

— If the decayed types of E and F differ, compare_strong_order_fallback(E, F) is ill-formed.

— Otherwise, strong_order(E, F) if it is a well-formed expression.

— Otherwise, if the expressions E == F and E < F are both well-formed and convertible to bool,

```cpp
E == F ? strong_ordering::equal :
E < F ? strong_ordering::less :
      strong_ordering::greater
```

except that E and F are evaluated only once.

— Otherwise, compare_strong_order_fallback(E, F) is ill-formed.

[Note 4: Ill-formed cases above result in substitution failure when compare_strong_order_fallback(E, F) appears in the immediate context of a template instantiation. — end note]

The name compare_weak_order_fallback denotes a customization point object (16.3.3.3.6). Given subexpressions E and F, the expression compare_weak_order_fallback(E, F) is expression-equivalent (3.21) to:

— If the decayed types of E and F differ, compare_weak_order_fallback(E, F) is ill-formed.

— Otherwise, weak_order(E, F) if it is a well-formed expression.

— Otherwise, if the expressions E == F, E < F, and F < E are all well-formed and convertible to bool,

```cpp
E == F ? weak_ordering::equivalent :
E < F ? weak_ordering::less :
      weak_ordering::greater
```

except that E and F are evaluated only once.

— Otherwise, compare_weak_order_fallback(E, F) is ill-formed.

[Note 5: Ill-formed cases above result in substitution failure when compare_weak_order_fallback(E, F) appears in the immediate context of a template instantiation. — end note]

The name compare_partial_order_fallback denotes a customization point object (16.3.3.3.6). Given subexpressions E and F, the expression compare_partial_order_fallback(E, F) is expression-equivalent (3.21) to:

— If the decayed types of E and F differ, compare_partial_order_fallback(E, F) is ill-formed.

— Otherwise, partial_order(E, F) if it is a well-formed expression.

— Otherwise, if the expressions E == F, E < F, and F < E are all well-formed and convertible to bool,
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.

(6.4) — 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 [support.coroutine]

17.12.1 General [support.coroutine.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 [coroutine.syn]

```cpp
#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>;
    noop_coroutine_handle noop_coroutine() noexcept;

    // 17.12.6, trivial awaitables
    struct suspend_never;
    struct suspend_always;
}
```

17.12.3 Coroutine traits [coroutine.traits]

17.12.3.1 General [coroutine.traits.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 [coroutine.traits.primary]

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:

```cpp
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

namespace std {

template<>
struct coroutine_handle<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
};
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`.
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;  [coroutine.handle.promise]

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;  [coroutine.handle.compare]

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>>;  [coroutine.handle.hash]

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 {};  [coroutine.promise.noop]

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> {
        // 17.12.5.2.1, conversion
        constexpr operator coroutine_handle<>() const noexcept;

        // 17.12.5.2.2, observers
        constexpr explicit operator bool() const noexcept;
        constexpr bool done() const noexcept;

        // 17.12.5.2.3, resumption
        constexpr void operator()() const noexcept;
        constexpr void resume() const noexcept;
        constexpr void destroy() const noexcept;

        // 17.12.5.2.4, promise access
        noop_coroutine_promise& promise() const noexcept;
    };
}

§ 17.12.5.2 539
// 17.12.5.2.5, address
constexpr void* address() const noexcept;
private:
coroutine_handle(unspecified);
void* ptr;  // exposition only
};

17.12.5.2.1 Conversion
constexpr operator coroutine_handle<>() const noexcept;

Effects: Equivalent to: return coroutine_handle<>::from_address(address());

17.12.5.2.2 Observers
constexpr explicit operator bool() const noexcept;

Returns: true.

constexpr bool done() const noexcept;

Returns: false.

17.12.5.2.3 Resumption
constexpr void operator()() const noexcept;
constexpr void resume() const noexcept;
constexpr void destroy() const noexcept;

Effects: None.

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.

17.12.5.2.4 Promise access
noop_coroutine_promise& promise() const noexcept;

Returns: A reference to the promise object associated with this coroutine handle.

17.12.5.2.5 Address
constexpr void* address() const noexcept;

Returns: ptr.

Remarks: A noop_coroutine_handle’s ptr is always a non-null pointer value.

17.12.5.3 Function noop_coroutine
noop_coroutine_handle noop_coroutine() noexcept;

Returns: A handle to a coroutine that has no observable effects when resumed or destroyed.

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
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

1 Headers <csetjmp> (nonlocal jumps), <csignal> (signal handling), <cstdarg> (variable arguments), and <cstdlib> (runtime environment getenv, system), provide further compatibility with C code.

2 Calls to the function getenv (17.2.2) shall not introduce a data race (16.4.6.10) provided that nothing modifies the environment.

3 A call to the setlocale function (30.5) may introduce a data race with other calls to the setlocale function or with calls to functions that are affected by the current C locale. The implementation shall behave as if no library function other than locale::global calls the setlocale function.

17.13.2 Header <cstdarg> synopsis

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 <cstdarg> are the same as the C standard library header <stdarg.h>, with the following changes: The restrictions that ISO 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 (7.5.5), 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 C 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 C 7.13

17.13.4 Header <csignal> synopsis

namespace std {
    using sig_atomic_t = see below;

    // 17.13.5, signal handlers
    extern "C" using signal-handler = void(int); // exposition only
    signal-handler* signal(int sig, signal-handler* func);

---

206) Note that va_start is required to work as specified even if unary operator& is overloaded for the type of parmN.
int raise(int sig);
}

#define SIG_DFL see below
#define SIG_ERR see below
#define SIG_IGN see below
#define SIGABRT see below
#define SIGFPE see below
#define SIGILL see below
#define SIGINT see below
#define SIGSEGV see below
#define SIGTERM see below

1 The contents of the header `<csignal>` are the same as the C standard library header `<signal.h>`.

17.13.5 Signal handlers

A call to the function `signal` synchronizes with any resulting invocation of the signal handler so installed.

2 A plain lock-free atomic operation is an invocation of a function \( f \) from 33.5, such that:

- \( f \) is the function `atomic_is_lock_free()

2.1`, or
- \( f \) is the member function `is_lock_free()

2.2`, or
- \( f \) is a non-static member function invoked on an object \( A \), such that `A.is_lock_free()` yields `true`, or
- \( f \) 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:

- 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 allocators. — end note]

- an access to an object with thread storage duration;

- a `dynamic_cast` expression;

- throwing of an exception;

- control entering a try-block or function-try-block;

- initialization of a variable with static storage duration requiring dynamic initialization (6.9.3.3, 8.8)\(^{207} \); or

- 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.

4 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 C 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 39. 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 ISO C. Source files that are not intended to also be valid ISO C should not use any of the C headers.

[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 `<c
name>` 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 ISO C. Viewed as C++, it declares a function with C language linkage; viewed as C it simply declares a function (and provides a prototype).

\(^{207}\) Such initialization can occur because it is the first odr-use (6.3) of that variable.
```c
#include <stdbool.h>    // for bool in C, no effect in C++
#include <stddef.h>     // for size_t

#ifdef __cplusplus
extern "C"
#else
#endif

void f(bool b[], size_t n);

— end example
```

Table 39: C headers [tab:c.headers]

<table>
<thead>
<tr>
<th>Header</th>
<th>Specified Headers</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;assert.h&gt;</td>
<td>&lt;inttypes.h&gt;</td>
</tr>
<tr>
<td>&lt;complex.h&gt;</td>
<td>&lt;iso646.h&gt;</td>
</tr>
<tr>
<td>&lt;ctype.h&gt;</td>
<td>&lt;limits.h&gt;</td>
</tr>
<tr>
<td>&lt;errno.h&gt;</td>
<td>&lt;locale.h&gt;</td>
</tr>
<tr>
<td>&lt;fenv.h&gt;</td>
<td>&lt;math.h&gt;</td>
</tr>
<tr>
<td>&lt;float.h&gt;</td>
<td>&lt;setjmp.h&gt;</td>
</tr>
<tr>
<td>&lt;stdbool.h&gt;</td>
<td>&lt;stddef.h&gt;</td>
</tr>
<tr>
<td>&lt;stdarg.h&gt;</td>
<td>&lt;stddef.h&gt;</td>
</tr>
<tr>
<td>&lt;stdalign.h&gt;</td>
<td>&lt;time.h&gt;</td>
</tr>
<tr>
<td>&lt;stdatomic.h&gt;</td>
<td>&lt;stdbool.h&gt;</td>
</tr>
<tr>
<td>&lt;stdio.h&gt;</td>
<td>&lt;stdlib.h&gt;</td>
</tr>
<tr>
<td>&lt;string.h&gt;</td>
<td>&lt;tgmath.h&gt;</td>
</tr>
<tr>
<td>&lt;tgmath.h&gt;</td>
<td>&lt;uchar.h&gt;</td>
</tr>
<tr>
<td>&lt;wchar.h&gt;</td>
<td>&lt;wchar.h&gt;</td>
</tr>
<tr>
<td>&lt;wctype.h&gt;</td>
<td>&lt;wctype.h&gt;</td>
</tr>
</tbody>
</table>

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
#define __alignas_is_defined 1
```

1 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 C 7.15

17.14.5 Header <stdbool.h> synopsis [stdbool.h.syn]

```c
#define __bool_true_false_are_defined 1
```

1 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 C 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 [support.c.headers.other]

1 Every C header other than <complex.h> (17.14.2), <iso646.h> (17.14.3), <stdalign.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 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 (6.4.5) of the namespace std and are then injected into the global namespace scope by explicit using-declarations (9.9).

2 [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 the C Standard. 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 40.

Table 40: Fundamental concepts library summary

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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 (7.5.4), 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 \( a = \text{std::move}(b) \) are \( a \) and \( \text{std::move}(b) \). —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.

§ 18.2
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 == std::move(b);
std::move(c) == std::move(b);
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 = std::move(c);
```

had been declared.

— 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
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
// 18.5.3, concept equality_comparable
template<class T>
concept equality_comparable = see below;
template<class T, class U>
concept equality_comparable_with = see below;

// 18.5.4, 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<Base, Derived> &&
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 \( \text{From} \) and \( \text{To} \) and an expression \( E \) whose type and value category are the same as those of \( \text{declval<From>()} \), \( \text{convertible_to<From, To>} \) requires \( E \) to be both implicitly and explicitly convertible to type \( \text{To} \). The implicit and explicit conversions are required to produce equal results.

\[
\text{template<class From, class To>}
\]
\[
\text{concept convertible_to =}
\]
\[
is_convertible_v<\text{From}, \text{To}> \&\&
\]
\[
\text{requires}
\]
\[
\text{static_cast<To>(declval<From>());
}\]

2

Let \( \text{FromR} \) be \( \text{add_rvalue_reference_t<From>} \) and \( \text{test} \) be the invented function:

\[
\text{To test(FromR (&f)()) {
return f();
}}
\]

and let \( f \) be a function with no arguments and return type \( \text{FromR} \) such that \( f() \) is equality-preserving. Types \( \text{From} \) and \( \text{To} \) model \( \text{convertible_to<From, To>} \) only if:

\[ (2.1) \quad \text{To is not an object or reference-to-object type, or static_cast<To>(f()) is equal to test(f).} \]

\[ (2.2) \quad \text{FromR is not a reference-to-object type, or} \]

\[ (2.2.1) \quad \text{If FromR is an rvalue reference to a non const-qualified type, the resulting state of the object referenced by f() after either above expression is valid but unspecified (16.4.6.15).} \]

\[ (2.2.2) \quad \text{Otherwise, the object referred to by f() is not modified by either above expression.} \]

18.4.5 Concept common_reference_with

For two types \( T \) and \( U \), if \( \text{common_reference_t<T, U>} \) is well-formed and denotes a type \( C \) such that both \( \text{convertible_to<T, C>} \) and \( \text{convertible_to<U, C>} \) are modeled, then \( T \) and \( U \) share a common reference type, \( C \).

[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]

\[
\text{template<class T, class U>}
\]
\[
\text{concept common_reference_with =}
\]
\[
same_as<common_reference_t<T, U>, common_reference_t<U, T>> \&\&
\]
\[
\text{convertible_to<T, common_reference_t<T, U>>} \&\&
\]
\[
\text{convertible_to<U, common_reference_t<T, U>>};
\]

2

Let \( C \) be \( \text{common_reference_t<T, U>} \). Let \( t1 \) and \( t2 \) be equality-preserving expressions (18.2) such that \( \text{decltype}((t1)) \) and \( \text{decltype}((t2)) \) are each \( T \), and let \( u1 \) and \( u2 \) be equality-preserving expressions such that \( \text{decltype}((u1)) \) and \( \text{decltype}((u2)) \) are each \( U \). \( T \) and \( U \) model \( \text{common_reference_with<T, U>} \) only if:

\[ (2.1) \quad \text{C(t1) equals C(t2) if and only if t1 equals t2, and} \]

\[ (2.2) \quad \text{C(u1) equals C(u2) if and only if u1 equals u2.} \]

[Note 2: Users can customize the behavior of \( \text{common_reference_with} \) by specializing the \( \text{basic_common_reference} \) 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, \( C \).

[Note 1: \( C \) can be the same as \( T \) or \( U \), or can be a different type. \( C \) is not necessarily unique. — end note]

\[
\text{template<class T, class U>}
\]
\[
\text{concept common_with =}
\]
\[
same_as<common_type_t<T, U>, common_type_t<U, T>> \&\&
\]
\[
\text{requires}
\]
\[
\text{static_cast<common_type_t<T, U>>(declval<T>())};
\]
\[
\text{static_cast<common_type_t<T, U>>(declval<U>())};
\]

§ 18.4.6
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 $t_1$ and $t_2$ be equality-preserving expressions (18.2) such that
decltype((t1)) and decltype((t2)) are each $T$, and let $u_1$ and $u_2$ 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 $t_1$ equals $t_2$, and
(2.2) $C(u1)$ equals $C(u2)$ if and only if $u_1$ equals $u_2$.

[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 \( \text{common_reference_with}\langle \text{decltype}\langle t_1 \rangle, \text{decltype}\langle u_1 \rangle \rangle \) 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 \( \text{common_reference_t}\langle \text{decltype}\langle t_1 \rangle, \text{decltype}\langle u_1 \rangle \rangle \).

The name \texttt{ranges::swap} denotes a customization point object (16.3.3.3.6). The expression \texttt{ranges::swap(E1, E2)} for subexpressions \( E_1 \) and \( E_2 \) is expression-equivalent to an expression \( S \) determined as follows:

1. \( S \) is \texttt{(void)swap(E1, E2)} \(^{208}\) if \( E_1 \) or \( E_2 \) has class or enumeration type (6.8.3) 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 \texttt{ranges::swap}. If the function selected by overload resolution does not exchange the values denoted by \( E_1 \) and \( E_2 \), the program is ill-formed, no diagnostic required.

2. Otherwise, if \( E_1 \) and \( E_2 \) are lvalues of array types (6.8.3) with equal extent and \texttt{ranges::swap(*E1, *E2)} is a valid expression, \( S \) is \texttt{(void)ranges::swap_ranges(E1, E2)} except that \texttt{noexcept(S)} is equal to \texttt{is_nothrow_move_constructible_v<T> && is_nothrow_move_assignable_v<T>}. 

3. Otherwise, if \( E_1 \) and \( E_2 \) are lvalues of the same type \( T \) that models \texttt{move_constructible<T>} and \texttt{assignable_from<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 \( E_1 = \text{std::move}(E2) \) and \( E_2 = \text{std::move}(E1) \) are constant subexpressions (3.14), and
   3. the full-expressions of the initializers in the declarations

      ```cpp
      T t1(\text{std::move}(E1));
      T t2(\text{std::move}(E2));
      ```

      are constant subexpressions.

   \( \text{noexcept(S)} \) is equal to \texttt{is_nothrow_move_constructible_v<T> \&\& is_nothrow_move_assignable_v<T>}. 

4. Otherwise, \texttt{ranges::swap(E1, E2)} is ill-formed.

[Note 2: This case can result in substitution failure when \texttt{ranges::swap(E1, E2)} appears in the immediate context of a template instantiation. — end note]

[Note 3: Whenever \texttt{ranges::swap(E1, E2)} is a valid expression, it exchanges the values denoted by \( E_1 \) and \( E_2 \) and has type \texttt{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 =
   \text{common_reference_with}\langle T, U \rangle \&\&
   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));
   };
```

[Note 4: The semantics of the \texttt{swappable} and \texttt{swappable_with} concepts are fully defined by the \texttt{ranges::swap} customization point object. — end note]

\(^{208}\) The name \texttt{swap} is used here unqualified.
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]

18.4.10 Concept destructible [concept.destructible]

The `destructible` concept specifies properties of all types, instances of which can be destroyed at the end of their lifetime, or reference types.

```cpp
template<class T>
concept destructible = is_nothrow_destructible_v<T>;
```

[Note 1: Unlike the Cpp17Destructible requirements (Table 34), this concept forbids destructors that are potentially throwing, even if a particular invocation of the destructor does not actually throw. —end note]

18.4.11 Concept constructible_from [concept.constructible]

The `constructible_from` concept constrains the initialization of a variable of a given type with a particular set of argument types.

```cpp
template<class T, class... Args>
concept constructible_from = destructible<T> && is_constructible_v<T, Args...>;
```

18.4.12 Concept default_initializable [concept.default.init]

```cpp
template<class T>
inline constexpr bool is-default-initializable = see below; // exposition only
```

§ 18.4.12
For a type T, \( \text{is-default-initializable}\langle T \rangle \) 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

\[ \text{move_constructible}\langle T \rangle \]

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. After the definition T u = rv;, u is equal to u2.
2. \( T(rv) \) is equal to u2.
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

\[ \text{copy_constructible}\langle T \rangle \]

If T is an object type, then let v be an lvalue of type (possibly const) T or an rvalue of type const T.
T models copy_constructible only if

1. After the definition T u = v; , u is equal to v (18.2) and v is not modified.
2. \( T(v) \) is equal to v and does not modify v.

18.5 Comparison concepts

18.5.2 Boolean testability

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.

\[ \text{boolean-testable-impl}\langle T \rangle = \text{convertible_to}\langle T, \text{bool}\rangle; \]

Let e be an expression such that decltype((e)) is T. T models boolean-testable-impl only if:

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. 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

1. is not dependent on a template parameter, and there exists an implicit conversion sequence (12.2.4.2)
   from e to P; or
2. is dependent on one or more template parameters, and either
   1. P contains no template parameter that participates in template argument deduction (13.10.3.6), or
(3.2.2) template argument deduction using the rules for deducing template arguments in a function call (13.10.3.2) and e as the argument succeeds.

4 A key parameter of a function template D is a function parameter of type 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
namespace Z {
    template<class> struct C {};
    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::operator& & contains one key parameter, C<T> x, and the declaration of Z::operator|| contains no key parameters. —end example]

5 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 T1 and T2 that each model boolean-testable-impl, the && and || operators within the expressions declval<T1>() && declval<T2>() and declval<T1>() || declval<T2>() resolve to the corresponding built-in operators. —end note]

template<class T>
    concept boolean-testable =
        // exposition only
        boolean-testable-impl<T> & & requires(T& & t) {
            // std::forward<T>(t) -> boolean-testable-impl;
        }

7 Let e be an expression such that decltype((e)) is T. T models boolean-testable only if bool(e) == !bool(!e).

[Example 2: The types bool, true_type (21.3.3), int*, and bitset<N>::reference (22.9.2) model boolean-testable. —end example]

18.5.3 Concept equality_comparable [concept.equalitycomparable]

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
(1.1) t == u, u == t, t != u, and u != t have the same domain.
(1.2) bool(u == t) == bool(t == u).
(1.3) bool(t != u) == !bool(t == u).
(1.4) bool(u != t) == bool(t != u).
2 template<class T>
   concept equality_comparable = weakly-equality-comparable-with<T, T>;

   Let a and b be objects of type T. T models equality_comparable only if \( \text{bool}(a == b) \) is true when a is equal to b (18.2), and false otherwise.

   \[ \text{Note 1: The requirement that the expression } a == b \text{ is equality-preserving implies that } == \text{ is transitive and symmetric. } \] — end note

3 template<class T, class U>
   concept equality_comparable_with =
   equality_comparable<T> && equality_comparable<U> &&
   common_reference_with<const remove_reference_t<T>&, const remove_reference_t<U>&> &&
   equality_comparable<
   common_reference_t<
   const remove_reference_t<T>&, constellation remove_reference_t<U>&>
   && weakly-equality-comparable-with<T, U>;

4 template<class T, class U>
   concept equality_comparable_with =
   equality_comparable<T> && equality_comparable<U> &&
   common_reference_with<const remove_reference_t<T>&, const remove_reference_t<U>&> &&
   equality_comparable<
   common_reference_t<
   const remove_reference_t<T>&, const remove_reference_t<U>&>
   && weakly-equality-comparable-with<T, U>;

4 Given types T and U, let t be an lvalue of type const remove_reference_t<T>, u be an lvalue of type const remove_reference_t<U>, and C be:

   common_reference_t<const remove_reference_t<T>&, const remove_reference_t<U>&>

   T and U model equality_comparable_with<T, U> only if \( \text{bool}(t == u) == \text{bool}(C(t) == C(u)) \).

18.5.4 Concept totally_ordered [concept.totallyordered]

1 template<class T>
   concept totally_ordered =
   equality_comparable<T> && partially-ordered-with<T, T>;

1 Given a type T, let a, b, and c be lvalues of type const remove_reference_t<T>. T models totally_ordered only if

   \( \text{(1.1)} \) — Exactly one of \( \text{bool}(a < b) \), \( \text{bool}(a > b) \), or \( \text{bool}(a == b) \) is true.

   \( \text{(1.2)} \) — If \( \text{bool}(a < b) \) and \( \text{bool}(b < c) \), then \( \text{bool}(a < c) \).

   \( \text{(1.3)} \) — \( \text{bool}(a <= b) == !\text{bool}(b < a) \).

   \( \text{(1.4)} \) — \( \text{bool}(a >= b) == !\text{bool}(a < b) \).

2 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 be an lvalue of type const remove_reference_t<T>, u be an lvalue of type const remove_reference_t<U>, and C be:

   common_reference_t<const remove_reference_t<T>&, const remove_reference_t<U>&>

   T and U model totally_ordered_with<T, U> only if

   \( \text{(2.1)} \) — \( \text{bool}(t < u) == \text{bool}(C(t) < C(u)) \).

   \( \text{(2.2)} \) — \( \text{bool}(t > u) == \text{bool}(C(t) > C(u)) \).

   \( \text{(2.3)} \) — \( \text{bool}(t <= u) == \text{bool}(C(t) <= C(u)) \).

   \( \text{(2.4)} \) — \( \text{bool}(t >= u) == \text{bool}(C(t) >= C(u)) \).

   \( \text{(2.5)} \) — \( \text{bool}(u < t) == \text{bool}(C(u) < C(t)) \).

   \( \text{(2.6)} \) — \( \text{bool}(u > t) == \text{bool}(C(u) > C(t)) \).

   \( \text{(2.7)} \) — \( \text{bool}(u <= t) == \text{bool}(C(u) <= C(t)) \).

   \( \text{(2.8)} \) — \( \text{bool}(u >= t) == \text{bool}(C(u) >= C(t)) \).

§ 18.5.4
18.6 Object concepts

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>;

template<class T>
concept copyable = copy_constructible<T> && movable<T> && assignable_from<T&, T> &&
                   assignable_from<T&, const T&> && assignable_from<T&, const T>;

template<class T>
concept semiregular = copyable<T> && default_initializable<T>;

template<class T>
concept regular = semiregular<T> && equality_comparable<T>;
```

18.7 Callable concepts

18.7.1 General

The concepts in subclause 18.7 describe the requirements on function objects (22.10) and their arguments.

18.7.2 Concept `invocable`

```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
};
```

18.7.3 Concept `regular_invocable`

```cpp
template<class F, class... Args>
concept regular_invocable = invocable<F, Args...>;
```

18.7.4 Concept `predicate`

```cpp
template<class F, class... Args>
concept predicate =
  regular_invocable<F, Args...> && boolean-testable<invoke_result_t<F, Args...>>;
```

18.7.5 Concept `relation`

```cpp
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

```cpp
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

```cpp
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:

1. `comp(a, b) && comp(b, c)` implies `comp(a, c)`
2. `equiv(a, b) && equiv(b, c)` implies `equiv(a, c)`

[Note 1: Under these conditions, it can be shown that

1. `equiv` is an equivalence relation,
2. `comp` induces a well-defined relation on the equivalence classes determined by `equiv`, and
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 41.

Table 41: Diagnostics library summary

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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.

2  The distinguishing characteristic of logic errors is that they are due to errors in the internal logic of the program. In theory, they are preventable.

3  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);
    };
}
```

1  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.
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);
    };
}

1 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);
    };
}

1 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);
    };
}

1 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`  

```cpp
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);
    };
}
```

The class `out_of_range` defines the type of objects thrown as exceptions to report an argument value not in its expected range.

```cpp
out_of_range(const string& what_arg);
```

Postconditions: `strcmp(what(), what_arg.c_str()) == 0`.

```cpp
out_of_range(const char* what_arg);
```

Postconditions: `strcmp(what(), what_arg) == 0`.

19.2.8 Class `runtime_error`  

```cpp
namespace std {
    class runtime_error : public exception {
    public:
        explicit runtime_error(const string& what_arg);
        explicit runtime_error(const char* what_arg);
    };
}
```

The class `runtime_error` defines the type of objects thrown as exceptions to report errors presumably detectable only when the program executes.

```cpp
runtime_error(const string& what_arg);
```

Postconditions: `strcmp(what(), what_arg.c_str()) == 0`.

```cpp
runtime_error(const char* what_arg);
```

Postconditions: `strcmp(what(), what_arg) == 0`.

19.2.9 Class `range_error`  

```cpp
namespace std {
    class range_error : public runtime_error {
    public:
        explicit range_error(const string& what_arg);
        explicit range_error(const char* what_arg);
    };
}
```

The class `range_error` defines the type of objects thrown as exceptions to report range errors in internal computations.

```cpp
range_error(const string& what_arg);
```

Postconditions: `strcmp(what(), what_arg.c_str()) == 0`.

```cpp
range_error(const char* what_arg);
```

Postconditions: `strcmp(what(), what_arg) == 0`.

19.2.10 Class `overflow_error`  

```cpp
namespace std {
    class overflow_error : public runtime_error {
    public:
        explicit overflow_error(const string& what_arg);
        explicit overflow_error(const char* what_arg);
    };
}
```

```
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` [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);
};
}
```

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 [assertions]

19.3.1 General [assertions.general]

The header `<cassert>` provides a macro for documenting C++ program assertions and a mechanism for disabling the assertion checks.

19.3.2 Header `<cassert>` synopsis [cassert.syn]

```cpp
#define assert(E) see below
```

The contents are the same as the C standard library header `<assert.h>`, except that a macro named `static_assert` is not defined.

**See also:** ISO C 7.2

19.3.3 The assert macro [assertions.assert]

An expression `assert(E)` is a constant subexpression (3.14), if

(1.1) — `NDEBUG` is defined at the point where `assert` is last defined or redefined, or

(1.2) — `E` contextually converted to `bool` (7.3) is a constant subexpression that evaluates to the value `true`.

19.4 Error numbers [errno]

19.4.1 General [errno.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:** The intent is to remain in close alignment with the POSIX standard. — end note

A separate `errno` value shall be provided for each thread.

19.4.2 Header `<cerrno>` synopsis [cerrno.syn]

```cpp
#define errno see below
```


#define E2BIG see below
#define EACCES see below
#define EADDRINUSE see below
#define EADDRNOTAVAIL see below
#define EAFNOSUPPORT see below
#define EAGAIN see below
#define EALREADY see below
#define EBADF see below
#define EBADMSG see below
#define EBUSY see below
#define ECANCELED see below
#define ECHILD see below
#define ECONNABORTED see below
#define ECONNREFUSED see below
#define ECONNRESET see below
#define EDEADLK see below
#define EDESTADDRREQ see below
#define EDOM see below
#define EEXIST see below
#define EFAULT see below
#define EFBIG see below
#define EHOSTUNREACH see below
#define EIDRM see below
#define EILSEQ see below
#define EINPROGRESS see below
#define EINTR see below
#define EINVAL see below
#define EIO see below
#define EISCONN see below
#define EISDIR see below
#define ELOOP see below
#define EMFILE see below
#define EMLINK see below
#define EMSGSIZE see below
#define ENAMETOOLONG see below
#define ENETDOWN see below
#define ENETRESET see below
#define ENETUNREACH see below
#define ENFILE see below
#define ENOBUFS see below
#define ENODATA see below
#define ENODEV see below
#define ENOENT see below
#define ENOEXEC see below
#define ENOLCK see below
#define ENOLINK see below
#define ENOMEM see below
#define ENOMSG see below
#define ENOPROTOOPT see below
#define ENOSPC see below
#define ENOSR see below
#define ENOSTR see below
#define ENOSYS see below
#define ENOTCONN see below
#define ENOTDIR see below
#define ENOTEMPTY see below
#define ENOTRECOVERABLE see below
#define ENOTSOCK see below
#define ENOTSUP see below
#define ENOTTY see below
#define ENXIO see below
#define EOPNOTSUPP see below
#define EOVERFLOW see below
#define EOWNERDEAD see below
The meaning of the macros in this header is defined by the POSIX standard.

See also: ISO C 7.5

19.5 System error support [syserr]

19.5.1 General [syserr.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 shall not change the value of errno (19.4). Implementations should leave the error states provided by other libraries unchanged.

19.5.2 Header <system_error> synopsis [system.error.syn]

```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, //EFAULT
        bad_file_descriptor, //EBADF
        bad_message, //EBADMSG
        broken_pipe, // EPIPE
        connection_aborted, // ECONNABORTED
        connection_already_in_progress, // EALREADY
        connection_refused, // ECONNREFUSED
        connection_reset, // ECONNRESET
        cross_device_link, // EXDEV
        destination_address_required, // EDESTADDRREQ
        device_or_resource_busy, // EBUSY
        directory_not_empty, // ENOTEMPTY
    }
```
executable_format_error, // ENOEXEC
file_exists, // EXIST
file_too_large, // EFBIG
filename-too-long, // ENAMETOOLONG
function_not_supported, // ENOSYS
host_unreachable, // EHOSTUNREACH
identifier_removed, // EIDRM
illegal_byte_sequence, // EILSEQ
inappropriate_io_control_operation, // ENOTTY
interrupted, // EINTR
invalid_argument, // EINVAL
invalid_seek, // ESPIPE
io_error, // EIO
is_a_directory, // EISDIR
message_size, // EMSGSIZE
network_down, // ENETDOWN
network_reset, // ENETRESET
network_unreachable, // ENETUNREACH
no_buffer_space, // ENOBUFS
no_child_process, // ECHILD
no_link, // ENOLINK
no_lock_available, // ENOLCK
no_message_available, // ENODATA
no_message, // ENOMSG
no_protocol_option, // ENOPROTOOPT
no_space_on_device, // ENOSPC
no_stream_resources, // ENOSR
no_such_device_or_address, // ENXIO
no_such_device, // ENODEV
no_such_file_or_directory, // ENOENT
no_such_process, // ENOTPD
not_a_directory, // ENOTDIR
not_a_socket, // ENOTSOCK
not_a_stream, // ENOTSTR
not_connected, // ENOTCONN
not_enough_memory, // ENOMEM
not_supported, // ENOTSUP
operation_cancelled, // ECANCELED
operation_in_progress, // EINPROGRESS
operation_not_permitted, // EPERM
operation_not_supported, // EOPNOTSUPP
operation_would_block, // EWOULDBLOCK
owner_dead, // EOWNERDEAD
permission_denied, // EACCES
protocol_error, // EPROTONOSUPPORT
read_only_file_system, // EROFS
resource_deadlock_would_occur, // EDEADLK
resource_unavailable_try_again, // EAGAIN
result_out_of_range, // ERANGE
state_not_recoverable, // ENOTRECOVERABLE
stream_timeout, // ETIME
text_file_busy, // ETXTBSY
timed_out, // ETIMEDOUT
too_many_files_open_in_system, // EMFILE
too_many_files_open, // EMFILE
too_many_links, // EMLINK
too_many_symbolic_link_levels, // ELINK
value-too-large, // EOVERFLOW
wrong_protocol_type, // EPROTOTYPE
};

template<> struct is_error_condition_enum<errc> : true_type {};

§ 19.5.2
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
template<class T>
inline constexpr bool is_error_code_enum_v = is_error_code_enum<T>::value;
template<class T>
inline constexpr bool is_error_condition_enum_v = is_error_condition_enum<T>::value;

1 The value of each enum errc constant shall be 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(error_category&) = delete;
error_category(error_category&&) = delete;
virtual const char* name() const noexcept = 0;
virtual error_condition default_error_condition(int ev) const noexcept;
virtual bool equivalent(int code, const error_condition& condition) const noexcept;
virtual bool equivalent(const error_code& code, int condition) const noexcept;
virtual string message(int ev) const noexcept;

bool operator==(const error_category& rhs) const noexcept;
strong_ordering operator<=>(const error_category& rhs) const noexcept;
};
const error_category& generic_category() noexcept;
const error_category& system_category() noexcept;
}

19.5.3.2 Virtual members

virtual const char* name() const noexcept = 0;

1 Returns: A string naming the error category.

virtual error_condition default_error_condition(int ev) const noexcept;

2 Returns: error_condition(ev, *this).

virtual bool equivalent(int code, const error_condition& condition) const noexcept;

3 Returns: default_error_condition(code) == condition.

virtual bool equivalent(const error_code& code, int condition) const noexcept;

4 Returns: *this == code.category() && code.value() == condition.

virtual string message(int ev) const = 0;

5 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;

1 Returns: this == &rhs.

strong_ordering operator<=>(const error_category& rhs) const noexcept;

2 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;

1 Returns: A string naming the error category.

virtual error_condition default_error_condition(int ev) const noexcept;

2 Returns: An object of type error_condition that corresponds to ev.

virtual bool equivalent(int code, const error_condition& condition) const noexcept;

3 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;

4 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;

1 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;

3 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.

§ 19.5.3.5
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` [syserr.errcode]

19.5.4.1 Overview [syserr.errcode.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]

```cpp
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);
    }
```

19.5.4.2 Constructors [syserr.errcode.constructors]

```cpp
error_code() noexcept;
```

1 Postconditions: `val_ == 0` and `cat_ == &system_category()`.

```cpp
error_code(int val, const error_category& cat) noexcept;
```

2 Postconditions: `val_ == val` and `cat_ == &cat`.

§ 19.5.2
template<class ErrorCodeEnum>
  error_code(ErrorCodeEnum e) noexcept;

  Constraints: is_error_code_enum_v<ErrorCodeEnum> is true.

  Postconditions: *this == make_error_code(e).

19.5.4.3 Modifiers [syserr.errcode.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.

  Postconditions: *this == make_error_code(e).

  Returns: *this.

void clear() noexcept;

  Postconditions: value() == 0 and category() == system_category().

19.5.4.4 Observers [syserr.errcode.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 [syserr.errcode.nonmembers]

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 [syserr.errcondition]

19.5.5.1 Overview [syserr.errcondition.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]
// 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;
  Postconditions: val_ == 0 and cat_ == &generic_category().
error_condition(int val, const error_category& cat) noexcept;
  Postconditions: val_ == val and cat_ == &cat.
template<class ErrorConditionEnum>
  error_condition(ErrorConditionEnum e) noexcept;
    Constraints: is_error_condition_enum_v<ErrorConditionEnum> is true.
  Postconditions: *this == make_error_condition(e).

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.
  Postconditions: *this == make_error_condition(e).
  Returns: *this.
void clear() noexcept;
  Postconditions: value() == 0 and category() == generic_category().

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;
1
    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;
1
    Returns:
    lhs.category() == rhs.category() && lhs.value() == rhs.value()

bool operator==(const error_code& lhs, const error_condition& rhs) noexcept;
2
    Returns:
    lhs.category().equivalent(lhs.value(), rhs) || rhs.category().equivalent(lhs, rhs.value())

bool operator==(const error_condition& lhs, const error_condition& rhs) noexcept;
3
    Returns:
    lhs.category() == rhs.category() && lhs.value() == rhs.value()

strong_ordering operator<=>(const error_code& lhs, const error_code& rhs) noexcept;
4
    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;
5
    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>;
1
    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);

Postconditions: code() == ec and
string_view(what()).find(what_arg.c_str()) != string_view::npos.

system_error(error_code ec, const char* what_arg);

Postconditions: code() == ec and string_view(what()).find(what_arg) != string_view::npos.

system_error(error_code ec);

Postconditions: code() == ec.

system_error(int ev, const error_category& ecat, const string& what_arg);

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);

Postconditions: code() == error_code(ev, ecat) and
string_view(what()).find(what_arg) != string_view::npos.

system_error(int ev, const error_category& ecat);

Postconditions: code() == error_code(ev, ecat).

const error_code& code() const noexcept;

Returns: ec or error_code(ev, ecat), from the constructor, as appropriate.

const char* what() const noexcept override;

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]
template<class Allocator>
string to_string(const basic_stacktrace<Allocator>& st);

template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const stacktrace_entry& f);

template<class charT, class traits, class Allocator>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const basic_stacktrace<Allocator>& st);

namespace pmr {
    using stacktrace = basic_stacktrace<polymorphic_allocator<stacktrace_entry>>;
}

// 19.6.4.7, 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;
    };
}

1 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
constexpr stacktrace_entry() noexcept;

Postconditions: *this is empty.
19.6.3.3 Observers

constexpr native_handle_type native_handle() const noexcept;
1 The semantics of this function are implementation-defined.
2 Remarks: Successive invocations of the native_handle function for an unchanged stacktrace_entry object return identical values.

constexpr explicit operator bool() const noexcept;
3 Returns: false if and only if *this is empty.

19.6.3.4 Query

string description() const;
2 Returns: A description of the evaluation represented by *this, or an empty string.
3 Throws: bad_alloc if memory for the internal data structures or the resulting string cannot be allocated.

string source_file() const;
4 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.
5 Throws: bad_alloc if memory for the internal data structures or the resulting string cannot be allocated.

uint_least32_t source_line() const;
6 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.
7 Throws: bad_alloc if memory for the internal data structures cannot be allocated.

19.6.3.5 Comparison

friend constexpr bool operator==(const stacktrace_entry& x, const stacktrace_entry& y) noexcept;
1 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

namespace std {
    template<class Allocator>
    class basic_stacktrace {
        public:
            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>;
            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;

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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(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

(1.1) — only move, assignment, swap, and operations defined for const-qualified sequence containers are
       supported and,

(1.2) — 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

---

1 This is a numbered note that explains the differences between the behavior of the basic_stacktrace class and a standard container. It highlights the limitations in terms of supported operations and comparison semantics.

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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]

```cpp
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.

```cpp
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.

```cpp
basic_stacktrace() noexcept(is_nothrow_default_constructible_v<allocator_type>);
```

Postconditions: empty() is true.

```cpp
explicit basic_stacktrace(const allocator_type& alloc) noexcept;
```

Effects: alloc is passed to the frames_ constructor.

Postconditions: empty() is true.

```cpp
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);
```

```cpp
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 Observes

```cpp
using const_iterator = implementation-defined;
```

1 The type models random_access_iterator (25.3.4.13) and meets the Cpp17RandomAccessIterator requirements (25.3.5.7).

```cpp
allocator_type get_allocator() const noexcept;
```

Returns: frames_.get_allocator().

```cpp
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().

```cpp
const_iterator end() const noexcept;
const_iterator cend() const noexcept;
```

Returns: The end iterator.

```cpp
const_reverse_iterator rbegin() const noexcept;
const_reverse_iterator crbegin() const noexcept;
```

Returns: reverse_iterator(cend()).
Returns:
reverse_iterator(cbegin()).
[[nodiscard]] bool empty() const noexcept;
Returns: frames_.empty().

Returns:
frames_.size().

Returns:
frames_.max_size().

Preconditions: frame_no < size() is true.
Returns: frames_[frame_no].
Throws: Nothing.

Returns:
frames_[frame_no].
Throws: out_of_range if frame_no >= size().

19.6.4.4 Comparisons

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()).
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.

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);
Effects: Exchanges the contents of *this and other.

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)));
Effects: Equivalent to a.swap(b).

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().
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]
template<class charT, class traits>
basic_ostream<charT, traits>&
    operator<<((basic_ostream<charT, traits>& os, const stacktrace_entry& f));
4
    Effects: Equivalent to: return os << to_string(f);

template<class charT, class traits, class Allocator>
basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const basic_stacktrace<Allocator>& st);
5
    Effects: Equivalent to: return os << to_string(st);

19.6.4.7 Hash support

[stacktrace.basic.hash]
template<> struct hash<stacktrace_entry>;
template<class Allocator> struct hash<basic_stacktrace<Allocator>>;

1 The specializations are enabled (22.10.19).
20 Memory management library [mem]

20.1 General [mem.general]

This Clause describes components for memory management.

The following subclauses describe general memory management facilities, smart pointers, memory resources, and scoped allocators, as summarized in Table 42.

Table 42: Memory management library summary [tab:mem.summary]

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20.2 Memory [memory]

20.2.1 In general [memory.general]

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]

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 (20.2.3–20.2.10 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).

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) — otherwise, `T::element_type*` if the qualified-id `T::element_type` is valid and denotes a type,
(2.3) — otherwise, `pointer_traits<T>::element_type*`.

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;
    template<class T> struct pointer_traits<T*>;

    // 20.2.4, pointer conversion
    template<class T>
        constexpr T* to_address(T* p) noexcept;
    template<class Ptr>
        constexpr auto to_address(const Ptr& p) noexcept;

    // 20.2.5, pointer alignment
    void* align(size_t alignment, size_t size, void*& ptr, size_t& space);
    template<size_t N, class T>
        [[nodiscard]] constexpr T* assume_aligned(T* ptr);
```

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// 20.2.6, allocator argument tag
struct allocator_arg_t { explicit allocator_arg_t() = default; };
inline constexpr allocator_arg_t allocator_arg{};

// 20.2.7, uses_allocator
template<class T, class Alloc> struct uses_allocator;

// 20.2.7.1, uses_allocator
template<class T, class Alloc>
inline constexpr bool uses_allocator_v = uses_allocator<T, Alloc>::value;

// 20.2.7.2, uses-allocator construction

// 20.2.8, allocator traits
template<class Alloc> struct allocator_traits;

// 20.2.9, the default allocator

// 20.2.10, addressof

template<class T>
    const T* addressof(const T&&) = delete;

    // 27.11, specialized algorithms
    // 27.11.2, special memory concepts

template<class I>
    concept nothrow-input-iterator = see below; // exposition only

template<class I>
    concept nothrow-forward-iterator = see below; // exposition only

template<class S, class I>
    concept nothrow-sentinel-for = see below; // exposition only


template<class R>
    concept nothrow-input-range = see below; // exposition only

template<class R>
    concept nothrow-forward-range = see below; // exposition only

template<class NoThrowForwardIterator>
    void uninitialized_default_construct(NoThrowForwardIterator first,
                                       NoThrowForwardIterator 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);

    template<class ExecutionPolicy, class NoThrowForwardIterator, class Size>
        NoThrowForwardIterator
            uninitialized_default_construct_n(ExecutionPolicy&& exec,
                                              NoThrowForwardIterator first, Size n);

    namespace ranges {
        template<nothrow-forward-iterator I, nothrow-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);

        template<nothrow-forward-iterator I>
            requires default_initializable<iter_value_t<I>>
                I uninitialized_default_construct_n(I first, iter_difference_t<I> n);
    }

    template<class NoThrowForwardIterator>
        void uninitialized_value_construct(NoThrowForwardIterator first,
                                           NoThrowForwardIterator last);

    template<class ExecutionPolicy, class NoThrowForwardIterator>
        void uninitialized_value_construct(ExecutionPolicy&& exec,
                                           NoThrowForwardIterator first,
                                           NoThrowForwardIterator last);

    template<class NoThrowForwardIterator, class Size>
        NoThrowForwardIterator
            uninitialized_value_construct_n(NoThrowForwardIterator first, Size n);

    template<class ExecutionPolicy, class NoThrowForwardIterator, class Size>
        NoThrowForwardIterator
            uninitialized_value_construct_n(ExecutionPolicy&& exec,
                                              NoThrowForwardIterator first, Size n);

    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);

template<nothrow-forward-iterator I>
    requires default_initializable<iter_value_t<I>>
    I uninitialized_value_construct_n(I first, iter_difference_t<I> n);

namespace ranges {

    template<class I, class O>
    using uninitialized_copy_result = in_out_result<I, O>;

    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);

    template<class I, class O>
        using uninitialized_copy_n_result = in_out_result<I, O>;

    template<input_iterator I, nothrow-forward-iterator 0, nothrow-sentinel_for<O> S>
        requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
        uninitialized_copy_n_result<I, O>
        uninitialized_copy_n(I ifirst, iter_difference_t<I> n, 0 ofirst, S olast);

    template<class I, class O>
        using uninitialized_move_result = in_out_result<I, O>;

    template<input_iterator I, nothrow-forward-iterator 0, nothrow-sentinel_for<O> S>
        requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
        uninitialized_move_result<I, O>
        uninitialized_move(I ifirst, S1 ilast, O ofirst, S2 olast);

    template<class I, class O>
        using uninitialized_move_n_result = pair<input_iterator, NoThrowForwardIterator>;

    template<input_iterator I, nothrow-forward-iterator 0, nothrow-sentinel_for<O> S>
        requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
        uninitialized_move_n_result<I, O>
        uninitialized_move_n(I ifirst, iter_difference_t<I> n, 0 ofirst, S olast);

    template<class InputIterator, class NoThrowForwardIterator>
        NoThrowForwardIterator uninitialized_copy(InputIterator first, InputIterator last,
                                                   NoThrowForwardIterator result);

    template<class ExecutionPolicy, class ForwardIterator, class NoThrowForwardIterator>
        NoThrowForwardIterator uninitialized_copy(ExecutionPolicy&& exec, // see 27.3.5
                                                   ForwardIterator first, ForwardIterator last,
                                                   NoThrowForwardIterator result);

    template<class InputIterator, class Size, class NoThrowForwardIterator>
        NoThrowForwardIterator uninitialized_copy_n(InputIterator first, Size n,
                                                   NoThrowForwardIterator result);

    template<class ExecutionPolicy, class ForwardIterator, class Size,
             class NoThrowForwardIterator>
        NoThrowForwardIterator uninitialized_copy_n(ExecutionPolicy&& exec, // see 27.3.5
                                                   ForwardIterator first, Size n,
                                                   NoThrowForwardIterator result);

    template<class InputIterator, class NoThrowForwardIterator>
        NoThrowForwardIterator uninitialized_move(InputIterator first, InputIterator last,
                                                 NoThrowForwardIterator result);

    template<class ExecutionPolicy, class ForwardIterator, class NoThrowForwardIterator>
        NoThrowForwardIterator uninitialized_move(ExecutionPolicy&& exec, // see 27.3.5
                                                   ForwardIterator first, ForwardIterator last,
                                                   NoThrowForwardIterator result);

    template<class InputIterator, class Size, class NoThrowForwardIterator>
        pair<InputIterator, NoThrowForwardIterator>
        uninitialized_move_n(InputIterator first, Size n, NoThrowForwardIterator result);

    template<class ExecutionPolicy, class ForwardIterator, class Size,
             class NoThrowForwardIterator>
        pair<ForwardIterator, NoThrowForwardIterator>
        uninitialized_move_n(ExecutionPolicy&& exec, // see 27.3.5
                             ForwardIterator first, Size n, NoThrowForwardIterator result);

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namespace ranges {
    template<class I, class O>
    using uninitialized_move_result = in_out_result<I, O>;
    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_rvalue_reference_t<I>>
    uninitialized_move_result<I, O>
    uninitialized_move(I ifirst, S1 ilast, O ofirst, S2 olast);
    template<input_range IR, nothrow-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);
}

namespace ranges {
    template<class I, class O>
    using uninitialized_move_n_result = in_out_result<I, O>;
    template<input_iterator I, nothrow-forward_iterator O, nothrow-sentinel_for<O> S>
    requires constructible_from<iter_value_t<O>, iter_rvalue_reference_t<I>>
    uninitialized_move_n_result<I, O>
    uninitialized_move_n(I ifirst, iter_difference_t<I> n, O ofirst, S olast);
}

namespace ranges {
    template<class NoThrowForwardIterator, class T>
    void uninitialized_fill(NoThrowForwardIterator first, NoThrowForwardIterator last, const T& x);
    template<class ExecutionPolicy, class NoThrowForwardIterator, class T>
    void uninitialized_fill(ExecutionPolicy&& exec, NoThrowForwardIterator first, NoThrowForwardIterator last, const T& x);
    template<class NoThrowForwardIterator, class Size, class T>
    NoThrowForwardIterator
    uninitialized_fill_n(NoThrowForwardIterator first, Size n, const T& x);
    template<class ExecutionPolicy, class NoThrowForwardIterator, class Size, class T>
    NoThrowForwardIterator
    uninitialized_fill_n(ExecutionPolicy&& exec, NoThrowForwardIterator first, Size n, const T& x);
}

namespace ranges {
    template<nothrow-forward_iterator I, nothrow-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);
    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);
    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);
}

// 27.11.8, construct_at
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);
}

// 27.11.9, destroy
template<class T>
constexpr void destroy_at(T* location);
template<class NoThrowForwardIterator>
constexpr void destroy(NoThrowForwardIterator first, NoThrowForwardIterator last);
template<class ExecutionPolicy, class NoThrowForwardIterator>
void destroy(ExecutionPolicy&& exec, // see 27.3.5
NoThrowForwardIterator first, NoThrowForwardIterator last);

template<class NoThrowForwardIterator, class Size>
constexpr NoThrowForwardIterator destroy_n(NoThrowForwardIterator first, Size n);

namespace ranges {
    template<destructible T>
    constexpr void destroy_at(T* location) noexcept;

    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;

    template<nothrow-input-iterator I>
    requires destructible<iter_value_t<I>>
    constexpr I destroy_n(I first, iter_difference_t<I> n) noexcept;
}

// 20.3.1, class template unique_ptr
template<class T> struct default_delete;
template<class T> struct default_delete<T[]>;
template<class T, class D = default_delete<T>> class unique_ptr;
template<class T, class D> class unique_ptr<T[], D>;

template<class T, class... Args> // T is not array
constexpr unique_ptr<T> make_unique(Args&&... args);
template<class T> // T is U[]
constexpr unique_ptr<T> make_unique(size_t n);
template<class T, class... Args> // T is U[N]
unspecified make_unique(Args&&... ) = delete;

template<class T> // T is not array
constexpr unique_ptr<T> make_unique_for_overwrite();
template<class T> // T is U[]
constexpr unique_ptr<T> make_unique_for_overwrite(size_t n);
template<class T, class... Args> // T is U[N]
unspecified make_unique_for_overwrite(Args&&... ) = delete;

template<class T, class D> // T is not array
constexpr void swap(unique_ptr<T, D>& x, unique_ptr<T, D>& y) noexcept;
template<class T1, class D1, class T2, class D2> // T is U[]
constexpr bool operator==(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);
template<class T1, class D1, class T2, class D2> // T is U[N]
bool operator<(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);

requires three_way_comparable_with<typename unique_ptr<T1, D1>::pointer,
type_name unique_ptr<T2, D2>::pointer>
operator<=>(const unique_ptr<T1, D1>& x, const unique_ptr<T2, D2>& y);
template<class T, class D>
constexpr bool operator==(const unique_ptr<T, D>& x, nullptr_t) noexcept;

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>& y);

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>& y);

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>& y);

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>& y);

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);

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);

// 20.3.2.1, class bad_weak_ptr
class bad_weak_ptr;

// 20.3.2.2, class template shared_ptr
template<class 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[]

template<class T, class A>
shared_ptr<T> allocate_shared(const A& a, size_t N); // T is U[]

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[]

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[]

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[]

template<class T, class A>
shared_ptr<T> allocate_shared_for_overwrite(const A& a); // T is not U[]
template<class T>
  shared_ptr<T> make_shared_for_overwrite(size_t N); // T is U[]

template<class T, class A>
  shared_ptr<T> allocate_shared_for_overwrite(const A& a, size_t N); // T is U[]

// 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;

// 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, class template enable_shared_from_this
template<class T> class enable_shared_from_this;

// 20.3.3, hash support
template<class T> struct hash;

template<class T, class D> struct hash<unique_ptr<T, D>>;

template<class T> struct hash<shared_ptr<T>>;

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// 33.5.8.7, atomic smart pointers
template<class T> struct atomic;
template<class T> struct atomic<shared_ptr<T>>;
template<class T> struct atomic<weak_ptr<T>>;

// 20.3.4.1, class template out_ptr_t
template<class Smart, class Pointer, class... Args>
class out_ptr_t;

// 20.3.4.2, function template out_ptr
template<class Pointer = void, class Smart, class... Args>
auto out_ptr(Smart& s, Args&&... args);

// 20.3.4.3, class template inout_ptr_t
template<class Smart, class Pointer, class... Args>
class inout_ptr_t;

// 20.3.4.4, function template inout_ptr
template<class Pointer = void, class Smart, class... Args>
auto inout_ptr(Smart& s, Args&&... args);

20.2.3 Pointer traits [pointer.traits]
20.2.3.1 General [pointer.traits.general]

1 The class template pointer_traits supplies a uniform interface to certain attributes of pointer-like types.

namespace std {
  template<class Ptr> struct pointer_traits {
    using pointer = Ptr;
    using element_type = see below;
    using difference_type = see below;
    template<class U> using rebind = see below;

    static pointer pointer_to(see below r);
  };

  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(see below r) noexcept;
  };
}

20.2.3.2 Member types [pointer.traits.types]

using element_type = see below;

1 Type: Ptr::element_type if the qualified-id Ptr::element_type is valid and denotes a type (13.10.3); otherwise, T if Ptr is a class template instantiation of the form SomePointer<T, Args>, where Args is zero or more type arguments; otherwise, the specialization is ill-formed.

using difference_type = see below;

2 Type: Ptr::difference_type if the qualified-id Ptr::difference_type is valid and denotes a type (13.10.3); otherwise, ptrdiff_t.

template<class U> using rebind = see below;

3 Alias template: Ptr::rebind<U> if the qualified-id Ptr::rebind<U> is valid and denotes a type (13.10.3); otherwise, 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

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

Specializations of pointer_traits may define the member declared in this subclause to customize the
behavior of the standard library.

static element_type* to_address(pointer p) noexcept;

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

template<class T> constexpr T* to_address(T* p) noexcept;

Mandates: T is not a function type.

template<class Ptr> constexpr auto to_address(const Ptr& p) noexcept;

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

void* align(size_t alignment, size_t size, void*& ptr, size_t& space);

Preconditions:

(1.1) alignment is a power of two
(1.2) ptr represents the address of contiguous storage of at least space bytes

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.

Returns: A null pointer if the requested aligned buffer would not fit into the available space, otherwise
the adjusted value of ptr.

[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]

template<size_t N, class T>
[[nodiscard]] constexpr T* assume_aligned(T* ptr);

Mandates: N is a power of two.

Preconditions: ptr points to an object X of a type similar (7.3.6) to T, where X has alignment N (6.7.6).

Returns: ptr.

Throws: Nothing.

[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 Allocator argument tag

```cpp
namespace std {
    struct allocator_arg_t { explicit allocator_arg_t() = default; 
    inline constexpr allocator_arg_t allocator_arg{};
}
```

The `allocator_arg_t` struct is an empty class type used as a unique type to disambiguate constructor and function overloading. Specifically, several types (see `tuple` 22.4) have constructors with `allocator_arg_t` as the first argument, immediately followed by an argument of a type that meets the `Cpp17Allocator` requirements (16.4.4.6.1).

20.2.7 uses_allocator

20.2.7.1 uses_allocator trait

```cpp
template<class T, class Alloc> struct uses_allocator;
```

Remarks: Automatically detects whether `T` has a nested `allocator_type` that is convertible from `Alloc`. Meets the `Cpp17BinaryTypeTrait` requirements (21.3.2). The implementation shall provide a definition that is derived from `true_type` if the qualified-id `T::allocator_type` is valid and denotes a type (13.10.3) and `is_convertible_v<Alloc, T::allocator_type>` != false, otherwise it shall be derived from `false_type`. A program may specialize this template to derive from `true_type` for a program-defined type `T` that does not have a nested `allocator_type` but nonetheless can be constructed with an allocator where either:

1. the first argument of a constructor has type `allocator_arg_t` and the second argument has type `Alloc` or
2. the last argument of a constructor has type `Alloc`.

20.2.7.2 Uses-allocator construction

```cpp
template<class T, class Alloc, class... Args>
constexpr auto uses_allocator_construction_args(const Alloc& alloc, 
Args&&... args) noexcept;
```

Constraints: `T` is not a specialization of `pair`.

Returns: A tuple value determined as follows:

1. If `uses_allocator_v<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<T, Alloc>` is true and `is_constructible_v<T, allocator_arg_t, const Alloc&, Args...>` is true, return

[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]
Otherwise, if `uses_allocator_v<T, Alloc>` is true and `is_constructible_v<T, Args..., const Alloc&>` is true, return `forward_as_tuple(std::forward<Args>(args)..., alloc)`. 

— 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]
const pair<U, V>&& pr) noexcept;

Constraints: T is a specialization of pair.

Effects: Equivalent to:

return uses_allocator_construction_args<T>(alloc, piecewise_construct,
    forward_as_tuple(get<0>(std::move(pr))),
    forward_as_tuple(get<1>(std::move(pr))));

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:

template<class A, class B>
void FUN(const pair<A, B>&);

Constraints: T is a specialization of pair, and the expression FUN(u) is not well-formed when considered
as an unevaluated operand.

Let pair-constructor be an exposition-only class defined as follows:

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);        // exposition only
    }

    constexpr auto do-construct(pair-type&& p) const {
        return make_obj_using_allocator<pair-type>(alloc_, std::move(p));        // exposition only
    }

    const Alloc& alloc_;    // exposition only
    U& u_;                   // exposition only

public:
    constexpr operator pair-type() const {
        return do-construct(std::forward<U>(u_));
    }
};

Returns: make_tuple(pc), where pc is a pair-constructor object whose alloc_member is initialized
with alloc and whose u_member is initialized with u.

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)...));

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)...));

20.2.8 Allocator traits

20.2.8.1 General

The class template allocator_traits supplies a uniform interface to all allocator types. An allocator cannot
be a non-class type, however, even if allocator_traits supplies the entire required interface.

[Note 1: Thus, it is always possible to create a derived class from an allocator. — end note]

namespace std {
    template<class Alloc> struct allocator_traits {
        using allocator_type = Alloc;

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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;

using rebind_alloc = see below;
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);

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);

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);
}  

## 20.2.8.2 Member types

**Note:** The following sections describe the member types of the allocator_traits template class.

1. **Type:** Alloc::pointer if the qualified-id Alloc::pointer is valid and denotes a type (13.10.3); otherwise, value_type*.

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>.

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>.

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>.

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>::difference_type.

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;

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;

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.

20.2.8.3 Static member functions

[[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).

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.

20.2.8.4 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.

template<class Allocator>
[[nodiscard]] constexpr allocation_result<typename allocator_traits<Allocator>::pointer> allocate_at_least(Allocator& a, size_t n);

Returns: a.allocate_at_least(n) if that expression is well-formed; otherwise, {a.allocate(n), n}. 

§ 20.2.8.4
20.2.9 The default allocator

20.2.9.1 General

All specializations of the default allocator meet the allocator completeness requirements (16.4.4.6.2).

```cpp
namespace std {
    template<class T> class allocator {
        public:
            using value_type = T;
            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);
    };
}
```

allocator_traits<allocator<T>>::is_always_equal::value is true for any T.

20.2.9.2 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.

```cpp
[[nodiscard]] constexpr T* allocate(size_t n);
```

Mandates: T is not an incomplete type (6.8.1).

Returns: A pointer to the initial element of an array of n T.

Throws: bad_array_new_length if numeric_limits<size_t>::max() / sizeof(T) < n, or bad_alloc if the storage cannot be obtained.

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.

```cpp
[[nodiscard]] constexpr allocation_result<T*> allocate_at_least(size_t n);
```

Mandates: T is not an incomplete type (6.8.1).

Returns: allocation_result<T*>(ptr, count), where ptr is a pointer to the initial element of an array of count T and count ≥ n.

Throws: bad_array_new_length if numeric_limits<size_t>::max() / sizeof(T) < n, or bad_alloc if the storage cannot be obtained.

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.

```cpp
constexpr void deallocate(T* p, size_t n);
```

Preconditions:

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.
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.

### 20.2.9.3 Operators

```cpp
template<class T, class U>
constexpr bool operator==(const allocator<T>&, const allocator<U>&) noexcept;
```

**Returns:** true.

### 20.2.10 `addressof`

```cpp
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.

### 20.2.11 C library memory allocation

See also: ISO C 7.22.3

1  **[note 1]:** The header `<cstdlib>` (17.2.2) declares the functions described in this subclause. —end note

```cpp
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.

```cpp
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()`.

### 20.3 Smart pointers

### 20.3.1 Unique-ownership pointers

**[note 1]:** The types 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

### 20.3.1.1 General

**[unique.ptr] [smartptr] [unique.ptr.general] [cpp17moveconstructible] [cpp17moveassignable] [cpp17copyconstructible] [cpp17copyassignable]

1  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`.

2  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).

3  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.

4  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 `Cpp17MoveAssignable`, but is not `Cpp17CopyConstructible` nor `Cpp17CopyAssignable`. The template parameter `T` of `unique_ptr` may be an incomplete type.

5  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 In general

1 The class template `default_delete` serves as the default deleter (destruction policy) for the class template `unique_ptr`.

2 The template parameter `T` of `default_delete` may be an incomplete type.

20.3.1.2.2 `default_delete`

```cpp
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;
    };
}
```

```cpp
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.

```cpp
constexpr void operator()(T* ptr) const;
```

3 Mandates: `T` is a complete type.

4 Effects: Calls `delete` on `ptr`.

20.3.1.2.3 `default_delete<T[]>`

```cpp
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;
    };
}
```

```cpp
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.

```cpp
template<class U> constexpr void operator()(U* ptr) const;
```

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

```cpp
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(type_identity_t<pointer> p, see below d1) noexcept;
            constexpr unique_ptr(type_identity_t<pointer> p, see below d2) noexcept;
            constexpr unique_ptr(unique_ptr&& u) noexcept;
            constexpr unique_ptr(nullptr_t) noexcept;
    }
}
```

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template<class U, class E>
    constexpr unique_ptr(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(
        see below);
    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 34).

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 35).

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;

1 Constraints: is_pointer_v<deleter_type> is false and is_default_constructible_v<deleter_type> is true.

2 Preconditions: D meets the Cpp17DefaultConstructible requirements (Table 29), and that construction does not throw an exception.

3 Effects: Constructs a unique_ptr object that owns nothing, value-initializing the stored pointer and the stored deleter.

4 Postconditions: get() == nullptr. get_deleter() returns a reference to the stored deleter.

    constexpr explicit unique_ptr(type_identity_t<pointer> p) noexcept;

5 Constraints: is_pointer_v<deleter_type> is false and is_default_constructible_v<deleter_type> is true.
Preconditions: D meets the Cpp17DefaultConstructible requirements (Table 29), 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:
D d;
unique_ptr<int, D> p1(new int, D()); // D must be Cpp17MoveConstructible
unique_ptr<int, D> p2(new int, d); // D must be Cpp17CopyConstructible
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
— 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 30). 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.

template<class U, class E> constexpr unique_ptr(unique_ptr<U, E>&& u) noexcept;

Constraints:

(19.1) unique_ptr<U, E>::pointer is implicitly convertible to pointer.
(19.2) U is not an array type, and
(19.3) 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

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

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 32) 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.

template<class U, class E> constexpr unique_ptr& operator=(unique_ptr<U, E>&& u) noexcept;

Constraints:

— unique_ptr<U, E>::pointer is implicitly convertible to pointer, and
— U is not an array type, and
— 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.

constexpr unique_ptr& operator=(nullptr_t) noexcept;

Effects: As if by reset().

Postconditions: get() == nullptr.

Returns: *this.

20.3.1.3.5 Observers

constexpr add_lvalue_reference_t<T> operator*() const noexcept(noexcept(*declval<pointer>()));

Preconditions: get() != nullptr.

Returns: *get().

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]

constexpr pointer get() const noexcept;

Returns: The stored pointer.
constexpr deleter_type& get_deleter() noexcept;
constexpr const deleter_type& get_deleter() const noexcept;

Returns: A reference to the stored deleter.

constexpr explicit operator bool() const noexcept;

Returns: get() != nullptr.

20.3.1.3.6 Modifiers

constexpr pointer release() noexcept;

Postconditions: get() == nullptr.

Returns: The value get() had at the start of the call to release.

constexpr void reset(pointer p = pointer()) noexcept;

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

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

Remarks: The behavior is undefined if the evaluation of get_deleter()(old_p) throws an exception.

constexpr void swap(unique_ptr& u) noexcept;

Preconditions: get_deleter() is swappable (16.4.4.3) and does not throw an exception under swap.

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;
            template<class U, class E>
                constexpr unique_ptr(unique_ptr< U, E>&& u) noexcept;
            template<class U, class E>
                constexpr unique_ptr_unique_ptr< U, E>&& u) noexcept;
            template<class U, class E>
                constexpr unique_ptr_unique_ptr< U, E>&& u) noexcept;
            template<class U, class E>
                constexpr unique_ptr_unique_ptr< U, E>&& u) 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;

§ 20.3.1.4.1
constexpr const deleter_type& 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;

// disable copy from lvalue
unique_ptr(const unique_ptr&) = delete;
unique_ptr& operator=(const unique_ptr&) = delete;
};

1 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.

3 The template argument T shall be a complete type.

20.3.1.4.2 Constructors

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(*)(*)[].

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(*)(*)[].

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
— 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
[unique.ptr.runtime.asgn]

```
template<class U, class E> constexpr unique_ptr& operator=(unique_ptr<U, E>&& u) noexcept;
```

This operator behaves the same as in the primary template.

**Constraints:** Where \( \text{UP} \) is \( \text{unique_ptr}<U, E> \):

1. \( U \) is an array type, and
2. \( \text{pointer} \) is the same type as \( \text{element_type}* \), and
3. \( \text{UP}::\text{pointer} \) is the same type as \( \text{UP}::\text{element_type}* \), and
4. \( \text{UP}::\text{element_type(*)[]} \) is convertible to \( \text{element_type(*)[]} \), and
5. \( \text{is_assignable_v<D&, E&&>} \) is true.

[Note 1: This replaces the Constraints: specification of the primary template. — end note]

### 20.3.1.4.4 Observers
[unique.ptr.runtime.observers]

```
constexpr T& operator[](size_t i) const;
```

**Preconditions:** \( i < \) the number of elements in the array to which the stored pointer points.

**Returns:** \( \text{get()}[i] \).

### 20.3.1.4.5 Modifiers
[unique.ptr.runtime.modifiers]

```
constexpr void reset(nullptr_t p = nullptr) noexcept;
```

**Effects:** Equivalent to \( \text{reset} \left( \text{nullptr()} \right) \).

```
constexpr template<class U> void reset(U p) noexcept;
```

This function behaves the same as the \( \text{reset} \) member of the primary template.

**Constraints:**

1. \( U \) is the same type as \( \text{pointer} \), or
2. \( \text{pointer} \) is the same type as \( \text{element_type}* \), \( U \) is a pointer type \( V* \), and \( V(*)[] \) is convertible to \( \text{element_type(*)[]} \).

### 20.3.1.5 Creation
[unique.ptr.create]

```
template<class T, class... Args> constexpr unique_ptr<T> make_unique(Args&&... args);
```

**Constraints:** \( T \) is not an array type.

```
template<class T> constexpr unique_ptr<T> make_unique(size_t n);
```

**Constraints:** \( T \) is an array of unknown bound.

```
template<class T, class... Args> unspecified make_unique(Args&&... = delete;
```

**Constraints:** \( T \) is an array of known bound.

```
template<class T> constexpr unique_ptr<T> make_unique_for_overwrite();
```

**Constraints:** \( T \) is not an array type.

```
template<class T> constexpr unique_ptr<T> make_unique_for_overwrite(size_t n);
```

**Constraints:** \( T \) is an array of unknown bound.

```
template<class T> constexpr unique_ptr<T> make_unique_for_overwrite(size_t n);
```

**Constraints:** \( T \) is an array of unknown bound.
template<class T, class... Args> unspecified make_unique_for_overwrite(Args&&...) = delete;

20.3.1.6 Specialized algorithms

Constraints: T is an array of known bound.

template<class T, class D> constexpr void swap(unique_ptr<T, D>& x, unique_ptr<T, D>& y) noexcept;

Constraints: is_swappable_v<D> is true.

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:

— unique_ptr<T1, D1>::pointer is implicitly convertible to CT and
— 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: !(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: 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

\[
\text{less<unique_ptr<T, D>::pointer>()(nullptr, x.get())}
\]

\[\text{template<class T, class D>}
\text{constexpr bool operator>(const unique_ptr<T, D>& x, nullptr_t);}\]

\[\text{template<class T, class D>}
\text{constexpr bool operator>(nullptr_t, const unique_ptr<T, D>& x);}\]

\[\text{Returns: The first function template returns nullptr < x. The second function template returns x < nullptr.}\]

\[\text{template<class T, class D>}
\text{constexpr bool operator<=(const unique_ptr<T, D>& x, nullptr_t);}\]

\[\text{template<class T, class D>}
\text{constexpr bool operator<=(nullptr_t, const unique_ptr<T, D>& x);}\]

\[\text{Returns: The first function template returns !(nullptr < x). The second function template returns !(x < nullptr).}\]

\[\text{template<class T, class D>}
\text{requires three_way_comparable<typename unique_ptr<T, D>::pointer>}
\text{constexpr compare_three_way_result_t<typename unique_ptr<T, D>::pointer>}
\text{operator<=>(const unique_ptr<T, D>& x, nullptr_t);}\]

\[\text{Returns: compare_three_way(x.get(), static_cast<typename unique_ptr<T, D>::pointer>(nullptr)).}\]

20.3.1.7 I/O [unique.ptr.io]

\[\text{template<class E, class T, class Y, class D>}
\text{basic_ostream<E, T>& operator<<(basic_ostream<E, T>& os, const unique_ptr<Y, D>& p);}\]

\[\text{1 Constraints: os << p.get() is a valid expression.}\]

\[\text{2 Effects: Equivalent to: os << p.get();}\]

\[\text{3 Returns: os.}\]

20.3.2 Shared-ownership pointers [util.sharedptr]

20.3.2.1 Class bad_weak_ptr [util.smartptr.weak.bad]

\[\text{namepsace std {}
\text{class bad_weak_ptr : public exception {}
\text{public:
\text{// see 17.9.3 for the specification of the special member functions}
\text{const char* what() const noexcept override;}
\text{}};}
\text{}}\]

\[\text{1 An exception of type bad_weak_ptr is thrown by the shared_ptr constructor taking a weak_ptr.}\]

\[\text{const char* what() const noexcept override;}\]

\[\text{2 Returns: An implementation-defined ntbs.}\]

20.3.2.2 Class template shared_ptr [util.smartptr.shared]

20.3.2.2.1 General [util.smartptr.shared.general]

\[\text{1 The shared_ptr class template stores a pointer, usually obtained via new. shared_ptr implements semantics of shared ownership; the last remaining owner of the pointer is responsible for destroying the object, or}\]
otherwise releasing the resources associated with the stored pointer. A `shared_ptr` is said to be empty if it does not own a pointer.

```cpp
namespace std {
  template<class T> class shared_ptr {
    public:
      using element_type = remove_extent_t<T>;
      using weak_type = weak_ptr<T>;

      // 20.3.2.2.2, constructors
      constexpr shared_ptr() noexcept;
      constexpr shared_ptr(nullptr_t) noexcept : shared_ptr() { }
      template<class Y>
        explicit shared_ptr(Y* p);
      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);
      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;
      shared_ptr(const shared_ptr& r) noexcept;
      template<class Y>
        shared_ptr(const shared_ptr<Y>& r) noexcept;
      shared_ptr(shared_ptr&& r) noexcept;
      template<class Y>
        explicit shared_ptr(const weak_ptr<Y>& r);
      template<class Y, class D>
        shared_ptr(unique_ptr<Y, D>&& r);

      // 20.3.2.2.3, destructor
      ~shared_ptr();

      // 20.3.2.2.4, assignment
      shared_ptr& operator=(const shared_ptr& r) noexcept;
      template<class Y>
        shared_ptr& operator=(const shared_ptr<Y>& r) noexcept;
      shared_ptr& operator=(shared_ptr&& r) noexcept;
      template<class Y>
        shared_ptr& operator=(shared_ptr<Y>&& r) noexcept;
      template<class Y, class D>
        shared_ptr& operator=(unique_ptr<Y, D>&& r);

      // 20.3.2.2.5, modifiers
      void swap(shared_ptr& r) noexcept;
      void reset() noexcept;
      template<class Y>
        void reset(Y* p);
      template<class Y, class D>
        void reset(Y* p, D d);
      template<class Y, class D, class A>
        void reset(Y* p, D d, A a);

      // 20.3.2.2.6, observers
      element_type* get() const noexcept;
      T& operator*() const noexcept;
      T* operator->() const noexcept;
  }

  constexpr shared_ptr() noexcept;
  constexpr shared_ptr(nullptr_t) noexcept : shared_ptr() { }
  template<class Y>
    explicit shared_ptr(Y* p);
  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);
  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;
  shared_ptr(const shared_ptr& r) noexcept;
  template<class Y>
    shared_ptr(const shared_ptr<Y>& r) noexcept;
  shared_ptr(shared_ptr&& r) noexcept;
  template<class Y>
    explicit shared_ptr(const weak_ptr<Y>& r);
  template<class Y, class D>
    shared_ptr(unique_ptr<Y, D>&& r);

  // 20.3.2.2.1 604
```
element_type& operator[](ptrdiff_t i) const;
long use_count() const noexcept;
explicit operator bool() 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;
};

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>;

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.

The template parameter T of shared_ptr may be an incomplete type.

[Note 1: T can be a function type. — end note]

[Example 1:
  if (shared_ptr<X> px = dynamic_pointer_cast<X>(py)) {
    // do something with px
  }
  — end example]

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.

For the purposes of subclause 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]

In the constructor definitions below, enables shared_from_this with p, for a pointer p of type Y*, means that if Y has an unambiguous and accessible base class that is a specialization of enable_shared_from_this (20.3.2.5), 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<Type>>(*this, const_cast<remove_cv_t<Type>*>(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;

template<class Y> explicit shared_ptr(Y* p);

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*.

Mandates: Y is a complete type.

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.

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.

Postconditions: use_count() == 1 && get() == p.
Throws: bad_alloc, or an implementation-defined exception when a resource other than memory cannot be obtained.

```cpp
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 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 std::move(d) do not throw exceptions. The expression d(p) has well-defined behavior and does not throw exceptions. A meets the Cpp17Allocator requirements (16.4.4.6.1).

Effects: Constructs a 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 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, d(p) is called.

Postconditions: use_count() == 1 && get() == p.

Throws: bad_alloc, or an implementation-defined exception when a resource other than memory cannot be obtained.

```cpp
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 shared_ptr instance that stores p and shares ownership with the initial value of r.

Postconditions: get() == p. For the second overload, r is empty and r.get() == 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 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 shared_ptr object; otherwise, constructs a shared_ptr object that shares ownership with r.

Postconditions: get() == r.get() && use_count() == r.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 shared_ptr instance from r.

Postconditions: *this contains the old value of r. r is empty, and r.get() == nullptr.

```cpp
template<class Y> explicit shared_ptr(const weak_ptr<Y>& r);
```

Constraints: Y* is compatible with T*.

Effects: Constructs a 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: use_count() == r.use_count().

Throws: bad_weak_ptr when r.expired().
template<class Y, class D> shared_ptr(unique_ptr<Y, D>&& r);

Constraints: Y* is compatible with T* and unique_ptr<Y, D>::pointer is convertible to element_type*.

Effects: If r.get() == nullptr, equivalent to shared_ptr(). Otherwise, if D is not a reference type, equivalent to shared_ptr(r.release(), std::move(r.get_deleter())). Otherwise, equivalent to shared_ptr(r.release(), ref(r.get_deleter())). If an exception is thrown, the constructor has no effect.

20.3.2.2.3 Destructor

~shared_ptr();

Effects:
(1.1) If *this is empty or shares ownership with another shared_ptr instance (use_count() > 1), there are no side effects.
(1.2) Otherwise, if *this owns an object p and a deleter d, d(p) is called.
(1.3) Otherwise, *this owns a pointer p, and delete p is called.

[Note 1: Since the destruction of *this decreases the number of instances that share ownership with *this by one, after *this has been destroyed all shared_ptr instances that shared ownership with *this will report a use_count() that is one less than its previous value. — end note]

20.3.2.2.4 Assignment

shared_ptr& operator=(const shared_ptr& r) noexcept;
template<class Y> shared_ptr& operator=(const shared_ptr<Y>& r) noexcept;

Effects: Equivalent to shared_ptr(r).swap(*this).

Returns: *this.

[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:
shared_ptr<int> p(new int);
shared_ptr<void> q(p);
p = p;
q = p;
both assignments can be no-ops. — end note]

shared_ptr& operator=(shared_ptr&& r) noexcept;
template<class Y> shared_ptr& operator=(shared_ptr<Y>&& r) noexcept;

Effects: Equivalent to shared_ptr(std::move(r)).swap(*this).

Returns: *this.

template<class Y, class D> shared_ptr& operator=(unique_ptr<Y, D>&& r);

Effects: Equivalent to shared_ptr(std::move(r)).swap(*this).

Returns: *this.

20.3.2.2.5 Modifiers

void swap(shared_ptr& r) noexcept;

Effects: Exchanges the contents of *this and r.

void reset() noexcept;

Effects: Equivalent to shared_ptr().swap(*this).

template<class Y> void reset(Y* p);

Effects: Equivalent to shared_ptr(p).swap(*this).

template<class Y, class D> void reset(Y* p, D d);

Effects: Equivalent to shared_ptr(p, d).swap(*this).

§ 20.3.2.2.5
template<class Y, class D, class A> void reset(Y* p, D d, A a);

Effects: Equivalent to shared_ptr(p, d, a).swap(*this).

20.3.2.2.6 Observers

element_type* get() const noexcept;
Returns: The stored pointer.

T& operator*() const noexcept;
Preconditions: get() != 0.
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() != 0.
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() != 0 && 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 shared_ptr objects, *this included, that share ownership with *this, or 0 when *this is empty.

[Note 1: get() == nullptr does not imply a specific return value of use_count(). — end note]

[Note 2: weak_ptr<T>::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 shared_ptr have in any sense completed. — end note]

explicit operator bool() const noexcept;
Returns: get() != 0.

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

— x.owner_before(y) defines a strict weak ordering as defined in 27.8;
— under the equivalence relation defined by owner_before, !a.owner_before(b) && !b.owner_before(a), two shared_ptr or weak_ptr instances are equivalent if and only if they share ownership or are both empty.

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.
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);

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() != 0 && 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, l...)

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.

(7.9) — Array elements are initialized in ascending order of their addresses.

(7.10) — 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.
(7.11) — When a (sub)object of non-array type U that was initialized by \texttt{make\_shared} is to be destroyed, it is destroyed via the expression \(pv\rightarrow\text{U}()\) where \(pv\) points to that object of type U.

(7.12) — When a (sub)object of non-array type U that was initialized by \texttt{allocate\_shared} is to be destroyed, it is destroyed via the expression \texttt{allocator\_traits<A2>::destroy(a2, pv)} where \(pv\) points to that object of type remove\_cv\_t\langle U \rangle and a2 of type A2 is a rebound copy of the allocator a passed to \texttt{allocate\_shared} such that its \texttt{value\_type} is remove\_cv\_t\langle U \rangle.

[Note 2: These functions will typically allocate more memory than \texttt{sizeof(T)} to allow for internal bookkeeping structures such as reference counts. — end note]

\[
\begin{align*}
\text{template<class T, class... Args>}
& \quad \text{shared\_ptr<T> make\_shared(Args&&... args);} \quad \text{\texttt{\textbackslash// T is not array}} \\
\text{template<class T, class A, class... Args>}
& \quad \text{shared\_ptr<T> allocate\_shared(const A& a, Args&&... args);} \quad \text{\texttt{\textbackslash// T is not array}}
\end{align*}
\]

\texttt{Constraints: T is not an array type.}

\texttt{Returns: A shared\_ptr to an object of type T with an initial value T(forward<Args>(args)\ldots).

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:]
\[
\begin{align*}
\text{shared\_ptr<int> p = make\_shared<int>();} \quad \text{\texttt{\textbackslash// shared\_ptr to int()}} \\
\text{shared\_ptr<vector<int>> q = make\_shared<vector<int>>(16, 1);} \quad \text{\texttt{\textbackslash// shared\_ptr to vector of 16 elements with value 1}} \\
\text{— end example}
\end{align*}
\]

\[
\begin{align*}
\text{template<class T> shared\_ptr<T> make\_shared(size_t N);} \quad \text{\texttt{\textbackslash// T is U[]}} \\
\text{template<class T, class A>}
& \text{shared\_ptr<T> allocate\_shared(const A& a, size_t N);} \quad \text{\texttt{\textbackslash// T is U[]}}
\end{align*}
\]

\texttt{Constraints: T is of the form U[].}

\texttt{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:]
\[
\begin{align*}
\text{shared\_ptr<double[]> p = make\_shared<double[]>(1024);} \quad \text{\texttt{\textbackslash// shared\_ptr to a value\_initialized double[1024]}} \\
\text{shared\_ptr<double[]> q = make\_shared<double[]>[2][2](6);} \quad \text{\texttt{\textbackslash// shared\_ptr to a value\_initialized double[6][2][2]}} \\
\text{— end example}
\end{align*}
\]

\[
\begin{align*}
\text{template<class T>}
& \quad \text{shared\_ptr<T> make\_shared();} \quad \text{\texttt{\textbackslash// T is U[]}} \\
\text{template<class T, class A>}
& \quad \text{shared\_ptr<T> allocate\_shared(const A& a);} \quad \text{\texttt{\textbackslash// T is U[]}}
\end{align*}
\]

\texttt{Constraints: T is of the form U[].}

\texttt{Returns: A shared\_ptr to an object of type T with a default initial value.

[Example 3:]
\[
\begin{align*}
\text{shared\_ptr<double[1024]> p = make\_shared<double[1024]>();} \quad \text{\texttt{\textbackslash// shared\_ptr to a value\_initialized double[1024]}} \\
\text{shared\_ptr<double[6][2][2]> q = make\_shared<double[6][2][2]>();} \quad \text{\texttt{\textbackslash// shared\_ptr to a value\_initialized double[6][2][2]}} \\
\text{— end example}
\end{align*}
\]

\[
\begin{align*}
\text{template<class T>}
& \quad \text{shared\_ptr<T> make\_shared(size_t N, const remove\_extent\_t<T>& u);} \quad \text{\texttt{\textbackslash// T is U[]}} \\
\text{template<class T, class A>}
& \quad \text{shared\_ptr<T> allocate\_shared(const A& a, size_t N,}
\end{align*}
\]

\section*{§ 20.3.2.2.7}

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N4910
const remove_extent_t<T>& u); // T is U[]

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][2], 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(const remove_extent_t<T>& u); // T is U[N]

Constraints: T is of the form U[N].

Returns: A shared_ptr to an object of type T, where each array element of type remove_extent_t<T> has an initial value of u.

[Example 5:
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][2], 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);()
  // 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:
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
— end example]
20.3.2.2.8 Comparison

template<class T, class U>
bool operator==(const shared_ptr<T>& a, const shared_ptr<U>& b) noexcept;

Returns: a.get() == b.get.

template<class T>
bool operator==(const shared_ptr<T>& a, nullptr_t) noexcept;

Returns: !a.

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

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

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

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;

Mandates: The expression static_cast<T*>(static_cast<typename shared_ptr<T>::element_type*>(r.get())) is well-formed.

Returns:

shared_ptr<T>(R, 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.

Note 1: The seemingly equivalent expression shared_ptr<T>(static_cast<T*>(r.get())) will eventually result in undefined behavior, attempting to delete the same object twice. — end note

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;

Mandates: The expression dynamic_cast<T*>(static_cast<typename shared_ptr<T>::element_type*>(r.get())) is well-formed. The expression dynamic_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()) has well-defined behavior.

Returns:

(6.1) When 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.

(6.2) Otherwise, shared_ptr<T>().

Note 2: The seemingly equivalent expression shared_ptr<T>(dynamic_cast<T*>(r.get())) will eventually result in undefined behavior, attempting to delete the same object twice. — end note
§ 20.3.2.2.11 get_deleter

template<class D, class T>  
D* get_deleter(const shared_ptr<T>& p) noexcept;

Returns: If p owns a deleter d of type cv-unqualified D, returns addressof(d); otherwise returns nullptr. The returned pointer remains valid as long as there exists a shared_ptr instance that owns 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 weak_ptr instances that share ownership with p have been destroyed. — end note]

20.3.2.2.12 I/O

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: os << p.get();

Returns: os.

20.3.3 Class template weak_ptr

20.3.3.1 General

The weak_ptr class template stores a weak reference to an object that is already managed by a shared_ptr. To access the object, a weak_ptr can be converted to a shared_ptr using the member function lock.

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;
            template<class Y>
                weak_ptr(weak_ptr<Y>& r) noexcept;
            template<class Y>
                weak_ptr(const weak_ptr<Y>& r) noexcept;
            template<class Y>
                weak_ptr(weak_ptr<Y>&& r) noexcept;
        }  
    }  
}  

§ 20.3.2.3.1
template<class Y>
    weak_ptr(weak_ptr<Y>&& r) noexcept;

// 20.3.2.3.3, destructor
~weak_ptr();

// 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;
};

template<class T>
    weak_ptr(shared_ptr<T>) -> weak_ptr<T>;

2 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 [util.smartptr.weak.const]

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 [util.smartptr.weak.dest]

~weak_ptr();

1 Effects: Destroys this weak_ptr object but has no effect on the object its stored pointer points to.

20.3.2.3.4 Assignment [util.smartptr.weak.assign]

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;

1 Effects: Equivalent to weak_ptr(r).swap(*this).
2 Returns: *this.
3 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;
template<class Y> weak_ptr& operator=(weak_ptr<Y>&& r) noexcept;

4 Effects: Equivalent to weak_ptr(std::move(r)).swap(*this).
5 Returns: *this.

20.3.2.3.5 Modifiers [util.smartptr.weak.mod]

void swap(weak_ptr& r) noexcept;

1 Effects: Exchanges the contents of *this and r.

void reset() noexcept;

2 Effects: Equivalent to weak_ptr().swap(*this).

20.3.2.3.6 Observers [util.smartptr.weak.obs]

long use_count() const noexcept;

1 Returns: 0 if *this is empty; otherwise, the number of shared_ptr instances that share ownership with *this.

bool expired() const noexcept;

2 Returns: use_count() == 0.

shared_ptr<T> lock() const noexcept;

3 Returns: expired() ? shared_ptr<T>() : 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;

4 Returns: An unspecified value such that

— x.owner_before(y) defines a strict weak ordering as defined in 27.8;

— under the equivalence relation defined by owner_before, !(a.owner_before(b) && !b.owner_before(a)), two shared_ptr or weak_ptr instances are equivalent if and only if they share ownership or are both empty.

20.3.2.3.7 Specialized algorithms [util.smartptr.weak.spec]

template<class T>
void swap(weak_ptr<T>& a, weak_ptr<T>& b) noexcept;

1 Effects: Equivalent to a.swap(b).

20.3.2.4 Class template owner_less [util.smartptr.ownerless]

1 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
— operator() defines a strict weak ordering as defined in 27.8; 
— two shared_ptr or weak_ptr instances are equivalent under the equivalence relation defined by operator(), !operator()(a, b) && !operator()(b, a), if and only if they share ownership or are both empty.
 — end note]

20.3.2.5 Class template enable_shared_from_this

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.

[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_before(q) && !q.owner_before(p)); // 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();

    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;
    


§ 20.3.2.5
private:
    mutable weak_ptr<T> weak_this; // exposition only
};

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;

Effects: Value-initializes weak_this.

enable_shared_from_this<T>& operator=(const enable_shared_from_this<T>&) noexcept;

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;

Returns: shared_ptr<T>(weak_this).

weak_ptr<T> weak_from_this() noexcept;
weak_ptr<T const> weak_from_this() const noexcept;

Returns: weak_this.

### 20.3.3 Smart pointer hash support

[util.smartptr.hash]

template<class T, class D> struct hash<unique_ptr<T, D>>;

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>>;

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.

[Example 1:

```cpp
#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;
    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

```cpp
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
  };  // exposition only
}
```

3 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]

4 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.

5 Evaluations of the conversion functions on the same object may conflict (6.9.2.2).

```cpp
explicit out_ptr_t(Smart& smart, Args... args);
```

6 Effects: Initializes s with smart, a with std::forward<Args>(args)..., and value-initializes p.

[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]

```cpp
~out_ptr_t();
```

7 Let SP be POINTER_OF_OR(Smart, Pointer) (20.2.1).

8 Effects: Equivalent to:

9.1 if (p) {
  apply([&](auto&&... args) {
    s.reset(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
}

9.2 if the expression s.reset(static_cast<SP>(p), std::forward<Args>(args)...) is well-formed;

9.3 otherwise,

9.4 if (p) {
  apply([&](auto&&... args) {
    s = Smart(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
}

9.5 if is_constructible_v<Smart, SP, Args...> is true;

9.6 otherwise, the program is ill-formed.

```cpp
operator Pointer*() const noexcept;
```

10 Preconditions: operator void**() has not been called on *this.

11 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:

1. the initial value *v is equivalent to static_cast<void*>(p) and
2. any modification of *v that is not followed by a 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]

20.3.4.2 Function template out_ptr

template<class Pointer = void, class Smart, class... Args>
auto out_ptr(Smart& s, Args&&... args);

Let P be Pointer if is_void_v<Pointer> is false, otherwise POINTER_OF(Smart).

Returns: out_ptr_t<Smart, P, Args&&...>(s, std::forward<Args>(args)...)
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, 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]

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.

Evaluations of the conversion functions on the same object may conflict (6.9.2.2).

explicit inout_ptr_t(Smart& smart, Args... args);

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().

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]

~inout_ptr_t();

Let SP be POINTER_OF_OR(Smart, Pointer) (20.2.1).

Let release-statement be s.release(); if an implementation does not call s.release() in the constructor. Otherwise, it is empty.

Effects: Equivalent to:

(11.1) — if (p) {
    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,
    if (p) {
        apply([&](auto&&... args) {
            release-statement;
            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,
    if (p) {
        apply([&](auto&&... args) {
            release-statement;
            s = Smart(static_cast<SP>(p), std::forward<Args>(args)...); }, std::move(a));
        }
    if is_constructible_v<Smart, SP, Args...> is true;
(11.4) — 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:

\[(17.1) \text{the initial value } *v \text{ is equivalent to } \text{static}\_\text{cast}<\text{void*>}(p) \text{ and}\]

\[(17.2) \text{any modification of } *v \text{ that is not followed by subsequent modification of } *\text{this} \text{ affects the value of } p \text{ during the destruction of } *\text{this}, \text{ such that } \text{static}\_\text{cast}<\text{void*>}(p) == *v.\]

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

```
#include <cstddef>

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<class Tp = 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.

```
#include <cstddef>

namespace std::pmr {

class memory_resource {

    static constexpr size_t max_align = alignof(max_align_t);  // exposition only

} // namespace std::pmr
```
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

[mem.res.public]

~memory_resource();

Effects: Destroys this memory_resource.

[[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.

void deallocate(void* p, size_t bytes, size_t alignment = max_align);

Effects: Equivalent to do_deallocate(p, bytes, alignment).

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

[mem.res.private]

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.

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.

Throws: Nothing.

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 D, an implementation of this function can immediately return false if dynamic_cast<const D*>(other)
== nullptr. — end note]
20.4.2.4 Equality

```cpp
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

20.4.3.1 General

A specialization of class template `pmr::polymorphic_allocator` meets the `Cpp17Allocator` requirements (16.4.4.6.1). 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.

All specializations of class template `pmr::polymorphic_allocator` meet the allocator completeness requirements (16.4.4.6.2).

```cpp
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);
            polymorphic_allocator select_on_container_copy_construction() const;
            memory_resource* resource() const;
    };
}
```

20.4.3.2 Constructors

```cpp
polymorphic_allocator() noexcept;
```

_returns:_ Sets `memory_rsrc` to `get_default_resource()`.

```cpp
polymorphic_allocator(memory_resource* r);
```

_preconditions:_ $r$ is non-null.

_returns:_ Sets `memory_rsrc` to $r$. 

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4  Throws: Nothing.
5  [Note 1: This constructor provides an implicit conversion from 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 x.allocate(n * sizeof(Tp), alignof(Tp)).
3  Effects: Equivalent to memory_rsrc->deallocate(p, n * sizeof(Tp), alignof(Tp)).
4  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);

   [Note 1: The return type is void* (rather than, e.g., byte*) to support conversion to an arbitrary pointer type U* by static_cast<U*>(...) thus facilitating construction of a U object in the allocated memory. — end note]

void deallocate_bytes(void* p, size_t nbytes, size_t alignment = alignof(max_align_t));
6  Effects: Equivalent to memory_rsrc->deallocate(p, nbytes, alignment).

template<class T>
[[nodiscard]] T* allocate_object(size_t n = 1);
7  Effects: Allocates memory suitable for holding an array of n objects of type T, as follows:
   (8.1) if numeric_limits<size_t>::max() / sizeof(T) < n, throws bad_array_new_length,
   (8.2) otherwise equivalent to:
      return static_cast<T*>(allocate_bytes(n*sizeof(T), alignof(T)));

   [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);
8  Effects: Equivalent to deallocate_bytes(p, n*sizeof(T), alignof(T)).

template<class T, class... CtorArgs>
[[nodiscard]] T* new_object(CtorArgs&&... ctor_args);
9  Effects: Allocates and constructs an object of type T, as follows. Equivalent to:
   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>
void delete_object(T* p);
10  Effects: Equivalent to:
allocator_traits<polymorphic_allocator>::destroy(*this, p);
deallocate_object(p);

template<class T, class... Args>
void construct(T* p, Args&&... args);

Mandates: Uses-allocator construction of T with allocator *this (see 20.2.7.2) 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.

polymorphic_allocator select_on_container_copy_construction() const;

Returns: polymorphic_allocator().

[Note 4: The memory resource is not propagated. — end note]

memory_resource* resource() const;

Returns: memory_rsrc.

20.4.3.4 Equality

template<class T1, class T2>
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() 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() 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.

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;

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().

Returns: The previous value of the default memory resource pointer.

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;

Returns: The current value of the default memory resource pointer.
20.4.5 Pool resource classes

20.4.5.1 Classes synchronized_pool_resource and unsynchronized_pool_resource

The synchronized_pool_resource and unsynchronized_pool_resource classes (collectively called pool resource classes) are general-purpose memory resources having the following qualities:

1. Each resource frees its allocated memory on destruction, even if deallocate has not been called for some of the allocated blocks.

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.

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]

4. Allocation requests that exceed the largest block size of any pool are fulfilled directly from the upstream allocator.

5. A pool_options struct may be passed to the pool resource constructors to tune the largest block size and the maximum chunk size.

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()
    : unsynchronized_pool_resource(pool_options(), get_default_resource()) {}
explicit unsynchronized_pool_resource(memory_resource* upstream)
    : unsynchronized_pool_resource(pool_options(), upstream) {}
explicit unsynchronized_pool_resource(const pool_options& opts)
    : unsynchronized_pool_resource(opts, get_default_resource()) {}

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 field 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 field.

20.4.5.3 Constructors and destructors

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().
virtual ~synchronized_pool_resource();
virtual ~unsynchronized_pool_resource();

Effects: Calls release().

20.4.5.4 Members

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]

memory_resource* upstream_resource() const;

Returns: The value of the upstream argument provided to the constructor of this object.

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.

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.

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.

bool do_is_equal(const memory_resource& other) const noexcept override;

Returns: this == &other.

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(monotonic_buffer_resource) = default;
    monotonic_buffer_resource& operator=(monotonic_buffer_resource other) = default;
    operator memory_resource*() const noexcept;

    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.

    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.

    bool do_is_equal(const memory_resource& other) const noexcept override;

    Returns: this == &other.

    } // namespace std::pmr

§ 20.4.6.1
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

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]

memory_resource* upstream_resource() const;

3 Returns: The value of upstream_rsrc.

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.
void do_deallocate(void* p, size_t bytes, size_t alignment) override;

Effects: None.

Throws: Nothing.

Remarks: Memory used by this resource increases monotonically until its destruction.

bool do_is_equal(const memory_resource& other) const noexcept override;

Returns: this == &other.

20.5 Class template scoped_allocator_adaptor

20.5.1 Header <scoped_allocator> synopsis

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;

} /* std */

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.

[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>;
  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;

} /* scoped_allocator_adaptor */
} /* std */
```
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;
sScoped_allocator_adaptor(const scoped_allocator_adaptor& other) noexcept;
sScoped_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();

    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);

    scoped_allocator_adaptor select_on_container_copy_construction() const;
};
```

§ 20.5.2  Member types

```
using propagate_on_container_swap = see below;

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;

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();

Effects: Value-initializes the OuterAlloc base class and the inner allocator object.

template<class OuterA2>
scoped_allocator_adaptor(OuterA2& outerAlloc, const InnerAllocs&... innerAllocs) noexcept;

Constraints: is_constructible_v<OuterAlloc, OuterA2> is true.

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;

Effects: Initializes each allocator within the adaptor with the corresponding allocator from other.

scoped_allocator_adaptor(scoped_allocator_adaptor&& other) noexcept;

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;

Constraints: is_constructible_v<OuterAlloc, const OuterA2&> is true.

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;

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;

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);
5
   Returns: allocator_traits<OuterAlloc>::allocate(outer_allocator(), n).

[[nodiscard]] pointer allocate(size_type n, const void_pointer hint);
6
   Returns: allocator_traits<OuterAlloc>::allocate(outer_allocator(), n, hint).

void deallocate(pointer p, size_type n) noexcept;
7
   Effects: As if by: allocator_traits<OuterAlloc>::deallocate(outer_allocator(), p, n);

size_type max_size() const;
8
   Returns: allocator_traits<OuterAlloc>::max_size(outer_allocator()).

template<class T, class... Args>
   void construct(T* p, Args&&... args);
9
   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);
10
   Effects: Calls OUTERMOST_ALLOC_TRAITS(*this)::destroy(OUTERMOST(*this), p).

scoped_allocator_adaptor select_on_container_copy_construction() const;
11
   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

   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
   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

21.1  General

This Clause describes metaprogramming facilities. These facilities are summarized in Table 43.

Table 43: Metaprogramming library summary

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21.2  Compile-time integer sequences

21.2.1  In 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 22.4.5. — end note]

21.2.2  Class template integer_sequence

```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

```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

21.3.1  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.

2 All functions specified in 21.3 are signal-safe (17.13.5).
21.3.2 Requirements

1 A **`CppType17UnaryTypeTrait`** 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 `CppType17DefaultConstructible`, `CppType17CopyConstructible`, 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 `CppType17UnaryTypeTrait`.

2 A **`CppType17BinaryTypeTrait`** 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 `CppType17DefaultConstructible`, `CppType17CopyConstructible`, 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 `CppType17BinaryTypeTrait`.

3 A **`CppType17TransformationTrait`** 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.

4 Unless otherwise specified, the behavior of a program that adds specializations for any of the templates specified in 21.3 is undefined.

5 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

```cpp
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;

// 21.3.5.3, 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 is_scoped_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, class U> 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 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 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...>
  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>
  inline constexpr bool is_void_v = is_void<T>::value;

template<class T>
  inline constexpr bool is_null_pointer_v = is_null_pointer<T>::value;
template<class T>
inline constexpr bool is_integral_v = is_integral<T>::value;

template<class T>
inline constexpr bool is_floating_point_v = is_floating_point<T>::value;

template<class T>
inline constexpr bool is_array_v = is_array<T>::value;

template<class T>
inline constexpr bool is_pointer_v = is_pointer<T>::value;

template<class T>
inline constexpr bool is_lvalue_reference_v = is_lvalue_reference<T>::value;

template<class T>
inline constexpr bool is_rvalue_reference_v = is_rvalue_reference<T>::value;

template<class T>
inline constexpr bool is_member_object_pointer_v = is_member_object_pointer<T>::value;

template<class T>
inline constexpr bool is_member_function_pointer_v = is_member_function_pointer<T>::value;

template<class T>
inline constexpr bool is_enum_v = is_enum<T>::value;

template<class T>
inline constexpr bool is_union_v = is_union<T>::value;

template<class T>
inline constexpr bool is_class_v = is_class<T>::value;

template<class T>
inline constexpr bool is_function_v = is_function<T>::value;

// 21.3.5.3, composite type categories

template<class T>
inline constexpr bool is_reference_v = is_reference<T>::value;

template<class T>
inline constexpr bool is_arithmetic_v = is_arithmetic<T>::value;

template<class T>
inline constexpr bool is_fundamental_v = is_fundamental<T>::value;

template<class T>
inline constexpr bool is_object_v = is_object<T>::value;

template<class T>
inline constexpr bool is_scalar_v = is_scalar<T>::value;

template<class T>
inline constexpr bool is_compound_v = is_compound<T>::value;

template<class T>
inline constexpr bool is_member_pointer_v = is_member_pointer<T>::value;

// 21.3.5.4, type properties

template<class T>
inline constexpr bool is_const_v = is_const<T>::value;

template<class T>
inline constexpr bool is_volatile_v = is_volatile<T>::value;

template<class T>
inline constexpr bool is_trivial_v = is_trivial<T>::value;

template<class T>
inline constexpr bool is_trivially_copyable_v = is_trivially_copyable<T>::value;

template<class T>
inline constexpr bool is_standard_layout_v = is_standard_layout<T>::value;

template<class T>
inline constexpr bool is_empty_v = is_empty<T>::value;

template<class T>
inline constexpr bool is_polymorphic_v = is_polymorphic<T>::value;

template<class T>
inline constexpr bool is_abstract_v = is_abstract<T>::value;

template<class T>
inline constexpr bool is_final_v = is_final<T>::value;

template<class T>
inline constexpr bool is_aggregate_v = is_aggregate<T>::value;

template<class T>
inline constexpr bool is_signed_v = is_signed<T>::value;
template<
class T>
    inline constexpr bool is_unsigned_v = is_unsigned<T>::value;
template<
class T>
    inline constexpr bool is_bounded_array_v = is_bounded_array<T>::value;
template<
class T>
    inline constexpr bool is_unbounded_array_v = is_unbounded_array<T>::value;
template<
class T>
    inline constexpr bool is_scoped_enum_v = is_scoped_enum<T>::value;
template<
class T, class... Args>
    inline constexpr bool is_constructible_v = is_constructible<T, Args...>::value;
template<
class T>
    inline constexpr bool is_default_constructible_v = is_default_constructible<T>::value;
template<
class T>
    inline constexpr bool is_copy_constructible_v = is_copy_constructible<T>::value;
template<
class T>
    inline constexpr bool is_move_constructible_v = is_move_constructible<T>::value;
template<
class T, class U>
    inline constexpr bool is_assignable_v = is_assignable<T, U>::value;
template<
class T, class... U>
    inline constexpr bool is_copy_assignable_v = is_copy_assignable<T, U>::value;
template<
class T, class U>
    inline constexpr bool is_move_assignable_v = is_move_assignable<T, U>::value;
template<
class T, class U>
    inline constexpr bool is_swappable_with_v = is_swappable_with<T, U>::value;
template<
class T>
    inline constexpr bool is_swappable_v = is_swappable<T>::value;
template<
class T>
    inline constexpr bool is_destructible_v = is_destructible<T>::value;
template<
class T, class... Args>
    inline constexpr bool is_trivially_constructible_v = is_trivially_constructible<T, Args...>::value;
template<
class T>
    inline constexpr bool is_trivially_default_constructible_v = is_trivially_default_constructible<T>::value;
template<
class T>
    inline constexpr bool is_trivially_copy_constructible_v = is_trivially_copy_constructible<T>::value;
template<
class T, class U>
    inline constexpr bool is_trivially_move_constructible_v = is_trivially_move_constructible<T, U>::value;
template<
class T>
    inline constexpr bool is_trivially_destructible_v = is_trivially_destructible<T>::value;
template<
class T, class... Args>
    inline constexpr bool is_nothrow_constructible_v = is_nothrow_constructible<T, Args...>::value;
template<
class T>
    inline constexpr bool is_nothrow_default_constructible_v = is_nothrow_default_constructible<T>::value;
template<
class T>
    inline constexpr bool is_nothrow_copy_constructible_v = is_nothrow_copy_constructible<T>::value;
template<
class T>
    inline constexpr bool is_nothrow_move_constructible_v = is_nothrow_move_constructible<T>::value;
template<
class T, class U>
    inline constexpr bool is_nothrow_assignable_v = is_nothrow_assignable<T, U>::value;
template<class T>
    inline constexpr bool is_nothrow_copy_assignable_v = is_nothrow_copy_assignable<T>::value;

template<class T>
    inline constexpr bool is_nothrow_move_assignable_v = is_nothrow_move_assignable<T>::value;

template<class T, class U>
    inline constexpr bool is_nothrow_swappable_with_v = is_nothrow_swappable_with<T, U>::value;

template<class T>
    inline constexpr bool is_nothrow_swappable_v = is_nothrow_swappable<T>::value;

template<class T>
    inline constexpr bool has_virtual_destructor_v = has_virtual_destructor<T>::value;

template<class T>
    inline constexpr bool has_unique_object_representations_v
        = has_unique_object_representations<T>::value;

template<class T, class U>
    inline constexpr bool reference_constructs_from_temporary_v
        = reference_constructs_from_temporary<T, U>::value;

template<class T, class U>
    inline constexpr bool reference_converts_from_temporary_v
        = reference_converts_from_temporary<T, U>::value;

// 21.3.6, type property queries

template<class T>
    inline constexpr size_t alignment_of_v = alignment_of<T>::value;

template<class T>
    inline constexpr size_t rank_v = rank<T>::value;

template<class T, unsigned I = 0>
    inline constexpr size_t extent_v = extent<T, I>::value;

// 21.3.7, type relations

template<class T, class U>
    inline constexpr bool is_same_v = is_same<T, U>::value;

template<class Base, class Derived>
    inline constexpr bool is_base_of_v = is_base_of<Base, Derived>::value;

template<class From, class To>
    inline constexpr bool is_convertible_v = is_convertible<From, To>::value;

template<class From, class To>
    inline constexpr bool is_nothrow_convertible_v = is_nothrow_convertible<From, To>::value;

template<class T, class U>
    inline constexpr bool is_layout_compatible_v = is_layout_compatible<T, U>::value;

template<class Base, class Derived>
    inline constexpr bool is_pointer_interconvertible_base_of_v
        = is_pointer_interconvertible_base_of<Base, Derived>::value;

template<class Fn, class... ArgTypes>
    inline constexpr bool is_invocable_v = is_invocable<Fn, ArgTypes...>::value;

template<class R, class Fn, class... ArgTypes>
    inline constexpr bool is_invocable_r_v = is_invocable_r<R, Fn, ArgTypes...>::value;

template<class Fn, class... ArgTypes>
    inline constexpr bool is_nothrow_invocable_v = is_nothrow_invocable<Fn, ArgTypes...>::value;

template<class R, class Fn, class... ArgTypes>
    inline constexpr bool is_nothrow_invocable_r_v
        = is_nothrow_invocable_r<R, Fn, ArgTypes...>::value;

// 21.3.9, logical operator traits

template<class... B>
    inline constexpr bool conjunction_v = conjunction<B...>::value;

template<class... B>
    inline constexpr bool disjunction_v = disjunction<B...>::value;

template<class B>
    inline constexpr bool negation_v = negation<B>::value;

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21.3.10 Member relationships

```cpp
// 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

```cpp
constexpr bool is_constant_evaluated() noexcept;
```

21.3.4 Helper classes

```cpp
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

1 Subclause 21.3.5 contains templates that may be used to query the properties of a type at compile time.

2 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

1 The primary type categories correspond to the descriptions given in subclause 6.8 of the C++ standard.

2 For any given type `T`, the result of applying one of these templates to `T` and to `cv T` shall yield the same result.

3 [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 44: Primary type category predicates

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>template&lt;class T&gt; struct is_void;</code></td>
<td><code>T is void</code></td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_null_pointer;</code></td>
<td><code>T is </code>nullptr_t<code> (6.8.2)</code></td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_integral;</code></td>
<td><code>T is an integral type (6.8.2)</code></td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_floating_point;</code></td>
<td><code>T is a floating-point type (6.8.2)</code></td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_array;</code></td>
<td><code>T is an array type (6.8.3) of known or unknown extent Class template </code>array<code> (24.3.7) is not an array type.</code></td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_pointer;</code></td>
<td><code>T is a pointer type (6.8.3) Includes pointers to functions but not pointers to non-static members.</code></td>
<td></td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_lvalue_reference;</code></td>
<td><code>T is an lvalue reference type (9.3.4.3)</code></td>
<td></td>
</tr>
</tbody>
</table>
Table 44: 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_rvalue_reference;</td>
<td>T is an rvalue reference</td>
<td>type (9.3.4.3)</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_object_pointer;</td>
<td>T is a pointer to member</td>
<td>function</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_function_pointer;</td>
<td>T is an enumeration</td>
<td>type (6.8.3)</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_enum;</td>
<td>T is an enumeration</td>
<td>type (6.8.3)</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_union;</td>
<td>T is a union type (6.8.3)</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_class;</td>
<td>T is a non-union class</td>
<td>type (6.8.3)</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_function;</td>
<td>T is a function type (6.8.3)</td>
<td></td>
</tr>
</tbody>
</table>

21.3.5.3 Composite type traits [meta.unary.comp]

1 These templates provide convenient compositions of the primary type categories, corresponding to the descriptions given in subclause 6.8.

2 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 45: Composite type category predicates [tab:meta.unary.comp]

<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>
<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_member_pointer;</td>
<td>T is a pointer-to-member</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_function_pointer;</td>
<td>T is a member function pointer</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_member_object_pointer;</td>
<td>T is a member object pointer</td>
<td></td>
</tr>
</tbody>
</table>

21.3.5.4 Type properties [meta.unary.prop]

1 These templates 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>().

§ 21.3.5.4
— Otherwise, \( \text{VAL} < \text{T} > \) is a prvalue that initially has type \( \text{T} \).

[Note 1: If \( \text{T} \) is cv-qualified, the cv-qualification is subject to adjustment (7.2.2). — end note]
Table 46: 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, class... Args&gt; struct is_constructible;</td>
<td>For a function type T or for a cv void type T, <code>is_constructible_v&lt;T, Args...&gt;</code> is <code>false</code>, otherwise see below</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_default_constructible;</td>
<td><code>is_constructible_v&lt;T&gt;</code> is <code>true</code>.</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_copy_constructible;</td>
<td>For a referenceable type T (3.46), 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, cv void, or an array of unknown bound.</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct is_move_constructible;</td>
<td>For a referenceable type T, the same result as <code>is_constructible_v&lt;T, T&amp;&gt;</code>, 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 <code>declval&lt;T&gt;() = declval&lt;U&gt;()</code> 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 <code>is_assignable_v&lt;T&amp;, const T&amp;&gt;</code>, 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 <code>is_assignable_v&lt;T&amp;, T&amp;&amp;&gt;</code>, otherwise false.</td>
<td>T shall be a complete type, cv void, or an array of unknown bound.</td>
</tr>
</tbody>
</table>
Table 46: 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;U&gt;(), declval&lt;T&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 <code>T</code> and <code>U</code>. Only the validity of the immediate context of the <code>swap</code> expressions is considered.</td>
<td><code>T</code> and <code>U</code> shall be complete types, <code>cv void</code>, 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><code>template&lt;class T&gt; struct is_swappable;</code></td>
<td>For a referenceable type <code>T</code>, the same result as <code>is_trivially_constructible_with_v&lt;T&amp;, T&amp;&gt;</code>, otherwise <code>false</code>.</td>
<td><code>T</code> shall be a complete type, <code>cv void</code>, or an array of unknown bound.</td>
</tr>
</tbody>
</table>

<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_destructible;</code></td>
<td>Either <code>T</code> is a reference type, or <code>T</code> is a complete object type for which the expression <code>declval&lt;U&amp;&gt;() .~U()</code> is well-formed when treated as an unevaluated operand (7.2.3), where <code>U</code> is <code>remove_all_extents_&lt;T&gt;</code>.</td>
<td><code>T</code> shall be a complete type, <code>cv void</code>, or an array of unknown bound.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>template&lt;class T, class... Args&gt; struct is_trivially_constructible;</code></td>
<td><code>is_constructible_v&lt;T, Args...&gt;</code> is <code>true</code> and the variable definition for <code>is_constructible</code>, as defined below, is known to call no operation that is not trivial (6.8.1, 11.4.4).</td>
<td><code>T</code> 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>
</tbody>
</table>

<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_trivially_default_constructible;</code></td>
<td><code>is_trivially_default_constructible_v&lt;T&gt;</code> is <code>true</code>.</td>
<td><code>T</code> shall be a complete type, <code>cv void</code>, 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><code>template&lt;class T&gt; struct is_trivially_copy_constructible;</code></td>
<td>For a referenceable type ( T ), the same result as <code>is_trivially_constructible_v&lt;T, const T&amp;&gt;</code>, otherwise <code>false</code>.</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_trivially_move_constructible;</code></td>
<td>For a referenceable type ( T ), the same result as <code>is_trivially_constructible_v&lt;T, T&amp;&amp;&gt;</code>, otherwise <code>false</code>.</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, class U&gt; struct is_trivially_assignable;</code></td>
<td><code>is_assignable_v&lt;T, U&gt;</code> is <code>true</code> and the assignment, as defined by <code>is_assignable</code>, 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, <code>cv void</code>, or arrays of unknown bound.</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct is_trivially_copy_assignable;</code></td>
<td>For a referenceable type ( T ), the same result as <code>is_trivially_assignable_v&lt;T&amp;, const T&amp;&gt;</code>, otherwise <code>false</code>.</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_trivially_move_assignable;</code></td>
<td>For a referenceable type ( T ), the same result as <code>is_trivially_assignable_v&lt;T&amp;, T&amp;&amp;&gt;</code>, otherwise <code>false</code>.</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_trivially_destructible;</code></td>
<td><code>is_destructible_v&lt;T&gt;</code> is <code>true</code> and <code>remove_all_extents_t&lt;T&gt;</code> is either a non-class type or a class type with a trivial destructor.</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, class... Args&gt; struct is_nothrow_constructible;</code></td>
<td><code>is_constructible_v&lt;T, Args...&gt;</code> is <code>true</code> and the variable definition for <code>is_constructible</code>, 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 <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_nothrow_default_constructible;</code></td>
<td><code>nothrow_constructible_v&lt;T&gt;</code> is <code>true</code>.</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_nothrow_copy_constructible;</code></td>
<td>For a referenceable type ( T ), the same result as <code>nothrow_constructible_v&lt;T, const T&amp;&gt;</code>, otherwise <code>false</code>.</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_nothrow_move_constructible;</code></td>
<td>For a referenceable type ( T ), the same result as <code>nothrow_constructible_v&lt;T, T&amp;&amp;&gt;</code>, otherwise <code>false</code>.</td>
<td>( T ) shall be a complete type, <code>cv void</code>, or an array of unknown bound.</td>
</tr>
</tbody>
</table>
Table 46: Type property predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
</table>
| `template<class T, class U>
struct is_nothrow_assignable;`
| `is_assignable_v<T, U>`
is true and the assignment is known not to throw any exceptions (7.6.2.7).

T and U shall be complete types, cv void, or arrays of unknown bound.

| `template<class T>
struct is_nothrow_copyAssignable;`
| For a referenceable type T, the same result as
`is_nothrow_assignable_v<T&, const T&>`, otherwise false.

T shall be a complete type, cv void, or an array of unknown bound.

| `template<class T>
struct is_nothrow_moveAssignable;`
| For a referenceable type T, the same result as
`is_nothrowAssignable_v<T&, T&&>`, otherwise false.

T shall be a complete type, cv void, or an array of unknown bound.

| `template<class T, class U>
struct is_nothrow_swappable_with;`
| `is_swappable_with_v<T, U>`
is true and each swap expression of the definition of
`is_swappable_with_v<T, U>` is known not to throw any exceptions (7.6.2.7).

T and U shall be complete types, cv void, or arrays of unknown bound.

| `template<class T>
struct is_nothrow_swappable;`
| For a referenceable type T, the same result as
`is_nothrow_swappable_v<T&, T&>`, otherwise false.

T shall be a complete type, cv void, or an array of unknown bound.

| `template<class T>
struct is_nothrow_destructible;`
| `is_destructible_v<T>`
is true and the indicated destructor is known not to throw any exceptions (7.6.2.7).

T shall be a complete type, cv void, or an array of unknown bound.

| `template<class T>
struct has_virtual_destructor;`
| T has a virtual destructor (11.4.7)

If T is a non-union class type, T shall be a complete type.

| `template<class T>
struct has_unique_object_representations;`
| For an array type T, the same result as
`has_unique_object_representations_v<remove_all_extents_t<T>, t<>>`, otherwise see below.

T shall be a complete type, cv void, or an array of unknown bound.

| `template<class T, class U>
struct reference_constructs_from_temporary;`
| `conjunction_v<is_reference<T>, is_constructible<T, U>>`
is true, and the initialization T
t(VAL<U>); binds t to a temporary object whose lifetime is extended (6.7.7).

T and U shall be complete types, cv void, or arrays of unknown bound.
Table 46: Type property predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
</table>
| template<class T, class U> struct reference_converts_from_temporary; | conjunction_v<is_<-
| | reference<T>, is_convertible<U, T>> is true, and the initialization T t = VAL<U>; binds t to a temporary object whose lifetime is extended (6.7.7). | T and U shall be complete types, cv void, or arrays of unknown bound. |

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]

7 [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]

8 [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]

9 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(declval<Args>());

[Note 5: 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 6: 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]

10 The predicate condition for a template specialization has_unique_object_representations<T> shall be satisfied if and only if:

(10.1) — T is trivially copyable, and
(10.2) — any two objects of type T with the same value have the same object representation, where two objects of array or non-union class type are considered to have the same value if their respective sequences of direct subobjects have the same values, and two objects of union type are considered to have the same value if they have the same active member and the corresponding members have the same value.

The set of scalar types for which this condition holds is implementation-defined.
21.3.6 Type property queries

This subclause contains templates that 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; struct alignment_of;</td>
<td><code>alignof(T)</code>.&lt;br&gt;<strong>Mandates:</strong> <code>alignof(T)</code> is a valid expression (7.6.2.6)</td>
</tr>
<tr>
<td>template&lt;class T&gt; struct rank;</td>
<td>If T names an array type, an integer value representing the number of 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 I, or if I is 0 and T has type “array of unknown bound of U”, then 0; otherwise, the bound (9.3.4.5) of the I&lt;sup&gt;th&lt;/sup&gt; dimension of T, where indexing of I is zero-based</td>
</tr>
</tbody>
</table>

Each of these templates shall be a `Cpp17UnaryTypeTrait` (21.3.2) with a base characteristic of `integral_constant<size_t, Value>`. 

21.3.7 Relationships between types

This subclause contains templates that may be used to query relationships between types at compile time.

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>
<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</td>
<td>with the same cv-qualifications</td>
</tr>
</tbody>
</table>
Table 48: Type relationship predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<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&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 (6.8.3) 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&lt;declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...&gt; 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&lt;declval&lt;Fn&gt;(), declval&lt;ArgTypes&gt;()...&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>
</tbody>
</table>
Table 48: Type relationship predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
</table>
| template<class R, class Fn, class... ArgTypes> struct is_nothrow_invocable_r; | is_invocable_r_v<
R, Fn, ArgTypes...> is true and the expression
INVOKE<R>(declval<Fn>(),
declval<ArgTypes>()...) is known not to throw any exceptions (7.6.2.7) | Fn, R, and all types in the template parameter pack |
| | | ArgTypes shall be complete types, cv void, or arrays of unknown bound. |

3 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.

4 [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<B, const B> //false
is_base_of_v<B&, D&> //false
is_base_of_v<B[3], D[3]> //false
is_base_of_v<int, int> //false
```

—end example]

5 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 2: This requirement gives well-defined results for reference types, array types, function types, and cv void. —end note]

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 3: 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]

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.

Each of the templates in 21.3.8 shall be a Cpp17TransformationTrait (21.3.2).
Table 49: Const-volatile modifications  [tab:meta.trans.cv]

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
</table>
| template<class T> struct remove_const; | The member typedef type names the same type as T except that any top-level const-qualifier has been removed. 
[Example 1: remove_const_t<const volatile int> evaluates to volatile int, whereas remove_const_t<const int*> evaluates to const int*. — end example] |
| template<class T> struct remove_volatile; | The member typedef type names the same type as T except that any top-level volatile-qualifier has been removed. 
[Example 2: remove_volatile_t<const volatile int> evaluates to const int, whereas remove_volatile_t<volatile int*> evaluates to volatile int*. — end example] |
| template<class T> struct remove_cv; | The member typedef type shall be the same as T except that any top-level cv-qualifier has been removed. 
[Example 3: remove_cv_t<const volatile int> evaluates to int, whereas remove_cv_t<volatile int*> evaluates to volatile int*]. — end example] |
| template<class T> struct add_const; | If T is a reference, function, or top-level const-qualified type, then type names the same type as T, otherwise T const. |
| template<class T> struct add_volatile; | If T is a reference, function, or top-level volatile-qualified type, then type names the same type as T, otherwise T volatile. |
| template<class T> struct add_cv; | The member typedef type names the same type as 
add_const_t<add_volatile_t<T>>. |

21.3.8.3 Reference modifications  [meta.trans.ref]

Table 50: Reference modifications  [tab:meta.trans.ref]

<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 names T1; otherwise, type names T.</td>
</tr>
</tbody>
</table>
| template<class T> struct add_lvalue_reference; | If T names a referenceable type (3.46) then the member typedef type names T&; otherwise, type names T. 
[Note 1: This rule reflects the semantics of reference collapsing (9.3.4.3). — end note] |
| template<class T> struct add_rvalue_reference; | If T names a referenceable type then the member typedef type names T&&; otherwise, type names T. 
[Note 2: This rule reflects the semantics of reference collapsing (9.3.4.3). For example, when a type T names a type T1&&, the type add_rvalue_reference_t<T> is not an rvalue reference. — end note] |

21.3.8.4 Sign modifications  [meta.trans.sign]

Table 51: Sign modifications  [tab:meta.trans.sign]

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
</table>
| template<class T> struct make_signed; | If T names a (possibly cv-qualified) signed integer type (6.8.2) then the member typedef type names the type T; otherwise, if T names a (possibly cv-qualified) unsigned integer type then type names the corresponding signed integer type, with the same cv-qualifiers as T; otherwise, type names the signed integer type with smallest rank (6.8.5) 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

Table 52: Array modifications

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt;</td>
<td>struct remove_extent;</td>
</tr>
<tr>
<td>If T names a type “array of U”, the member typedef type shall be U, otherwise T.</td>
<td></td>
</tr>
<tr>
<td>[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]</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td>struct remove_all_extents;</td>
</tr>
<tr>
<td>If T is “multi-dimensional array of U”, the resulting member typedef type is U, otherwise T.</td>
<td></td>
</tr>
</tbody>
</table>

1 [Example 1:

// the following assertions hold:
assert((is_same_v<remove_extent_t<int>, int>));
assert((is_same_v<remove_extent_t<int[2], int>));
assert((is_same_v<remove_extent_t<int[2][3], int[3]>));
assert((is_same_v<remove_extent_t<int[1][3], int[3]>));
— end example]

2 [Example 2:

// the following assertions hold:
assert((is_same_v<remove_all_extents_t<int>, int>));
assert((is_same_v<remove_all_extents_t<int[2], int>));
assert((is_same_v<remove_all_extents_t<int[2][3], int>));
assert((is_same_v<remove_all_extents_t<int[1][3], int>));
— end example]

21.3.8.6 Pointer modifications

Table 53: Pointer modifications

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt;</td>
<td>struct remove_pointer;</td>
</tr>
<tr>
<td>If T has type “(possibly cv-qualified) pointer to T1” then the member typedef type names T1; otherwise, it names T.</td>
<td></td>
</tr>
<tr>
<td>template&lt;class T&gt;</td>
<td>struct add_pointer;</td>
</tr>
<tr>
<td>If T names a referenceable type (3.46) or a cv void type then the member typedef type names the same type as remove_reference_t&lt;T&gt;*; otherwise, type names T.</td>
<td></td>
</tr>
</tbody>
</table>

21.3.8.7 Other transformations

Table 54: Other transformations

<table>
<thead>
<tr>
<th>Template</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>template&lt;class T&gt;</td>
<td>struct type_identity;</td>
</tr>
<tr>
<td>The member typedef type names the type T.</td>
<td></td>
</tr>
<tr>
<td>Template</td>
<td>Comments</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><code>template&lt;class T&gt; struct remove_cvref;</code></td>
<td>The member typedef <code>type</code> names the same type as <code>remove_cv_t&lt;remove_reference_t&lt;T&gt;&gt;</code>.</td>
</tr>
</tbody>
</table>
| `template<class T> struct decay;`            | Let `U` be `remove_reference_t<T>`. If `is_array_v<U>` is `true`, the member typedef `type` equals `remove_extent_t<U>`. If `is_function_v<U>` is `true`, the member typedef `type` equals `add_pointer_t<U>`. Otherwise the member typedef `type` equals `remove_cv_t<U>`.  
|                                               | [Note 1: This behavior is similar to the value-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] |
| `template<bool B, class T = void> struct enable_if;` | If `B` is `true`, the member typedef `type` shall equal `T`; otherwise, there shall be no member `type`.                                    |
| `template<bool B, class T, class F> struct conditional;` | If `B` is `true`, the member typedef `type` shall equal `T`. If `B` is `false`, the member typedef `type` shall equal `F`.                  |
| `template<class... T> struct common_type;`   | Unless this trait is specialized (as specified in Note B, below), the member `type` is defined or omitted as specified in Note A, 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. |
| `template<class, class, template<class> class, template<class> class> struct basic_common_reference;` | The member `typedef-name type` is defined or omitted as specified in Note C, below. Each type in the parameter pack `T` shall be complete or `cv void`. |
| `template<class... T> struct common_reference;` | The member typedef `type` names the underlying type of `T` (9.7.1); otherwise, there is no member `type`.  
|                                               | *Mandates:* `T` is not an incomplete enumeration type.                                                                                  |
| `template<class Fn, class... ArgTypes> struct invoke_result;` | If the expression `INVOKE(declval<Fn>(), declval<ArgTypes>()...)` is well-formed when treated as an unevaluated operand (7.2.3), the member typedef `type` names the type `decltype(INVOKE(declval<Fn>(), declval<ArgTypes>()...))`; 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. |
| `template<class T> struct unwrap_reference;`  | If `T` is a specialization `reference_wrapper<X>` for some type `X`, the member typedef `type` of `unwrap_reference<T>` is `X&`, otherwise it is `T`. |
| `template<class T> unwrap_ref_decay;`         | The member typedef `type` of `unwrap_refdecay<T>` denotes the type `unwrap_reference_t<decay_t<T>>>`.                                    |
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.

Let:

1. `CREF(A)` be `add_lvalue_reference_t<const remove_reference_t<A>>`,
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. `COPYCV(FROM, TO)` be an alias for type `TO` with the addition of `FROM`'s top-level cv-qualifiers,
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:

1. If `A` and `B` are both lvalue reference types, `COMMON-REF(A, B)` is `COND-RES(COPYCV(X, Y) &, COPYCV(Y, X) &)`, `T0` if that type exists and is a reference type.
2. Otherwise, let `C` be `remove_reference_t<COMMON-REF(Xk, Yk)>`. If `A` and `B` are both rvalue reference types, `C` is well-formed, and `is_convertible_v<A, C> && is_convertible_v<B, C>` is true, then `COMMON-REF(A, B)` is `C`.
3. Otherwise, let `D` be `COMMON-REF(const Xk, Yk)`. 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`.
4. Otherwise, if `A` is an lvalue reference and `B` is an rvalue reference, then `COMMON-REF(A, B)` is `COMMON-REF(B, A)`.
5. 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.

Note A: 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:

1. If `sizeof...(T)` is zero, there shall be no member `type`.
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`.
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.
   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>`.
   2. `[Note 3: None of the following will apply if there is a specialization `common_type_t<D1, D2>`._ end note]
3. Otherwise, if `decay_t<decltype(false ? declval<D1>() : declval<D2>())>` denotes a valid type, let `C` denote that type.
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))>`. In either case, the member `typedef-name type` shall denote the same type, if any, as `C`. Otherwise, there shall be no member `type`.
5. 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`. 

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4 Note B: 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.

5 Note C: 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:

(5.1) — If `sizeof...(T)` is zero, there shall be no member `type`.
(5.2) — 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`.
(5.3) — Otherwise, if `sizeof...(T)` is two, let `T1` and `T2` denote the two types in the pack T. Then
(5.3.1) — If `T1` and `T2` are reference types and `COMMON-REF(T1, T2)` is well-formed, then the member typedef `type` denotes that type.
(5.3.2) — 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.
(5.3.3) — Otherwise, if `COND-RES(T1, T2)` is well-formed, then the member typedef `type` denotes that type.
(5.3.4) — Otherwise, if `common_type_t<T1, T2>` is well-formed, then the member typedef `type` denotes that type.
(5.3.5) — Otherwise, there shall be no member `type`.
(5.4) — 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:
(5.4.1) — If there is such a type `C`, the member typedef `type` shall denote the same type, if any, as `common_reference_t<C, Rest...>`.
(5.4.2) — Otherwise, there shall be no member `type`.

6 Note D: 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.

7 [Example 2: Given these definitions:

```cpp
using PF1 = bool (&)();
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

This subclause describes type traits for applying logical operators to other type traits.

```cpp
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 `B_i` in the list `true_type`, `B1, ..., BN` for which `bool(B_i::value)` is `false`, or
- if there is no such `B_i`, 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`.

```cpp
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 `B_i` in the list `false_type`, `B1, ..., BN` for which `bool(B_i::value)` is `true`, or
- if there is no such `B_i`, 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`.

```cpp
template<class B> struct negation : see below {}
```

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

```cpp
template<class S, class M>
```

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constexpr bool is_pointer_interconvertible_with_class(M S::*m) noexcept;

Mandates: S is a complete type.

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 (6.8.3) 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;

Mandates: S1 and S2 are complete types.

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.

[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:

```cpp
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 [meta.const.eval]

constexpr bool is_constant_evaluated() noexcept;

Effects: Equivalent to:

```cpp
if constexpr {
    return true;
} else {
    return false;
}
```

[Example 1:

```cpp
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
    }
}
```

—end example]

21.4 Compile-time rational arithmetic [ratio]

21.4.1 In general [ratio.general]

Subclause 21.4 describes the ratio library. It provides a class template ratio which exactly represents any finite rational number with a numerator and denominator representable by compile-time constants of type intmax_t.
Throughout subclause 21.4, the names of template parameters are used to express type requirements. If a template parameter is named `R1` or `R2`, and the template argument is not a specialization of the `ratio` template, the program is ill-formed.

### 21.4.2 Header `<ratio>` synopsis

```cpp
namespace std {

    // 21.4.3, class template ratio
    template<intmax_t N, intmax_t D = 1> class ratio;

    // 21.4.4, ratio arithmetic
    template<class R1, class R2> using ratio_add = see below;
    template<class R1, class R2> using ratio_subtract = see below;
    template<class R1, class R2> using ratio_multiply = see below;
    template<class R1, class R2> using ratio_divide = see below;

    // 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> inline constexpr bool ratio_equal_v = ratio_equal<R1, R2>::value;
    template<class R1, class R2> inline constexpr bool ratio_not_equal_v = ratio_not_equal<R1, R2>::value;
    template<class R1, class R2> inline constexpr bool ratio_less_v = ratio_less<R1, R2>::value;
    template<class R1, class R2> inline constexpr bool ratio_less_equal_v = ratio_less_equal<R1, R2>::value;
    template<class R1, class R2> inline constexpr bool ratio_greater_v = ratio_greater<R1, R2>::value;
    template<class R1, class R2> inline constexpr bool ratio_greater_equal_v = ratio_greater_equal<R1, R2>::value;

    // 21.4.6, convenience SI typedefs
    using yocto = ratio<1, 1'000'000'000'000'000'000'000'000'; // see below
    using zepto = ratio<1, 1'000'000'000'000'000'000'000'; // see below
    using atto = ratio<1, 1'000'000'000'000'; // see below
    using femto = ratio<1, 1'000'000'; // see below
    using pico = ratio<1, 1'000'; // see below
    using nano = ratio<1, 1'; // see below
    using milli = ratio<1, 1'; // see below
    using centi = ratio<1, 1'; // see below
    using deci = ratio<1, 10'; // see below
    using deca = ratio<1, 100'; // see below
    using hecto = ratio<1, 1'000'; // see below
    using kilo = ratio<1, 1'000'; // see below
    using mega = ratio<1, 1'000'; // see below
    using giga = ratio<1, 1'; // see below
    using tera = ratio<1, 1'; // see below
    using peta = ratio<1, 1'; // see below
    using exa = ratio<1, 1'; // see below
    using zetta = ratio<1, 1'; // see below
    using yotta = ratio<1, 1'; // see below
}
```

### 21.4.3 Class template ratio

```cpp
namespace std {

    template<intmax_t N, intmax_t D = 1> class ratio {

    public:

    // 21.4.3, class template ratio
    template<intmax_t N, intmax_t D = 1> class ratio {
```
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]

2 The static data members num and den shall have the following values, where gcd represents the greatest common divisor of the absolute values of N and D:

   \[ (2.1) \] num shall have the value \( \text{sign}(N) \times \text{sign}(D) \times \text{abs}(N) / \text{gcd} \).

   \[ (2.2) \] den shall have the value \( \text{abs}(D) / \text{gcd} \).

21.4.4 Arithmetic on ratios

Each of the alias templates ratio_add, ratio_subtract, ratio_multiply, and ratio_divide denotes the result of an arithmetic computation on two ratios R1 and R2. With X and Y computed (in the absence of arithmetic overflow) as specified by Table 55, each alias denotes a ratio<U, V> such that U is the same as ratio<X, Y>::num and V is the same as ratio<X, Y>::den.

2 If it is not possible to represent U or V with intmax_t, the program is ill-formed. Otherwise, an implementation should yield correct values of U and V. If it is not possible to represent X or Y with intmax_t, the program is ill-formed unless the implementation yields correct values of U and V.

<table>
<thead>
<tr>
<th>Type</th>
<th>Value of X</th>
<th>Value of Y</th>
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<td>ratio_add&lt;R1, R2&gt;</td>
<td>R1::num * R2::den + R1::den * R2::den</td>
<td>R1::den * R2::den</td>
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<td>ratio_subtract&lt;R1, R2&gt;</td>
<td>R1::num * R2::den - R1::den * R2::den</td>
<td>R1::den * R2::den</td>
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<tr>
<td>ratio_multiply&lt;R1, R2&gt;</td>
<td>R1::num * R2::num R1::den * R2::den</td>
<td>R1::den * R2::den</td>
</tr>
<tr>
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<td>R1::num * R2::num R1::den * R2::den</td>
<td>R1::den * R2::den</td>
</tr>
</tbody>
</table>

3 [Example 1:]

    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 example]

21.4.5 Comparison of ratios

```cpp
template<class R1, class R2>
struct ratio_equal : bool_constant<R1::num == R2::num && R1::den == R2::den> { };
```

```cpp
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 \( R1::\text{num} \times R2::\text{den} \) is less than \( R2::\text{num} \times R1::\text{den} \), ratio_less\(<R1, R2> \) shall be derived from bool_constant<true>; otherwise it shall be derived from bool_constant>false>. Implementations may use other algorithms to compute this relationship to avoid overflow. If overflow occurs, the program is ill-formed.

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

1 For each of the typedef-names yocto, zepto, zetta, and yotta, 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 56.

Table 56: General utilities library summary

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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>
    constexpr remove_reference_t<T>&& move(T&&) noexcept;
    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;
```

§ 22.1
// 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&) = 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 bool in_range(T t) noexcept;

// 22.2.8, to_underlying
template<class T>
constexpr underlying_type_t<T> to_underlying(T value) noexcept;

// 22.2.9, unreachable
[[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_integer_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, class TQual, 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&lt;pair&lt;T1, T2&gt;, pair&lt;U1, U2&gt;&gt; {
    using type = pair&lt;common_type_t&lt;T1, U1&gt;, common_type_t&lt;T2, U2&gt;&gt;;
};

// 22.3.3, pair specialized algorithms
-template&lt;class T1, class T2&gt;
    constexpr bool operator==(const pair&lt;T1, T2&gt;&, const pair&lt;T1, T2&gt;&amp);
-template&lt;class T1, class T2&gt;
    constexpr common_comparison_category_t&lt;synth-three-way-result&lt;T1&gt;, synth-three-way-result&lt;T2&gt;&gt;
    operator&lt;=&gt;(const pair&lt;T1, T2&gt;&, const pair&lt;T1, T2&gt;&amp);

-template&lt;class T1, class T2&gt;
    constexpr void swap(pair&lt;T1, T2&gt;&amp x, pair&lt;T1, T2&gt;&amp y) noexcept(noexcept(x.swap(y)));
-template&lt;class T1, class T2&gt;
    constexpr void swap(const pair&lt;T1, T2&gt;&amp x, const pair&lt;T1, T2&gt;&amp y)
    noexcept(noexcept(x.swap(y)));

-template&lt;class T1, class T2&gt;
    constexpr see below make_pair(T1&amp, T2&amp);

// 22.3.4, tuple-like access to pair
-template&lt;class T&gt; struct tuple_size;
-template&lt;size_t I, class T&gt; struct tuple_element;
-template&lt;class T1, class T2&gt; struct tuple_size&lt;pair&lt;T1, T2&gt;&gt;;
-template&lt;size_t I, class T1, class T2&gt; struct tuple_element&lt;I, pair&lt;T1, T2&gt;&gt;;

-template&lt;size_t I, class T1, class T2&gt;
    constexpr tuple_element_t&lt;I, pair&lt;T1, T2&gt;&gt;&amp get(pair&lt;T1, T2&gt;&amp) noexcept;
-template&lt;size_t I, class T1, class T2&gt;
    constexpr tuple_element_t&lt;I, pair&lt;T1, T2&gt;&amp&amp get(pair&lt;T1, T2&gt;&amp&amp) noexcept;
-template&lt;size_t I, class T1, class T2&gt;
    constexpr const tuple_element_t&lt;I, pair&lt;T1, T2&gt;&gt;&amp get(const pair&lt;T1, T2&gt;&amp) noexcept;
-template&lt;size_t I, class T1, class T2&gt;
    constexpr const tuple_element_t&lt;I, pair&lt;T1, T2&gt;&amp&amp get(const pair&lt;T1, T2&gt;&amp&amp) noexcept;

-template&lt;class T1, class T2&gt;
    constexpr T1&amp get(pair&lt;T1, T2&gt;&amp p) noexcept;
-template&lt;class T1, class T2&gt;
    constexpr const T1&amp get(const pair&lt;T1, T2&gt;&amp p) noexcept;
-template&lt;class T1, class T2&gt;
    constexpr T1&amp&amp get(pair&lt;T1, T2&gt;&amp&amp p) noexcept;
-template&lt;class T1, class T2&gt;
    constexpr const T1&amp&amp get(const pair&lt;T1, T2&gt;&amp&amp p) noexcept;
-template&lt;class T2, class T1&gt;
    constexpr T2&amp get(pair&lt;T1, T2&gt;&amp p) noexcept;
-template&lt;class T2, class T1&gt;
    constexpr const T2&amp get(const pair&lt;T1, T2&gt;&amp p) noexcept;
-template&lt;class T2, class T1&gt;
    constexpr T2&amp&amp get(pair&lt;T1, T2&gt;&amp&amp p) noexcept;
-template&lt;class T2, class T1&gt;
    constexpr const T2&amp&amp get(const pair&lt;T1, T2&gt;&amp&amp p) noexcept;

// 22.3.5, pair piecewise construction
-struct piecewise_construct_t {
    explicit piecewise_construct_t() = default;
};
-inline constexpr piecewise_construct_t() = default;
-template&lt;class... Types&gt; class tuple;  // defined in &lt;tuple&gt; (22.4.2)

// in-place construction
-struct in_place_t {
    explicit in_place_t() = default;
};

§ 22.2.1
inline constexpr in_place_t in_place{};

template<class T>
   struct in_place_type_t {
      explicit in_place_type_t() = default;
   };

template<class T> inline 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> inline constexpr in_place_index_t<I> in_place_index{};

22.2.2 swap [utility.swap]

template<class T>
   constexpr void swap(T& a, T& b) noexcept;

Constraints: is_move_constructible_v<T> is true and is_move_assignable_v<T> is true.

Preconditions: Type T meets the Cpp17MoveConstructible (Table 30) and Cpp17MoveAssignable (Table 32) requirements.

Effects: Exchanges values stored in two locations.

Remarks: This function is a designated customization point (16.4.5.2.1). 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>);

Constraints: is_swappable_v<T> is true.

Preconditions: a[i] is swappable with (16.4.4.3) b[i] for all i in the range [0, N).

Effects: As if by swap_ranges(a, a + N, b).

22.2.3 exchange [utility.exchange]

template<class T, class U = T>
   constexpr T exchange(T& obj, U&& new_val) noexcept;

Effects: Equivalent to:
   T old_val = std::move(obj);
   obj = std::forward<U>(new_val);
   return old_val;

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 [forward]

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;

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
default 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 a rvalue. — end example

template<class T> constexpr remove_reference_t<T>&& move(T&& t) noexcept;

Returns:
static_cast<remove_reference_t<T>&&>(t).

Example 2:

template<class T, class A1>
shared_ptr<T> factory(A1&& a1) {
    return shared_ptr<T>(new T(std::forward<A1>(a1)));   
}

struct 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 remove_reference_t<T>&& move(T&& t) noexcept;

Returns: std::move(x).

22.2.5 Function template as_const

template<class T> constexpr add_const_t<T>& as_const(T& t) noexcept;

Returns: t.

22.2.6 Function template declval

The library provides the function template declval to simplify the definition of expressions which occur as
unevaluated operands (7.2.3).

template<class T> 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

```cpp
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);
```

```cpp
template<class T, class U>
constexpr bool cmp_not_equal(T t, U u) noexcept;
Effects: Equivalent to: return !cmp_equal(t, u);
```

```cpp
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);
```

```cpp
template<class T, class U>
constexpr bool cmp_greater(T t, U u) noexcept;
Effects: Equivalent to: return cmp_less(u, t);
```

```cpp
template<class T, class U>
constexpr bool cmp_less_equal(T t, U u) noexcept;
Effects: Equivalent to: return !cmp_greater(t, u);
```

```cpp
template<class T, class U>
constexpr bool cmp_greater_equal(T t, U u) noexcept;
Effects: Equivalent to: return !cmp_less(t, u);
```

```cpp
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

```cpp
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

```cpp
[[noreturn]] void unreachable();
```

Preconditions: `false` is `true`.

[Note 1: This precondition cannot be satisfied, thus the behavior of calling unreachable is undefined. — end note]

22.3 Pairs

22.3.1 In 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 22.4.6 and 22.4.7).

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(pair<U1, U2>& p));
        template<class U1, class U2>
        constexpr explicit(pair(pair<U1, U2>&& p));
        template<class U1, class U2>
        constexpr explicit(pair(const pair<U1, U2>& p));
        template<class U1, class U2>
        constexpr explicit(pair(const pair<U1, U2>&& p));
        template<class... Args1, class... Args2>
        constexpr pair(piecewise_construct_t,
                        tuple<Args1...> first_args,
                        tuple<Args2...> second_args);
    }
}
```
constexpr pair& operator=(const pair& p);
constexpr const pair& operator=(const pair& p) const;
template<class U1, class U2>
  constexpr pair& operator=(const pair<U1, U2>& p);
  constexpr const pair& operator=(const pair<U1, U2>& p) const;
template<class U1, class U2>
  constexpr pair& operator=(pair<U1, U2>& p);
  constexpr const pair& operator=(pair<U1, U2>& p) const;
constexpr pair& operator=(pair&& p) noexcept;
constexpr const pair& operator=(pair&& p) const;
template<class U1, class U2>
  constexpr pair& operator=(pair<U1, U2>&& p);
  constexpr const pair& operator=(pair<U1, U2>&& p) const;
constexpr void swap(pair& p) noexcept;
constexpr void swap(const pair& p) const noexcept;
}

template<class T1, class T2>
pair(T1, T2) -> pair<T1, T2>;

1 Constructors and member functions of pair do not throw exceptions unless one of the element-wise operations specified to be called for that operation throws an exception.

2 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 satisfy the requirements for a constexpr function.

3 If (is_trivially_destructible_v<T1> && is_trivially_destructible_v<T2>) is true, then the destructor of pair is trivial.

4 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:
(5.1) — is_default_constructible_v<T1> is true and
(5.2) — 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:
(8.1) — is_copy_constructible_v<T1> is true and
(8.2) — 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:
(11.1) — is_constructible_v<T1, U1> is true and
(11.2) — 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:

\[ !\text{is_convertible_v}<U1, T1> \ || !\text{is_convertible_v}<U2, T2> \]

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.

```cpp
template<class U1, class U2> constexpr explicit(pair<U1, U2>& p);
template<class U1, class U2> constexpr explicit(const pair<U1, U2>& p);
template<class U1, class U2> constexpr explicit(pair<U1, U2>&& p);
template<class U1, class U2> constexpr explicit(const pair<U1, U2>&& p);
```

Let \(FWD(u)\) be `static_cast<decltype(u)>(u)`.

Constraints:

\( (15.1) \)  
- `is_constructible_v<T1, decltype(get<0>(FWD(p)))>` is true and
\( (15.2) \)  
- `is_constructible_v<T2, decltype(get<1>(FWD(p)))>` is true.

Effects: Initializes first with `get<0>(FWD(p))` and second with `get<1>(FWD(p))`.

Remarks: The expression inside `explicit` is equivalent to:

\[ !\text{is_convertible_v}<\text{decltype(get<0>(FWD(p)))}, T1> \ || !\text{is_convertible_v}<\text{decltype(get<1>(FWD(p)))}, T2> \]

The constructor is defined as deleted if

\[ \text{reference_constructs_from_temporary_v<first_type, decltype(get<0>(FWD(p)))>} \ || \text{reference_constructs_from_temporary_v<second_type, decltype(get<1>(FWD(p)))>} \]

is true.

```cpp
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]

```cpp
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.

```cpp
constexpr const pair& operator=(const pair& p) const;
```

Constraints:

\( (23.1) \)  
- `is_copy_assignable_v<const T1>` is true
\( (23.2) \)  
- `is_copy_assignable_v<const T2>` is true.

Effects: Assigns `p.first` to first and `p.second` to second.

Returns: `*this`.

```cpp
template<class U1, class U2> constexpr pair& operator=(const pair<U1, U2>& p);
```

Constraints:
isAssignable_v<T1&, const U1&> is true and
isAssignable_v<T2&, const U2&> is true.

Effects: Assigns p.first to first and p.second to second.
Returns: *this.

Effects: Assigns p.first to first and p.second to second.
Returns: *this.

Effects: Assigns to first with std::forward<T1>(p.first) and to second with std::forward<T2>(p.second).
Returns: *this.
Remarks: The exception specification is equivalent to:

isNothrow_move_assignable_v<T1> && isNothrow_move_assignable_v<T2>

Effects: Assigns std::forward<T1>(p.first) to first and std::forward<T2>(p.second) to second.
Returns: *this.

Effects: Assigns to first with std::forward<U1>(p.first) and to second with std::forward<U2>(p.second).
Returns: *this.

Mandates:
— For the first overload, is_swap_v<T1> is true and is_swap_v<T2> is true.
For the second overload, \(\text{is\_swappable\_v<\text{const T1}>}\) is true and \(\text{is\_swappable\_v<\text{const T2}>}\) is true.

**Preconditions:** \(\text{first}\) is swappable with (16.4.4.3) \(\text{p.first}\) and \(\text{second}\) is swappable with \(\text{p.second}\).

**Effects:** Swaps \(\text{first}\) with \(\text{p.first}\) and \(\text{second}\) with \(\text{p.second}\).

**Remarks:** The exception specification is equivalent to:

- \(\text{is\_nothrow\_swappable\_v<T1> && is\_nothrow\_swappable\_v<T2>}\) for the first overload, and
- \(\text{is\_nothrow\_swappable\_v<\text{const T1}> && is\_nothrow\_swappable\_v<\text{const T2}>}\) for the second overload.

### 22.3.3 Specialized algorithms

**Template:**

```cpp
template<class T1, class T2>
constexpr bool operator==(const pair<T1, T2>& x, const pair<T1, T2>& y);
```

**Returns:** \(x.\text{first} == y.\text{first} && x.\text{second} == y.\text{second}\).

**Effects:** Equivalent to:

- If \(c = \text{synth\_three\_way}(x.\text{first}, y.\text{first})\) and \(c != 0\), return \(c\),
- Return \(\text{synth\_three\_way}(x.\text{second}, y.\text{second})\).

**Constraints:**

- For the first overload, \(\text{is\_swappable\_v<T1>}\) is true and \(\text{is\_swappable\_v<T2>}\) is true.
- For the second overload, \(\text{is\_swappable\_v<\text{const T1}>}\) is true and \(\text{is\_swappable\_v<\text{const T2}>}\) is true.

**Effects:** Equivalent to \(x.\text{swap}(y)\).

**Template:**

```cpp
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, \(\text{is\_swappable\_v<T1>}\) is true and \(\text{is\_swappable\_v<T2>}\) is true.
- For the second overload, \(\text{is\_swappable\_v<\text{const T1}>}\) is true and \(\text{is\_swappable\_v<\text{const T2}>}\) is true.

**Effects:** Equivalent to \(x.\text{swap}(y)\).

**Template:**

```cpp
template<class T1, class T2>
constexpr pair<unwrap_ref_decay_t<T1>, unwrap_ref_decay_t<T2>> make_pair(T1&& x, T2&& y);
```

**Returns:**

- \(\text{pair<unwrap\_ref\_decay\_t<T1>, unwrap\_ref\_decay\_t<T2>>}(\text{std::forward<T1>(x)}, \text{std::forward<T2>(y)})\)

**Example:** In place of:

```cpp
return pair<int, double>(5, 3.1415926); // explicit types
```

a C++ program may contain:

```cpp
return make_pair(5, 3.1415926); // types are deduced
```

--- end example

### 22.3.4 Tuple-like access to pair

**Template:**

```cpp
template<class T1, class T2>
struct tuple_size<pair<T1, T2>> : integral_constant<size_t, 2> {}; // pair.astuple
```

**Mandates:** \(I < 2\).

**Type:** The type \(T1\) if \(I\) is 0, otherwise the type \(T2\).
Mandates: I < 2.

Returns:

(4.1) — If I is 0, returns a reference to p.first.
(4.2) — If I is 1, returns a reference to p.second.

Mandates: T1 and T2 are distinct types.

Returns: A reference to p.first.

Mandates: T1 and T2 are distinct types.

Returns: A reference to p.second.

22.3.5 Piecewise construction [pair.piecewise]

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_t 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 In 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.
namespace std {
  // 22.4.3, class template tuple
  template<class... Types>
  class tuple;

  template<class... TTypes, class... UTypes, template<class> class TQual,
    template<class> class UQual>
  requires requires { typename tuple<common_reference_t<TQual<TTypes>, UQual<UTypes>>...>; }
  struct basic_common_reference<tuple<TTypes...>, tuple<UTypes...>, TQual, UQual> {
    using type = tuple<common_reference_t<TQual<TTypes>, UQual<UTypes>>...>;
  };

  template<class... TTypes, class... UTypes>
  requires requires { typename tuple<common_type_t<TTypes, UTypes>...>; }
  struct common_type<tuple<TTypes...>, tuple<UTypes...>> {
    using type = tuple<common_type_t<TTypes, UTypes>...>;
  };

  // 22.4.4, tuple creation functions
  inline constexpr
  unspecified ignore;

  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<class... Tuples>
  constexpr tuple<CTypes...> tuple_cat(Tuples&&...);

  // 22.4.5, calling a function with a tuple of arguments
  template<class F, class Tuple>
  constexpr decltype(auto) apply(F&& f, Tuple&& t);

  template<class T, class Tuple>
  constexpr T make_from_tuple(Tuple&& t);

  // 22.4.6, tuple helper classes
  template<class T> struct tuple_size;          // not defined
  template<class T> struct tuple_size<const T>;

  template<class... Types> struct tuple_size<tuple<Types...>>;

  template<size_t I, class T> struct tuple_element;

  template<size_t I, class... Types> struct tuple_element<I, tuple<Types...>>;

  template<size_t I, class T>
  using tuple_element_t = typename tuple_element<I, T>::type;

  // 22.4.7, 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, tuple<Types...>>& get(const tuple<Types...>&) noexcept;
  template<size_t I, class... Types>
  constexpr tuple_element_t<I, tuple<Types...>>& get(const tuple<Types...>&&) noexcept;

  template<size_t I, class... Types>
  constexpr tuple_element_t<I, tuple<Types...>>& get(const tuple<Types...>&&&) noexcept;
  template<size_t I, class... Types>
  constexpr tuple_element_t<I, tuple<Types...>>& get(const tuple<Types...>&&&) noexcept;

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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;

// 22.4.8, 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...>&);

// 22.4.9, allocator-related traits
template<class... Types, class Alloc>
struct uses_allocator<tuple<Types...>, Alloc>;

// 22.4.10, specialized algorithms
template<class... Types>
constexpr bool operator==(const tuple<Types...>&, const tuple<Types...>&);

// 22.4.6, tuple helper classes
template<class T>
inline constexpr size_t tuple_size_v = tuple_size<T>::value;

22.4.3  Class template tuple

namespace std {
    template<class... Types>
    class tuple {
public:
        // 22.4.3.1, tuple construction
        constexpr explicit(see below) tuple();
        constexpr explicit(see below) tuple(const Types&...);
        template<class... UTypes>
        constexpr explicit(see below) tuple(UTypes&&...);
        tuple(const tuple&) = default;
        tuple(tuple&&) = default;
        template<class... UTypes>
        constexpr explicit(see below) tuple(const tuple<UTypes...>&);
        template<class... UTypes>
        constexpr explicit(see below) tuple(const 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>&&);
    } // class tuple
} // namespace std
// allocator-extended constructors

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, 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 tuple& operator=(const pair<U1, U2>&); // only if sizeof...(Types) == 2

template<class Alloc, class U1, class U2>
constexpr const tuple& operator=(const pair<U1, U2>&) const; // only if sizeof...(Types) == 2

template<class Alloc, class U1, class U2>
constexpr tuple& operator=(pair<U1, U2>&&); // only if sizeof...(Types) == 2

template<class Alloc, class U1, class U2>
constexpr const tuple& operator=(pair<U1, U2>&&) const; // only if sizeof...(Types) == 2

§ 22.4.3
22.4.3.1 Construction [tuple.cnstr]

1 In the descriptions that follow, let \( i \) be in the range \( [0, \text{sizeof...(Types)}) \) 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.

2 For each \texttt{tuple} constructor, an exception is thrown only if the construction of one of the types in \( \text{Types} \) throws an exception.

3 The defaulted move and copy constructor, respectively, of \texttt{tuple} is a constexpr function if and only if all required element-wise initializations for move and copy, respectively, would satisfy the requirements for a constexpr function. The defaulted move and copy constructor of \texttt{tuple<>} are constexpr functions.

4 If \texttt{is_trivially_destructible_v<T_i>} is true for all \( T_i \), then the destructor of \texttt{tuple} is trivial.

5 The default constructor of \texttt{tuple<>} is trivial.

6 constexpr explicit(see below) \texttt{tuple()};

   \begin{itemize}
   \item \textbf{Constraints:} \texttt{is_default_constructible_v<T_i>} is true for all \( i \).
   \end{itemize}

7 Effects: Value-initializes each element.

8 Remarks: The expression inside \texttt{explicit} evaluates to true if and only if \( T_i \) is not copy-list-initializable from an empty list for at least one \( i \).

9 \begin{itemize}
   \item \texttt{constraints explicit(see below) tuple(const Types&...)};
   \end{itemize}

10 \begin{itemize}
   \item \textbf{Constraints:} \texttt{sizeof...(Types)} \( \geq 1 \) and \texttt{is_copy_constructible_v<T_i>} is true for all \( i \).
   \end{itemize}

11 Effects: Initializes each element with the value of the corresponding parameter.

12 Remarks: The expression inside \texttt{explicit} is equivalent to:

13 \begin{itemize}
   \item !\texttt{conjunction_v<\texttt{is_convertible<const Types&, Types>...>}}
   \end{itemize}

14 template<class... UTypes> constexpr explicit(see below) \texttt{tuple(UTypes&amp;... u)};

15 Let \texttt{disambiguating-constraint} be:

16 \begin{itemize}
   \item \texttt{negation<is_same<\texttt{remove_cvref_t<U_0>, U_0}, \texttt{tuple burner> if sizeof...(Types) is 1;}
   \item otherwise, \texttt{bool_constant<!is_same_v<\texttt{remove_cvref_t<U_0>, allocator_arg_t}> \|
   \texttt{is_same_v<\texttt{remove_cvref_t<T_0>, allocator_arg_t}> if sizeof...(Types) is 2 or 3;}
   \item otherwise, \texttt{true_type}.
   \end{itemize}

17 Constraints:

18 \begin{itemize}
   \item \texttt{sizeof...(Types)} equals \texttt{sizeof...(UTypes)},
   \item \texttt{sizeof...(Types)} \( \geq 1 \), and
   \item \texttt{conjunction_v<\texttt{disambiguating-constraint, is_constructible<Types, UTypes>...>}} is true.
   \end{itemize}
**Effects:** Initializes the elements in the tuple with the corresponding value in `std::forward<UTypes>(u)`.

**Remarks:** The expression inside `explicit` is equivalent to:

\[
\lnot \text{conjunction}_v<\text{is\_convertible<UTypes, Types>>}\ldots
\]

This constructor is defined as deleted if

\[
(\text{reference\_constructs\_from\_temporary_v<Types, UTypes\&\&> || \ldots})
\]

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`.

```cpp
tuple(tuple&& u) = default;
```

**Constraints:**

- `sizeof...(Types)` equals `sizeof...(UTypes)`, and
- `(is_constructible_v<T_i, decltype(get<i>(FWD(u)))> && \ldots)` is true, and
- 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.

**Effects:** For all `i`, initializes the `i`th element of `*this` with `std::forward<T_i>(get<i>(u))`.

**Remarks:** The expression inside `explicit` is equivalent to:

\[
!(is\_convertible_v<decltype(get<i>(FWD(u))), T_i> && \ldots)
\]

The constructor is defined as deleted if

\[
(\text{reference\_constructs\_from\_temporary_v<Types, decltype(get<i>(FWD(u)))> || \ldots})
\]

is true.

```cpp
template<class U1, class U2> constexpr explicit(see below) tuple<pair<U1, U2>& u);
template<class U1, class U2> constexpr explicit(see below) tuple(const pair<U1, U2>& u);
template<class U1, class U2> constexpr explicit(see below) tuple<pair<U1, U2>&& u);
template<class U1, class U2> constexpr explicit(see below) tuple(const pair<U1, U2>&& u);
```

Let `FWD(u)` be `static\_cast<decltype(u)>`(u).

**Constraints:**

- `(21.1)` `sizeof...(Types)` is 2,
- `(21.2)` `is\_constructible_v<T_i, decltype(get<i>(FWD(u)))> && \ldots)` is true, and
- `(21.3)` `is\_constructible_v<T_i, decltype(get<i>(FWD(u)))> && \ldots)` is true.

**Effects:** Initializes the first element with `get<0>(FWD(u))` and the second element with `get<1>(FWD(u))`.

**Remarks:** The expression inside `explicit` is equivalent to:

\[
!(is\_convertible_v<decltype(get<0>(FWD(u))), T_0> ||
!is\_convertible_v<decltype(get<1>(FWD(u))), T_1>)
\]

The constructor is defined as deleted if

\[
\text{reference\_constructs\_from\_temporary_v<Types, decltype(get<0>(FWD(u)))> ||
\text{reference\_constructs\_from\_temporary_v<Types, decltype(get<1>(FWD(u)))> ||}
\]

§ 22.4.3.1
reference_constructs_from_temporary_v<T_0, decltype(get<0>(FWD(u)))> ||
reference_constructs_from_temporary_v<T_1, decltype(get<1>(FWD(u)))>

is true.

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, 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>&);

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>&&);

Preconditions: Alloc meets the Cpp17Allocator requirements (16.4.4.6.1).

Effects: Equivalent to the preceding constructors except that each element is constructed with use-allocator construction (20.2.7.2).

22.4.3.2 Assignment [tuple.assign]

For each tuple assignment operator, an exception is thrown only if the assignment of one of the types in Types throws an exception. In the function 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.

constexpr tuple& operator=(const tuple& u);

Effects: Assigns each element of u to the corresponding element of *this.

Returns: *this.

Remarks: This operator is defined as deleted unless is_copy_assignable_v<T_i> is true for all i.

constexpr const tuple& operator=(const tuple& u) const;

Constraints: (is_copy_assignable_v<const Types> && ...) is true.

Effects: Assigns each element of u to the corresponding element of *this.

Returns: *this.
constexpr tuple& operator=(tuple&& u) noexcept(see below);

Constraints: \( \text{is\_move\_assignable\_v<T_i>} \) is true for all \( i \).
Effects: For all \( i \), assigns \( \text{std::forward<T_i>}(\text{get<i>}(u)) \) to \( \text{get<i>}(*\text{this}) \).
Returns: *this.
Remarks: The exception specification is equivalent to the logical AND of the following expressions:
where \( T_i \) is the \( i \)th type in \( \text{Types} \).

constexpr const tuple& operator=(tuple&& u) const;

Constraints: \( \text{is\_assignable\_v<const Types&, Types> 

Effects: For all \( i \), assigns \( \text{std::forward<T_i>}(\text{get<i>}(u)) \) to \( \text{get<i>}(*\text{this}) \).
Returns: *this.

template<class... UTypes> constexpr tuple& operator=(const tuple<UTypes...>& u);

Constraints:

- \( \text{sizeof...(Types)} \) equals \( \text{sizeof...(UTypes)} \) and
- \( \text{is\_assignable\_v<T_i, const U_i&>} \) is true for all \( i \).
Effects: Assigns each element of \( u \) to the corresponding element of \( *\text{this} \).
Returns: *this.

template<class... UTypes> constexpr const tuple& operator=(const tuple<UTypes...>& u) const;

Constraints:

- \( \text{sizeof...(Types)} \) equals \( \text{sizeof...(UTypes)} \) and
- \( \text{is\_assignable\_v<const Types&, const UTypes&> 

Effects: Assigns each element of \( u \) to the corresponding element of \( *\text{this} \).
Returns: *this.

template<class... UTypes> constexpr tuple& operator=(tuple<UTypes...>&& u);

Constraints:

- \( \text{sizeof...(Types)} \) equals \( \text{sizeof...(UTypes)} \) and
- \( \text{is\_assignable\_v<T_i, U_i>} \) is true for all \( i \).
Effects: For all \( i \), assigns \( \text{std::forward<U_i>}(\text{get<i>}(u)) \) to \( \text{get<i>}(*\text{this}) \).
Returns: *this.

template<class... UTypes> constexpr const tuple& operator=(tuple<UTypes...>&& u) const;

Constraints:

- \( \text{sizeof...(Types)} \) equals \( \text{sizeof...(UTypes)} \) and
- \( \text{is\_assignable\_v<const Types&, UTypes> 

Effects: For all \( i \), assigns \( \text{std::forward<U_i>}(\text{get<i>}(u)) \) to \( \text{get<i>}(*\text{this}) \).
Returns: *this.

template<class U1, class U2> constexpr tuple& operator=(const pair<U1, U2>& u);

Constraints:

- \( \text{sizeof...(Types)} \) is 2 and
- \( \text{is\_assignable\_v<T_i, U1&>} \) is true, and
- \( \text{is\_assignable\_v<T_i, U2&>} \) is true.
Effects: Assigns \( u.\text{first} \) to the first element of \( *\text{this} \) and \( u.\text{second} \) to the second element of \( *\text{this} \).
Returns: *this.

§ 22.4.3.2
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 T0&, const U1&> is true, and
(30.3) is_assignable_v<const T1&, 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<T0&, U1> is true, and
(33.3) is_assignable_v<T1&, U2> is true.

Effects: Assigns std::forward<U1>(u.first) to the first element of *this and std::forward<U2>(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 T0&, U1> is true, and
(36.3) is_assignable_v<const T1&, U2> is true.

Effects: Assigns std::forward<U1>(u.first) to the first element and std::forward<U2>(u.second) to the second element.
Returns: *this.

22.4.3.3 swap

constexpr void swap(tuple& rhs) noexcept(see below);
constexpr void swap(const tuple& rhs) const noexcept(see below);

Mandates:
(1.1) For the first overload, (is_swappable_v<Types> && ...) is true.
(1.2) For the second overload, (is_swappable_v<const Types> && ...) is true.

Preconditions: Each element in *this is swappable with (16.4.4.3) the corresponding element in rhs.

Effects: Calls swap for each element in *this and its corresponding element in rhs.

Throws: Nothing unless one of the element-wise swap calls throws an exception.

Remarks: The exception specification is equivalent to
(5.1) (is_nothrow_swappable_v<Types> && ...) for the first overload and
(5.2) (is_nothrow_swappable_v<const Types> && ...) for the second overload.

22.4.4 Tuple creation functions

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(i, ref(i), cref(j))
creates a tuple of type tuple<int, int&, const float&>. — end example]
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)...).

Returns: tuple<TTypes&...>(t...).

Returns: A tuple object constructed by initializing the k_{i}th type element e_{i} in e_{i}... with

get<k_{i}>(std::forward<T>(tp...))
for each valid k_{i} and each group e_{i} in order.

[Note 1: An implementation can support additional types in the template parameter pack Tuples that support the tuple-like protocol, such as pair and array. —end note]

22.4.5 Calling a function with a tuple of arguments [tuple.apply]

Effects: Given the exposition-only function:

namespace std {
  template<class F, class Tuple>
  constexpr decltype(auto) apply(F&& f, Tuple&& t);
}

Equivalent to:

return apply-impl(std::forward<F>(f), std::forward<Tuple>(t), make_index_sequence<tuple_size_v<remove_reference_t<Tuple>>>{});
template<class T, class Tuple>
constexpr T make_from_tuple(Tuple&& t);

Mandates: If \(\text{tuple\_size\_v<\text{remove\_reference\_t\langle Tuple\rangle}>}=1\), then \(\text{reference\_constructs\_from\_temporary\_v\langle T\rangle, decltype(get<0>(\text{declval\langle Tuple\rangle}())))\) is false.

Effects: Given the exposition-only function:

```cpp
namespace std {
    template<class T, class 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:

```cpp
return make-from-tuple-impl<
    std::forward<Tuple>(t),
    make_index_sequence<
        tuple_size_v<\text{remove\_reference\_t\langle Tuple\rangle}>>{}`

[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]

22.4.6 Tuple helper classes

```cpp
template<class T>
struct tuple_size;
```

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: \(I < \text{sizeof...\langle Types\rangle}\).

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 `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.
22.4.7 Element access

.template<size_t I, class... Types>
  constexpr tuple_element_t<I, tuple<Types...>>&
  get(tuple<Types...>& t) noexcept; // Note A
.template<size_t I, class... Types>
  constexpr tuple_element_t<I, tuple<Types...>>&
  get(tuple<Types...>&& t) noexcept; // Note A
.template<size_t I, class... Types>
  constexpr const tuple_element_t<I, tuple<Types...>>&
  get(const tuple<Types...>& t) noexcept; // Note B
.template<size_t I, class... Types>
  constexpr const tuple_element_t<I, tuple<Types...>>&
  get(const tuple<Types...>&& t) noexcept; // Note B

Mandates: I < sizeof...(Types).

Returns: A reference to the I\textsuperscript{th} element of t, where indexing is zero-based.

[Note 1: [Note A] 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: [Note B] Constness is shallow. If a type T in Types is some reference type X&, the return type is X&, not const X&. However, if the element type is a non-reference type T, the return type is 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; // Note 3
.template<class T, class... Types>
  constexpr T&&
  get(tuple<Types...>&& t) noexcept; // Note 3
.template<class T, class... Types>
  constexpr const T&
  get(const tuple<Types...>& t) noexcept; // Note 3
.template<class T, class... Types>
  constexpr const T&&
  get(const tuple<Types...>&& t) noexcept; // Note 3

Mandates: The type T occurs exactly once in Types.

Returns: A reference to the element of t corresponding to the type T in Types.

[Note 3: The reason 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 template keyword. —end note]

22.4.8 Relational operators

.template<class... TTypes, class... UTypes>
  constexpr bool operator==(const tuple<TTypes...>& t, const tuple<UTypes...>& u);

Mandates: For all i, where 0 ≤ i < sizeof...(TTypes), get<i>(t) == get<i>(u) is a valid expression returning a type that is convertible to bool. sizeof...(TTypes) equals sizeof...(UTypes).

Returns: true if get<i>(t) == get<i>(u) for all i, otherwise false. For any two zero-length tuples e and f, e == f returns true.

Remarks: 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 false.

.template<class... TTypes, class... UTypes>
  common_comparison_category_t<
synth-three-way-result<TTypes, UTypes>...
>
operator<=>(const tuple<TTypes...>& t, const tuple<UTypes...>&& u);

Effects: Performs a lexicographical comparison between t and u. For any two zero-length tuples t and u, t <=> u returns strong_ordering::equal. Otherwise, equivalent to:
if (auto c = synth-three-way(get<0>(t), get<0>(u)); c != 0) return c;
return t_tail <=> u_tail;

where r_tail for some tuple r is a tuple containing all but the first element of r.

[Note 1: 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 required to determine the result of the comparison. — end note]

22.4.9 Tuple traits

```cpp
template<class... Types, class Alloc>
struct uses_allocator<tuple<Types...>, Alloc> : true_type {};
```

1 Preconditions: Alloc meets the Cpp17Allocator requirements (16.4.4.6.1).

2 [Note 1: Specialization of this trait informs other library components that tuple can be constructed with an allocator, even though it does not have a nested allocator_type. — end note]

22.4.10 Tuple specialized algorithms

```cpp
template<class... Types>
constexpr void swap(tuple<Types...>& x, tuple<Types...>& y) noexcept;
```

```cpp
template<class... Types>
constexpr void swap(const tuple<Types...>& x, const tuple<Types...>& y) noexcept;
```

1 Constraints:

- For the first overload, (is_swappable_v<Types> && ...) is true.
- For the second overload, (is_swappable_v<const Types> && ...) is true.

2 Effects: As if by x.swap(y).

3 Remarks: The exception specification is equivalent to:

```cpp
noexcept(x.swap(y))
```

22.5 Optional objects

22.5.1 In 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

```cpp
#include <optional> // see 17.11.1

namespace std {
    // 22.5.3, class template optional
    template<class T>
    class optional;

    template<class T>
    constexpr bool is-optional = false; // exposition only
    template<class T>
    constexpr bool is-optional<optional<T>> = true; // exposition only

    // 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;
} // 22.5.2

§ 22.5.2
```
// 22.5.6, relational operators
template<class T, class U>
constexpr bool operator==(const optional<T>&, const optional<U>&);

template<class T, class U>
constexpr bool operator!=(const optional<T>&, const optional<U>&);

template<class T, class U>
constexpr bool operator<(const optional<T>&, const optional<U>&);

template<class T, class U>
constexpr bool operator>(const optional<T>&, const optional<U>&);

template<class T, class U>
constexpr bool operator<=(const optional<T>&, const optional<U>&);

template<class T, class U>
constexpr bool operator>=(const optional<T>&, const optional<U>&);

template<class T, class U>
constexpr compare_three_way_result_t<T, U>
operator<=>(const optional<T>&, const 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&);

template<class T, class U> constexpr bool operator==(const T&, const optional<U>&);

template<class T, class U> constexpr bool operator!=(const optional<T>&, const U&);

template<class T, class U> constexpr bool operator!=(const T&, const optional<U>&);

template<class T, class U> constexpr bool operator<(const optional<T>&, const U&);

template<class T, class U> constexpr bool operator<(const T&, const optional<U>&);

template<class T, class U> constexpr bool operator>(const optional<T>&, const U&);

template<class T, class U> constexpr bool operator>(const T&, const optional<U>&);

template<class T, class U> constexpr bool operator<=(const optional<T>&, const U&);

template<class T, class U> constexpr bool operator<=(const T&, const optional<U>&);

template<class T, class U> constexpr bool operator>=(const optional<T>&, const U&);

template<class T, class U> constexpr bool operator>=(const T&, const optional<U>&);

template<class T, class U> requires (!is-optional<U>) && three_way_comparable_with<T, U>
constexpr compare_three_way_result_t<T, U>
operator<=>(const optional<T>&, const U&);

// 22.5.9, specialized algorithms
template<class T>
constexpr void swap(optional<T>&, optional<T>&) noexcept(see below);

template<class T>
constexpr optional<see below> make_optional(T&&);

template<class T, class... Args>
constexpr optional<T> make_optional(Args&&... args);

template<class T, class U, class... Args>
constexpr optional<T> make_optional(initializer_list<U> il, Args&&... args);

// 22.5.10, hash support
template<class T> struct hash;

// 22.5.3 Class template optional

namespace std {

template<class T>
class optional {
public:
  using value_type = T;

...}

}}
// 22.5.3.2, constructors
constexpr optional() noexcept;
constexpr optional(nullopt_t) noexcept;
constexpr optional(const optional&);
constexpr optional(optional&&) noexcept;  
template<class... Args>
    constexpr optional(in_place_t, Args&&...);
template<class U, class... Args>
    constexpr optional(in_place_t, initializer_list<U>, Args&&...);
template<class U = T>
    constexpr optional(U&&);
    template<class U>
    constexpr optional(const optional<U>&);
template<class U>
    constexpr 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;
    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>&&);

// 22.5.3.5, swap
constexpr void swap(optional&) noexcept;

// 22.5.3.6, observers
constexpr const T* operator->() const noexcept;
constexpr T* operator->() noexcept;
constexpr const T& operator*() const & noexcept;
constexpr T& operator*() & noexcept;
constexpr T&& operator*() && noexcept;
constexpr const T&& operator*() const && noexcept;
constexpr explicit operator bool() const noexcept;
constexpr bool has_value() const noexcept;
constexpr const T& value() const &;
constexpr T& value() &;
constexpr T&& value() &&;
constexpr const T&& value() const &&;
template<class U> constexpr T value_or(U&&) const &;
    template<class U> constexpr T value_or(U&&) &&;

// 22.5.3.7, 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 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) const &;

// 22.5.3.8, modifiers
constexpr void reset() noexcept;
private:
  T *val;  // exposition only
};

template<class T>
optional(T) -> optional<T>;
}

1 Any instance of `optional<T>` at any given time either contains a value or does not contain a value. When an instance of `optional<T>` contains a value, it means that an object of type `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. The contained value shall be allocated in a region of the `optional<T>` storage suitably aligned for the type `T`. When an object of type `optional<T>` is contextually converted to `bool`, the conversion returns `true` if the object contains a value; otherwise the conversion returns `false`.

2 Member `val` is provided for exposition only. When an `optional<T>` object contains a value, `val` points to the contained value.

3 `T` shall be a type other than `cv in_place_t` or `cv nullopt_t` that meets the `Cpp17Destructible` requirements (Table 34).

### 22.5.3.2 Constructors

```cpp
constexpr optional() noexcept;
constexpr optional(nullopt_t) noexcept;
```

1 Postconditions: `*this` does not contain a value.
2 Remarks: No contained value is initialized. For every object type `T` these constructors are constexpr constructors (9.2.6).

```cpp
constexpr optional(const optional& rhs);
```

3 Effects: If `rhs` contains a value, direct-non-list-initializes the contained value with `*rhs`.
4 Postconditions: `rhs.has_value()` == `this->has_value()`.
5 Throws: Any exception thrown by the selected constructor of `T`.
6 Remarks: This constructor is defined as deleted unless `is_copy_constructible_v<T>` is true. If `is_trivially_copy_constructible_v<T>` is true, this constructor is trivial.

```cpp
constexpr optional(optional&& rhs) noexcept;
```

7 Constraints: `is_move_constructible_v<T>` is true.
8 Effects: If `rhs` contains a value, direct-non-list-initializes the contained value with `std::move(*rhs)`. `rhs.has_value()` is unchanged.
9 Postconditions: `rhs.has_value()` == `this->has_value()`.
10 Throws: Any exception thrown by the selected constructor of `T`.
11 Remarks: The exception specification is equivalent to `is_nothrow_move_constructible_v<T>`.
12 If `is_trivially_move_constructible_v<T>` is true, this constructor is trivial.

```cpp
template<class... Args> constexpr explicit optional(in_place_t, Args&&... args);
```

13 Constraints: `is_constructible_v<T, Args...>` is true.
14 Effects: Direct-non-list-initializes the contained value with `std::forward<Args>(args)....`
15 Postconditions: `*this` contains a value.
16 Throws: Any exception thrown by the selected constructor of `T`.
17 Remarks: If `T`’s constructor selected for the initialization is a constexpr constructor, this constructor is a constexpr constructor.

```cpp
template<class U, class... Args>
constexpr explicit optional(in_place_t, initializer_list<U> il, Args&&... args);
```

18 Constraints: `is_constructible_v<T, initializer_list<U>&, Args...>` is true.
Effects: Direct-non-list-initializes the contained value with \texttt{il, std::forward<Args>(args)}....

Postconditions: \texttt{*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.

\begin{verbatim}
template<class U = T> constexpr explicit(see below) optional(U& v);
\end{verbatim}

Constraints: \texttt{is_constructible_v<T, U is true, is_same_v<remove_cvref_t<U>, in_place_t> is false, and is_same_v<remove_cvref_t<U>, optional> is false.}

Effects: Direct-non-list-initializes the contained value with \texttt{std::forward<U>(v)}.

Postconditions: \texttt{*this} contains a value.

Throws: Any exception thrown by the selected constructor of \texttt{T}.

Remarks: If \texttt{T}'s selected constructor is a constexpr constructor, this constructor is a constexpr constructor. The expression inside \texttt{explicit} is equivalent to:

\begin{verbatim}
!is_convertible_v<U, T>
\end{verbatim}

\begin{verbatim}
template<class U> constexpr explicit(see below) optional(optional<U>& rhs);
\end{verbatim}

Constraints:

(27.1) \texttt{is_constructible_v<T, const U&> is true,}

(27.2) \texttt{is_constructible_v<T, optional<U>&> is false,}

(27.3) \texttt{is_constructible_v<T, optional<U>&&> is false,}

(27.4) \texttt{is_constructible_v<T, const optional<U>&> is false,}

(27.5) \texttt{is_constructible_v<T, const optional<U>&&> is false,}

(27.6) \texttt{is_convertible_v<optional<U>&, T> is false,}

(27.7) \texttt{is_convertible_v<optional<U>&& , T> is false,}

(27.8) \texttt{is_convertible_v<optional<U>&, T> is false, and}

(27.9) \texttt{is_convertible_v<optional<U>&& , T> is false.}

Effects: If \texttt{rhs} contains a value, direct-non-list-initializes the contained value with \texttt{*rhs}.

Postconditions: \texttt{rhs.has_value() == this->has_value()}.  

Throws: Any exception thrown by the selected constructor of \texttt{T}.

Remarks: The expression inside \texttt{explicit} is equivalent to:

\begin{verbatim}
!is_convertible_v<const U, T>
\end{verbatim}

\begin{verbatim}
template<class U> constexpr explicit(see below) optional(optional<U>&& rhs);
\end{verbatim}

Constraints:

(32.1) \texttt{is_constructible_v<T, U> is true,}

(32.2) \texttt{is_constructible_v<T, optional<U>&> is false,}

(32.3) \texttt{is_constructible_v<T, optional<U>&&> is false,}

(32.4) \texttt{is_constructible_v<T, const optional<U>&> is false,}

(32.5) \texttt{is_constructible_v<T, const optional<U>&&> is false,}

(32.6) \texttt{is_convertible_v<optional<U>&, T> is false,}

(32.7) \texttt{is_convertible_v<optional<U>&& , T> is false,}

(32.8) \texttt{is_convertible_v<optional<U>&, T> is false, and}

(32.9) \texttt{is_convertible_v<optional<U>&& , T> is false.}

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() == this->has_value()}.  

§ 22.5.3.2 690
35  **Throws**: Any exception thrown by the selected constructor of \( T \).

36  **Remarks**: The expression inside `explicit` is equivalent to:

\[
!\text{is_convertible_v<U, T>}
\]

22.5.3.3  **Destructor**  

```cpp
constexpr ~optional();
```

1  **Effects**: If `is_trivially_destructible_v<T> != true` and *this contains a value, calls `val->T::~T()`.

2  **Remarks**: If `is_trivially_destructible_v<T>` is true, then this destructor is trivial.

22.5.3.4  **Assignment**  

```cpp
constexpr optional<T>& operator=(nullopt_t) noexcept;
```

1  **Effects**: If *this contains a value, calls `val->T::~T()` to destroy the contained value; otherwise no effect.

2  **Postconditions**: *this does not contain a value.

3  **Returns**: *this.

```cpp
constexpr optional<T>& operator=(const optional& rhs);
```

4  **Effects**: See Table 57.

Table 57: `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 <code>*rhs</code> to the contained value</td>
</tr>
<tr>
<td>rhs does not contain a value</td>
<td>destroys the contained value by calling <code>val-&gt;T::~T()</code></td>
</tr>
</tbody>
</table>

5  **Postconditions**: `rhs.has_value() == this->has_value()`.

6  **Returns**: *this.

7  **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.

```cpp
constexpr optional& operator=(optional&& rhs) noexcept(see below);
```

8  **Constraints**: `is_move_constructible_v<T>` is true and `is_move_assignable_v<T>` is true.

9  **Effects**: See Table 58. The result of the expression `rhs.has_value()` remains unchanged.

Table 58: `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 <code>std::move(*rhs)</code> to the contained value</td>
</tr>
<tr>
<td>rhs does not contain a value</td>
<td>destroys the contained value by calling <code>val-&gt;T::~T()</code></td>
</tr>
</tbody>
</table>

§ 22.5.3.4
**Postconditions:** rhs.has_value() == this->has_value().

**Returns:** *this.

**Remarks:** The exception specification is equivalent to:

```cpp
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 true, this assignment operator is trivial.

```cpp
template<class U = T> constexpr optional<T>& operator=(U&& v);
```

**Constraints:**

- is_constructible_v<T, const U&> is true,
- isAssignable_v<T&*, const U&> is true,
- isConstructible_v<T*, optional<U&&>> is false,
- isConstructible_v<T*, optional<U>&&> is false,
- isConstructible_v<T*, const optional<U>&> is false,
- isConstructible_v<T*, const optional<U>&&> is false,
- isConvertible_v<optional<U>&, T> is false,
- isConvertible_v<optional<U>&&*, T> is false,
- isConvertible_v<optional<U>&, const T&> is false,
- isConvertible_v<optional<U>&&*, const T&> is false,
- isAssignable_v<T&*, optional<U>&> is false,
- isAssignable_v<T*, optional<U>&&> is false,
- isAssignable_v<T&, optional<U>&> is false,
- isAssignable_v<T&, optional<U>&&> is false, and
- isAssignable_v<T&, const optional<U>&> is false.

**Effects:** See Table 59.

---

Table 59: optional::operator=(const optional<U>&&) effects

<table>
<thead>
<tr>
<th>Cont.</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>*this contains a value</td>
<td>assigns *rha to the contained value</td>
</tr>
<tr>
<td>*this does not contain a value</td>
<td>destroys the contained value by calling val-&gt;T::~T()</td>
</tr>
</tbody>
</table>

§ 22.5.3.4
Postconditions: \( \text{rhs}.\text{has_value}() == \text{this->has_value}() \).

Returns: \(*\text{this}.*\)

Remarks: If any exception is thrown, the result of the expression \( \text{this->has_value}() \) remains unchanged. If an exception is thrown during the call to \( T \)'s constructor, the state of \(*\text{rhs}.\text{val} \) 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 \(*\text{val} \) and \(*\text{rhs}.\text{val} \) is determined by the exception safety guarantee of \( T \)'s assignment.

\[
\text{template<class } U \text{> constexpr optional<} T \text{>& operator=(optional<} U \text{>&& rhs);}
\]

Constraints:

\[
\begin{align}
(24.1) & \quad \text{is_constructible_v<} T, U \text{> is true,} \\
(24.2) & \quad \text{is_assignable_v<} T & & U \text{> is true,} \\
(24.3) & \quad \text{is_constructible_v<} T, \text{optional<} U \text{>&> is false,} \\
(24.4) & \quad \text{is_constructible_v<} T, \text{optional<} U \text{>&&> is false,} \\
(24.5) & \quad \text{is_constructible_v<} T, \text{const optional<} U \text{>&> is false,} \\
(24.6) & \quad \text{is_constructible_v<} T, \text{const optional<} U \text{>&&> is false,} \\
(24.7) & \quad \text{is_convertible_v<optional<} U \text{>&, } T \text{> is false,} \\
(24.8) & \quad \text{is_convertible_v<optional<} U \text{>&&, } T \text{> is false,} \\
(24.9) & \quad \text{is_convertible_v<const optional<} U \text{>&, } T \text{> is false,} \\
(24.10) & \quad \text{is_convertible_v<const optional<} U \text{>&&, } T \text{> is false,} \\
(24.11) & \quad \text{is_assignable_v<} T & & U \text{> is false,} \\
(24.12) & \quad \text{is_assignable_v<} T, \text{optional<} U \text{>&> is false,} \\
(24.13) & \quad \text{is_assignable_v<} T, \text{const optional<} U \text{>&> is false,} \\
(24.14) & \quad \text{is_assignable_v<} T, \text{const optional<} U \text{>&&> is false.}
\end{align}
\]

Effects: See Table 60. The result of the expression \( \text{rhs}.\text{has_value}() \) remains unchanged.

Table 60: optional::operator=(optional<} U \text{>&&) effects

<table>
<thead>
<tr>
<th></th>
<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 \text{std::move(*rhs)} to the contained value</td>
<td>direct-non-list-initializes the contained value with \text{std::move(*rhs)}</td>
</tr>
<tr>
<td>rhs does not contain a value</td>
<td>destroys the contained value by calling \text{val-&gt;T::~T()}</td>
<td>no effect</td>
</tr>
</tbody>
</table>

Postconditions: \( \text{rhs}.\text{has_value}() == \text{this->has_value}() \).

Returns: \(*\text{this}.*\)

Remarks: If any exception is thrown, the result of the expression \( \text{this->has_value}() \) remains unchanged. If an exception is thrown during the call to \( T \)'s constructor, the state of \(*\text{rhs}.\text{val} \) 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 \(*\text{val} \) and \(*\text{rhs}.\text{val} \) is determined by the exception safety guarantee of \( T \)'s assignment.

\[
\text{template<class... Args> constexpr } T & \text{ emplace(Args&&... args);}
\]

Mandates: is_constructible_v<} T, Args...> is true.

Effects: Calls \(*\text{this} = \text{nullopt} \). Then direct-non-list-initializes the contained value with \text{std::forward}\<Args\>(args)....

Postconditions: \(*\text{this} \) contains a value.

Returns: A reference to the new contained value.
33. **Throws**: Any exception thrown by the selected constructor of T.
34. **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);
```
35. **Constraints**: is_constructible_v<T, initializer_list<U>&, Args...> is true.
36. **Effects**: Calls *this = nullopt. Then direct-non-list-initializes the contained value with il, std::forward<Args>(args)....
37. **Postconditions**: *this contains a value.
38. **Returns**: A reference to the new contained value.
39. **Throws**: Any exception thrown by the selected constructor of T.
40. **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;
```
1. **Mandates**: is_move_constructible_v<T> is true.
2. **Preconditions**: Lvalues of type T are swappable.
3. **Effects**: See Table 61.

<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>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>
</tbody>
</table>

4. **Throws**: Any exceptions thrown by the operations in the relevant part of Table 61.
5. **Remarks**: The exception specification is equivalent to:

   ```cpp
   is_nothrow_move_constructible_v<T> & is_nothrow_swappable_v<T>
   ``

6. 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 *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 Observers

```cpp
constexpr const T* operator->() const noexcept;
constexpr T* operator->() noexcept;
```
1. **Preconditions**: *this contains a value.
2.5.3.7 Monadic operations  

Let \( U \) be \( \text{invoke\_result\_t}\langle F, \text{decltype(value())} \rangle \).

Mandates: \( \text{remove\_cvref\_t}\langle U \rangle \) is a specialization of \( \text{optional} \).

Effects: Equivalent to:

\[
\text{if } (*\text{this}) \\
\quad \text{return invoke(std::forward<F>(f), value());} \\
\text{else} \\
\quad \text{return remove\_cvref\_t\langle U \rangle();} \\
\]
template<class F> constexpr auto and_then(F&& f) &&;
template<class F> constexpr auto and_then(F&& f) const &&;

4 Let \( U \) be \( \text{invoke\_result\_t\<F, decltype(std::move(value()))>\<F, value()\>\>}. 

5 **Mandates:** \( \text{remove\_cv\_ref\_t<U> is a specialization of optional.} \)

6 **Effects:** Equivalent to:

   ```
   if (*this) {
       return invoke(std::forward<F>(f), std::move(value()));
   } else {
       return remove_cvref_t<U>();
   }
   ```

template<class F> constexpr auto transform(F&& f) &;
template<class F> constexpr auto transform(F&& f) const &;

7 Let \( U \) be \( \text{remove\_cv\_t<\text{invoke\_result\_t\<F, decltype(value())>\<F, value()\>\>}}. 

8 **Mandates:** \( U \) is a non-array object type other than \( \text{in\_place\_t} \) or \( \text{nullopt\_t} \). The declaration

   ```
   U u(invoke(std::forward<F>(f), value()));
   ```

   is well-formed for some invented variable \( u \).

   [Note 1: There is no requirement that \( U \) is movable (9.4.1). — end note]

9 **Returns:** If \( *this \) contains a value, an \text{optional\<U\> object whose contained value is direct-non-list-}

   ```
   initialized with \( \text{invoke(std::forward<F>(f), value())} \); otherwise, \text{optional\<U\>}. 
   ```

template<class F> constexpr auto transform(F&& f) &&;
template<class F> constexpr auto transform(F&& f) const &&;

10 Let \( U \) be \( \text{remove\_cv\_t<\text{invoke\_result\_t\<F, decltype(value())>\<F, value()\>\>}}. 

11 **Mandates:** \( U \) is a non-array object type other than \( \text{in\_place\_t} \) or \( \text{nullopt\_t} \). The declaration

   ```
   U u(invoke(std::forward<F>(f), std::move(value())));
   ```

   is well-formed for some invented variable \( u \).

   [Note 2: There is no requirement that \( U \) is movable (9.4.1). — end note]

12 **Returns:** If \( *this \) contains a value, an \text{optional\<U\> object whose contained value is direct-non-list-}

   ```
   initialized with \( \text{invoke(std::forward<F>(f), std::move(value())} )\); otherwise, \text{optional\<U\>}. 
   ```

template<class F> constexpr optional or_else(F&& f) const &;

13 **Constraints:** \( F \) models \text{invocable<\> and T models copy\_constructible.} 

14 **Mandates:** \text{is\_same\_v<remove\_cv\_ref\_t<invoke\_result\_t\<F\>\<F\>\>\>, optional> is true.} 

15 **Effects:** Equivalent to:

   ```
   if (*this) {
       return *this;
   } else {
       return std::forward<F>(f());
   }
   ```

template<class F> constexpr optional or_else(F&& f) &&;

16 **Constraints:** \( F \) models \text{invocable<\> and T models move\_constructible.} 

17 **Mandates:** \text{is\_same\_v<remove\_cv\_ref\_t<invoke\_result\_t\<F\>\<F\>\>\>, optional> is true.} 

18 **Effects:** Equivalent to:

   ```
   if (*this) {
       return std::move(*this);
   } else {
       return std::forward<F>(f());
   }
   ```
22.5.3.8 Modifiers

```cpp
constexpr void reset() noexcept;
```

1 Effects: If *this contains a value, calls val->T::~T() to destroy the contained value; otherwise no effect.

2 Postconditions: *this does not contain a value.

22.5.4 No-value state indicator

```cpp
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

```cpp
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.

```cpp
const char* what() const noexcept override;
```

2 Remarks: Specializations of this function template for which *x == *y is a core constant expression are constexpr functions.

22.5.6 Relational operators

```cpp
template<class T, class U> constexpr bool operator==(const optional<T>& x, const optional<U>& y);
```

1 Mandates: The expression *x == *y is well-formed and its result is convertible to bool.

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.

```cpp
template<class T, class U> constexpr bool operator!=(const optional<T>& x, const optional<U>& y);
```

4 Mandates: 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.

```cpp
template<class T, class U> constexpr bool operator<(const optional<T>& x, const optional<U>& y);
```

7 Mandates: *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);

**Mandates:** The expression \( \star x > \star y \) is well-formed and its result is convertible to bool.

**Returns:** If \(!x\), false; otherwise, if \(!y\), true; otherwise \( \star x > \star y \).

**Remarks:** Specializations of this function template for which \( \star x > \star y \) is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator<=(const optional<T>& x, const optional<U>& y);

**Mandates:** The expression \( \star x \leq \star y \) is well-formed and its result is convertible to bool.

**Returns:** If \(!x\), true; otherwise, if \(!y\), false; otherwise \( \star x \leq \star y \).

**Remarks:** Specializations of this function template for which \( \star x \leq \star y \) is a core constant expression are constexpr functions.

template<class T, class U> constexpr bool operator>=(const optional<T>& x, const optional<U>& y);

**Mandates:** The expression \( \star x \geq \star y \) is well-formed and its result is convertible to bool.

**Returns:** If \(!y\), true; otherwise, if \(!x\), false; otherwise \( \star x \geq \star y \).

**Remarks:** Specializations of this function template for which \( \star x \geq \star y \) is a core constant expression are constexpr functions.

template<class T, class U> constexpr compare_three_way_result_t<T, U> operator<=>(const optional<T>& x, const optional<U>& y);

**Returns:** If \( x \&\& y \), \( \star x \<=> \star y \); otherwise \( x\.has\_value() \<=> y\.has\_value() \).

**Remarks:** Specializations of this function template for which \( \star x \<=> \star y \) 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);

**Mandates:** The expression \( \star x == v \) 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() ? \( \star x == v \) : false;

template<class T, class U> constexpr bool operator==(const T& v, const optional<U>& x);

**Mandates:** The expression \( v == \star x \) is well-formed and its result is convertible to bool.

**Effects:** Equivalent to: return x\.has\_value() ? v == \( \star x \) : false;

template<class T, class U> constexpr bool operator!=(const optional<T>& x, const U& v);

**Mandates:** The expression \( \star x != v \) is well-formed and its result is convertible to bool.

**Effects:** Equivalent to: return x\.has\_value() ? \( \star x != v \) : true;

template<class T, class U> constexpr bool operator!=(const T& v, const optional<U>& x);

**Mandates:** The expression \( v != \star x \) is well-formed and its result is convertible to bool.

**Effects:** Equivalent to: return x\.has\_value() ? v != \( \star x \) : true;

template<class T, class U> constexpr bool operator<(const optional<T>& x, const U& v);

**Mandates:** The expression \( \star x < v \) is well-formed and its result is convertible to bool.

**Effects:** Equivalent to: return x\.has\_value() ? \( \star x < v \) : true;
Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x < v \ : \ \text{true}; \)

template<class T, class U> constexpr bool operator<(const T& v, const optional<U>& x);

Mandates: The expression \( v < *x \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v < *x \ : \ \text{false}; \)

template<class T, class U> constexpr bool operator<(const optional<T>& x, const U& v);

Mandates: The expression \( *x > v \) is well-formed and its result is convertible to bool.

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x > v \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v > *x \ : \ \text{true}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v > *x \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v <= *x \ : \ \text{true}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v <= *x \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v >= *x \ : \ \text{true}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v >= *x \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x <= v \ : \ \text{true}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x <= v \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v > *x \ : \ \text{true}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ v > *x \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x >= v \ : \ \text{true}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x >= v \ : \ \text{false}; \)

Effects: Equivalent to: \( \text{return } x.\text{has}\_\text{value}() \ ? \ *x <= v \ : \ \text{strong\_ordering::less}; \)

22.5.9 Specialized algorithms

template<class T>
constexpr void swap(optional<T>& x, optional<T>& y) noexcept(noexcept(x.swap(y)));

Constraints: is_move_constructible_v<T> is true and is_swappable_v<T> is true.

Effects: Calls x.swap(y).

Returns: optional<decay_t<T>>(std::forward<T>(v)).

template<class T, class...Args>
constexpr optional<T> make_optional(T&& v);

Effects: Equivalent to: return optional<T>(in_place, std::forward<Args>(args)...);

Effects: Equivalent to: return optional<T>(in_place, il, std::forward<Args>(args)...);
22.5.10 Hash support

template<class T> struct hash<optional<T>>;

The specialization `hash<optional<T>>` is enabled (22.10.19) if and only if `hash<remove_const_t<T>>` is enabled. When enabled, for an object `o` of type `optional<T>`, if `o.has_value() == true`, then `hash<optional<T>>()(o)` evaluates to the same value as `hash<remove_const_t<T>>()(o);` otherwise it evaluates to an unspecified value. The member functions are not guaranteed to be `noexcept`.

22.6 Variants

22.6.1 In general

A variant object holds and manages the lifetime of a value. If the `variant` holds a value, that value's type has to be one of the template argument types given to `variant`. These template arguments are called alternatives.

22.6.2 Header `<variant>` synopsis

```cpp
#include <compare> // see 17.11.1

namespace std {
    // 22.6.3, class template
    template<class... Types>
    class variant;

    // 22.6.4, variant helper classes
    template<class T> struct variant_size;
    template<class T> struct variant_size<const T>;
    template<class T> inline 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;
    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...>&);
    template<size_t I, class... Types>
    constexpr variant_alternative_t<I, variant<Types...>>&& get(variant<Types...>&&);
    template<size_t I, class... Types>
    constexpr const variant_alternative_t<I, variant<Types...>>& get(const variant<Types...>&);
    template<size_t I, class... Types>
    constexpr const variant_alternative_t<I, variant<Types...>>&& get(const variant<Types...>&&);
    template<class T, class... Types>
    constexpr T& get(variant<Types...>&);
    template<class T, class... Types>
    constexpr T&& get(variant<Types...>&&);
    template<class T, class... Types>
    constexpr const T& get(const variant<Types...>&);
    template<class T, class... Types>
    constexpr const T&& get(const variant<Types...>&&);
```
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;

template<class T, class... Types>
constexpr add_pointer_t<T>
get_if(variant<Types...>*) noexcept;

template<class T, class... Types>
constexpr add_pointer_t<const T>
get_if(const variant<Types...>*) noexcept;

// 22.6.6, relational operators

template<class... Types>
constexpr bool operator==(const variant<Types...>&, const variant<Types...>&);

template<class... Types>
constexpr bool operator!=(const variant<Types...>&, const variant<Types...>&);

template<class... Types>
constexpr bool operator<(const variant<Types...>&, const variant<Types...>&);

template<class... Types>
constexpr bool operator>(const variant<Types...>&, const variant<Types...>&);

template<class... Types>
constexpr bool operator<=(const variant<Types...>&, const variant<Types...>&);

template<class... Types>
constexpr bool operator>=(const variant<Types...>&, const variant<Types...>&);

template<class... Types> requires (three_way_comparable<Types> && ...)
constexpr common_comparison_category_t<
    compare_three_way_result_t<Types>...>
operator<=>(const variant<Types...>&, const variant<Types...>&);

// 22.6.7, visitation

template<class Visitor, class... Variants>
constexpr see below visit(Visitor&&, Variants&&...);

template<class R, class Visitor, class... Variants>
constexpr R visit(Visitor&&, Variants&&...);

// 22.6.8, class monostate

struct monostate;

// 22.6.9, monostate relational operators

constexpr bool operator==(monostate, monostate) noexcept;
constexpr strong_ordering operator<=>(monostate, monostate) noexcept;

// 22.6.10, specialized algorithms

template<class... Types>
constexpr void swap(variant<Types...>&, variant<Types...>&) noexcept(see below);

// 22.6.11, class bad_variant_access

class bad_variant_access;

// 22.6.12, hash support

template<class T> struct hash;

template<class... Types> struct hash<variant<Types...>>;

template<> struct hash<monostate>;

}
// 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... Args>
constexpr explicit variant(in_place_type_t<T>, Args&&...);

template<class T, class U, class... Args>
constexpr explicit variant(in_place_type_t<T>, initializer_list<U>, Args&&...);

template<size_t I, class... Args>
constexpr explicit variant(in_place_index_t<I>, Args&&...);

template<size_t I, class U, class... Args>
constexpr explicit variant(in_place_index_t<I>, initializer_list<U>, Args&&...);

// 22.6.3.3, destructor
constexpr ~variant();

// 22.6.3.4, assignment
constexpr variant& operator=(const variant&);
constexpr variant& operator=(variant&&) noexcept(see below);

template<class T>
constexpr variant& operator=(T&&) noexcept(see below);

// 22.6.3.5, modifiers

template<class T, class... Args>
constexpr T& emplace(Args&&...);

template<class T, class U, class... Args>
constexpr T& emplace(initializer_list<U>, Args&&...);

template<size_t I, class... Args>
constexpr variant_alternative_t<I, variant<Types...>>& emplace(Args&&...);

template<size_t I, class U, class... Args>
constexpr variant_alternative_t<I, variant<Types...>>&
    emplace(initializer_list<U>, Args&&...);

// 22.6.3.6, value status
constexpr bool valueless_by_exception() const noexcept;
constexpr size_t index() const noexcept;

// 22.6.3.7, swap
constexpr void swap(variant&) noexcept(see below);
};

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. The contained value shall be allocated in a region of the variant storage suitably aligned for all types in Types.

2 All types in Types shall meet the Cpp17Destructible requirements (Table 34).

3 A program that instantiates the definition of variant with no template arguments is ill-formed.

22.6.3.2 Constructors

1 In the descriptions that follow, let i be in the range [0, sizeof...(Types)), and Ti be the ith type in Types.

constexpr variant() noexcept(see below);

Constraints: is_default_constructible_v<T0> is true.

Effects: Constructs a variant holding a value-initialzed value of type T0.
Postconditions: `valueless_by_exception()` is `false` and `index()` is `0`.

Throws: Any exception thrown by the value-initialization of \( T_0 \).

Remarks: This function is `constexpr` if and only if the value-initialization of the alternative type \( T_0 \) would satisfy the requirements for a `constexpr` function. The exception specification is equivalent to `is_nothrow_default_constructible_v<T_0>`.

[Note 1: See also class `monostate` — end note]

```cpp
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 \( T_i \) for all \( i \).

Remarks: This constructor is defined as deleted unless `is_copy_constructible_v<T_i>` is `true` for all \( i \). If `is_trivially_copy_constructible_v<T_i>` is `true` for all \( i \), this constructor is trivial.

```cpp
constexpr variant(variant&& w) noexcept(see below);
```

Constraints: `is_move_constructible_v<T_i>` 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 \( T_i \) for all \( i \).

Remarks: The exception specification is equivalent to the logical AND of `is_nothrow_move_constructible_v<T_i>` for all \( i \). If `is_trivially_move_constructible_v<T_i>` is `true` for all \( i \), this constructor is trivial.

```cpp
template<class T> constexpr variant(T&& t) noexcept(see below);
```

Let \( T_j \) be a type that is determined as follows: build an imaginary function `FUN(T_i)` for each alternative type \( T_i \) for which \( T_i \times = {std::forward<T>(t)} \) is well-formed for some invented variable \( x \). The overload `FUN(T_j)` selected by overload resolution for the expression `FUN(std::forward<T>(t))` defines the alternative \( T_j \) 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<T_j, 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 \( T_j \) and direct-non-list-initializes the contained value with `std::forward<T>(t)`.

Postconditions: `holds_alternative<T_j>(*this)` is `true`.

Throws: Any exception thrown by the initialization of the selected alternative \( T_j \).

Remarks: The exception specification is equivalent to `is_nothrow_constructible_v<T_j, T>`. If \( T_j \)'s selected constructor is a `constexpr` constructor, this constructor is a `constexpr` constructor.

```cpp
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

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— 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 il, 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 [variant.dtor]

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 [variant.assign]

constexpr variant& operator=(const variant& rhs);

Let j be rhs.index().

Effects:
— 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 index() == j, assigns the value contained in rhs to the value contained in *this.

— Otherwise, if either is_nothrow_copy_constructible_v<T> is true or is_nothrow_move_constructible_v<T> is false, equivalent to emplace<j>(get<j>(rhs)).

— Otherwise, equivalent to operator=(variant(rhs)).

Postconditions: index() == rhs.index().

Returns: *this.

Remarks: This operator is defined as deleted unless is_copy_constructible_v<T> && is_copyAssignable_v<T> is true for all i. If is_trivially_copy_constructible_v<T> && is_trivially_copyAssignable_v<T> && is_trivially_destructible_v<T> is true for all i, this assignment operator is trivial.

constexpr variant& operator=(variant&& rhs) noexcept;

Let j be rhs.index().

Constraints: is_move_constructible_v<T>, && is_moveAssignable_v<T> is true for all i.

Effects:

— 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 index() == j, assigns get<j>(std::move(rhs)) to the value contained in *this.

— Otherwise, equivalent to emplace<j>(get<j>(std::move(rhs))).

Returns: *this.

Remarks: If is_trivially_move_constructible_v<T> && is_trivially_moveAssignable_v<T> && is_trivially_destructible_v<T> for all i, this assignment operator is trivial. The exception specification is equivalent to is_nothrow_move_constructible_v<T>, && is_nothrow_moveAssignable_v<T> for all i.

— If an exception is thrown during the call to T’s move construction (with j being rhs.index()), the variant will hold no value.

— If an exception is thrown during the call to T’s move assignment, the state of the contained value is as defined by the exception safety guarantee of T’s move assignment; index() will be j.

template<class T> constexpr variant& operator=(T&& t) noexcept;

Let T be a type that is determined as follows: build an imaginary function FUN(T) for each alternative type T for which T x[] = {std::forward<T>(t)}; is well-formed for some invented variable x. The overload FUN(T) selected by overload resolution for the expression FUN(std::forward<T>(t)) defines the alternative T which is the type of the contained value after assignment.

Constraints:

— is_same_v<remove_cvref_t<T>, variant> is false,

— isAssignable_v<T, T> && isConstructible_v<T> is true, and

— the expression FUN(std::forward<T>(t)) (with FUN being the above-mentioned set of imaginary functions) is well-formed.

[Note 1:

variant<string, string> v;
  v = "abc";

is ill-formed, as both alternative types have an equally viable constructor for the argument. — end note]

Effects:

— If *this holds a T, assigns std::forward<T>(t) to the value contained in *this.
— Otherwise, if `is_nothrow_constructible_v<T_j, T> || !is_nothrow_move_constructible_v<T_j, T>` is true, equivalent to `emplace<T>(std::forward<T>(t))`.

— Otherwise, equivalent to `emplace<T_j>(T_j(std::forward<T>(t)))`.

Postconditions: `holds_alternative<T_j>(*this)` is true, with `T_j` selected by the imaginary function overload resolution described above.

Returns: `*this`.

Remarks: The exception specification is equivalent to:

`is_nothrow_assignable_v<T_j&, T> && is_nothrow_constructible_v<T_j, T>`

— If an exception is thrown during the assignment of `std::forward<T>(t)` to the value contained in `*this`, the state of the contained value and `t` are as defined by the exception safety guarantee of the assignment expression; `valueless_by_exception()` will be false.

— If an exception is thrown during the initialization of the contained value, the `variant` object is permitted to not hold a value.

22.6.3.5 Modifiers

```c++
template<class T, class... Args> constexpr T& emplace(Args&&... args);
```

Constraints: `is_constructible_v<T, Args...>` is true, and `T` occurs exactly once in `Types`.

Effects: Equivalent to:

```c++
return emplace<I>(std::forward<Args>(args)...);
```

where `I` is the zero-based index of `T` in `Types`.

```c++
template<class T, class U, class... Args>
constexpr T& emplace(initializer_list<U> il, Args&&... args);
```

Constraints: `is_constructible_v<T, initializer_list<U>&, Args...>` is true, and `T` occurs exactly once in `Types`.

Effects: Equivalent to:

```c++
return emplace<I>(il, std::forward<Args>(args)...);
```

where `I` is the zero-based index of `T` in `Types`.

```c++
template<size_t I, class... Args>
constexpr variant_alternative_t<I, variant<Types...>>& emplace(Args&&... args);
```

Mandates: `I < sizeof...(Types)`.

Constraints: `is_constructible_v<T_I, Args...>` is true.

Effects: Destroys the currently contained value if `valueless_by_exception()` is false. Then direct-
non-list-initializes the contained value of type `T_I` with the arguments `std::forward<Args>(args)`....

Postconditions: `index()` is `I`.

Returns: A reference to the new contained value.

Remarks: If an exception is thrown during the initialization of the contained value, the `variant` is permitted to not hold a value.

```c++
template<size_t I, class U, class... Args>
constexpr variant_alternative_t<I, variant<Types...>>&
emplace(initializer_list<U> il, Args&&... args);
```

Mandates: `I < sizeof...(Types)`.

Constraints: `is_constructible_v<T_I, initializer_list<U>&, Args...>` is true.

Effects: Destroys the currently contained value if `valueless_by_exception()` is false. Then direct-
non-list-initializes the contained value of type `T_I` with `il`, `std::forward<Args>(args)`....

Postconditions: `index()` is `I`.

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.

**Note 1:** It is possible for a variant to hold no value if an exception is thrown during a type-changing assignment or emplacement. The latter means that even a `variant<float, int>` can become `valueless_by_exception()`, for instance by:

```cpp
struct S { operator int() { throw 42; };
    variant<float, int> v{12.f};
    v.emplace<1>(S());
```

**Note 2:**

22.6.3.7 Swap

```cpp
constexpr void swap(variant& rhs) noexcept;
```

**Mandates:** is_move_constructible_v<T_i> is true for all i.

**Preconditions:** Lvalues of type T_i are swappable (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_swapable_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>`.

**Mandates**: I < sizeof...(Types).

**Type**: The type `T_I`.

### 22.6.5 Value access

**Mandates**: The type `T` occurs exactly once in `Types`.

**Returns**: If `v.index()` is equal to the zero-based index of `T` 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**: The type `T` occurs exactly once in `Types`.

**Returns**: A pointer to the value stored in the `variant`, if `v` != `nullptr` and `v->index()` == `I`. Otherwise, returns `nullptr`.

**Effects**: Equivalent to: `return get_if<i>(v)`; with `i` being the zero-based index of `T` in `Types`.

### 22.6.6 Relational operators

**Mandates**: The type `T` occurs exactly once in `Types`.

**Effects**: Equivalent to: `return get_if<i>(v)`; with `i` being the zero-based index of `T` in `Types`.

**Mandates**: The type `T` occurs exactly once in `Types`.

**Effects**: Equivalent to: `return get_if<i>(v)`; with `i` being the zero-based index of `T` in `Types`.
constexpr bool operator==(const variant<Types...>& v, const variant<Types...>& w);

Mandates: 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);

Mandates: 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);

Mandates: 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);

Mandates: 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);

Mandates: 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);

Mandates: get<i>(v) >= get<i>(w) is a valid expression that is convertible to bool, for all i.

Returns: If w.valueless_by_exception(), true; otherwise if v.valueless_by_exception(), false; otherwise if v.index() > w.index(), false; otherwise if v.index() < w.index(), false; otherwise get<i>(v) >= get<i>(w) with i being v.index().

template<class... Types> requires (three_way_comparable<Types> && ...)
constexpr common_comparison_category_t<compare_three_way_result_t<Types>...>
operator<=>(const variant<Types...>& v, const variant<Types...>& w);

Effects: Equivalent to:
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

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 \texttt{as-variant} denote the following exposition-only function templates:

\begin{verbatim}
template<class... Ts>
auto&& as-variant(variant<Ts...>&& var) { return var; }
template<class... Ts>
auto&& as-variant(variant<Ts...>& var) { return var; }
template<class... Ts>
auto&& as-variant(const variant<Ts...>&& var) { return std::move(var); }
template<class... Ts>
auto&& as-variant(const variant<Ts...>& var) { return std::move(var); }
\end{verbatim}

Let \( n \) be \( \text{sizeof...}(\text{Variants}) \). For each \( 0 \leq i < n \), let \( V_i \) denote the type \( \text{decltype(as-variant(std::forward<Variants_i>(vars_i)))} \).

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:

\[ \text{INVOKExx:} (std::forward<Visitor>(vis), get<m>(std::forward<V>(vars))...) \] // see 22.10.4

for the first form and

\[ \text{INVOKExx:<R>(std::forward<Visitor>(vis), get<m>(std::forward<V>(vars))...)} \] // 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: \texttt{bad_variant_access} if \( \text{as-variant(vars).valueless_by_exception()} || \ldots \) 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.

### 22.6.8 Class monostate

\begin{verbatim}
struct monostate{};
\end{verbatim}

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

\begin{verbatim}
constexpr bool operator==(monostate, monostate) noexcept { return true; }
constexpr strong_ordering operator<=>(monostate, monostate) noexcept { return strong_ordering::equal; }
\end{verbatim}

[Note 1: \texttt{monostate} objects have only a single state; they thus always compare equal. — end note]

### 22.6.10 Specialized algorithms

\begin{verbatim}
template<class... Types>
constexpr void swap(variant<Types...>& v, variant<Types...>& w) noexcept(see below);
\end{verbatim}

Constraints: \texttt{is_move_constructible_v<T,_>} \&\& \texttt{is_swappable_v<T,_>} is true for all \( i \).

Effects: Equivalent to \( v\text{.swap}(w) \).

Remarks: The exception specification is equivalent to \texttt{noexcept(v.swap(w))}.
22.6.11 Class bad_variant_access
[variant.bad.access]
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;
    };
}

1 Objects of type bad_variant_access are thrown to report invalid accesses to the value of a variant object.

const char* what() const noexcept override;

2 Returns: An implementation-defined ntbs.

22.6.12 Hash support
[variant.hash]
template<class... Types> struct hash<variant<Types...>>;

1 The specialization hash<variant<Types...>> is enabled (22.10.19) if and only if every specialization in hash<remove_const_t<Types>>... is enabled. The member functions are not guaranteed to be noexcept.

template<> struct hash<monostate>;

2 The specialization is enabled (22.10.19).

22.7 Storage for any type
[any]
22.7.1 General
[any.general]
1 Subclause 22.7 describes components that C++ programs may use to perform operations on objects of a discriminated type.

2 [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 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
[any.synop]
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;
}

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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();
        // 22.7.4.3, assignments
        any& operator=(const any& rhs);
        any& operator=(any&& rhs) noexcept;
        template<class T>
        any& operator=(T&& rhs);
        // 22.7.4.4, modifiers
        template<class T, class... Args>
        decay_t<T>& emplace(Args&&...);
        template<class T, class U, class... Args>
        decay_t<T>& emplace(initializer_list<U>, Args&&...);
        void reset() noexcept;
        void swap(any& rhs) noexcept;
        // 22.7.4.5, observers
        bool has_value() const noexcept;
        const type_info& type() const noexcept;
    };
}

1 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.

2 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 \code{is_nothrow_move_constructible_v\langle T\rangle} is true.

[Example 1: A contained value of type \code{int} could be stored in an internal buffer, not in separately-allocated memory.
—end example]

### § 22.7.4.2 Construction and destruction

**constexpr** \code{any()} noexcept;

**Postconditions:** \code{has_value()} is false.

\code{any(const any& other)};

**Effects:** If \code{other.has_value()} is false, constructs an object that has no value. Otherwise, equivalent to \code{any(in_place_type\langle T\rangle, any_cast\langle const T&\rangle(other))} where \( T \) is the type of the contained value.

**Throws:** Any exceptions arising from calling the selected constructor for the contained value.

\code{any(any&& other) noexcept};

**Effects:** If \code{other.has_value()} is false, constructs an object that has no value. Otherwise, constructs an object of type \code{any} that contains either the contained value of \code{other}, or contains an object of the same type constructed from the contained value of \code{other} considering that contained value as an rvalue.

**Constraints:** \( VT \) is not the same type as \code{any}, \( VT \) is not a specialization of \code{in_place_type_t}, and \code{is_copy_constructible_v\langle VT\rangle} is true.

**Preconditions:** \( VT \) meets the \code{Cpp17CopyConstructible} requirements.

**Effects:** Constructs an object of type \code{any} that contains an object of type \( VT \) direct-initialized with \code{std::forward\langle T\rangle(value)}.

**Throws:** Any exception thrown by the selected constructor of \( VT \).

**template<class T>**

\code{any(T&& value)};

**Let \( VT \) be \code{decay\_t\langle T\rangle}.**

**Constraints:** \( VT \) is not the same type as \code{any}, \( VT \) is not a specialization of \code{in_place_type_t}, and \code{is_copy_constructible_v\langle VT\rangle} is true.

**Preconditions:** \( VT \) meets the \code{Cpp17CopyConstructible} requirements.

**Effects:** Direct-non-list-initializes the contained value of type \( VT \) with \code{std::forward\langle Args\rangle(args)\ldots}.

**Postconditions:** \code{*this} contains a value of type \( VT \).

**Throws:** Any exception thrown by the selected constructor of \( VT \).

**template<class T, class... Args>**

\code{explicit any(in_place_type\langle T\rangle, Args&&... args)};

**Let \( VT \) be \code{decay\_t\langle T\rangle}.**

**Constraints:** \code{is_copy_constructible_v\langle VT\rangle} is true and \code{is_constructible_v\langle VT, Args\ldots\rangle} is true.

**Preconditions:** \( VT \) meets the \code{Cpp17CopyConstructible} requirements.

**Effects:** Direct-non-list-initializes the contained value of type \( VT \) with \code{std::forward\langle Args\rangle(args)\ldots}.

**Postconditions:** \code{*this} contains a value of type \( VT \).

**Throws:** Any exception thrown by the selected constructor of \( VT \).

**template<class T, class U, class... Args>**

\code{explicit any(in_place_type\langle T\rangle, initializer_list\langle U\rangle il, Args&&... args)};

**Let \( VT \) be \code{decay\_t\langle T\rangle}.**

**Constraints:** \code{is_copy_constructible_v\langle VT\rangle} is true and \code{is_constructible_v\langle VT, initializer\_list\langle U\&\rangle, Args\ldots\rangle} is true.

**Preconditions:** \( VT \) meets the \code{Cpp17CopyConstructible} requirements.

**Effects:** Direct-non-list-initializes the contained value of type \( VT \) with \code{il, std::forward\langle Args\rangle(args)\ldots}.

**Postconditions:** \code{*this} contains a value.

**Throws:** Any exception thrown by the selected constructor of \( VT \).

\code{~any();}

**Effects:** As if by \code{reset()}.
22.7.4.3 Assignment

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

template<class T, class... Args>
declay_t<T>& emplace(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: Calls reset(). Then direct-non-list-initializes the contained value of type VT 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 VT.
Remarks: If an exception is thrown during the call to VT's constructor, *this does not contain a value, and any previously contained value has been destroyed.

template<class T, class U, class... Args>
declay_t<T>& emplace(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: Calls reset(). Then direct-non-list-initializes the contained value of type VT 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 VT.
Remarks: If an exception is thrown during the call to VT's constructor, *this does not contain a value, and any previously contained value has been destroyed.
void reset() noexcept;

Effects: If has_value() is true, destroys the contained value.

Postconditions: has_value() is false.

void swap(any& rhs) noexcept;

Effects: Exchanges the states of *this and rhs.

22.7.4.5 Observers

bool has_value() const noexcept;

Returns: true if *this contains an object, otherwise false.

cast type_info& type() const noexcept;

Returns: typeid(T) if *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]

22.7.5 Non-member functions

void swap(any& x, any& y) noexcept;

Effects: Equivalent to x.swap(y).

template<class T, class... Args>
any make_any(Args&&... args);

Effects: Equivalent to: return any(in_place_type<T>, std::forward<Args>(args)...);

template<class T, class U, class... Args>
any make_any(initializer_list<U> il, Args&&... args);

Effects: Equivalent to: return any(in_place_type<T>, il, std::forward<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);

Let U be the type remove_cvref_t<T>.

Mandates: For the first overload, is_constructible_v<T, const U&> is true. For the second overload, is_constructible_v<T, U&> is true. For the third overload, is_constructible_v<T, U> is true.

Returns: For the first and second overload, static_cast<T>(any_cast<U>(&operand)). For the third overload, static_cast<T>(std::move(any_cast<U>(&operand))).

Throws: bad_any_cast if operand.type() != typeid(remove_reference_t<T>.

[Example 1:

any x(5); // x holds int
assert(any_cast<int>(x) == 5); // cast to value
any_cast<int&>(x) = 10; // cast to reference
assert(any_cast<int>(x) == 10);

x = "Meow"; // x holds const char*
assert(strcmp(any_cast<const char*>(x), "Meow") == 0);
any_cast<const char*>(x) = "Harry";
assert(strcmp(any_cast<const char*>(x), "Harry") == 0);

x = string("Meow"); // x holds string
string s, s2("Jane");
s = move(any_cast<string&>(x)); // move from any
assert(s == "Meow");
any_cast<string&>(x) = move(s2); // move to any
assert(any_cast<const string&>(x) == "Jane");

§ 22.7.5
```cpp
string cat("Meow");
const any y(cat);    // const y holds string
assert(any_cast<const string&>(y) == cat);

any_cast<string&>(y);     // error: cannot any_cast away const
```

```cpp
Returns: If operand != nullptr && operand->type() == typeid(T), a pointer to the object contained by operand; otherwise, nullptr.
```

```cpp
[Example 2]:
bool is_string(const any& operand) {
    return any_cast<string&>(operand) != nullptr;
}
```

### 22.8 Expected objects

#### 22.8.1 In 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 `unexpected<E>` and manages the lifetime of the contained objects.

#### 22.8.2 Header `<expected>` synopsis

```cpp
namespace std {
    // 22.8.3.2, 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;
    // 22.8.7, partial specialization of expected for void types
    template<class T, class E> requires is_void_v<T> class expected<T, E>;
}
```

#### 22.8.3 Unexpected objects

##### 22.8.3.1 General

Subclause 22.8.3 describes the class template `unexpected` that represents unexpected objects stored in `expected` objects.

##### 22.8.3.2 Class template unexpected

#### 22.8.3.2.1 General

```cpp
namespace std {
    template<class E> class unexpected {
    }
}
```
public:
constexpr unexpected(const unexpected&) = default;
customexpr unexpected(unexpected&&) = default;
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&&...);
template<class Err = E>
  constexpr explicit unexpected(Err&&);
constexpr unexpected& operator=(const unexpected&) = default;
customexpr unexpected& operator=(unexpected&&) = default;
customexpr const E& value() const & noexcept;
customexpr E& value() & noexcept;
customexpr const E&& value() const && noexcept;
customexpr E&& value() && noexcept;
customexpr void swap(unexpected& other) noexcept;
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 val;                     // exposition only
};
template<class E> unexpected(E) -> unexpected<E>;

1 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.

22.8.3.2.2 Constructors

template<class Err = E>
  constexpr explicit unexpected(Err&& e);

1 Constraints:
(1.1) — is_same_v<remove_cvref_t<Err>, unexpected> is false; and
(1.2) — is_same_v<remove_cvref_t<Err>, in_place_t> is false; and
(1.3) — is_constructible_v<E, Err> is true.
2 Effects: Direct-non-list-initializes val with std::forward<Err>(e).
3 Throws: Any exception thrown by the initialization of val.

template<class... Args>
  constexpr explicit unexpected(in_place_t, Args&&... args);
4 Constraints: is_constructible_v<E, Args...> is true.
5 Effects: Direct-non-list-initializes val with std::forward<Args>(args)....
6 Throws: Any exception thrown by the initialization of val.

template<class U, class... Args>
  constexpr explicit unexpected(in_place_t, initializer_list<U> il, Args&&... args);
7 Constraints: is_constructible_v<E, initializer_list<U>&, Args...> is true.
8 Effects: Direct-non-list-initializes val with il, std::forward<Args>(args)....
9 Throws: Any exception thrown by the initialization of val.
22.8.3.2.3 Observers

```cpp
constexpr const E& value() const & noexcept;
constexpr E& value() & noexcept;
```

1 Returns: val.

```cpp
constexpr E&& value() && noexcept;
constexpr const E&& value() const && noexcept;
```

2 Returns: std::move(val).

22.8.3.2.4 Swap

```cpp
constexpr void swap(unexpected& other) noexcept(is_nothrow_swappable_v<E>);
```

1 Mandates: is_swappable_v<E> is true.

2 Effects: Equivalent to: using std::swap; swap(val, other.val);

```cpp
friend constexpr void swap(unexpected& x, unexpected& y) noexcept(noexcept(x.swap(y)));
```

3 Constraints: is_swappable_v<E> is true.

4 Effects: Equivalent to x.swap(y).

22.8.3.2.5 Equality operator

```cpp
template<class E2>
template<

friend constexpr bool operator==(const unexpected& x, const unexpected<E2>& y);
```

1 Mandates: The expression x.value() == y.value() is well-formed and its result is convertible to bool.

2 Returns: x.value() == y.value().

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;
        private:
            E val; // exposition only
    };
}
```

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<T, E> object for which has_value() is false.

```cpp
explicit bad_expected_access(E e);
```

2 Effects: Initializes val with std::move(e).

```cpp
const E& error() const & noexcept;
E& error() & noexcept;
```

3 Returns: val.

```cpp
E&& error() && noexcept;
const E&& error() const && noexcept;
```

4 Returns: std::move(val).

```cpp
const char* what() const noexcept override;
```

5 Returns: An implementation-defined NTBS.
22.8.5 Class template specialization bad_expected_access<void>  

namespace std {
    template<>  
    class bad_expected_access<void> : public exception {
        protected:  
            bad_expected_access() noexcept;  
            bad_expected_access(const bad_expected_access&);  
            bad_expected_access(bad_expected_access&);  
            bad_expected_access(bad_expected_access&&);  
            bad_expected_access& operator=(const bad_expected_access&);  
            bad_expected_access& operator=(bad_expected_access&&);  
            ~bad_expected_access();  
        public:  
            const char* what() const noexcept override;
    };
}

const char* what() const noexcept override;

1 Returns: An implementation-defined NTBS.

22.8.6 Class template expected  

22.8.6.1 General

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>;

            constexpr expected();
            constexpr explicit(const expected&);
            constexpr explicit(expected&&) noexcept;
            template<class U, class G>
            constexpr explicit(expected<U, G>&&);
            template<class U, class G>
            constexpr explicit(expected<U, G>&);
            template<class U = T>
            constexpr explicit(U&& v);
            template<class G>
            constexpr expected(const unexpected<G>&);
            template<class G>
            constexpr 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&&...);
            template<class... Args>
            constexpr explicit(unexpect_t, Args&&...);
            template<class U, class... Args>
            constexpr explicit(unexpect_t, initializer_list<U>, Args&&...);

            // 22.8.6.2, constructors
            constexpr expected();
            constexpr explicit(see below) expected(const expected&);
            constexpr explicit(see below) 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 expected(const unexpected<G>&);
            template<class G>
            constexpr expected(unexpected<G>&&);

            template<class... Args>
            constexpr explicit(expected(in_place_t, Args&&...);
            template<class U, class... Args>
            constexpr explicit(expected(in_place_t, initializer_list<U>, Args&&...);
            template<class... Args>
            constexpr explicit(expected(unexpect_t, Args&&...);
            template<class U, class... Args>
            constexpr explicit(expected(unexpect_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 const T& value() const &;
constexpr T& value() &;
constexpr const T&& value() const &&;
constexpr T&& value() &&;
constexpr const E& error() const &;
constexpr E& error() &;
constexpr const E&& error() const &&;
constexpr E&& error() &&;
template<class U> constexpr T value_or(U&&) const &;
template<class U> constexpr T value_or(U&&) &&;

// 22.8.6.7, 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 unex;   // 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. These objects are allocated in a region of the expected<T, E> storage suitably aligned for the types T and E. Members has_val, val, and unex are provided for exposition only. has_val indicates whether the expected<T, E> object contains an object of type T.

2 A program that instantiates the definition of template expected<T, E> for a reference type, a function type, or for possibly cv-qualified types in_place_t, unexpected_t, or a specialization of unexpected for the T
parameter 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.

When T is not cv void, it shall meet the `Cpp17Destructible` requirements (Table 34). E shall meet the `Cpp17Destructible` requirements.

### 22.8.6.2 Constructors

```cpp
constexpr expected();

Constraints: is_default_constructible_v<T> is true.

Effects: Value-initializes val.

Postconditions: has_value() is true.

Throws: Any exception thrown by the initialization of val.
```

```cpp
constexpr expected(const expected& rhs);

Effects: If rhs.has_value() is true, direct-non-list-initializes val with *rhs. Otherwise, direct-non-list-initializes unex with rhs.error().

Postconditions: rhs.has_value() == this->has_value().

Throws: Any exception thrown by the initialization of val or unex.

Remarks: This constructor is defined as deleted unless

(8.1) — is_copy_constructible_v<T> is true and
(8.2) — is_copy_constructible_v<E> is true.

This constructor is trivial if

(9.1) — is_trivially_copy_constructible_v<T> is true and
(9.2) — is_trivially_copy_constructible_v<E> is true.
```

```cpp
constexpr expected(expected&& rhs) noexcept(see below);

Constraints:

(10.1) — is_move_constructible_v<T> is true and
(10.2) — is_move_constructible_v<E> is true.

Effects: If rhs.has_value() is true, direct-non-list-initializes val with std::move(*rhs). Otherwise, 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 val or unex.

Remarks: The exception specification is equivalent to is_nothrow_move_constructible_v<T> && is_nothrow_move_constructible_v<E>.

This constructor is trivial if

(15.1) — is_trivially_move_constructible_v<T> is true and
(15.2) — is_trivially_move_constructible_v<E> is true.
```

```cpp
template<class U, class G>
constexpr explicit(see below) expected(const expected<U, G>& rhs);

class U;

class G;
```

Let:

(16.1) — UF be const Uk for the first overload and U for the second overload.
(16.2) — GF be const Gk for the first overload and G for the second overload.

### Constraints:

(17.1) — is_constructible_v<T, UF> is true; and
(17.2) — is_constructible_v<E, GF> is true; and
is_constructible_v<T, expected<U, G>&> is false; and
— is_constructible_v<T, expected<U, G>>& is false; and
— is_constructible_v<T, const expected<U, G>&> is false; and
— is_convertible_v<expected<U, G>&, T> is false; and
— is_convertible_v<expected<U, G>&&, T> is false; and
— is_convertible_v<const expected<U, G>&, T> is false; and
— is_convertible_v<const expected<U, G>&&, T> is false; and
— is_constructible_v<unexpected<E>, expected<U, G>&> is false; and
— is_constructible_v<unexpected<E>, expected<U, G>> is false; and
— is_constructible_v<unexpected<E>, const expected<U, G>&> is false; and
— is_constructible_v<unexpected<E>, const expected<U, G>> is false.

Effects: If rhs.has_value(), direct-non-list-initializes val with std::forward<UF>(*rhs). Otherwise, direct-non-list-initializes unex 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 val or unex.

Remarks: The expression inside explicit is equivalent to !is_convertible_v<UF, T> || !is_convertible_v<GF, E>.

template<class U = T>
constexpr explicit(!is_convertible_v<U, T>) expected(U&& v);

Constraints:
— is_same_v<remove_cvref_t<U>, in_place_t> is false; and
— is_same_v<expected<T, E>, remove_cvref_t<U>>& is false; and
— remove_cvref_t<U> is not a specialization of unexpected; and
— is_constructible_v<T, U> is true.

Effects: Direct-non-list-initializes val with std::forward<U>(v).

Postconditions: has_value() is true.

Throws: Any exception thrown by the initialization of val.

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 unex with std::forward<GF>(e.value()).

Postconditions: has_value() is false.

Throws: Any exception thrown by the initialization of unex.

template<class... Args>
constexpr explicit(expected(in_place_t, Args&&... args);

Constraints: is_constructible_v<T, Args&&... args> is true.

Effects: Direct-non-list-initializes val with std::forward<Args>(args). . .

Postconditions: has_value() is true.

Throws: Any exception thrown by the initialization of val.

§ 22.8.6.2
template<class U, class... Args>
constexpr explicit expected(in_place_t, initializer_list<U> il, Args&&... args);

Constraints: `is_constructible_v<T, initializer_list<U>&, Args...>` is true.
Effects: Direct-non-list-initializes `val` with `il, std::forward<Args>(args)`.
Postconditions: `has_value()` is true.
Throws: Any exception thrown by the initialization of `val`.

22.8.6.3 Destructor

constexpr ~expected();

Effects: If `has_value()` is true, destroys `val`, otherwise destroys `unex`.
Remarks: If `is_trivially_destructible_v<T>` is true, and `is_trivially_destructible_v<E>` is true, then this destructor is a trivial destructor.

22.8.6.4 Assignment

This subclause makes use of the following exposition-only function:

```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);

Effects:
(2.1) If `this->has_value() && rhs.has_value()` is true, equivalent to `val = *rhs`.
(2.2) Otherwise, if `this->has_value()` is true, equivalent to:
```cpp
reinit-expected(unex, val, rhs.error())
```
Otherwise, if \( \text{rhs}.\text{has\_value()} \) is \text{true}, equivalent to:
\[ \text{reinit-expected}(\text{val}, \text{unex}, *\text{rhs}) \]

Otherwise, equivalent to \( \text{unex} = \text{rhs}.\text{error()} \).

Then, if no exception was thrown, equivalent to: \( \text{has\_val} = \text{rhs}.\text{has\_value()}; \) \text{return } \ast\text{this};

\textbf{Remarks:} This operator is defined as deleted unless:

- \( \text{is\_copy\_assignable\_v<T> is true} \)
- \( \text{is\_copy\_constructible\_v<T> is true} \)
- \( \text{is\_copy\_assignable\_v<E> is true} \)
- \( \text{is\_copy\_constructible\_v<E> is true} \)
- \( \text{is\_nothrow\_move\_constructible\_v<T> } || \text{is\_nothrow\_move\_constructible\_v<E> is true} \)

\begin{verbatim}
closeexpr \text{expected}& \text{operator=} (\text{expected}& \text{rhs}) \text{noexcept (see below)};
\end{verbatim}

\textbf{Constraints:}

- \( \text{is\_move\_constructible\_v<T> is true} \)
- \( \text{is\_move\_assignable\_v<T> is true} \)
- \( \text{is\_move\_constructible\_v<E> is true} \)
- \( \text{is\_move\_assignable\_v<E> is true} \)
- \( \text{is\_nothrow\_move\_constructible\_v<T> } || \text{is\_nothrow\_move\_constructible\_v<E> is true} \)

\textbf{Effects:}

- If \( \text{this->has\_value()} && \text{rhs}.\text{has\_value()} \) is \text{true}, equivalent to \( \text{val} = \text{std::move(*rhs)} \).
- Otherwise, if \( \text{this->has\_value()} \) is \text{true}, equivalent to:
  \[ \text{reinit-expected}(\text{unex}, \text{val}, \text{std::move(rhs.error())}) \]
- Otherwise, if \( \text{rhs}.\text{has\_value()} \) is \text{true}, equivalent to:
  \[ \text{reinit-expected}(\text{val}, \text{unex}, \text{std::move(*rhs)}) \]
- Otherwise, equivalent to \( \text{unex} = \text{std::move(rhs.error())} \).

Then, if no exception was thrown, equivalent to: \( \text{has\_val} = \text{rhs}.\text{has\_value()}; \) \text{return } \ast\text{this};

\textbf{Remarks:} The exception specification is equivalent to:

\[ \text{is\_nothrow\_move\_assignable\_v<T> } && \text{is\_nothrow\_move\_constructible\_v<T> } && \text{is\_nothrow\_move\_assignable\_v<E> } && \text{is\_nothrow\_move\_constructible\_v<E> } \]

\textbf{template<class } \text{U } = \text{T>}
\text{constexpr expected& } \text{operator=} (\text{U}& \text{v});

\textbf{Constraints:}

- \( \text{is\_same\_v<expected, remove\_cvref\_t<U>> is false} ; \text{and} \)
- \( \text{remove\_cvref\_t<U>} \) is not a specialization of \text{unexpected} ; \text{and} \)
- \( \text{is\_constructible\_v<T, U> is true} ; \text{and} \)
- \( \text{is\_assignable\_v<T\&, U> is true} ; \text{and} \)
- \( \text{is\_nothrow\_constructible\_v<T, U> } || \text{is\_nothrow\_move\_constructible\_v<T> } || \text{is\_nothrow\_move\_constructible\_v<E> } \)

\textbf{Effects:}

- If \text{has\_value()} is \text{true}, equivalent to: \( \text{val} = \text{std::forward<U>(v)} \);
- Otherwise, equivalent to:
  \[ \text{reinit-expected}(\text{val}, \text{unex}, \text{std::forward<U>(v)}) \]
  \( \text{has\_val} = \text{true} \);

\textbf{Returns: } \ast\text{this}.
Let GF be const G& for the first overload and G for the second overload.

Constraints:
(11.1) — is_constructible_v<E, GF> is true; and
(11.2) — is_assignable_v<E&, GF> is true; and
(11.3) — is_nothrow_constructible_v<E, GF> || is_nothrow_move_constructible_v<T> || is_nothrow_move_constructible_v<E> is true.

Effects:
(12.1) — If has_value() is true, equivalent to:
  reinit-expected(unex, val, std::forward<GF>(e.value()));
  has_val = false;
(12.2) — Otherwise, equivalent to: unex = std::forward<GF>(e.value());

Returns: *this.

template<class... Args>
constexpr T& emplace(Args&&... args) noexcept;

Constraints: is_nothrow_constructible_v<T, Args...> is true.

Effects: Equivalent to:
if (has_value()) {
  destroy_at(addressof(val));
} else {
  destroy_at(addressof(unex));
  has_val = true;
}
return *construct_at(addressof(val), std::forward<Args>(args)...);

Effects: Equivalent to:
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)...);

22.8.6.5 Swap

constexpr void swap(expected& rhs) noexcept((see below);

Constraints:
(1.1) — is_swappable_v<T> is true and
(1.2) — is_swappable_v<E> is true and
(1.3) — is_move_constructible_v<T> && is_move_constructible_v<E> is true, and
(1.4) — is_nothrow_move_constructible_v<T> || is_nothrow_move_constructible_v<E> is true.

Effects: See Table 62.

For the case where rhs.value() is false and this->has_value() is true, equivalent to:
if constexpr (is_nothrow_move_constructible_v<E>) {
  E tmp(std::move(rhs.unex));
Table 62: swap(expected&) effects

<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>equivalent to: using std::swap; calls rhs.swap(*this)</td>
</tr>
<tr>
<td>!rhs.has_value()</td>
<td>see below</td>
</tr>
</tbody>
</table>

```
destroy_at(addressof(rhs.uex));
try {
    construct_at(addressof(rhs.val), std::move(val));
    destroy_at(addressof(val));
    construct_at(addressof(uex), std::move(tmp));
} catch(...) {
    construct_at(addressof(rhs.uex), std::move(tmp));
    throw;
}
else {
    T tmp(std::move(val));
    destroy_at(addressof(val));
    try {
        construct_at(addressof(uex), std::move(rhs.uex));
        destroy_at(addressof(rhs.uex));
        construct_at(addressof(rhs.val), std::move(tmp));
    } catch (...) {
        construct_at(addressof(val), std::move(tmp));
        throw;
    }
}
has_val = false;
rhs.has_val = true;
```

3 Throws: Any exception thrown by the expressions in the Effects.

4 Remarks: The exception specification is equivalent to:

```
friend constexpr void swap(expected& x, expected& y) noexcept(noexcept(x.swap(y)));
```

5 Effects: Equivalent to x.swap(y).

### 22.8.6.6 Observers

```
constexpr const T* operator->() const noexcept;
constexpr T* operator->() noexcept;
```

1 Preconditions: has_value() is true.

2 Returns: addressof(val).

```
constexpr const T& operator*() const & noexcept;
constexpr T& operator*() & noexcept;
```

3 Preconditions: has_value() is true.

4 Returns: val.

```
constexpr T&& operator*() && noexcept;
constexpr const T&& operator*() const && noexcept;
```

5 Preconditions: has_value() is true.

6 Returns: std::move(val).

```
constexpr explicit operator bool() const noexcept;
```
constexpr bool has_value() const noexcept;

Returns: has_val.

constexpr const T& value() const &;
constexpr T& value() &;

Returns: val, if has_value() is true.

Throws: bad_expected_access(error()) if has_value() is false.

constexpr T&& value() &&;
constexpr const T&& value() const &&;

Returns: std::move(val), if has_value() is true.

Throws: bad_expected_access(std::move(error())) if has_value() is false.

constexpr E& error() & noexcept;
constexpr const E& error() const & noexcept;

Preconditions: has_value() is false.

constexpr E&& error() && noexcept;
constexpr const E&& error() const && noexcept;

Preconditions: has_value() is false.

Mandates: The expressions *x == *y and x.error() == y.error() are well-formed and their results are convertible to bool.

Returns: If x.has_value() does not equal y.has_value(), false; otherwise if x.has_value() is true, *x == *y; otherwise x.error() == y.error().

Mandates: The expression x.error() == e.value() is well-formed and its result is convertible to bool.

Returns: !x.has_value() && static_cast<bool>(x.error() == e.value()).

22.8.7 Partial specialization of expected for void types

22.8.7.1 General

Mandates: The expression x.error() == e.value() is well-formed and its result is convertible to bool.

Returns: !x.has_value() && static_cast<brool>(x.error() == e.value()).
using error_type = E;
using unexpected_type = unexpected<E>;

template<class U>
using rebind = expected<U, error_type>;

// 22.8.7.2, constructors
constexpr expected() noexcept;
constexpr explicit(see below) expected(const expected&);
constexpr explicit(see below) 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 G>
  constexpr explicit expected(const unexpected<G>&);
template<class G>
  constexpr expected(unexpected<G>&&);

constexpr explicit expected(in_place_t) noexcept;
template<class... Args>
  constexpr explicit expected(unexpect_t, Args&&...);
template<class U, class... Args>
  constexpr explicit expected(unexpect_t, initializer_list<U>, Args&&...);

// 22.8.7.3, destructor
constexpr ~expected();

// 22.8.7.4, assignment
constexpr expected& operator=(const expected&);
constexpr expected& operator=(expected&&) noexcept(see below);
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(see below);
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 &;
constexpr E& error() &;
constexpr const E&& error() const &&;
constexpr E&& error() &&;

// 22.8.7.7, 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 E2>
  friend constexpr bool operator==(const expected&, const unexpected<E2>&);

private:
  bool has_val;       // exposition only
  union {
    E unex;           // exposition only
  }
E shall meet the requirements of Cpp17Destructible (Table 34).

### 22.8.7.2 Constructors

```cpp
constexpr expected() noexcept;
1
Postconditions: has_value() is true.

constexpr expected(const expected& rhs);
2
Effects: If rhs.has_value() is false, direct-non-list-initializes unez with rhs.error().
3
Postconditions: rhs.has_value() == this->has_value().
4
Throws: Any exception thrown by the initialization of unez.
5
Remarks: This constructor is defined as deleted unless is_copy_constructible_v<E> is true.
6
This constructor is trivial if is_trivially_copy_constructible_v<E> is true.

constexpr expected(expected&& rhs) noexcept(is_nothrow_move_constructible_v<E>);
7
Constraints: is_move_constructible_v<E> is true.
8
Effects: If rhs.has_value() is false, direct-non-list-initializes unez with std::move(rhs.error()).
9
Postconditions: rhs.has_value() is unchanged; rhs.has_value() == this->has_value() is true.
10
Throws: Any exception thrown by the initialization of unez.
11
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);
12
Let GF be const G& for the first overload and G for the second overload.
13
Constraints:
(13.1) is_void_v<U> is true; and
(13.2) is_constructible_v<E, GF> is true; and
(13.3) is_constructible_v<unexpected<E>, expected<U, G>&> is false; and
(13.4) is_constructible_v<unexpected<E>, expected<U, G>>& is false; and
(13.5) is_constructible_v<unexpected<E>, const expected<U, G>&> is false; and
(13.6) is_constructible_v<unexpected<E>, const expected<U, G>> is false.
14
Effects: If rhs.has_value() is false, direct-non-list-initializes unez with std::forward<GF>(rhs.error()).
15
Postconditions: rhs.has_value() is unchanged; rhs.has_value() == this->has_value() is true.
16
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);
17
Let GF be const G& for the first overload and G for the second overload.
18
Constraints: is_constructible_v<E, GF> is true.
19
Effects: Direct-non-list-initializes unez with std::forward<GF>(e.value()).
20
Postconditions: has_value() is false.
21
Throws: Any exception thrown by the initialization of unez.
```
constexpr explicit expected(in_place_t) noexcept;

Postconditions: has_value() is true.

template<class... Args>
constexpr explicit expected(unexpect_t, Args&&... args);

Constraints: is_constructible_v<E, Args...> is true.
Effects: Direct-non-list-initializes unez with std::forward<Args>(args)....
Postconditions: has_value() is false.
Throws: Any exception thrown by the initialization of unez.

template<class U, class... Args>
constexpr explicit expected(unexpect_t, initializer_list<U> il, Args&&... args);

Constraints: is_constructible_v<E, initializer_list<U>&, Args...> is true.
Effects: Direct-non-list-initializes unez with il, std::forward<Args>(args)....
Postconditions: has_value() is false.
Throws: Any exception thrown by the initialization of unez.

22.8.7.3 Destructor

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

constexpr expected& operator=(const expected& rhs);

Effects:
1. If this->has_value() && rhs.has_value() is true, no effects.
2. Otherwise, if this->has_value() is true, equivalent to: construct_at(addressof(unex), rhs.unex); has_val = false;
3. Otherwise, if rhs.has_value() is true, destroys unez and sets has_val to true.
4. Otherwise, equivalent to unex = rhs.error().
Returns: *this.
Remarks: This operator is defined as deleted unless is_copyAssignable_v<E> is true and is_copyConstructible_v<E> is true.

constexpr expected& operator=(expected&& rhs) noexcept(see below);

Effects:
1. If this->has_value() && rhs.has_value() is true, no effects.
2. Otherwise, if this->has_value() is true, equivalent to:
   construct_at(addressof(unex), std::move(rhs.unex));
   has_val = false;
3. Otherwise, if rhs.has_value() is true, destroys unez and sets has_val to true.
4. Otherwise, equivalent to unex = rhs.error().
Returns: *this.
Remarks: The exception specification is equivalent to is_nothrowMoveConstructible_v<E> && is_nothrowMoveAssignable_v<E>.
This operator is defined as deleted unless is_moveConstructible_v<E> is true and is_moveAssignable_v<E> is true.
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<G, GF> is true and is_assignable_v<G, GF> is true.

Effects:

(10.1) — If has_value() is true, equivalent to:
construct_at(addressof(unex), std::forward<G>(e.value()));
has_val = false;

(10.2) — Otherwise, equivalent to: unex = std::forward<G>(e.value());

Returns: *this.

constexpr void emplace() noexcept;

Effects: If has_value() is false, destroys unex and sets has_val to true.

22.8.7.5 Swap

constexpr void swap(expected& rhs) noexcept;

Constraints: is_swappable_v<G> is true and is_move_constructible_v<G> is true.

Effects: See Table 63.

Table 63: swap(expected&) effects

<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>calls rhs.swap(*this)</td>
</tr>
</tbody>
</table>
| !rhs.has_value() | see below            | equivalent to: using std::swap;
|                  |                      | swap(unex, rhs.unex); |

For the case where rhs.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<G> &&
is_nothrow_swappable_v<G>.

friend constexpr void swap(expected& x, expected& y) noexcept(noexcept(x.swap(y)));

Effects: Equivalent to x.swap(y).

22.8.7.6 Observers

constexpr explicit operator bool() const noexcept;
constexpr bool has_value() const noexcept;

Returns: has_val.

constexpr void operator*() const noexcept;

Preconditions: has_value() is true.

constexpr void value() const &;

Throws: bad_expected_access(error()) if has_value() is false.

constexpr void value() &&;

Throws: bad_expected_access(std::move(error())) if has_value() is false.
constexpr const E& error() const &;  
constexpr E& error() &;  

Preconditions: has_value() is false.  

Returns: unex.

constexpr E&& error() &&;  
constexpr const E&& error() const &&;  

Preconditions: has_value() is false.  

Returns: std::move(unex).

22.8.7.7 Equality operators

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.value() is well-formed and its result is convertible to bool.

Returns: !x.has_value() && static_cast<bool>(x.error() == e.value()).

22.9 Bitsets

22.9.1 Header <bitset> synopsis

The header <bitset> defines a class template and several related functions for representing and manipulating fixed-size sequences of bits.

#include <string>  
#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>  
    bitset<N> operator&(const bitset<N>&, const bitset<N>&) noexcept;
    template<size_t N>  
    bitset<N> operator|(const bitset<N>&, const bitset<N>&) noexcept;
    template<size_t N>  
    bitset<N> operator^(const bitset<N>&, const bitset<N>&) noexcept;
    template<class charT, class traits, size_t N>  
    basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>&& is, bitset<N>& x);  
    template<class charT, class traits, size_t N>  
    basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const bitset<N>& x);
}

22.9.2 Class template bitset

22.9.2.1 General

namespace std {  
    template<size_t N> class bitset {  
        public:  
            // bit reference
            friend class bitset;  
            reference() noexcept;

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public:
    reference(const reference&) = default;
    ~reference()
    reference operator=(bool x) noexcept;  // for b[i] = x;
    reference operator=(const reference&) noexcept; // for b[i] = b[j];
    bool operator~() const noexcept;  // flips the bit
    operator bool() const noexcept;  // for x = b[i];
    reference& flip() noexcept;  // for b[i].flip();

// 22.9.2.2, constructors
constexpr bitset() noexcept;
constexpr bitset(unsigned long long val) noexcept;
template<class charT, class traits, class Allocator>
    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>
        explicit bitset(
            const charT* str,
            typename basic_string<charT>::size_type n = basic_string<charT>::npos,
            charT zero = charT('0'),
            charT one = charT('1'));

// 22.9.2.3, bitset operations
bitset& operator&=(const bitset& rhs) noexcept;
bitset& operator|=(const bitset& rhs) noexcept;
bitset& operator^=(const bitset& rhs) noexcept;
bitset& operator<<=(size_t pos) noexcept;
bitset& operator>>=(size_t pos) noexcept;
bitset& set() noexcept;
bitset& set(size_t pos, bool val = true);
bitset& reset() noexcept;
bitset& reset(size_t pos);
bitset operator~() const noexcept;
bitset& flip() noexcept;
bitset& flip(size_t pos);

// element access
constexpr bool operator[](size_t pos) const;  // for b[i];
reference operator[](size_t pos);  // for b[i];

unsigned long to_ulong() const;
unsigned long long to_ullong() const;
template<class charT = char,
    class traits = char_traits<charT>,
    class Allocator = allocator<charT>>
    basic_string<charT, traits, Allocator>
to_string(charT zero = charT('0'), charT one = charT('1')) const;

size_t count() const noexcept;
constexpr size_t size() const noexcept;
bool operator==(const bitset& rhs) const noexcept;
bool test(size_t pos) const;
bool all() const noexcept;
bool any() const noexcept;
bool none() const noexcept;
bitset operator<<(size_t pos) const noexcept;
bitset operator>>(size_t pos) const noexcept;

§ 22.9.2.1
The class template `bitset<N>` describes an object that can store a sequence consisting of a fixed number of bits, N.

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.

The functions described in 22.9.2 can report three kinds of errors, each associated with a distinct exception:

- (3.1) — an invalid-argument error is associated with exceptions of type `invalid_argument` (19.2.5);
- (3.2) — an out-of-range error is associated with exceptions of type `out_of_range` (19.2.7);
- (3.3) — an overflow error is associated with exceptions of type `overflow_error` (19.2.10).

### 22.9.2.2 Constructors

**constexpr bitset() noexcept;**

*Effects:* Initializes all bits in `*this` to zero.

**constexpr bitset(unsigned long long val) noexcept;**

*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.

**template<class charT, class traits, class Allocator>
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'));**

*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.

**template<class charT>
explicit bitset(const charT* str, typename basic_string<charT>::size_type n = basic_string<charT>::npos, charT zero = charT('0'), charT one = charT('1'));**

*Effects:* As if by:

```cpp
bitset(n == basic_string<charT>::npos
    ? basic_string<charT>(str)
    : basic_string<charT>(str, n),
    0, n, zero, one)
```
22.9.2.3 Members

bitset& operator&=(const bitset& rhs) noexcept;
1  Effects: Clears each bit in *this for which the corresponding bit in rhs is clear, and leaves all other
2    bits unchanged.
3  Returns: *this.

bitset& operator|=(const bitset& rhs) noexcept;
3  Effects: Sets each bit in *this for which the corresponding bit in rhs is set, and leaves all other bits
4    unchanged.
5  Returns: *this.

bitset& operator^=(const bitset& rhs) noexcept;
5  Effects: Toggles each bit in *this for which the corresponding bit in rhs is set, and leaves all other
6    bits unchanged.
7  Returns: *this.

bitset& operator<<=(size_t pos) noexcept;
7  Effects: Replaces each bit at position I in *this with a value determined as follows:
8                   — If I < pos, the new value is zero;
9                   — If I >= pos, the new value is the previous value of the bit at position I - pos.
10 Returns: *this.

bitset& operator>>=(size_t pos) noexcept;
9  Effects: Replaces each bit at position I in *this with a value determined as follows:
10                  — If pos >= N - I, the new value is zero;
11                  — If pos < N - I, the new value is the previous value of the bit at position I + pos.
12 Returns: *this.

bitset& set() noexcept;
11  Effects: Sets all bits in *this.
12  Returns: *this.

bitset& set(size_t pos, bool val = true);
13  Effects: Stores a new value in the bit at position pos in *this. If val is true, the stored value is one,
14    otherwise it is zero.
15  Returns: *this.
16  Throws: out_of_range if pos does not correspond to a valid bit position.

bitset& reset() noexcept;
16  Effects: Resets all bits in *this.
17  Returns: *this.

bitset& reset(size_t pos);
18  Effects: Resets the bit at position pos in *this.
19  Returns: *this.
20  Throws: out_of_range if pos does not correspond to a valid bit position.

bitset operator~() const noexcept;
21  Effects: Constructs an object x of class bitset and initializes it with *this.
22  Returns: x.flip().
bitset & flip() noexcept;
   Effects: Toggles all bits in *this.
   Returns: *this.

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.

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.

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.

template<class charT = char,
         class traits = char_traits<charT>,
         class Allocator = allocator<charT>>
   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.

size_t count() const noexcept;
   Returns: A count of the number of bits set in *this.

constexpr size_t size() const noexcept;
   Returns: N.

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.

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.

bool all() const noexcept;
   Returns: count() == size().

bool any() const noexcept;
   Returns: count() != 0.

bool none() const noexcept;
   Returns: count() == 0.

bitset operator<<(size_t pos) const noexcept;
   Returns: bitset(*this) <<= pos.
bitset operator>>(size_t pos) const noexcept;

Returns: \( \text{bitset}(*\text{this}) >>= \text{pos} \).

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.

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.

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>
bitset<N> operator&(const bitset<N>& lhs, const bitset<N>& rhs) noexcept;

Returns: \( \text{bitset}<\text{N}>(\text{lhs}) &\text{ rhs} \).
```

```cpp
template<size_t N>
bitset<N> operator|(const bitset<N>& lhs, const bitset<N>& rhs) noexcept;

Returns: \( \text{bitset}<\text{N}>(\text{lhs}) |\text{ rhs} \).
```

```cpp
template<size_t N>
bitset<N> operator^(const bitset<N>& lhs, const bitset<N>& rhs) noexcept;

Returns: \( \text{bitset}<\text{N}>(\text{lhs}) ^\text{ rhs} \).
```

```cpp
template<class charT, class traits, size_t N>
basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& is, bitset<N>& x);

A formatted input function (31.7.4.3).

Effects: Extracts up to \( \text{N} \) characters from is. Stores these characters in a temporary object str of type basic_string<charT, traits>, then evaluates the expression \( \text{x} = \text{bitset}<\text{N}>(\text{str}) \). Characters are extracted and stored until any of the following occurs:

(5.1) \( \text{N} \) characters have been extracted and stored;
(5.2) end-of-file occurs on the input sequence;
(5.3) the next input character is neither is.widen('0') nor is.widen('1') (in which case the input character is not extracted).

If \( \text{N} > 0 \) and no characters are stored in str, calls is.setstate(ios_base::failbit) (which may throw ios_base::failure (31.5.4.4)).

Returns: is.
```

```cpp
template<class charT, class traits, size_t N>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const bitset<N>& x);

Returns:
```
os << x.template to_string<charT, traits, allocator<charT>>(
    use_facet<ctype<charT>>(os.getloc()).widen('0'),
    use_facet<ctype<charT>>(os.getloc()).widen('1'))

(see 31.7.5.3).

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

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...>);
  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;
  template<class T> constexpr reference_wrapper<T> ref(T&) noexcept;
  template<class T> constexpr reference_wrapper<const T> cref(const T&) noexcept;
  template<class T> void ref(const T&&) = delete;
  template<class T> void cref(const T&&) = delete;
  template<class T> constexpr reference_wrapper<T> ref(reference_wrapper<T>) noexcept;
  template<class T> constexpr reference_wrapper<const T> cref(reference_wrapper<T>) noexcept;

  // 22.10.7, arithmetic operations
  template<class T = void> struct plus;
  template<class T = void> struct minus;
  template<class T = void> struct multiplies;
  template<class T = void> struct divides;
  template<class T = void> struct modulus;
  template<class T = void> struct negate;
  template<> struct plus<void>;
  template<> struct minus<void>;
  template<> struct multiplies<void>;
  template<> struct divides<void>;
  template<> struct modulus<void>;
  template<> struct negate<void>;

  // 22.10.8, comparisons
  template<class T = void> struct equal_to;
  template<class T = void> struct not_equal_to;
  template<class T = void> struct greater;
  template<class T = void> struct less;
  template<class T = void> struct greater_equal;
  template<class T = void> struct less_equal;
  template<> struct equal_to<void>;
  template<> struct not_equal_to<void>;
  template<> struct greater<void>;
  template<> struct less<void>;

// 22.10.2 738

209) 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.

§ 22.10.2
template<> struct less<void>;
template<> struct greater_equal<void>;
template<> struct less_equal<void>;

// 22.10.8.8, class compare_three_way
struct compare_three_way;

// 22.10.10, logical operations
template<class T = void> struct logical_and;
template<class T = void> struct logical_or;
template<class T = void> struct logical_not;
template<> struct logical_and<void>;
template<> struct logical_or<void>;
template<> struct logical_not<void>;

// 22.10.11, bitwise operations
template<class T = void> struct bit_and;
template<class T = void> struct bit_or;
template<class T = void> struct bit_xor;
template<class T = void> struct bit_not;
template<> struct bit_and<void>;
template<> struct bit_or<void>;
template<> struct bit_xor<void>;
template<> struct bit_not<void>;

// 22.10.12, identity
struct identity;

// 22.10.13, function template not_fn
template<class F> constexpr unspecified not_fn(F&& f);

// 22.10.14, function templates bind_front and bind_back
template<class F, class... Args> constexpr unspecified bind_front(F&&, Args&&...);
template<class F, class... Args> constexpr unspecified bind_back(F&&, Args&&...);

// 22.10.15, bind
template<class T> struct is_bind_expression;
template<class T> inline constexpr bool is_bind_expression_v = is_bind_expression<T>::value;
template<class T> struct is_placeholder;
template<class T> inline constexpr int is_placeholder_v = is_placeholder<T>::value;
template<class F, class... BoundArgs>
  constexpr unspecified bind(F&&, BoundArgs&&...);
template<class R, class F, class... BoundArgs>
  constexpr unspecified bind(R, F, class... BoundArgs);

namespace placeholders {
  // M is the implementation-defined number of placeholders
  see below _1;
  see below _2;
  .
  .
  see below _M;
}

// 22.10.16, member function adaptors
template<class R, class T>
  constexpr unspecified mem_fn(R T::* noexcept;

// 22.10.17, polymorphic function wrappers
class bad_function_call;
template<class> class function;  // not defined
template<class R, class... ArgTypes> class function<R(ArgTypes...)>;

// 22.10.17.3.8, specialized algorithms
template<class R, class... ArgTypes>
    void swap(function<R(ArgTypes...)>&, function<R(ArgTypes...)>&) noexcept;

// 22.10.17.3.7, null pointer comparison operator functions
template<class R, class... ArgTypes>
    bool operator==(const function<R(ArgTypes...)>&, nullptr_t) noexcept;

// 22.10.17.4, move only wrapper
template<class... S> class move_only_function;  // not defined
template<class R, class... ArgTypes>
    class move_only_function<R(ArgTypes...)>
        cv ref noexcept(noex);
        // see below

// 22.10.18, searchers
template<class ForwardIterator, class BinaryPredicate = equal_to<>>
    class default_searcher;

template<class RandomAccessIterator, class Hash = hash<typename iterator_traits<RandomAccessIterator>::value_type>,
            class BinaryPredicate = equal_to<>>
    class boyer_moore_searcher;

// 22.10.19, class template hash
template<class T>
    struct hash;

namespace ranges {
    // 22.10.9, concept-constrained comparisons
    struct equal_to;
    struct not_equal_to;
    struct greater;
    struct less;
    struct greater_equal;
    struct less_equal;
}

1 [Example 1: If a C++ program wants to have a by-element addition of two vectors \texttt{a} and \texttt{b} containing \texttt{double} and put the result into \texttt{a}, it can do:
    
    \begin{verbatim}
    transform(a.begin(), a.end(), b.begin(), a.begin(), plus<double>());
    \end{verbatim}
    —end example]

2 [Example 2: To negate every element of \texttt{a}:
    
    \begin{verbatim}
    transform(a.begin(), a.end(), a.begin(), negate<double>());
    \end{verbatim}
    —end example]

22.10.3 Definitions

The following definitions apply to this Clause:

A \textit{call signature} is the name of a return type followed by a parenthesized comma-separated list of zero or more argument types.

A \textit{callable type} is a function object type (22.10) or a pointer to member.

A \textit{callable object} is an object of a callable type.
A call wrapper type is a type that holds a callable object and supports a call operation that forwards to that object.

A call wrapper is an object of a call wrapper type.

A target object is the callable object held by a call wrapper.

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.

The target object and bound argument entities of the call wrapper are collectively referred to as state entities.

### 22.10.4 Requirements

1. Define `INVOKE(f, t_1, t_2, ..., t_N)` as follows:
   
   - \((t_1.f)(t_2, \ldots, t_N)\) when \(f\) is a pointer to a member function of a class \(T\) and \(\text{is\_base\_of\_v<T, remove\_reference\_t<\text{decltype}(t_1)>>}\) is true;
   
   - \((t_1.get().f)(t_2, \ldots, t_N)\) when \(f\) is a pointer to a member function of a class \(T\) and \(\text{remove\_cvt\_t<\text{decltype}(t_1)>}\) is a specialization of `reference\_wrapper`;
   
   - \(((*t_1).f)(t_2, \ldots, t_N)\) when \(f\) is a pointer to a member function of a class \(T\) and \(t_1\) does not satisfy the previous two items;
   
   - \(t_1.f\) when \(N = 1\) and \(f\) is a pointer to data member of a class \(T\) and \(\text{is\_base\_of\_v<T, remove\_reference\_t<\text{decltype}(t_1)>}\) is true;
   
   - \(t_1.get().f\) when \(N = 1\) and \(f\) is a pointer to data member of a class \(T\) and \(\text{remove\_cvt\_t<\text{decltype}(t_1)>}\) is a specialization of `reference\_wrapper`;
   
   - \(((*t_1).f)\) when \(N = 1\) and \(f\) is a pointer to data member of a class \(T\) and \(t_1\) does not satisfy the previous two items;
   
   - \(f(t_1, t_2, \ldots, t_N)\) in all other cases.

2. Define `INVOKE<R>(f, t_1, t_2, ..., t_N)` as `static\_cast<void>(INVOKE(f, t_1, t_2, ..., t_N))` if \(R\) is `cv\_void` otherwise `INVOKE(f, t_1, t_2, ..., t_N)` implicitly converted to \(R\). If `reference\_converts\_from\_temporary\_v<R, declaring<INVOKE(f, t_1, t_2, ..., t_N)>>` is true, `INVOKE<R>(f, t_1, t_2, ..., t_N)` 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 arguments to the target object as references. This forwarding step delivers rvalue arguments as rvalue references and lvalue arguments as lvalue references.

4. In a typical implementation, argument forwarding call wrappers have an overloaded function call operator of the form

   ```cpp
   template<class... UnBoundArgs>
   constexpr R operator()(UnBoundArgs&&... unbound_args) cv-guaranteed;
   ```

5. 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`.

6. 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.

7. 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.

8. 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).

9. 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...>);
```

Constraints: is_invocable_v<F, Args...> is true.

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...>);
```

Constraints: is_invocable_r_v<R, F, Args...> is true.

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:
            using type = T;

            template<class U>
            constexpr reference_wrapper(U&&) noexcept;
            constexpr reference_wrapper(const reference_wrapper& x) noexcept;
            constexpr reference_wrapper& operator=(const reference_wrapper& x) noexcept;

            constexpr operator T& () const noexcept;
            constexpr T& get() const noexcept;

            template<class... ArgTypes>
            constexpr invoke_result_t<T&, ArgTypes...> operator()(ArgTypes&&...) const;
    };
```

1 reference_wrapper<T> is a Cpp17CopyConstructible and Cpp17CopyAssignable wrapper around a reference to an object or function of type T.

2 reference_wrapper<T> is a trivially copyable type (6.8.1).

3 The template parameter T of reference_wrapper may be an incomplete type.

22.10.6.2 Constructors

```cpp
template<class U>
constexpr reference_wrapper(U&& u) noexcept;
```

1 Let FUN denote the exposition-only functions

   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
constexpr reference_wrapper& operator=(const reference_wrapper& x) noexcept;
```

Postconditions: *this stores a reference to x.get().

22.10.6.4 Access

```cpp
constexpr T& get() const noexcept;
```

Returns: The stored reference.

22.10.6.5 Invocation

```cpp
template<class... ArgTypes>
constexpr invoke_result_t<T&, ArgTypes...> operator()(ArgTypes&&... args) const;
```

Mandates: T is a complete type.

Returns: INVOKE(get(), std::forward<ArgTypes>(args)...). (22.10.4)

22.10.6.6 Helper functions

```cpp
template<class T> constexpr reference_wrapper<T> ref(T& t) noexcept;
```

Returns: reference_wrapper<T>(t).

```cpp
template<class T> constexpr reference_wrapper<T> ref(reference_wrapper<T> t) noexcept;
```

Returns: t.

```cpp
template<class T> constexpr reference_wrapper<const T> cref(const T& t) noexcept;
```

Returns: reference_wrapper<const T>(t).

```cpp
template<class T> constexpr reference_wrapper<const T> cref(reference_wrapper<T> t) noexcept;
```

Returns: t.

22.10.7 Arithmetic operations

22.10.7.2 Class template plus

```cpp
template<class T = void> struct plus {
    constexpr T operator()(const T& x, const T& y) const;
};
```

```cpp
constexpr T operator()(const T& x, const T& y) const;
```

Returns: x + y.

§ 22.10.7.2
template<> struct plus<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).

22.10.7.3 Class template minus

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;

1 Returns: x - y.

template<> struct minus<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).

22.10.7.4 Class template multiplies

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;

1 Returns: x * y.

template<> struct multiplies<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).

22.10.7.5 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));
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, 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).

22.10.7.7 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;
};
template<class T> constexpr auto operator()(T&& t) const
-> decltype(-std::forward<T>(t));
2
Returns: -std::forward<T>(t).

22.10.8 Comparisons

22.10.8.1 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`  

```cpp
template<class T = void> struct equal_to {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

returns: `x == y`.

```cpp
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;
};
```

returns: `std::forward<T>(t) == std::forward<U>(u)`.

22.10.8.3 Class template `not_equal_to`  

```cpp
template<class T = void> struct not_equal_to {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

returns: `x != y`.

```cpp
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;
};
```

returns: `std::forward<T>(t) != std::forward<U>(u)`.

22.10.8.4 Class template `greater`  

```cpp
template<class T = void> struct greater {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

returns: `x > y`.

```cpp
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;
};
```

returns: `std::forward<T>(t) > std::forward<U>(u)`.

22.10.8.5 Class template `less`  

```cpp
template<class T = void> struct less {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

returns: `x < y`.
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;
};

castexpr 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;
};

castexpr 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));

Returns: 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;
  };

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template<class T, class U>
constexpr auto operator()(T&& t, U&& u) const;

Constraints: T and U satisfy three_way_comparable_with.

Preconditions: If the expression \( \text{std::forward<T>(t) <=> std::forward<U>(u) } \) 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.

Effects:

1. If the expression \( \text{std::forward<T>(t) <=> std::forward<U>(u) } \) 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.

2. Otherwise, equivalent to: return std::forward<T>(t) <=> std::forward<U>(u);

22.10.9 Concept-constrained comparisons [range cmp]

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;

Constraints: T and U satisfy equality_comparable_with.

Preconditions: If the expression \( \text{std::forward<T>(t) == std::forward<U>(u) } \) 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.

Effects:

1. If the expression \( \text{std::forward<T>(t) == std::forward<U>(u) } \) 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.

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 decltype((ET)) is T and decltype((EU)) is U, exactly one of ranges::less{}(ET, EU), ranges::less{}(EU, ET), or ranges::equal_to{}(ET, EU) is true.

Effects:
    — 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.
    — 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 [logical.operations]

22.10.10.1 General [logical.operations.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

```cpp
template<class T = void> struct logical_and {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

Returns: \( x \&\& y \).

```cpp
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;
};
```

Returns: \( \text{std::forward<T>(t)} \&\& \text{std::forward<U>(u)} \).

22.10.10.3 Class template logical_or

```cpp
template<class T = void> struct logical_or {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

Returns: \( x \|\| y \).

```cpp
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;
};
```

Returns: \( \text{std::forward<T>(t)} \|\| \text{std::forward<U>(u)} \).

22.10.10.4 Class template logical_not

```cpp
template<class T = void> struct logical_not {
    constexpr bool operator()(const T& x) const;
};
```

Returns: \( \neg x \).

```cpp
template<> struct logical_not<void> {
    template<class T> constexpr auto operator()(T&& t) const
        -> decltype(!std::forward<T>(t));
    using is_transparent = unspecified;
};
```

Returns: \( \neg \text{std::forward<T>(t)} \).
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;
};
```

```cpp
constexpr T operator()(const T& x, const T& y) const;
```

1 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));
```

2 Returns: \( \text{std::forward}(t) \& \text{std::forward}(u) \).

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;
};
```

```cpp
constexpr T operator()(const T& x, const T& y) const;
```

1 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));
```

2 Returns: \( \text{std::forward}(t) | \text{std::forward}(u) \).

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;
};
```

```cpp
constexpr T operator()(const T& x, const T& y) const;
```

1 Returns: \( x ^ y \).

```cpp
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;
};
```

```cpp
template<class T, class U> constexpr auto operator()(T&& t, U&& u) const
  -> decltype(std::forward<T>(t) ^ std::forward<U>(u));
```

2 Returns: \( \text{std::forward}(t) ^ \text{std::forward}(u) \).
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;

1 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&&) const
    -> decltype(~std::forward<T>(t));

2 Returns: ~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;

1 Effects: Equivalent to: return std::forward<T>(t);

22.10.13 Function template not_fn

template<class F> constexpr unspecified not_fn(F&& f);

1 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.

2 Mandates: is_constructible_v<FD, F> && is_move_constructible_v<FD> is true.
3 Preconditions: FD meets the Cpp17MoveConstructible requirements.
4 Returns: A perfect forwarding call wrapper (22.10.4) g with call pattern !invoke(fd, call_args...).
5 Throws: Any exception thrown by the initialization of fd.

22.10.14 Function templates bind_front and bind_back

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);

1 Within this subclause:
(1.1) g is a value of the result of a bind_front or bind_back 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),
BoundArgs is a pack that denotes decay_t<Args>..., bound_args is a pack of bound argument entities of g (22.10.3) of types BoundArgs..., direct-non-list-initialized with std::forward<Args>(args)..., respectively, and call_args is an argument pack used in a function call expression (7.6.1.3) of g.

Mandates:

\[
\text{is_constructible_v<FD, F>} \&\& \\
\text{is_move_constructible_v<FD>} \&\& \\
\text{(is_constructible_v<BoundArgs, Args>} \&\& \ldots) \&\& \\
\text{(is_move_constructible_v<BoundArgs} \&\& \ldots)
\]

is true.

Preconditions: FD meets the Cpp17MoveConstructible requirements. For each Ti in BoundArgs, if Ti is an object type, Ti meets the Cpp17MoveConstructible requirements.

Returns: A perfect forwarding call wrapper (22.10.4) g with call pattern:

1. `invoke(fd, bound_args..., call_args...)` for a bind_front invocation, or
2. `invoke(fd, call_args..., bound_args...)` for a bind_back invocation.

Throws: Any exception thrown by the initialization of the state entities of g (22.10.3).

22.10.15 Function object binders

22.10.15.1 General

Subclause 22.10.15 describes a uniform mechanism for binding arguments of callable objects.

22.10.15.2 Class template is_bind_expression

```
namespace std {
    template<class T> struct is_bind_expression; // see below
}
```

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.

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
}
```

The class template is_placeholder can be used to detect the standard placeholders _1, _2, and so on. The function template bind uses is_placeholder to detect placeholders.

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:

1. g is a value of the result of a bind invocation,
2. FD is the type decay_t<F>,
3. 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),
4. Ti is the i-th type in the template parameter pack BoundArgs,
TD is the type decay_t<T>,

- t 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 TD direct-non-list-initialized with std::forward<T, t>,
- Uj is the j-th deduced type of the UnBoundArgs... parameter of the argument forwarding call wrapper, and
- ui is the j-th argument associated with Uj.

```cpp
template<class F, class... BoundArgs>
constexpr unspecified bind(F&& f, BoundArgs&&... bound_args);
```

- Mandates: is_constructible_v<FD, F> is true. For each Ti in BoundArgs, is_constructible_v<TD, Ti> is true.
- Preconditions: FD and each TD meet the Cpp17MoveConstructible and Cpp17Destructible requirements.
- INVOKED(fd, w1, w2, ..., wN) (22.10.4) is a valid expression for some values w1, w2, ..., wN, where N has the value sizeof...(bound_args).
- 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(u1, u2, ..., uM) is expression-equivalent (3.21) to

```
INVOKED(static_cast<Inv<In>(vf1),
    static_cast<Inv<In>(vf1), static_cast<Inv<In>(vf2), ..., static_cast<Inv<In>(vfN))
```

for the first overload, and

```
INVOKED<Inv>(static_cast<Inv<In>(vf1),
    static_cast<Inv<In>(vf1), static_cast<Inv<In>(vf2), ..., static_cast<Inv<In>(vfN))
```

for the second overload, where the values and types of the target argument vf1 and of the bound arguments v1, v2, ..., vN are determined as specified below.

- Throws: Any exception thrown by the initialization of the state entities of g.

[Note 1: If all of FD and TD meet the requirements of Cpp17CopyConstructible, then the return type meets the requirements of Cpp17CopyConstructible. — end note]

The values of the bound arguments v1, v2, ..., vN and their corresponding types V1, V2, ..., VN depend on the types TD derived from the call to bind and the cv-qualifiers cv of the call wrapper g as follows:

- if TD is reference_wrapper<T>, the argument is td.get() and its type Vi is T;
- if the value of is_bind_expression_v<TD> is true, the argument is

```
    static_cast<Inv<In>>(td)(std::forward<U>(u) ...)
```

and its type Vi is invoke_result_t<Inv TD, Uj, Uj,...&&;
- if the value j of is_placeholder_v<TD> is not zero, the argument is std::forward<Uj>(uj) and its type Vi is Uj&&;
- otherwise, the value is td, and its type Vi is cv TD.

The value of the target argument vf1 is fd and its corresponding type V is cv FD.

### 22.10.15.5 Placeholders

```cpp
namespace std::placeholders {
    // M is the implementation-defined number of placeholders
    see below _1;
    see below _2;
    ...
    ...
    see below _M;
}
```

1 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 \texttt{Cpp17CopyAssignable} requirements, but if so, their copy assignment operators are \texttt{constexpr} functions that do not throw exceptions.

2 Placeholders should be defined as:

\begin{verbatim}
inline constexpr unspecified _1{};
\end{verbatim}

If they are not, they are declared as:

\begin{verbatim}
extern unspecified _1;
\end{verbatim}

22.10.16 Function template \texttt{mem\_fn} \hfill [\texttt{func.memfn}]

\begin{verbatim}
template<class R, class T> constexpr unspecified mem\_fn(R T::* pm) noexcept;
\end{verbatim}

\begin{enumerate}
\item \texttt{Returns:} A simple call wrapper (22.10.4) \texttt{fn} with call pattern \texttt{invoke(pmd, call\_args...)}, where \texttt{pmd} is the target object of \texttt{fn} of type \texttt{R T::*} direct-non-list-initialized with \texttt{pm}, and \texttt{call\_args} is an argument pack used in a function call expression (7.6.1.3) of \texttt{fn}.
\end{enumerate}

22.10.17 Polymorphic function wrappers \hfill [\texttt{func.wrap}]

22.10.17.1 General \hfill [\texttt{func.wrap.general}]

1 Subclause 22.10.17 describes polymorphic wrapper classes that encapsulate arbitrary callable objects.

22.10.17.2 Class \texttt{bad\_function\_call} \hfill [\texttt{func.wrap.badcall}]

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.

\begin{verbatim}
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;
    }
}
\end{verbatim}

\begin{enumerate}
\item \texttt{Returns:} An implementation-defined \texttt{ntbs}.
\end{enumerate}

22.10.17.3 Class template \texttt{function} \hfill [\texttt{func.wrap.func}]

22.10.17.3.1 General \hfill [\texttt{func.wrap.func.general}]

\begin{verbatim}
namespace std {
    template<class> class function; // not defined

    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, special member functions
\end{verbatim}
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).

A callable type (22.10.3) `F` is *Lvalue-Callable* for argument types `ArgTypes` and return type `R` if the expression 

```
INVOKER<R>(declval<F&>(), declval<ArgTypes>())...
```

considered as an unevaluated operand (7.2.3), is well-formed (22.10.4).

The `function` class template is a call wrapper (22.10.3) whose call signature (22.10.3) is `R(ArgTypes...)`.

**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;
```

Postconditions: `!*this`.

```
function(nullptr_t) noexcept;
```

Postconditions: `!*this`.

```
function(const function& f);
```

Postconditions: `!*this` if `!f`; otherwise, the target object of `*this` is a copy of `f.target()`. Throes: 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.

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;
```

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.

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:

- is_same_v<`remove_cvref_t<F>`, function> is false, and
- `FD` is Lvalue-Callable (22.10.17.3) for argument types `ArgTypes...` and return type `R`.

Mandates:
- is_copy_constructible_v<`FD`> is true, and
Preconditions: FD meets the Cpp17CopyConstructible requirements.

Postconditions: !*this is true if any of the following hold:

- f is a null function pointer value.
- f is a null member pointer value.
- 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.

### function

```cpp
template<class F> function(F) -> function<see below>;
```

Constraints: &F::operator() is well-formed when treated as an unevaluated operand and decltype( &F::operator() ) is of the form R(G::*)(A...) cv &opt noexcept opt for a class type G.

Remarks: The deduced type is function<R(A...)>

[Example 1:

```cpp
void f() {
    int i{5};
    function g = [&](double) { return i; }; // deduces function<int(double)>
}
```

—end example]

```cpp
function& operator=(const function& f);
```

Effects: As if by function(f).swap(*this);

Returns: *this.

```cpp
function& operator=(function&& f);
```

Effects: Replaces the target of *this with the target of f.

Returns: *this.

```cpp
function& operator=(nullptr_t) noexcept;
```

Effects: If *this != nullptr, destroys the target of this.

Returns: *this.

```cpp
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.

```cpp
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

```cpp
void swap(function& other) noexcept;
```

*Effects:* Interchanges the target objects of *this and other.*

22.10.17.3.4 Capacity

```cpp
explicit operator bool() const noexcept;
```

*Returns:* true if *this has a target, otherwise false.*

22.10.17.3.5 Invocation

```cpp
R operator()(ArgTypes... args) const;
```

*Returns:* \( \text{INVOKE}<R>(f, \text{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

```cpp
const type_info& target_type() const noexcept;
```

*Returns:* If *this has a target of type T, typeid(T); otherwise, typeid(void).

```cpp
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

```cpp
template<class R, class... ArgTypes>
bool operator==(const function<R(ArgTypes...)>& f, nullptr_t) noexcept;
```

*Returns:* !f.

22.10.17.3.8 Specialized algorithms

```cpp
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. `cv` is either const or empty,
2. `ref` is either `&`, `&&`, or empty, and
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:

1. If `ref` is empty, let `inv-quals` be `cv&`,
2. otherwise, let `inv-quals` be `cv ref`.

22.10.17.4.2 Class template move_only_function

```cpp
namespace std {
    template<class... S> class move_only_function; // not defined

    template<class R, class... ArgTypes>
    class move_only_function<R(ArgTypes...) cv ref noexcept(noex)> {
        public:
            using result_type = R;
    }
}
```

§ 22.10.17.4.2
move_only_function() noexcept;
move_only_function(nullptr_t) noexcept;
move_only_function(move_only_function&&) noexcept;

// 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.

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

move_only_function() noexcept;
move_only_function(nullptr_t) noexcept;
move_only_function(move_only_function&&) noexcept;

// 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.

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]
Constraints:

(5.1) \(\text{remove_cvref}_t<F>\) is not the same type as \(\text{move_only_function}\), and

(5.2) \(\text{remove_cvref}_t<F>\) is not a specialization of \(\text{in_place_type}_t\), and

(5.3) is-callable-from<VT> is true.

Mandates: \(\text{is_constructible}_v<\text{VT}, F>\) is true.

Preconditions: VT meets the Cpp17Destructible requirements, and if \(\text{is_move_constructible}_v<\text{VT}>\) 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) \(\text{remove_cvref}_t<F>\) is a specialization of the \(\text{move_only_function}\) class template, and \(f\) has no target object.

Otherwise, *this has a target object of type VT direct-non-list-initialized with \(\text{std::forward}<F>(f)\).

Throws: Any exception thrown by the initialization of the target object. May throw \text{bad_alloc} unless VT is a function pointer or a specialization of \text{reference_wrapper}.

\[
\text{template}<\text{class } T, \ldots \text{ Args}>
\]

\[
\text{explicit move_only_function}(\text{in_place_type}_t<T>, \text{Args}&& \ldots \text{ args});
\]

Let VT be \(\text{decay}_t<T>\).

Constraints:

(11.1) \(\text{is_constructible}_v<\text{VT}, \text{Args}&&>\) 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 \(\text{is_move_constructible}_v<\text{VT}>\) is true, VT meets the Cpp17MoveConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with \(\text{std::forward}<\text{Args}>(\text{args})\).

Throws: Any exception thrown by the initialization of the target object. May throw \text{bad_alloc} unless VT is a function pointer or a specialization of \text{reference_wrapper}.

\[
\text{template}<\text{class } T, \text{class } U, \ldots \text{ Args}>
\]

\[
\text{explicit move_only_function}(\text{in_place_type}_t<T>, \text{initializer_list}<U> ilist, \text{Args}&& \ldots \text{ args});
\]

Let VT be \(\text{decay}_t<T>\).

Constraints:

(17.1) \(\text{is_constructible}_v<\text{VT}, \text{initializer_list}<U>&, \text{ArgTypes}&&>\) 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 \(\text{is_move_constructible}_v<\text{VT}>\) is true, VT meets the Cpp17MoveConstructible requirements.

Postconditions: *this has a target object of type VT direct-non-list-initialized with ilist, \(\text{std::forward}<\text{ArgTypes}>(\text{args})\).

Throws: Any exception thrown by the initialization of the target object. May throw \text{bad_alloc} unless VT is a function pointer or a specialization of \text{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;

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.

22.10.17.4.5 Utility

void swap(move_only_function& other) noexcept;

Effects: Exchanges the target objects of *this and other.

friend void swap(move_only_function& f1, move_only_function& f2) noexcept;

Effects: Equivalent to f1.swap(f2).

friend bool operator==(const move_only_function& f, nullptr_t) noexcept;

Returns: true if f has no target object, otherwise false.

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

(2.1) — ForwardIterator,
(2.2) — ForwardIterator1,
(2.3) — ForwardIterator2,
(2.4) — RandomAccessIterator,
(2.5) — RandomAccessIterator1,
(2.6) — RandomAccessIterator2, and
(2.7) — 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 36).

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

```cpp
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
    };
}
```

1. **Effects:** Constructs a `default_searcher` object, initializing `pat_first_` with `pat_first`, `pat_last_` with `pat_last`, and `pred_` with `pred`.
2. **Throws:** Any exception thrown by the copy constructor of `BinaryPredicate` or `ForwardIterator1`.

22.10.18.3 Class template boyer_moore_searcher

```cpp
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
    };
}
```

1. **Effects:** Returns a pair of iterators `i` and `j` such that
   - `i == search(first, last, pat_first_, pat_last_, pred_)`, and
   - if `i == last`, then `j == last`, otherwise `j == next(i, distance(pat_first_, pat_last_))`.

§ 22.10.18.3 762
BinaryPredicate pred = BinaryPredicate();

1 Preconditions: The value type of RandomAccessIterator1 meets the Cpp17DefaultConstructible, the Cpp17CopyConstructible, and the Cpp17CopyAssignable requirements.

Let V be iterator_traits<RandomAccessIterator1>::value_type. For any two values A and B of type V, if pred(A, B) == true, then hf(A) == hf(B) is true.

2 Effects: Initializes pat_first_ with pat_first, pat_last_ with pat_last, hash_ with hf, and pred_ with pred.

3 Throws: Any exception thrown by the copy constructor of RandomAccessIterator1, or by the default constructor, copy constructor, or the copy assignment operator of the value type of RandomAccessIterator1, or the copy constructor or operator() of BinaryPredicate or Hash. May throw bad_alloc if additional memory needed for internal data structures cannot be allocated.

4 template<class RandomAccessIterator2>
   pair<RandomAccessIterator2, RandomAccessIterator2> operator()(RandomAccessIterator2 first, RandomAccessIterator2 last) const;

5 Mandates: RandomAccessIterator1 and RandomAccessIterator2 have the same value type.

6 Effects: Finds a subsequence of equal values in a sequence.

7 Returns: A pair of iterators i and j such that

   (7.1) — 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: pred(*(i + n), *(pat_first_ + n)) != false, and

   (7.2) — j == next(i, distance(pat_first_, pat_last_)).

Returns make_pair(first, first) if [pat_first_, pat_last_) is empty, otherwise returns make_pair(last, last) if no such iterator is found.

8 Complexity: At most \((last - first) * (pat_last_ - pat_first_)) applications of the predicate.

§ 22.10.18.4 Class template boyer_moore_horspool_searcher

namespace std {
  template<class RandomAccessIterator1,
   class Hash = hash<typename iterator_traits<RandomAccessIterator1>::value_type>,
   class BinaryPredicate = equal_to<>>
  class boyer_moore_horspool_searcher {
    public:
      boyer_moore_horspool_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_horspool_searcher(RandomAccessIterator1 pat_first, 
                              RandomAccessIterator1 pat_last, 
                              Hash hf = Hash(), 
                              BinaryPredicate pred = BinaryPredicate());

1 Preconditions: The value type of RandomAccessIterator1 meets the Cpp17DefaultConstructible, Cpp17CopyConstructible, and Cpp17CopyAssignable requirements.
Let $V$ be `iterator_traits<RandomAccessIterator1>::value_type`. For any two values $A$ and $B$ of type $V$, if $\text{pred}(A, B) == \text{true}$, then $hf(A) == hf(B)$ is true.

**Effects:** Initializes `pat_first_` with `pat_first`, `pat_last_` with `pat_last`, `hash_` with `hf`, and `pred_` with `pred`.

**Throws:** Any exception thrown by the copy constructor of `RandomAccessIterator1`, or by the default constructor, copy constructor, or the copy assignment operator of the value type of `RandomAccessIterator1`, or the copy constructor or `operator()` of `BinaryPredicate` or `Hash`. May throw `bad_alloc` if additional memory needed for internal data structures cannot be allocated.

```cpp
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

1. $i$ is the first iterator in the range $[\text{first}, \text{last} - (\text{pat_last} - \text{pat_first})]$ such that for every non-negative integer $n$ less than $\text{pat_last} - \text{pat_first}$ the following condition holds: $\text{pred}(*(i + n), *(\text{pat_first} + n)) != \text{false}$, and
2. $j == \text{next}(i, \text{distance}(\text{pat_first}, \text{pat_last}))$.

Returns `make_pair(first, first)` if $[\text{pat_first, pat_last})$ is empty, otherwise returns `make_pair(last, last)` if no such iterator is found.

**Complexity:** At most $(\text{last} - \text{first}) \times (\text{pat_last} - \text{pat_first})$ applications of the predicate.

### 22.10.19 Class template `hash` [unord.hash]

The unordered associative containers defined in 24.5 use specializations of the class template `hash` (22.10.2) as the default hash function.

Each specialization of `hash` is either enabled or disabled, as described below.

**Note 1:** Enabled specializations meet the `Cpp17Hash` requirements, and disabled specializations do not. — end note

Each header that declares the template `hash` provides enabled specializations of `hash` for `nullptr_t` and all cv-unqualified arithmetic, enumeration, and pointer types. For any type `Key` for which neither the library nor the user provides an explicit or partial specialization of the class template `hash`, `hash<Key>` is disabled.

If the library provides an explicit or partial specialization of `hash<Key>`, that specialization is enabled except as noted otherwise, and its member functions are `noexcept` except as noted otherwise.

If `H` is a disabled specialization of `hash`, these values are `false`: `is_default_constructible_v<H>`, `is_copy_constructible_v<H>`, `is_move_constructible_v<H>`, `is_copy_assignable_v<H>`, and `is_moveAssignable_v<H>`. Disabled specializations of `hash` are not function object types (22.10).

**Note 2:** This means that the specialization of `hash` exists, but any attempts to use it as a `Cpp17Hash` will be ill-formed. — end note

An enabled specialization `hash<Key>` will:

1. meet the `Cpp17Hash` requirements (Table 36), with `Key` as the function call argument type, the `Cpp17DefaultConstructible` requirements (Table 29), the `Cpp17CopyAssignable` requirements (Table 33),
2. be swappable (16.4.4.3) for lvalues,
3. meet the requirement that if $k1 == k2$ is true, $h(k1) == h(k2)$ is also true, where `h` is an object of type `hash<Key>` and $k1$ and $k2$ are objects of type `Key`;
4. meet the requirement that the expression $h(k)$, where `h` is an object of type `hash<Key>` and `k` is an object of type `Key`, shall not throw an exception unless `hash<Key>` is a program-defined specialization.

### 22.11 Class `type_index` [type.index]

#### 22.11.1 Header `<typeindex>` synopsis [type.index.synopsis]

```cpp
#include <compare>  // see 17.11.1
```
namespace std {
  class type_index;
  template<class T> struct hash;
  template<> struct hash<type_index>;
}

22.11.2 type_index overview

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_index& rhs) const noexcept;
    bool operator>(const type_index& rhs) const noexcept;
    bool operator<=(const type_index& rhs) const noexcept;
    bool operator>=(const type_index& 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.
  };
}

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).

22.11.3 type_index members

    type_index(const type_info& rhs) noexcept;
    bool operator==(const type_index& rhs) const noexcept;
    bool operator<(const type_index& rhs) const noexcept;
    bool operator>(const type_index& rhs) const noexcept;
    bool operator<=(const type_index& rhs) const noexcept;
    bool operator>=(const type_index& rhs) const noexcept;
    strong_ordering operator<=>(const type_index& rhs) const noexcept;
    size_t hash_code() const noexcept;

1 Effects: Constructs a type_index object, the equivalent of target = &rhs.

2 Returns: *target == *rhs.target.

3 Returns: target->before(*rhs.target).

4 Returns: rhs.target->before(*target).

5 Returns: !rhs.target->before(*target).


7 Effects: Equivalent to:

    if (*target == *rhs.target) return strong_ordering::equal;
    if (target->before(*rhs.target)) return strong_ordering::less;
    return strong_ordering::greater;

8 Returns: target->hash_code().
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 In 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:

```c++
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 standard as extensions to address parallel architectures that require idiosyncratic parameters for efficient execution. — end note]

22.12.2 Header <execution> synopsis

```c++
namespace std {
    // 22.12.3, execution policy type trait
    template<class T> struct is_execution_policy;
    template<class T> inline 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 }; 
}
```
22.12.3 Execution policy type trait

`template<class T> struct is_execution_policy { see below };`

`is_execution_policy` can be used to detect execution policies for the purpose of excluding function signatures from otherwise ambiguous overload resolution participation.

`is_execution_policy<T>` is a `Cpp17UnaryTypeTrait` with a base characteristic of `true_type` if `T` is the type of a standard or implementation-defined execution policy, otherwise `false_type`.

[Note 1: This provision reserves the privilege of creating non-standard execution policies to the library implementation. — end note]

The behavior of a program that adds specializations for `is_execution_policy` is undefined.

22.12.4 Sequenced execution policy

`class execution::sequenced_policy { unspecified };`

The class `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.

During the execution of a parallel algorithm with the `execution::sequenced_policy` policy, if the invocation of an element access function exits via an exception, `terminate` is invoked (14.6.2).

22.12.5 Parallel execution policy

`class execution::parallel_policy { unspecified };`

The class `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.

During the execution of a parallel algorithm with the `execution::parallel_policy` policy, if the invocation of an element access function exits via an exception, `terminate` is invoked (14.6.2).

22.12.6 Parallel and unsequenced execution policy

`class execution::parallel_unsequenced_policy { unspecified };`

The class `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.

During the execution of a parallel algorithm with the `execution::parallel_unsequenced_policy` policy, if the invocation of an element access function exits via an exception, `terminate` is invoked (14.6.2).

22.12.7 Unsequenced execution policy

`class execution::unsequenced_policy { unspecified };`

The class `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.

During the execution of a parallel algorithm with the `execution::unsequenced_policy` policy, if the invocation of an element access function exits via an exception, `terminate` is invoked (14.6.2).

22.12.8 Execution policy objects

`inline constexpr execution::sequenced_policy execution::seq{ unspecified };`

`inline constexpr execution::parallel_policy execution::par{ unspecified };`

`inline constexpr execution::parallel_unsequenced_policy execution::par_unseq{ unspecified };`

`inline constexpr execution::unsequenced_policy execution::unseq{ unspecified };`

The header `<execution>` declares global objects associated with each type of execution policy.
22.13 Primitive numeric conversions [charconv]

22.13.1 Header <charconv> synopsis [charconv.syn]
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 {
        char* ptr;
        errc ec;
        friend bool operator==(const to_chars_result&, const to_chars_result&) = default;
    };

    to_chars_result to_chars(char* first, char* last, see below value, int base = 10);
    to_chars_result to_chars(char* first, char* last, bool value, int base = 10) = delete;
    to_chars_result to_chars(char* first, char* last, float value);
    to_chars_result to_chars(char* first, char* last, double value);
    to_chars_result to_chars(char* first, char* last, long double value);
    to_chars_result to_chars(char* first, char* last, float value, chars_format fmt);
    to_chars_result to_chars(char* first, char* last, double value, chars_format fmt);
    to_chars_result to_chars(char* first, char* last, long double value, chars_format fmt);
    to_chars_result to_chars(char* first, char* last, float value, chars_format fmt, int precision);
    to_chars_result to_chars(char* first, char* last, double value, chars_format fmt, int precision);
    to_chars_result to_chars(char* first, char* last, long double value, chars_format fmt, int precision);

    // 22.13.3, primitive numerical input conversion
    struct from_chars_result {
        const char* ptr;
        errc ec;
        friend bool operator==(const from_chars_result&, const from_chars_result&) = default;
    };

    from_chars_result from_chars(const char* first, const char* last, see below & value, int base = 10);
    from_chars_result from_chars(const char* first, const char* last, float& value,
        chars_format fmt = chars_format::general);
    from_chars_result from_chars(const char* first, const char* last, double& value,
        chars_format fmt = chars_format::general);
    from_chars_result from_chars(const char* first, const char* last, long double& value,
        chars_format fmt = chars_format::general);
}

1 The type chars_format is a bitmask type (16.3.3.3.4) with elements scientific, fixed, and hex.
2 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 [charconv.to.chars]
1 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` (17.3.4.1).

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`.

```c++
to_chars_result to_chars(char* first, char* last, see below value, int base = 10);
```

4 **Preconditions:** `base` has a value between 2 and 36 (inclusive).

5 **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 `-`.

6 **Throws:** Nothing.

7 **Remarks:** The implementation shall provide overloads for all signed and unsigned integer types and `char` as the type of the parameter `value`.

```c++
to_chars_result to_chars(char* first, char* last, float value);
```

8 **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`.

9 **Throws:** Nothing.

```c++
to_chars_result to_chars(char* first, char* last, double value);
```

10 **Effects:** `value` is converted to a string in the style of `printf` in the "C" locale.

11 **Throws:** Nothing.

```c++
to_chars_result to_chars(char* first, char* last, long double value, chars_format fmt);
```

12 **Preconditions:** `fmt` has the value of one of the enumerators of `chars_format`.

13 **Effects:** `value` is converted to a string in the style of `printf` in the "C" locale.

14 **Throws:** Nothing.

```c++
to_chars_result to_chars(char* first, char* last, float value, chars_format fmt, int precision);
```

15 **Preconditions:** `fmt` has the value of one of the enumerators of `chars_format`.

16 **Effects:** `value` is converted to a string in the style of `printf` in the "C" locale with the given precision.

17 **Throws:** Nothing.

See also: ISO C 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`. 

§ 22.13.3 769
from_chars_result from_chars(const char* first, const char* last, 
   see below& 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.

Remarks: The implementation shall provide overloads for all signed and unsigned integer types and char as the referenced type of the parameter value.

from_chars_result from_chars(const char* first, const char* last, float& value, 
   chars_format fmt = chars_format::general);
from_chars_result from_chars(const char* first, const char* last, double& value, 
   chars_format fmt = chars_format::general);
from_chars_result from_chars(const char* first, const char* last, long double& 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
(7.1) the sign '+' may only appear in the exponent part;
(7.2) if fmt has chars_format::scientific set but not chars_format::fixed, the otherwise optional exponent part shall appear;
(7.3) if fmt has chars_format::fixed set but not chars_format::scientific, the optional exponent part shall not appear; and
(7.4) 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 C 7.22.1.3, 7.22.1.4

22.14 Formatting

22.14.1 Header <format> synopsis

namespace std {
   // 22.14.6.4, 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 >;

   // 22.14.7.3, 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; // exposition only

template<class... Args>
using format-string = basic-format-string<char, type_identity_t<Args>...>;
template<class... Args>
using wformat-string = basic-format-string<wchar_t, type_identity_t<Args>...>;

// 22.14.5, formatting functions

// exposition only

template<class... Args>
string format(string_view fmt, Args&&... args);
template<class... Args>
wstring format(wstring_view fmt, Args&&... args);
template<class... Args>
string format(const locale& loc, string_view fmt, Args&&... args);
template<class... Args>
wstring format(const locale& loc, wstring_view 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, string_view fmt, Args&&... args);
template<class Out, class... Args>
Out format_to(Out out, wstring_view fmt, Args&&... args);
template<class Out, class... Args>
Out format_to(Out out, const locale& loc, string_view fmt, Args&&... args);
template<class Out, class... Args>
Out format_to(Out out, const locale& loc, wstring_view fmt, Args&&... args);

template<class Out, class... Args>
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,
    string_view fmt, Args&&... args);
template<class Out, class... Args>
format_to_n_result<Out> format_to_n(Out out, iter_difference_t<Out> n,
    wstring_view 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, string_view 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, wstring_view fmt, Args&&... args);
The class template `formatter` 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 In 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

2 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.

3 [Example 1:
   string s = format("{0}-{" , 8); // value of s is "8-"
   — end example]

4 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.
   
   [Note 1: A format string cannot contain a mixture of automatic and manual indexing. — end note]

   [Example 2:
   string s0 = format("{} to {}", "a", "b"); // OK, automatic indexing
   string s1 = format("{1} to {0}", "a", "b"); // OK, manual indexing
   string s2 = format("{0} to {}", "a", "b"); // not a format string (mixing automatic and manual indexing), // ill-formed
   string s3 = format("{} to {1}", "a", "b"); // not a format string (mixing automatic and manual indexing), // ill-formed
   — end example]

5 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

Each formatter specializations described in 22.14.6.2 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 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:

\[
\text{std-format-spec:} \\
\text{fill-and-align_{opt} sign_{opt} \#_{opt} 0_{opt} width_{opt} precision_{opt} L_{opt} type_{opt}}
\]

fill-and-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 s x X

2 [Note 2: The fill character can be any character other than \{ or \}. The presence of a fill character 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 both the fill character and the alignment option are absent. —end note]

3 The align specifier applies to all argument types. The meaning of the various alignment options is as specified in Table 64.

[Example 1:]

```c
char c = 120;
string s0 = format("{:6}", 42); // value of s0 is " 42"
string s1 = format("{:6}"\', '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  
```

—end example

[Note 3: Unless a minimum field width is defined, the field width is determined by the size of the content and the alignment option has no effect. —end note]

Table 64: 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 field to be aligned to the start of the available space. This is the default for non-arithmetic non-pointer types, charT, and bool, unless an integer presentation type is specified.</td>
</tr>
<tr>
<td>&gt;</td>
<td>Forces the field to be aligned to the end of the available space. This is the default for arithmetic types other than charT and bool, pointer types, or when an integer presentation type is specified.</td>
</tr>
<tr>
<td>^</td>
<td>Forces the field to be centered within the available space by inserting ( \lfloor n/2 \rfloor ) characters before and ( \lceil n/2 \rceil ) characters after the value, where ( n ) is the total number of fill characters to insert.</td>
</tr>
</tbody>
</table>

4 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 65.

Table 65: 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 to_chars for non-negative numbers other than negative zero. [Note 4: For negative numbers and negative zero the output of to_chars 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>

5 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,-1"
string s2 = format("{0:},{0:+},{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"
```

—end example

6 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 67 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.

7 If `{arg-id,opt}` is used in a `width` or `precision`, the value of the corresponding formatting argument is used in its place. If the corresponding formatting argument is not of integral type, or its value is negative for `precision` or non-positive for `width`, an exception of type `format_error` is thrown.

8 The `positive-integer` in `width` is a decimal integer defining the minimum field width. If `width` is not specified, there is no minimum field width, and the field width is determined based on the content of the field.

9 The `width` of a string is defined as the estimated number of column positions appropriate for displaying it in a terminal.

[Note 5: This is similar to the semantics of the POSIX `wcswidth` function. —end note]

10 For the purposes of width computation, a string is assumed to be in a locale-independent, implementation-defined encoding. Implementations should use a Unicode encoding on platforms capable of displaying Unicode text in a terminal.

[Note 6: This is the case for Windows®-based and many POSIX-based operating systems. —end note]

11 For a string in a Unicode encoding, implementations should estimate the width of a string as the sum of estimated widths of the first code points in its extended grapheme clusters. The extended grapheme clusters of a string are defined by UAX #29. The estimated width of the following code points is 2:

(11.1) — U+1100 – U+115F
(11.2) — U+2329 – U+232A
(11.3) — U+2E80 – U+303E
(11.4) — U+3040 – U+A4CF
(11.5) — U+AC00 – U+D7A3
(11.6) — U+F900 – U+FAFF
(11.7) — U+FE10 – U+FE19
(11.8) — U+FE30 – U+FE6F
(11.9) — U+FF00 – U+FF60
(11.10) — U+FFE0 – U+FFE6
(11.11) — U+1F300 – U+1F64F
(11.12) — U+1F900 – U+1F9FF
(11.13) — U+20000 – U+2FFFD
(11.14) — U+30000 – U+3FFFD

The estimated width of other code points is 1.

12 For a string in a non-Unicode encoding, the width of a string is unspecified.

210) Windows® is a registered trademark of Microsoft Corporation. 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.
A zero (0) character preceding the width field pads the field with leading zeros (following any indication of sign or base) to the field width, except when applied to an infinity or NaN. This option is only valid for arithmetic types other than charT and bool or when an integer presentation type is specified. If the 0 character and an align option both appear, the 0 character is ignored.

[Example 3:]

```cpp
cchar c = 120;
string s1 = format("{:+06d}", c); // value of s1 is +00120
string s2 = format("{:06x}", 0xa); // value of s2 is 0x000a
string s3 = format("{:06}", -42);  // value of s3 is -42   " (0 is ignored because of < alignment)
```

The nonnegative-integer in precision is a decimal integer defining the precision or maximum field size. It can only be used with floating-point and string types. For floating-point types this field specifies the formatting precision. For string types, this field provides an upper bound for the estimated width of the prefix of the input string that is copied into the output. For a string in a Unicode encoding, the formatter copies to the output the longest prefix of whole extended grapheme clusters whose estimated width is no greater than the precision.

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.

(15.1) — For integral types, the locale-specific form causes the context’s locale to be used to insert the appropriate digit group separator characters.

(15.2) — 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.

(15.3) — 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 66.

Table 66: Meaning of type options for strings

<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>
</tbody>
</table>

The meaning of some non-string presentation types is defined in terms of a call to to_chars. In such cases, let [first, 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 67.

[Example 4:]

```cpp
string s0 = format("{}", 42); // value of s0 is "42"
string s1 = format("{:0b} {0:d} {0:o} {0:x}", 42); // value of s1 is "101010 42 52 2a"
string s2 = format("{: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)
```

The available charT presentation types are specified in Table 68.

The available bool presentation types are specified in Table 69.

The available floating-point presentation types and their meanings for values other than infinity and NaN are specified in Table 70. 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]
Table 67: Meaning of type options for integer types  

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td><code>to_chars(first, last, value, 2); the base prefix is 0b.</code></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 <code>static_cast&lt;charT&gt;(value)</code> to the output. Throws <code>format_error</code> if <code>value</code> is not in the range of representable values for <code>charT</code>.</td>
</tr>
<tr>
<td>d</td>
<td><code>to_chars(first, last, value).</code></td>
</tr>
<tr>
<td>o</td>
<td><code>to_chars(first, last, value, 8); the base prefix is 0 if value is nonzero and is empty otherwise.</code></td>
</tr>
<tr>
<td>x</td>
<td><code>to_chars(first, last, value, 16); the base prefix is 0x.</code></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 68: Meaning of type options for charT  

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>Copies the character to the output.</td>
</tr>
<tr>
<td>c</td>
<td>As specified in Table 67.</td>
</tr>
<tr>
<td>b, B, d, o, x, X</td>
<td>As specified in Table 67 for the value <code>static_cast&lt;unsigned char&gt;(value)</code>.</td>
</tr>
</tbody>
</table>

Table 69: Meaning of type options for bool  

<table>
<thead>
<tr>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</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 67 for the value <code>static_cast&lt;unsigned char&gt;(value)</code>.</td>
</tr>
</tbody>
</table>

Table 70: Meaning of type options for floating-point types  

<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 <code>a</code>, 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 <code>e</code>, 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 <code>g</code>, 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>
The available pointer presentation types and their mapping to `to_chars` are specified in Table 71.

[Note 10: Pointer presentation types also apply to `nullptr_t`. — end note]

Table 71: 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 added to the output; otherwise, implementation-defined.</td>
</tr>
</tbody>
</table>

22.14.3 Error reporting [format.err.report]

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 [format.fmt.string]

```
template<class charT, class... Args>
struct basic-format-string {
  // exposition only
  basic_string_view<charT> str;  // exposition only

  public:
    template<class T> consteval basic-format-string(const T& s);
    
  template<class T> consteval basic-format-string(const T& s);

  Constraints: `const T&` models convertible_to<basic_string_view<charT>>.
  Effects: Direct-non-list-initializes `str` with `s`.
  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.

```

```
template<class... Args>
string format(format-string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
  return vformat(fmt.str, make_format_args(args...));

```

```
template<class... Args>
wstring format(wformat-string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
  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...));

```

§ 22.14.5
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);

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.

Throws: As specified in 22.14.3.

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, uformat_string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
return vformat_to(std::move(out), fmt.str, make_uformat_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, uformat_string<Args...> fmt, Args&&... args);

Effects: Equivalent to:
return vformat_to(std::move(out), loc, fmt.str, make_uformat_args(args...));

template<class Out, class... Args>
Out format_to_n_result<Out>(Out out, iter_difference_t<Out> n, format_string<Args...> fmt, Args&&... args);

template<class Out, class... Args>
Out format_to_n_result<Out>(Out out, iter_difference_t<Out> n, uformat_string<Args...> fmt, Args&&... args);

template<class Out, class... Args>
Out format_to_n_result<Out>(Out out, iter_difference_t<Out> n, const locale& loc, format_string<Args...> fmt, 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.

§ 22.14.5
Let

\[ \text{charT be decltype(fmt.str)::value_type,} \]
\[ \text{N be formatted_size(fmt, args...)} \]
\[ \text{for the functions without a loc parameter and formatted_size(loc, fmt, args...)} \]
\[ \text{for the functions with a loc parameter, and} \]
\[ \text{M be clamp(n, 0, N).} \]

Constraints: Out satisfies \text{output_iterator<const charT&}.

Preconditions: Out models \text{output_iterator<const charT&}, and \text{formatter<remove_cvref_t<T_i>, charT>} meets the BasicFormatter requirements \text{(22.14.6.1)} for each \( T_i \) in Args.

Effects: Places the first \( M \) characters of the character representation of formatting the arguments provided by args, formatted according to the specifications given in fmt, into the range \([\text{out}, \text{out} + M)\). If present, \text{loc} is used for locale-specific formatting.

Returns: \{\text{out} + M, N\}.

Throws: As specified in \text{22.14.3}.

A type \( F \) meets the BasicFormatter requirements if:

1. it meets the

   \[ \text{Cpp17DefaultConstructible (Table 29)}, \]
   \[ \text{Cpp17CopyConstructible (Table 31)}, \]
   \[ \text{Cpp17CopyAssignable (Table 33)}, \]
   \[ \text{Cpp17Destructible (Table 34)} \]

   requirements,

2. it is swappable (16.4.4.3) for lvalues, and

3. the expressions shown in Table 72 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 73 are valid and have the indicated semantics.

Given character type \text{charT}, output iterator type \text{Out}, and formatting argument type \( T \), in Table 72 and Table 73:

1. \( f \) is a value of type \( F \),
2. \( u \) is an lvalue of type \( T \),

\[ \text{22.14.6.1 \hspace{1em} Formatter requirements} \]
(3.3) t is a value of a type convertible to (possibly const) T,
(3.4) PC is basic_format_parse_context<charT>,
(3.5) FC is basic_format_context<Out, charT>,
(3.6) pc is an lvalue of type PC, and
(3.7) 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 empty then either pc.begin() == pc.end() or *pc.begin() == '}'

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>f.parse(pc)</td>
<td>PC::iterator</td>
<td>Parses format-spec (22.14.2) for type T in the range [pc.begin(), pc.end()) until the first un-matched 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.</td>
</tr>
<tr>
<td>f.format(u, fc)</td>
<td>FC::iterator</td>
<td>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).</td>
</tr>
</tbody>
</table>

22.14.6.2 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. Each header that declares the template formatter provides the following enabled specializations:

(2.1) The 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 string type specializations
    template<> struct formatter<charT*, charT>;

Table 73: 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>
<tr>
<td>f.format(u, fc)</td>
<td>FC::iterator</td>
<td>As above, but does not modify u.</td>
</tr>
</tbody>
</table>

§ 22.14.6.2
template<> struct formatter<const charT*, charT>;
template<size_t N> struct formatter<const charT[N], charT>;
template<class traits, class Allocator>
    struct formatter<basic_string<charT, traits, Allocator>, charT>;
template<class traits>
    struct formatter<basic_string_view<charT, traits>, charT>;

(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<nullptr_t, charT>;
    template<> struct formatter<void*, charT>;
    template<> struct formatter<const void*, charT>;

The parse member functions of these formatters interpret the format specification as a std-format-spec as described in 22.14.2.2.

[Note 1: Specializations such as formatter<wchar_t, char> and formatter<const char*, wchar_t> that would require implicit multibyte / wide string or character conversion are disabled. — end note]

3 For any types T and charT for which neither the library nor the user provides an explicit or partial specialization of the class template formatter<T, charT>, that specialization is disabled.

4 If the library provides an explicit or partial specialization of formatter<T, charT>, that specialization is enabled and meets the Formatter requirements except as noted otherwise.

5 If F is a disabled specialization of formatter, these values are false:

(5.1) — is_default_constructible_v<F>,
(5.2) — is_copy_constructible_v<F>,
(5.3) — is_move_constructible_v<F>,
(5.4) — is_copy_assignable_v<F>, and
(5.5) — is_move_assignable_v<F>.

6 An enabled specialization formatter<T, charT> meets the BasicFormatter requirements (22.14.6.1).

[Example 1:
   #include <format>

   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) {
           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]

22.14.6.3 Class template basic_format_parse_context [format.parse.ctx]

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;

    };

§ 22.14.6.3
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,
                                                size_t num_args = 0) 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);

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.

constexpr explicit basic_format_parse_context(basic_string_view<charT> fmt,
                                            size_t num_args = 0) noexcept;

Effects: Initializes begin_ with fmt.begin(), end_ with fmt.end(), indexing_ with unknown, next_arg_id_ with 0, and num_args_ with num_args.

constexpr const_iterator begin() const noexcept;
Returns: begin_.

constexpr const_iterator end() const noexcept;
Returns: end_.

constexpr void advance_to(const_iterator it);
Preconditions: end() is reachable from it.
Effects: Equivalent to: begin_ = it;

constexpr size_t next_arg_id();
Effects: If indexing_ != manual, equivalent to:
    if (indexing_ == unknown)
        indexing_ = automatic;
    return next_arg_id_++;
Throws: format_error if indexing_ == manual which indicates mixing of automatic and manual argument indexing.

constexpr void check_arg_id(size_t id);
Effects: If indexing_ != automatic, equivalent to:
    if (indexing_ == unknown)
        indexing_ = manual;
Throws: format_error if indexing_ == automatic which indicates mixing of automatic and manual argument indexing.
Remarks: Call expressions where id >= num_args_ are not core constant expressions (7.7).
22.14.6.4 Class template basic_format_context

namespace std {
    template<class Out, class charT>
    class basic_format_context {
        basic_format_args<basic_format_context> args_; // exposition only
        Out out_; // exposition only

        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);
    }
}

An instance of basic_format_context holds formatting state consisting of the formatting arguments and the output iterator.

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;

Returns: args_.get(id).

std::locale locale();

Returns: The locale passed to the formatting function if the latter takes one, and std::locale() otherwise.

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 get_char = [&]() { return iter != ctx.end() ? *iter : 0; }; // exposition only
        if (get_char() != '{')
            throw format_error("invalid format");
        ++iter;
        char c = get_char();
        if (!isdigit(c) || (++iter, get_char()) != '}
            throw format_error("invalid format");
        width_arg_id = c - '0';
    }
};
ctx.check_arg_id(width_arg_id);
  return ++iter;
}

// Formats an S with width given by the argument width_arg_id.
auto format(S s, format_context& ctx) {
  int width = visit_format_arg([](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;
  }, ctx.arg(width_arg_id));
  return format_to(ctx.out(), "{0:x<{1}}", s.value, width);
};

std::string s = std::format("{0:{1}}", S{42}, 10);  // value of s is "xxxxxxxx42"

22.14.7 Arguments

22.14.7.1 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
    explicit basic_format_arg(float n) noexcept;  // exposition only
    explicit basic_format_arg(double n) noexcept;  // exposition only
    explicit basic_format_arg(long double n) noexcept;  // exposition only
    explicit basic_format_arg(const char_type* s);  // exposition only

    template<class traits>
    explicit basic_format_arg(
      basic_string_view<char_type, traits> s) noexcept;  // exposition only

    template<class traits, class Allocator>
    explicit basic_format_arg(
      const basic_string<char_type, traits, Allocator>& s) noexcept;  // exposition only

    explicit basic_format_arg(nullptr_t) noexcept;  // exposition only

    template<class T>
    explicit basic_format_arg(T* p) noexcept;  // exposition only

  public:
    basic_format_arg() noexcept;

    explicit operator bool() const noexcept;
  }
};
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: The template specialization
typename Context::template formatter_type<remove_cvref_t<T>>
meets the BasicFormatter requirements (22.14.6.1). The extent to which an implementation determines that the specialization meets the BasicFormatter requirements is unspecified, except that as a minimum the expression
typename Context::template formatter_type<remove_cvref_t<T>>::format(declval<T&>(), declval<Context&>())
shall be well-formed when treated as an unevaluated operand (7.2.3).

Effects:

(5.1) if T is bool or char_type, initializes value with v;
(5.2) otherwise, if T is char and char_type is wchar_t, initializes value with static_cast<wchar_t>(v);
(5.3) otherwise, if T is a signed integer type (6.8.2) and sizeof(T) <= sizeof(int), initializes value with static_cast<int>(v);
(5.4) otherwise, if T is an unsigned integer type and sizeof(T) <= sizeof(unsigned int), initializes value with static_cast<unsigned int>(v);
(5.5) otherwise, if T is a signed integer type and sizeof(T) <= sizeof(long long int), initializes value with static_cast<long long int>(v);
(5.6) otherwise, if T is an unsigned integer type and sizeof(T) <= sizeof(unsigned long long int), initializes value with static_cast<unsigned long long int>(v);
(5.7) otherwise, initializes value with handle(v).

explicit basic_format_arg(float n) noexcept;
explicit basic_format_arg(double n) noexcept;
explicit basic_format_arg(long double n) noexcept;

Effects: Initializes value with n.

explicit basic_format_arg(const char_type* s);

Preconditions: s points to a NTCTS (3.37).

Effects: Initializes value with s.

template<class traits>
explicit basic_format_arg(basic_string_view<char_type, traits> s) noexcept;

Effects: Initializes value with basic_string_view<char_type>(s.data(), s.size()).

template<class traits, class Allocator>
explicit basic_format_arg(
    const basic_string<char_type, traits, Allocator>& s) noexcept;

Effects: Initializes value with basic_string_view<char_type>(s.data(), s.size()).

explicit basic_format_arg(nullptr_t) noexcept;

Effects: Initializes value with static_cast<const void*>(nullptr).

template<class T> explicit basic_format_arg(T* p) noexcept;

Constraints: is_void_v<T* p> is true.

Effects: Initializes value with p.

§ 22.14.7.1
[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]

```cpp
explicit operator bool() const noexcept;
```

Returns: !holds_alternative<monostate>(value).

The class handle allows formatting an object of a user-defined type.

```cpp
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
  public:
    friend class basic_format_arg<Context>; // exposition only
    void format(basic_format_parse_context<char_type>&, Context& ctx) const;
  }
}
```

```cpp
template<class T> explicit handle(T& val) noexcept;
```

Let

(17.1) — TD be remove_cvref_t<T>,

(17.2) — const-formattable be true if typename Context::template formatter_type<TD>()

   .format(declval<const TD&>(), declval<Context&>()) is well-formed, otherwise false,

(17.3) — TQ be const TD if const-formattable is true and TD otherwise.

Mandates: const-formattable || !is_const_v<remove_reference_t<T>> is true.

Effects: Initializes ptr_ with addressof(val) and format_ with

```cpp
[](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_);

```cpp
template<class Visitor, class Context>
decltype(auto) visit_format_arg(Visitor&& vis, basic_format_arg<Context> arg);
```

Effects: Equivalent to: return visit(forward<Visitor>(vis), arg.value);

### 22.14.7.2 Class template format-arg-store

[format.arg.store]

```cpp
namespace std {
  template<class Context, class... Args>
  class format-arg-store {
    array<basic_format_arg<Context>, sizeof...(Args)> args; // exposition only
  };
}
```

An instance of format-arg-store stores formatting arguments.

```cpp
template<class Context = format_context, class... Args>
format-arg-store<Context, Args...> make_format_args(Args&&... fmt_args);
```

Preconditions: The type typename Context::template formatter_type<Ti> meets the BasicFormatter requirements (22.14.6.1) for each Ti in Args.
Returns: An object of type `format-arg-store<Context, Args...>` whose `args` data member is initialized with `{basic_format_arg<Context>((fmt_args)...)}.  

```cpp
template<class... Args>
  format-arg-store<wformat_context, Args...> make_wformat_args(Args&&... args);
```

Effects: Equivalent to: `return make_format_args<wformat_context>(args...)`;

#### 22.14.7.3 Class template `basic_format_args`  

```cpp
namespace std {
  template<class Context>
  class basic_format_args {
    size_t size_{}; // exposition only
    const basic_format_arg<Context>* data_{}; // exposition only
  public:
    basic_format_args() noexcept;
    template<class... Args>
      basic_format_args(const format-arg-store<Context, Args...>& store) noexcept;
    basic_format_arg<Context> get(size_t i) const noexcept;
  }
}
```

An instance of `basic_format_args` provides access to formatting arguments. Implementations should optimize the representation of `basic_format_args` for a small number of formatting arguments.

[Note 1: For example, by storing indices of type alternatives separately from values and packing the former. — end note]

```cpp
basic_format_args() noexcept;
```

Effects: Initializes `size_` with 0.

```cpp
template<class... Args>
  basic_format_args(const format-arg-store<Context, Args...>& store) noexcept;
```

Effects: Initializes `size_` with `sizeof...(Args)` and `data_` with `store.args.data()`.

```cpp
basic_format_arg<Context> get(size_t i) const noexcept;
```


#### 22.14.8 Class `format_error`  

```cpp
namespace std {
  class format_error : public runtime_error {
    public:
      explicit format_error(const string& what_arg);
      explicit format_error(const char* what_arg);
  }
}
```

The class `format_error` defines the type of objects thrown as exceptions to report errors from the formatting library.

```cpp
format_error(const string& what_arg);
```

Postconditions: `strcmp(what(), what_arg.c_str()) == 0`.

```cpp
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

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 T bit_width(T x) noexcept;

    // 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

template<class To, class From>
constexpr To bit_cast(const From& from) noexcept;

Constraints:

1

- sizeof(To) == sizeof(From) is true;
- is_trivially_copyable_v<To> is true; and
- is_trivially_copyable_v<From> is true.

2

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 of an object that is not within its lifetime or has an
indeterminate value (6.7.4). For each bit in the value representation of the result that is indeterminate, the smallest object containing that bit has an indeterminate value; the behavior is undefined unless that object is of unsigned ordinary character type or std::byte type. The result does not otherwise contain any indeterminate 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:

- is_union_v<T> is false;
- is_pointer_v<T> is false;
- is_member_pointer_v<T> is false;
- is_volatile_v<T> is false; and
- T has no non-static data members of reference type.

### 22.15.4 byteswap

```cpp
template<class T>
constexpr T byteswap(T value) noexcept;
```

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
5. T has no non-static data members of reference type.

### 22.15.5 Integral powers of 2

```cpp
template<class T>
constexpr bool has_single_bit(T x) noexcept;
```

Remarks: A function call expression that violates the precondition in the Preconditions: element is not a core constant expression (7.7).

### 22.15.6 Rotating

In the following descriptions, let N denote numeric_limits<T>::digits.
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) | (x >> (N - r)); if r is negative, rotr(x, -r).

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) | (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.

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]

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]

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]

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]

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.

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`. 
23 Strings library

23.1 General

1 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.

2 The following subclauses describe a character traits class, string classes, and null-terminated sequence utilities, as summarized in Table 74.

![Table 74: Strings library summary](tab:strings.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></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

1 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.

2 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.

3 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 75, 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 this subclause 23.2.2 shall exit via an exception.

![Table 75: Character traits requirements](tab:char.traits.req)

<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>(described in 23.2.3)</td>
<td></td>
<td>compile-time</td>
</tr>
<tr>
<td>X::off_type</td>
<td>(described in 31.2.3 and 31.3)</td>
<td></td>
<td>compile-time</td>
</tr>
<tr>
<td>X::pos_type</td>
<td>(described in 31.2.3 and 31.3)</td>
<td></td>
<td>compile-time</td>
</tr>
<tr>
<td>X::state_type</td>
<td>(described in 23.2.3)</td>
<td></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>
<tr>
<td>Expression</td>
<td>Return type</td>
<td>Assertion/note pre-/post-condition</td>
<td>Complexity</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------</td>
<td>-------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td><code>X::lt(c,d)</code></td>
<td>bool</td>
<td>Returns: whether c is to be treated as less than d.</td>
<td>constant</td>
</tr>
<tr>
<td><code>X::compare(p,q,n)</code></td>
<td>int</td>
<td>Returns: 0 if for each i in <code>[0,n), X::eq(p[i],q[i])</code> is true; else, a negative value if, for some j in <code>[0,n), X::lt(p[j],q[j])</code> is true and for each i in <code>[0,j) X::eq(p[i],q[i])</code> is true; else a positive value.</td>
<td>linear</td>
</tr>
<tr>
<td><code>X::length(p)</code></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><code>X::find(p,n,c)</code></td>
<td>const X::char_type*</td>
<td>Returns: the smallest q in <code>[p,p+n)</code> such that X::eq(*q,c) is true, zero otherwise.</td>
<td>linear</td>
</tr>
<tr>
<td><code>X::move(s,p,n)</code></td>
<td>X::char_type*</td>
<td>for each i in <code>[0,n), performs X::assign(s[i],p[i]). Copies correctly even where the ranges </code>[p,p+n)<code>and</code>[s,s+n)` overlap. Returns: s.</td>
<td>linear</td>
</tr>
<tr>
<td><code>X::copy(s,p,n)</code></td>
<td>X::char_type*</td>
<td>Preconditions: p not in <code>[s,s+n). Returns: s. for each i in </code>[0,n), performs X::assign(s[i],p[i]).</td>
<td>linear</td>
</tr>
<tr>
<td><code>X::assign(r,d)</code></td>
<td>(not used)</td>
<td>assigns r=d.</td>
<td>constant</td>
</tr>
<tr>
<td><code>X::assign(s,n,c)</code></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><code>X::not_eof(e)</code></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><code>X::to_char_type(e)</code></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><code>X::to_int_type(c)</code></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>
<tr>
<td><code>X::eq_int_type(e,f)</code></td>
<td>bool</td>
<td>Returns: for all c and d, X::eq(c,d) is equal to X::eq_int_type(X::to_int_type(c), X::to_int_type(d)); otherwise, yields true if e and f are both copies of X::eof(); otherwise, yields false if one of e and f is a copy of X::eof() and the other is not; otherwise the value is unspecified.</td>
<td>constant</td>
</tr>
</tbody>
</table>
Table 75: Character traits requirements (continued)

<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>\texttt{X::eof()}</td>
<td>\texttt{X::int_type}</td>
<td>\texttt{Returns: a value } e \texttt{ such that } X::eq_int_type(e,X::to_int_type(c)) \texttt{is false for all values } c.</td>
<td>constant</td>
</tr>
</tbody>
</table>

2 The class template

\begin{verbatim}
    template<class charT> struct char_traits;
\end{verbatim}

is provided in the header <string> as a basis for explicit specializations.

23.2.3 Traits typedefs

using \texttt{int\_type} = see below;

1 \textbf{Preconditions:} \texttt{int\_type} shall be able to represent all of the valid characters converted from the corresponding \texttt{char\_type} values, as well as an end-of-file value, \texttt{eof()}.\footnote{If \texttt{eof()} can be held in \texttt{char\_type} then some iostreams operations can give surprising results.}

using \texttt{state\_type} = see below;

2 \textbf{Preconditions:} \texttt{state\_type} meets the Cpp17Destructible (Table 34), Cpp17CopyAssignable (Table 33), Cpp17CopyConstructible (Table 31), and Cpp17DefaultConstructible (Table 29) requirements.

23.2.4 \texttt{char\_traits} specializations

23.2.4.1 General

\begin{verbatim}
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;
        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);
    }
}
\end{verbatim}

1 The header <string> defines five specializations of the class template \texttt{char\_traits}: \texttt{char\_traits<char>}, \texttt{char\_traits<char8\_t>}, \texttt{char\_traits<char16\_t>}, \texttt{char\_traits<char32\_t>}, and \texttt{char\_traits<wchar\_t>}.
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.

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`.

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 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;
  };
}
```

The two-argument members `assign`, `eq`, and `lt` are defined identically to the built-in operators `=`, `==`, and `<` respectively.

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;
    using state_type = mbstate_t;
    using comparison_category = strong_ordering;

    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;
  };
}
```
The two-argument members `assign`, `eq`, and `lt` are defined identically to the built-in operators `=`, `==`, and `<`, respectively.

The member `eof()` returns an implementation-defined constant that cannot appear as a valid UTF-16 code unit.

### 23.2.4.5 `struct char_traits<char32_t>`

```cpp
class char_traits<char32_t> { }
```

### 23.2.4.6 `struct char_traits<wchar_t>`

```cpp
class char_traits<wchar_t> { }
```
The two-argument members assign, eq, and lt are defined identically to the built-in operators =, ==, and <, respectively.

The member eof() returns WEOF.
// 23.3.6, inserters and extractors

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os,
          basic_string_view<charT, traits> str);
```

// basic_string_view typedef-names

```cpp
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>;
```

// 23.3.7, hash support

```cpp
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>;
```

```cpp
inline namespace literals {
    inline namespace string_view_literals {
        // 23.3.8, 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]

#### [string_view.template.general]

```cpp
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 23.3.3.3
            using iterator = const_iterator;\[212\]
            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);

            // 23.3.3.2, construction and assignment
            constexpr basic_string_view() noexcept;
            constexpr basic_string_view(const basic_string_view& other) noexcept = default;
            constexpr basic_string_view& operator=(const basic_string_view& other) noexcept = default;
            constexpr basic_string_view(const charT* str);
            static basic_string_view nullptr_t = delete;
```

\[212\] Because `basic_string_view` refers to a constant sequence, `iterator` and `const_iterator` are the same type.
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 basic_string_view(R&& r);

// 23.3.3.3, 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;

// 23.3.3.4, 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;

// 23.3.3.5, element access
constexpr const_reference operator[](size_type pos) const;
constexpr const_reference at(size_type pos) const;
constexpr const_reference front() const;
constexpr const_reference back() const;
constexpr const_pointer data() const noexcept;

// 23.3.3.6, modifiers
constexpr void remove_prefix(size_type n);
constexpr void remove_suffix(size_type n);
constexpr void swap(basic_string_view& s) noexcept;

// 23.3.3.7, string operations
constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;
constexpr basic_string_view substr(size_type pos = 0, size_type n = npos) const;
constexpr int compare(basic_string_view s) const noexcept;
constexpr int compare(size_type pos1, size_type n1, basic_string_view s) const;
constexpr int compare(size_type pos1, size_type n1, basic_string_view s,
  size_type pos2, size_type n2) const;
constexpr int compare(const charT* s) const;
constexpr int compare(size_type pos1, size_type n1, const charT* s) const;
constexpr int compare(size_type pos1, size_type n1, const charT* s, size_type n2) const;
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;

// 23.3.3.8, 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
};

// 23.3.4, 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 returned from str’s member functions.
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: [str, str + 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: \( O(1) \).
constexpr basic_string_view(const charT* str, size_type len);
    Preconditions: [str, str + len) is a valid range.
    Effects: Constructs a basic_string_view, initializing data_ with str and initializing size_ with len.

§ 23.3.3.2
template<class It, class End>
constexpr basic_string_view(It begin, End end);

Constraints:

— It satisfies contiguous_iterator.
— End satisfies sized_sentinel_for<It>.
— is_same_v<iter_value_t<It>, charT> is true.
— is_convertible_v<End, size_type> is false.

Preconditions:

— [begin, end) is a valid range.
— It models contiguous_iterator.
— End models sized_sentinel_for<It>.

Effects: Initializes data_ with to_address(begin) and initializes size_ with end - begin.

Throws: When and what end - begin throws.

template<class R>
constexpr basic_string_view(R&& r);

Let d be an lvalue of type remove_cvref_t<R>.

Constraints:

— remove_cvref_t<R> is not the same type as basic_string_view,
— R models ranges::contiguous_range and ranges::sized_range,
— is_same_v<ranges::range_value_t<R>, charT> is true,
— is_convertible_v<R, const charT*> is false,
— d.operator::std::basic_string_view<charT, traits>() is not a valid expression, and
— if the qualified-id remove_reference_t<R>::traits_type is valid and denotes a type, is_same_v<remove_reference_t<R>::traits_type, traits> is true.

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).

23.3.3.3 Iterator support

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: \texttt{const_reverse_iterator(begin())}.

23.3.3.4 Capacity \hspace{1cm} \texttt{[string.view.capacity]}

constexpr size_type size() const noexcept;
constexpr size_type length() const noexcept;
Returns: \texttt{size_}.

constexpr size_type max_size() const noexcept;
Returns: The largest possible number of char-like objects that can be referred to by a \texttt{basic_string_view}.
[[nondiscard]] constexpr bool empty() const noexcept;
Returns: \texttt{size_ == 0}.

23.3.3.5 Element access \hspace{1cm} \texttt{[string.view.access]}

constexpr const_reference operator[](size_type pos) const;
Preconditions: \texttt{pos < size()}.  
Returns: \texttt{data_[pos]}.  
Throws: Nothing.
[Note 1: Unlike \texttt{basic_string::operator[]}, \texttt{basic_string_view::operator[](size())} has undefined behavior instead of returning \texttt{charT()}. —end note]

constexpr const_reference at(size_type pos) const;
Returns: \texttt{data_[pos]}.  
Throws: \texttt{out_of_range} if \texttt{pos >= size()}.  

constexpr const_reference front() const;
Preconditions: \texttt{!empty()}.  
Returns: \texttt{data_[0]}.  
Throws: Nothing.

constexpr const_reference back() const;
Preconditions: \texttt{!empty()}.  
Returns: \texttt{data_[size() - 1]}.  
Throws: Nothing.

constexpr const_pointer data() const noexcept;
Returns: \texttt{data_}.  
[Note 2: Unlike \texttt{basic_string::data()} and \texttt{string-literals}, \texttt{data()} can return a pointer to a buffer that is not null-terminated. Therefore it is typically a mistake to pass \texttt{data()} to a function that takes just a \texttt{const charT*} and expects a null-terminated string. —end note]

23.3.3.6 Modifiers \hspace{1cm} \texttt{[string.view.modifiers]}

constexpr void remove_prefix(size_type n);
Preconditions: \texttt{n <= size()}.  
Effects: Equivalent to: \texttt{data_ += n; size_ -= n};  

constexpr void remove_suffix(size_type n);
Preconditions: \texttt{n <= size()}.  
Effects: Equivalent to: \texttt{size_ -= n};  

§ 23.3.3.6
constexpr void swap(basic_string_view& s) noexcept;

Effects: Exchanges the values of *this and s.

### 23.3.3.7 String operations

```cpp
constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;
```

1. Let rlen be the smaller of n and size() - pos.
2. Preconditions: [s, s + rlen) is a valid range.
3. Effects: Equivalent to traits::copy(s, data() + pos, rlen).
5. Throws: out_of_range if pos > size().
6. Complexity: $\Theta(rlen)$.

```cpp
constexpr basic_string_view substr(size_type pos = 0, size_type n = npos) const;
```

7. Let rlen be the smaller of n and size() - pos.
8. Effects: Determines rlen, the effective length of the string to reference.
9. Returns: basic_string_view(data() + pos, rlen).
10. Throws: out_of_range if pos > size().

```cpp
constexpr int compare(basic_string_view str) const noexcept;
```

11. Let rlen be the smaller of size() and str.size().
12. 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).
13. Returns: The nonzero result if the result of the comparison is nonzero. Otherwise, returns a value as indicated in Table 76.

**Table 76: compare() results**

<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>

14. Complexity: $\Theta(rlen)$.

```cpp
constexpr int compare(size_type pos1, size_type n1, basic_string_view str) const;
```

15. Effects: Equivalent to: return substr(pos1, n1).compare(str);

```cpp
constexpr int compare(size_type pos1, size_type n1, basic_string_view str, size_type pos2, size_type n2) const;
```

16. Effects: Equivalent to: return substr(pos1, n1).compare(str.substr(pos2, n2));

```cpp
constexpr int compare(const charT* s) const;
```

17. Effects: Equivalent to: return compare(basic_string_view(s));

```cpp
constexpr int compare(size_type pos1, size_type n1, const charT* s) const;
```

18. Effects: Equivalent to: return substr(pos1, n1).compare(basic_string_view(s));

```cpp
constexpr int compare(size_type pos1, size_type n1, const charT* s, size_type n2) const;
```

19. Effects: Equivalent to: return substr(pos1, n1).compare(basic_string_view(s, n2));

```cpp
constexpr bool starts_with(basic_string_view x) const noexcept;
```

20. Effects: Equivalent to: return substr(0, x.size()) == 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 size() >= x.size() && compare(size() - x.size(), npos, x) == 0;

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;

### 23.3.3.8 Searching

**[string.view.find]**

Member functions in this subclause have complexity $O(size() \times str.size())$ at worst, although implementations should do better.

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

```cpp
constexpr return-type F(const charT* s, size_type pos) const;
constexpr return-type F(const charT* s, size_type pos, size_type n) const;
constexpr return-type F(charT c, size_type pos) const noexcept;
```

has effects equivalent to:

- `F(basic_string_view(s), pos)`
- `F(basic_string_view(s, n), pos)`
- `F(basic_string_view(addressof(c), 1), pos)`

---

(3.1) Let $xpos$ be the lowest position, if possible, such that the following conditions hold:

- $pos \leq xpos$
- $xpos + str.size() \leq size()$
- traits::eq(at(xpos + I), str.at(I)) for all elements $I$ of the string referenced by $str$.

**Effects:** Determines $xpos$.

**Returns:** $xpos$ if the function can determine such a value for $xpos$. Otherwise, returns npos.

---

(6.3) Let $xpos$ be the highest position, if possible, such that the following conditions hold:

- $xpos \leq pos$
- $xpos + str.size() \leq size()$
- traits::eq(at(xpos + I), str.at(I)) for all elements $I$ of the string referenced by $str$.

**Effects:** Determines $xpos$.

**Returns:** $xpos$ if the function can determine such a value for $xpos$. Otherwise, returns npos.
constexpr size_type find_first_of(basic_string_view str, size_type pos = 0) const noexcept;

Let xpos be the lowest position, if possible, such that the following conditions hold:

- pos <= xpos
- xpos < size()
- traits::eq(at(xpos), str.at(I)) for some element I of the string referenced by str.

Effects: Determines xpos.

Returns: xpos if the function can determine such a value for xpos. Otherwise, returns npos.

constexpr size_type find_last_of(basic_string_view str, size_type pos = npos) const noexcept;

Let xpos be the highest position, if possible, such that the following conditions hold:

- xpos <= pos
- xpos < size()
- traits::eq(at(xpos), str.at(I)) for some element I of the string referenced by str.

Effects: Determines xpos.

Returns: xpos if the function can determine such a value for xpos. Otherwise, returns npos.

constexpr size_type find_first_not_of(basic_string_view str, size_type pos = 0) const noexcept;

Let xpos be the lowest position, if possible, such that the following conditions hold:

- pos <= xpos
- xpos < size()
- traits::eq(at(xpos), str.at(I)) for no element I of the string referenced by str.

Effects: Determines xpos.

Returns: xpos if the function can determine such a value for xpos. Otherwise, returns npos.

constexpr size_type find_last_not_of(basic_string_view str, size_type pos = npos) const noexcept;

Let xpos be the highest position, if possible, such that the following conditions hold:

- xpos <= pos
- xpos < size()
- traits::eq(at(xpos), str.at(I)) for no element I of the string referenced by str.

Effects: Determines xpos.

Returns: xpos if the function can determine such a value for xpos. Otherwise, returns npos.

23.3.4 Deduction guides

```
template<class It, class End>
basic_string_view(It, End) -> basic_string_view<iter_value_t<It>>;
```

1 Constraints:
- It satisfies contiguous_iterator.
- End satisfies sized_sentinel_for<It>.

```
template<class R>
basic_string_view(R&&) -> basic_string_view<ranges::range_value_t<R>>;
```

2 Constraints: R satisfies ranges::contiguous_range.

23.3.5 Non-member comparison functions

```
§ 23.3.5 806
```

Let S be basic_string_view<charT, traits>, and sv be an instance of S. Implementations shall provide sufficient additional overloads marked constexpr and noexcept so that an object t with an implicit conversion to S can be compared according to Table 77.

Example 1: A sample conforming implementation for operator== would be:
Table 77: Additional basic_string_view comparison overloads

<table>
<thead>
<tr>
<th>Expression</th>
<th>Equivalent to</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{t == sv}</td>
<td>\texttt{S(t) == sv}</td>
</tr>
<tr>
<td>\texttt{sv == t}</td>
<td>\texttt{sv == S(t)}</td>
</tr>
<tr>
<td>\texttt{t != sv}</td>
<td>\texttt{S(t) != sv}</td>
</tr>
<tr>
<td>\texttt{sv != t}</td>
<td>\texttt{sv != S(t)}</td>
</tr>
<tr>
<td>\texttt{t &lt; sv}</td>
<td>\texttt{S(t) &lt; sv}</td>
</tr>
<tr>
<td>\texttt{sv &lt; t}</td>
<td>\texttt{sv &lt; S(t)}</td>
</tr>
<tr>
<td>\texttt{t &gt; sv}</td>
<td>\texttt{S(t) &gt; sv}</td>
</tr>
<tr>
<td>\texttt{sv &gt; t}</td>
<td>\texttt{sv &gt; S(t)}</td>
</tr>
<tr>
<td>\texttt{t &lt;= sv}</td>
<td>\texttt{S(t) &lt;= sv}</td>
</tr>
<tr>
<td>\texttt{sv &lt;= t}</td>
<td>\texttt{sv &lt;= S(t)}</td>
</tr>
<tr>
<td>\texttt{t &gt;= sv}</td>
<td>\texttt{S(t) &gt;= sv}</td>
</tr>
<tr>
<td>\texttt{sv &gt;= t}</td>
<td>\texttt{sv &gt;= S(t)}</td>
</tr>
<tr>
<td>\texttt{t &lt;=&gt; sv}</td>
<td>\texttt{S(t) &lt;=&gt; sv}</td>
</tr>
<tr>
<td>\texttt{sv &lt;=&gt; t}</td>
<td>\texttt{sv &lt;=&gt; S(t)}</td>
</tr>
</tbody>
</table>

\texttt{template<class charT, class traits>}
\begin{verbatim}
constexpr bool operator==(basic_string_view<charT, traits> lhs, basic_string_view<charT, traits> rhs) noexcept {
    return lhs.compare(rhs) == 0;
}
\end{verbatim}

\texttt{template<class charT, class traits>}
\begin{verbatim}
constexpr bool operator==(basic_string_view<charT, traits> lhs, type_identity_t<basic_string_view<charT, traits>> rhs) noexcept {
    return lhs.compare(rhs) == 0;
}
\end{verbatim}

—end example—

\texttt{template<class charT, class traits>}
\begin{verbatim}
constexpr see below operator<=>(basic_string_view<charT, traits> lhs, basic_string_view<charT, traits> rhs) noexcept;
\end{verbatim}

\begin{enumerate}
\item Returns: \texttt{lhs.compare(rhs) == 0}.
\end{enumerate}

\texttt{template<class charT, class traits>}
\begin{verbatim}
constexpr see below operator<=>(basic_string_view<charT, traits> lhs, basic_string_view<charT, traits> rhs) noexcept;
\end{verbatim}

\begin{enumerate}
\item Returns: \texttt{static_cast<R>(lhs.compare(rhs) <=> 0)}.\end{enumerate}

\section*{23.3.6 Inserters and extractors}

\texttt{template<class charT, class traits>}
\begin{verbatim}
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, basic_string_view<charT, traits> str);
\end{verbatim}

\begin{enumerate}
\item \begin{enumerate}
\item Effects: Behaves as a formatted output function (31.7.5.3.1) of \texttt{os}. Forms a character sequence \texttt{seq}, initially consisting of the elements defined by the range \texttt{[str.begin(), str.end()]). Determines padding for \texttt{seq} as described in 31.7.5.3.1. Then inserts \texttt{seq} as if by calling \texttt{os.rdbuf()->sputn(seq, n)}, where \texttt{n} is the larger of \texttt{os.width()} and \texttt{str.size()}; then calls \texttt{os.width(0)}.\end{enumerate}
\item Returns: \texttt{os}.
\end{enumerate}

\section*{23.3.7 Hash support}

\texttt{template<> struct hash<string_view>;

\texttt{template<> struct hash<u8string_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]

23.3.8 Suffix for basic_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;
  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>;
  // 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+(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,
                basic_string<charT, traits, Allocator>&& rhs);
template<class charT, class traits, class Allocator>
    operator+(const basic_string<charT, traits, Allocator>& lhs,
                const charT* rhs);
template<class charT, class traits, class Allocator>
    operator+(const basic_string<charT, traits, Allocator>& lhs,
                charT rhs);

// § 23.4.2

// 23.4.4.3, swap
template<class charT, class traits, class Allocator>
    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);

// see below
// see below

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,
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,
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>
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);

// basic_string typedef-names

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);
float stof(const string& str, size_t* idx = nullptr);
double stod(const string& str, size_t* idx = nullptr);

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);
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(unsigned long long val);
wstring to_wstring(float val);
wstring to_wstring(double val);
wstring to_wstring(long double 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<> struct hash<string>;
template<> struct hash<u8string>;
template<> struct hash<u16string>;
template<> struct hash<u32string>;
template<> struct hash<wstring>;
template<> struct hash<pmr::string>;
template<> struct hash<pmr::u8string>;
template<> struct hash<pmr::u16string>;
template<> struct hash<pmr::u32string>;
template<> struct hash<pmr::wstring>;

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

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.

A specialization of basic_string is a contiguous container (24.2.2.1).

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());
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& a = Allocator());
constexpr basic_string(const basic_string&, const Allocator&);
constexpr basic_string(basic_string&&, const Allocator&);
constexpr ~basic_string();
constexpr 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;

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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& operator+=(initializer_list<charT>);
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;
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);
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(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 pos1, const T& 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 iterator insert(const_iterator p, charT c);
constexpr iterator 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 iterator insert(const_iterator p, initializer_list<charT>);

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 void pop_back();

constexpr basic_string& replace(size_type pos1, size_type n1, const basic_string& str);
constexpr basic_string& replace(size_type pos1, size_type n1, const basic_string& str,
  size_type pos2, size_type n2 = npos);
template<class T>
  constexpr basic_string& replace(size_type pos1, size_type n1, const T& t);
  constexpr basic_string& replace(size_type pos1, size_type n1, const T& t,
  size_type pos2, size_type n2 = npos);
constexpr basic_string& replace(size_type pos, size_type n1, const charT* s, size_type n2);
constexpr basic_string& replace(size_type pos, 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(const_iterator, const_iterator, initializer_list<charT>);

constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;
constexpr void swap(basic_string& str)
    noexcept(algorithm_traits<Allocator>::propagate_on_container_swap::value ||
              algorithm_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(const charT* s, 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(const charT* s, 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(const charT* s, 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(const charT* s, size_type pos = npos) const noexcept;

template<class T>
    constexpr size_type find_first_not_of(const T& t, size_type pos = 0) const noexcept;
constexpr size_type find_first_not_of(const basic_string& str, 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 noexcept;

template<class T>
    constexpr size_type find_last_not_of(const T& t, size_type pos = npos) const noexcept;
constexpr size_type find_last_not_of(const basic_string& str, 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 noexcept;

constexpr basic_string substr(size_type pos = 0, size_type n = npos) const;

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;

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template<class T>
  constexpr int compare(size_type pos1, size_type n1, const T& t,
                       size_type pos2, size_type n2 = npos) const;
  constexpr int compare(const basic_string& str) const noexcept;
  constexpr int compare(size_type pos1, size_type n1, const basic_string& str,
                       size_type pos2, size_type n2 = npos) const;
  constexpr int compare(const charT* s) const;
  constexpr int compare(size_type pos1, size_type n1, const charT* s) const;
  constexpr int compare(size_type pos1, size_type n1, const charT* s, size_type n2) const;
  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>;

4 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.

5 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 In every specialization basic_string<charT, traits, Allocator>, the type allocator_traits<All-
 ocator>::value_type shall name the same type as charT. 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 24.2.2.1. 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, but does not use the allocator's construct and destroy member functions (24.2.2.1). — end note]

[Note 2: The program is ill-formed if traits::char_type is not the same type as charT. — end note]

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:

(4.1) — Passing as an argument to any standard library function taking a reference to non-const basic_string as an argument.

(4.2) — Calling non-const member functions, except operator[], at, data, front, back, begin, rbegin, end, and rend.

23.4.3.3 Constructors and assignment operators

constexpr explicit basic_string(const Allocator& a) noexcept;

Postconditions: size() is equal to 0.

costexpr basic_string(const basic_string& str);
costexpr basic_string(basic_string&& str) noexcept;

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.

costexpr basic_string(const basic_string& str, size_type pos, const Allocator& a = Allocator());
costexpr basic_string(const basic_string& str, size_type pos, size_type n, const Allocator& a = Allocator());

Effects: Let n be npos for the first overload. Equivalent to:

basic_string(basic_string_view<charT, traits>(str).substr(pos, n), a)

template<class T>
costexpr basic_string(const T& t, size_type pos, size_type n, const Allocator& a = Allocator());

Constraints: is_convertible_v<const T&, basic_string_view<charT, traits>> is true.

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);

template<class T>
costexpr explicit basic_string(const T& t, const Allocator& a = Allocator());

Constraints:

(7.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and

(7.2) — is_convertible_v<const T&, const charT*> is false.

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).

costexpr basic_string(const charT* s, size_type n, const Allocator& a = Allocator());

Preconditions: [s, s + n) is a valid range.

Effects: Constructs an object whose initial value is the range [s, s + n).

Postconditions: size() is equal to n, and traits::compare(data(), s, n) is equal to 0.

213) 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().
constexpr basic_string(const charT* s, const Allocator& a = Allocator());

**Constraints:** `Allocator` is a type that qualifies as an allocator (24.2.2.1).

**Effects:** Equivalent to: `basic_string(s, traits::length(s), a)`.

customexpr basic_string(size_type n, charT c, const Allocator& a = Allocator());

**Constraints:** `Allocator` is a type that qualifies as an allocator (24.2.2.1).

**Effects:** Constructs an object whose value consists of `n` copies of `c`.

customexpr basic_string(InputIterator begin, InputIterator end, const Allocator& a = Allocator());

**Constraints:** `InputIterator` is a type that qualifies as an input iterator (24.2.2.1).

**Effects:** Constructs a string from the values in the range `[begin, end)`, as specified in 24.2.4.

customexpr basic_string(initializer_list<charT> il, const Allocator& a = Allocator());

**Effects:** Equivalent to `basic_string(il.begin(), il.end(), a)`.

customexpr basic_string(const basic_string& str, const Allocator& alloc);
custom_string(basic_string&& str, const Allocator& alloc);

**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.

**Throws:** The second form throws nothing if `alloc == str.get_allocator()`.

customexpr basic_string(const charT* s, const Allocator& a = Allocator());

**Effects:** Equivalent to: `basic_string(s, traits::length(s), a)`.

customexpr basic_string(size_type n, charT c, const Allocator& a = Allocator());

**Constraints:** `Allocator` is a type that qualifies as an allocator (24.2.2.1).

**Effects:** Constructs an object whose value consists of `n` copies of `c`.

customexpr basic_string(InputIterator begin, InputIterator end, const Allocator& a = Allocator());

**Constraints:** `InputIterator` is a type that qualifies as an input iterator (24.2.2.1).

**Effects:** Constructs a string from the values in the range `[begin, end)`, as specified in 24.2.4.

customexpr basic_string(initializer_list<charT> il, const Allocator& a = Allocator());

**Effects:** Equivalent to `basic_string(il.begin(), il.end(), a)`.

customexpr basic_string(const basic_string& str, const Allocator& alloc);
custom_string(basic_string&& str, const Allocator& alloc);

**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.

**Throws:** The second form throws nothing if `alloc == str.get_allocator()`.

customexpr basic_string(const charT* s, const Allocator& a = Allocator());

**Effects:** Equivalent to: `basic_string(s, traits::length(s), a)`.

customexpr basic_string(size_type n, charT c, const Allocator& a = Allocator());

**Constraints:** `Allocator` is a type that qualifies as an allocator (24.2.2.1).

**Effects:** Constructs an object whose value consists of `n` copies of `c`.
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), 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.
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:

(5.1) If `n <= size()`, erases the last `size() - n` elements.
(5.2) If `n > size()`, appends `n - size()` copies of `c`.

constexpr void resize(size_type n);

Effects: Equivalent to `resize(n, charT())`.

template<class Operation> constexpr void resize_and_overwrite(size_type n, Operation op);

Let

(7.1) `o = size()` before the call to `resize_and_overwrite`.
(7.2) `k = min(o, n)`.
(7.3) `p` be a `charT*`, such that the range `[p, p + n]` is valid and `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).
(7.4) `OP` be the expression `std::move(op)(p, n)`.
(7.5) `r = OP`.

Mandates: `OP` has an integer-like type (25.3.4.4).

 Preconditions:

(9.1) `OP` does not throw an exception or modify `p` or `n`.
(9.2) `r >= 0`.
(9.3) `r <= n`.
(9.4) After evaluating `OP` there are no indeterminate values in the range `[p, p + r)`.

Effects: Evaluates `OP`, replaces the contents of `*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 `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. 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()`.

Throws: `length_error` if `res_arg > max_size()` or any exceptions thrown by `allocator_traits<Allocator>::allocate`.

constexpr void shrink_to_fit();

Effects: `shrink_to_fit` is a non-binding request to reduce `capacity()` to `size()`.

[Note 1: 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.

Complexity: If the size is not equal to the old capacity, linear in the size of the sequence; otherwise constant.

§ 23.4.3.5
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]

constexpr void clear() noexcept;

Effects: Equivalent to: erase(begin(), end());

[[nodiscard]] constexpr bool empty() const noexcept;

Effects: Equivalent to: return size() == 0;

23.4.3.6 Element access

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.

constexpr const_reference at(size_type pos) const;
constexpr reference at(size_type pos);

Returns: operator[](pos).

Throws: out_of_range if pos >= size().

constexpr const charT& front() const;
constexpr charT& front();

Preconditions: !empty().

Effects: Equivalent to: return operator[](0);

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+=

constexpr basic_string& operator+=(const basic_string& str);

Effects: Equivalent to: return append(str);

template<class T>
constexpr basic_string& operator+=(const T& t);

Constraints:
(2.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(2.2) — is_convertible_v<const T&, const charT*> is false.

Effects: Equivalent to:

basic_string_view<charT, traits> sv = t;
return append(sv);

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

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:
— 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 append(sv.data(), sv.size());

template<class T>
constexpr basic_string& append(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 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 (24.2.2.1).

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:
(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.

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:
(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:
    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 (24.2.2.1).
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:

— 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 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:

— 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 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:

— out_of_range if pos > size(),
— length_error if n > max_size() - size(), or
— 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:
\(\text{(14.1)}\) \text{out_of_range} \text{if pos} > \text{size()},

\(\text{(14.2)}\) \text{length_error} \text{if n} > \text{max_size()} - \text{size()}, \text{or}

\(\text{(14.3)}\) any exceptions thrown by \text{allocator_traits<Allocator>::allocate}.

\text{constexpr iterator insert(const_iterator p, charT c);} 
\begin{align*}
\text{Preconditions:} & \text{p is a valid iterator on } *\text{this}. \\
\text{Effects:} & \text{Inserts a copy of c at the position p.} \\
\text{Returns:} & \text{An iterator which refers to the inserted character.}
\end{align*}

\text{constexpr iterator insert(const_iterator p, size_type n, charT c);} 
\begin{align*}
\text{Preconditions:} & \text{p is a valid iterator on } *\text{this}. \\
\text{Effects:} & \text{Inserts n copies of c at the position p.} \\
\text{Returns:} & \text{An iterator which refers to the first inserted character, or p if n == 0.}
\end{align*}

\text{template<class InputIterator>} 
\text{constexpr iterator insert(const_iterator p, InputIterator first, InputIterator last);} 
\begin{align*}
\text{Constraints:} & \text{InputIterator is a type that qualifies as an input iterator (24.2.2.1).} \\
\text{Preconditions:} & \text{p is a valid iterator on } *\text{this}. \\
\text{Effects:} & \text{Equivalent to insert(p - begin(), basic_string(first, last, get_allocator()))}. \\
\text{Returns:} & \text{An iterator which refers to the first inserted character, or p if first == last.}
\end{align*}

\text{template<container-compatible-range<charT> R>} 
\text{constexpr iterator insert_range(const_iterator p, R&& rg);} 
\begin{align*}
\text{Preconditions:} & \text{p is a valid iterator on } *\text{this}. \\
\text{Effects:} & \text{Equivalent to insert(p - begin(), basic_string(from_range, std::forward<R>(rg), get_allocator()))}. \\
\text{Returns:} & \text{An iterator which refers to the first inserted character, or p if rg is empty.}
\end{align*}

\text{constexpr iterator insert(const_iterator p, initializer_list<charT> il);} 
\begin{align*}
\text{Effects:} & \text{Equivalent to: return insert(p, il.begin(), il.end());}
\end{align*}

\text{23.4.3.7.5 basic_string::erase} 
\text{[string.erase]}
\begin{align*}
\text{constexpr basic_string& erase(size_type pos = 0, size_type n = npos);} 
\text{Effects:} & \text{Determines the effective length xlen of the string to be removed as the smaller of n and size()} 
\text{ - pos. Removes the characters in the range [begin() + pos, begin() + pos + xlen].} \\
\text{Returns:} & *\text{this}. \\
\text{Throws:} & \text{out_of_range if pos} > \text{size}().
\end{align*}

\text{constexpr iterator erase(const_iterator p);} 
\begin{align*}
\text{Preconditions:} & \text{p is a valid dereferenceable iterator on } *\text{this}. \\
\text{Effects:} & \text{Removes the character referred to by p.} \\
\text{Returns:} & \text{An iterator which points to the element immediately following p prior to the element being} 
\text{erased. If no such element exists, end() is returned.} \\
\text{Throws:} & \text{Nothing.}
\end{align*}

\text{constexpr iterator erase(const_iterator first, const_iterator last);} 
\begin{align*}
\text{Preconditions:} & \text{first and last are valid iterators on } *\text{this. [first, last) is a valid range.} \\
\text{Effects:} & \text{Removes the characters in the range [first, last).} \\
\text{Returns:} & \text{An iterator which points to the element pointed to by last prior to the other elements being} 
\text{erased. If no such element exists, end() is returned.} \\
\text{Throws:} & \text{Nothing.}
\end{align*}
constexpr void pop_back();

**Preconditions:** !empty().

**Effects:** Equivalent to erase(end() - 1).

**Throws:** Nothing.

### § 23.4.3.7.6 basic_string::replace [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
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>
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>
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
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<Alloc>::allocate.

```cpp
constexpr basic_string& replace(size_type pos, size_type n, const charT* s);
```

**Effects:** Equivalent to: return replace(pos, n, s, traits::length(s));

```cpp
constexpr basic_string& replace(size_type pos1, size_type n1, size_type n2, charT c);
```

**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.
Returns: \*this.

Throws:

- out_of_range if pos1 > size(),
- length_error if the length of the resulting string would exceed max_size(), or
- any exceptions thrown by allocator_traits<Allocator>::allocate.

```cpp
customexpr basic_string& replace(const_iterator i1, const_iterator i2, const basic_string& str);

Effects: Equivalent to: return replace(i1, i2, basic_string_view<charT, traits>(str));
```

template<class T>
customexpr basic_string& replace(const_iterator i1, const_iterator i2, 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.

Preconditions: [begin(), i1) and [i1, i2) are valid ranges.

Effects: Equivalent to:

```cpp
basic_string_view<charT, traits> sv = t;
return replace(i1 - begin(), i2 - i1, sv.data(), sv.size());
```

customexpr basic_string& replace(const_iterator i1, const_iterator i2, const charT* s, size_type n);

Effects: Equivalent to:

```cpp
return replace(i1, i2, basic_string_view<charT, traits>(s, n));
```

customexpr basic_string& replace(const_iterator i1, const_iterator i2, const charT* s);

Effects: Equivalent to:

```cpp
return replace(i1, i2, basic_string_view<charT, traits>(s));
```

Preconditions: [begin(), i1) and [i1, i2) are valid ranges.

Effects: Equivalent to: return replace(i1 - begin(), i2 - i1, n, c);

```cpp
template<class InputIterator>
customexpr basic_string& replace(const_iterator i1, const_iterator i2, InputIterator j1, InputIterator j2);

Constraints: InputIterator is a type that qualifies as an input iterator (24.2.2.1).

Effects: Equivalent to: return replace(i1, i2, basic_string(j1, j2, get_allocator()));
```

template<container-compatible-range<charT> R>
customexpr basic_string& replace_with_range(const_iterator i1, const_iterator i2, R&& rg);

Effects: Equivalent to:

```cpp
return replace(i1, i2, basic_string(from_range, std::forward<R>(rg), get_allocator()));
```

customexpr basic_string& replace(const_iterator i1, const_iterator i2, initializer_list<charT> il);

Effects: Equivalent to: return replace(i1, i2, il.begin(), il.size());

23.4.3.7.7 basic_string::copy

```cpp
constexpr size_type copy(charT* s, size_type n, size_type pos = 0) const;
```

Effects: Equivalent to: return basic_string_view<charT, traits>(*this).copy(s, n, pos);

[Note 1: This does not terminate s with a null object. — end note]

23.4.3.7.8 basic_string::swap

```cpp
constexpr void swap(basic_string& s);
```

Preconditions: allocator_traits<Allocator>::propagate_on_container_swap::value is true or get_allocator() == s.get_allocator().

§ 23.4.3.7.8
\section*{23.4.3.8 String operations \[string.ops\]}

\subsection*{23.4.3.8.1 Accessors \[string.accessors\]}

\begin{verbatim}
constexpr const charT* c_str() const noexcept;
constexpr const charT* data() const noexcept;

Returns: A pointer \( p \) such that \( p + i = \text{addressof}(\text{operator}[])(i) \) for each \( i \) in \([0, \text{size()}]\).
Complexity: Constant time.
Remarks: The program shall not modify any of the values stored in the character array; otherwise, the behavior is undefined.

constexpr charT* data() noexcept;

Returns: A pointer \( p \) such that \( p + i = \text{addressof}(\text{operator}[])(i) \) for each \( i \) in \([0, \text{size()}]\).
Complexity: Constant time.
Remarks: The program shall not modify the value stored at \( p + \text{size}() \) to any value other than \( \text{charT}()\); otherwise, the behavior is undefined.

constexpr operator basic_string_view<charT, traits>() const noexcept;

Effects: Equivalent to: \( \text{return basic_string_view<charT, traits>(data(), size())}; \)

constexpr allocator_type get_allocator() const noexcept;

Returns: A copy of the \text{Allocator} object used to construct the string or, if that allocator has been replaced, a copy of the most recent replacement.
\end{verbatim}

\subsection*{23.4.3.8.2 Searching \[string.find\]}

Let \( F \) be one of \text{find}, \text{rfind}, \text{find_first_of}, \text{find_last_of}, \text{find_first_not_of}, \text{and find_last_not_of}.

\subsection*{23.4.3.8.2.1 Each member function of the form}

\begin{verbatim}
constexpr size_type \( F \)\text{(const basic_string& str, size_type pos) const noexcept;}
has effects equivalent to: \( \text{return } F(\text{basic_string_view<charT, traits>(str), pos}); \)
\end{verbatim}

\subsection*{23.4.3.8.2.2 Each member function of the form}

\begin{verbatim}
constexpr size_type \( F \)\text{(const charT* s, size_type pos) const;}
has effects equivalent to: \( \text{return } F(\text{basic_string_view<charT, traits>(s), pos}); \)
\end{verbatim}

\subsection*{23.4.3.8.2.3 Each member function of the form}

\begin{verbatim}
constexpr size_type \( F \)\text{(const charT* s, size_type pos, size_type n) const;}
has effects equivalent to: \( \text{return } F(\text{basic_string_view<charT, traits>(s, n), pos}); \)
\end{verbatim}

\subsection*{23.4.3.8.2.4 Each member function of the form}

\begin{verbatim}
constexpr size_type \( F \)\text{(charT c, size_type pos) const noexcept;}
has effects equivalent to:
\( \text{return } F(\text{basic_string_view<charT, traits>(addressof(c), 1), pos}); \)
\end{verbatim}

\begin{verbatim}
template<class T>
constexpr size_type find(const T& t, size_type pos = 0) const noexcept(see below);
template<class T>
constexpr size_type rfind(const T& t, size_type pos = npos) const noexcept(see below);
template<class T>
constexpr size_type find_first_of(const T& t, size_type pos = 0) const noexcept(see below);
template<class T>
constexpr size_type find_last_of(const T& t, size_type pos = npos) const noexcept(see below);
template<class T>
constexpr size_type find_first_not_of(const T& t, size_type pos = 0) const noexcept(see below);
\end{verbatim}

§ 23.4.3.8.2 828
template<class T>
constexpr size_type find_last_not_of(const T& t, size_type pos = npos) const noexcept(see below);

2 Constraints:
(2.1) — is_convertible_v<const T&, basic_string_view<charT, traits>> is true and
(2.2) — is_convertible_v<const T&, const charT*> is false.
3 Effects: Let $G$ be the name of the function. Equivalent to:
\[
\text{basic_string_view<charT, traits> } s = \text{this, } sv = t;
\text{return } s.G(sv, pos);
\]
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;

1 Effects: Determines the effective length rlen of the string to copy as the smaller of n and size() - pos.
2 Returns: basic_string(data()+pos, rlen).
3 Throws: out_of_range if pos > size().

23.4.3.8.4 basic_string::compare

template<class T>
constexpr int compare(const T& t) const noexcept(see below);

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: 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 basic_string& str) 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.
7 Effects: Equivalent to:
\[
\text{basic_string_view<charT, traits> } s = \text{this, } sv = t;
\text{return } s.substr(pos1, n1).compare(sv.substr(pos2, n2));
\]

constexpr int compare(const basic_string& str) const noexcept;

8 Effects: Equivalent to: return compare(basic_string_view<charT, traits>(str));

constexpr int compare(size_type pos1, size_type n1, const basic_string& str) const;

9 Effects: Equivalent to: return compare(pos1, n1, basic_string_view<charT, traits>(str));

§ 23.4.3.8.4 829
constexpr int compare(size_type pos1, size_type n1, const basic_string& str,
            size_type pos2, size_type n2 = npos) const;

**Effects**: Equivalent to:

    return compare(pos1, n1, basic_string_view<charT, traits>(str), pos2, n2);

constexpr int compare(const charT* s) const;

**Effects**: Equivalent to:

    return compare(basic_string_view<charT, traits>(s));

constexpr int compare(size_type pos, size_type n1, const charT* s) const;

**Effects**: Equivalent to:

    return compare(pos, n1, basic_string_view<charT, traits>(s));

constexpr int compare(size_type pos, size_type n1, const charT* s, size_type n2) const;

**Effects**: Equivalent to:

    return compare(pos, n1, basic_string_view<charT, traits>(s, n2));

23.4.3.8.5 basic_string::starts_with

```cpp
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;
```

**Effects**: Equivalent to:

    return basic_string_view<charT, traits>(data(), size()).starts_with(x);

23.4.3.8.6 basic_string::ends_with

```cpp
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;
```

**Effects**: Equivalent to:

    return basic_string_view<charT, traits>(data(), size()).ends_with(x);

23.4.3.8.7 basic_string::contains

```cpp
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;
```

**Effects**: Equivalent to:

    return basic_string_view<charT, traits>(data(), size()).contains(x);

23.4.4 Non-member functions

23.4.4.1 operator+

```cpp
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);
```

**Effects**: Equivalent to:

    basic_string<charT, traits, Allocator> r = lhs;
    r.append(rhs);
    return r;

```cpp
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);
```

§ 23.4.4.1
template<class charT, class traits, class Allocator>  
constexpr basic_string<charT, traits, Allocator>
operator+(basic_string<charT, traits, Allocator>&& lhs, const charT* rhs);

2 Effects: Equivalent to:

lhs.append(rhs);
return std::move(lhs);

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);

3 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 basic_string<charT, traits, Allocator>& lhs,  
           basic_string<charT, traits, Allocator>&& rhs);

4 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, basic_string<charT, traits, Allocator>&& rhs);

5 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);

6 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+(const basic_string<charT, traits, Allocator>& lhs, charT rhs);

7 Effects: Equivalent to:

rhs.insert(rhs.begin(), rhs);
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);

8 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);

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);

Effects: Let op be the operator. Equivalent to:
return basic_string_view<charT, traits>(lhs)
oncall(lhs, rhs);

23.4.4.3 swap [string.special]

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)));

Effects: Equivalent to lhs.swap(rhs).

23.4.4.4 Inserters and extractors [string.io]

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 (31.7.4.3.1). After constructing a sentry object, if the sentry object returns true when converted to a value of type bool, calls str.erase() and then extracts characters from is and appends them to str as if by calling str.append(1, c). If is.width() is greater than zero, the maximum number n of characters appended is is.width(); otherwise n is str.max_size(). Characters are extracted and appended until any of the following occurs:

(1.1) n characters are stored;
(1.2) end-of-file occurs on the input sequence;
(1.3) isspace(c, is.getloc()) is true for the next available input character c.

After the last character (if any) is extracted, is.width(0) is called and the sentry object is destroyed.

If the function extracts no characters, it calls is.setstate(ios_base::failbit), which may throw ios_base::failure (31.5.4.4).

Returns: is.

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: Equivalent to: return os << basic_string_view<charT, traits>(str);
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,
    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,
    charT delim);

Effects: Behaves as an unformatted input function (31.7.4.4), except that it does not affect the value returned by subsequent calls to basic_istream<>::gcount(). After constructing a sentry object, if the sentry object returns true when converted to a value of type bool, calls str.erase() and then extracts characters from is and appends them to str as if by calling str.append(1, c) until any of the following occurs:

(6.1) end-of-file occurs on the input sequence (in which case, the getline function calls is.setstate(ios_base::eofbit)).

(6.2) traits::eq(c, delim) for the next available input character c (in which case, c is extracted but not appended) (31.5.4.4)

(6.3) str.max_size() characters are stored (in which case, the function calls is.setstate(ios_base::failbit)) (31.5.4.4)

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, it calls is.setstate(ios_base::failbit) which may throw ios_base::failure (31.5.4.4).

Returns: is.

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);

Returns: getline(is, str, is.widen(’\n’)).

23.4.4.5 Erasure [string.erase]

template<
class charT, class traits, class Allocator, class U>
constexpr typename basic_string<charT, traits, Allocator>::size_type
erase(basic_string<charT, traits, 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 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:

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

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)`, `strtoll(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.

float stof(const string& str, size_t* idx = nullptr);
double stod(const string& str, size_t* idx = nullptr);
long double stdold(const string& str, size_t* idx = nullptr);

Effects: These functions call `strtof(str.c_str(), ptr)`, `strtod(str.c_str(), ptr)`, and `strtold(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 `strtold` reports that no conversion can be performed. Throws `out_of_range` if `strtof`, `strtod`, or `strtold` sets `errno` to `ERANGE` or if the converted value is outside the range of representable values for the return type.

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: Each function returns a `string` object holding the character representation of the value of its argument that would be generated by calling `sprintf(buf, fmt, val)` with a format specifier of "%d", "%u", "%ld", "%lu", "%lld", "%llu", "%f", "%f", or "%Lf", respectively, where `buf` designates an internal character buffer of sufficient size.

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.

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**§ 23.4.6 Hash support**

template<> struct hash<string>;
template<> struct hash<u8string>;
template<> struct hash<u16string>;
template<> struct hash<u32string>;

**§ 23.4.7 Suffix for basic_string literals**

constexpr string operator"s(const char* str, size_t len);

Returns: string{str, len}.

constexpr u8string operator"s(const char8_t* str, size_t len);

Returns: u8string{str, len}.

constexpr u16string operator"s(const char16_t* str, size_t len);

Returns: u16string{str, len}.

constexpr u32string operator"s(const char32_t* str, size_t len);

Returns: u32string{str, len}.
constexpr wstring operator"s(const wchar_t* str, size_t len);

Returns: wstring(str, len).

[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 C 7.4

23.5.2 Header <cwctype> synopsis

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);
    int iswctype(wint_t wc, wctype_t desc);
    wctype_t wctype(const char* property);
    wint_t towlower(wint_t wc);
    wint_t toupper(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 C 7.30

23.5.3 Header <cstring> synopsis

namespace std {
    using size_t = see 17.2.4;
The contents and meaning of the header `<cstring>` are the same as the C standard library header `<string.h>`. The functions `strerror` and `strtok` are not required to avoid data races (16.4.6.10). 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.

[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 C 7.24

### 23.5.4 Header `<cwchar>` synopsis

```cpp
namespace std {
    using size_t = see 17.2.4;
    using mbstate_t = see below;
    using wint_t = see below;

    struct tm;

    int fwprintf(FILE* stream, const wchar_t* format, ...);
    int fwscanf(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, ...);
    int vfwpprintf(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 wprprintf(const wchar_t* format, va_list arg);
    int wscanf(const wchar_t* format, ...);
    int wprintf(const wchar_t* format, ...);
    wchar_t* fgetws(wchar_t* s, int n, FILE* stream);
    wchar_t* fgetwc(FILE* stream);
    wchar_t* fputws(wchar_t* s, int n, FILE* stream);
    wchar_t* fputwc(wchar_t c, FILE* stream);
}
```

#define NULL see 17.2.3
int fputws(const wchar_t* s, FILE* stream);
int fwrite(FILE* stream, int mode);
wint_t getwc(FILE* stream);
wint_t getwchar();
wint_t putwc(wchar_t c, FILE* stream);
wint_t putwchar(wchar_t c);
wint_t ungetwc(wint_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);
long int wcstol(const wchar_t* nptr, wchar_t** endptr, int base);
long long int wcstoll(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, size_t n);
 wchar_t* wmemcpy(wchar_t* s1, const wchar_t* s2, size_t n);
 wchar_t* wmemmove(wchar_t* s1, const wchar_t* s2, size_t n);
 wchar_t* wcscat(wchar_t* s1, const wchar_t* s2);
 wchar_t* wcsncat(wchar_t* s1, const wchar_t* s2, size_t n);
 int wcscmp(const wchar_t* s1, const wchar_t* s2);
 int wcscoll(const wchar_t* s1, const wchar_t* s2);
 int wcsncmp(const wchar_t* s1, const wchar_t* s2, size_t n);
 size_t wcsxfrm(wchar_t* s1, const wchar_t* s2, size_t n);
 int wmemcmp(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(wchar_t* s, wchar_t c);
 size_t wcsxcsn(const wchar_t* s1, const wchar_t* s2);
 const wchar_t* wcscspn(const wchar_t* s1, const wchar_t* s2);
 const wchar_t* wcspbrk(const wchar_t* s1, const wchar_t* s2);
 const wchar_t* wcsrchr(const wchar_t* s, wchar_t c);
 const wchar_t* wcsrchr(wchar_t* s, wchar_t c);
 size_t wcsxcsn(const wchar_t* s1, const wchar_t* s2);
 const wchar_t* wcsxcsn(const wchar_t* s1, const wchar_t* s2);
 const wchar_t* wcstok(const wchar_t* s, const wchar_t* t);
 const wchar_t* wcsxcsn(const wchar_t* s1, const wchar_t* s2);
 const wchar_t* wcstok(const wchar_t* s, const wchar_t* t);
 size_t wcsftime(const wchar_t* s, size_t maxsize, const wchar_t* format, const tm* timeptr);
 int wctob(wchar_t c);
 // see 16.2
 // 23.5.6, multibyte / wide string and character conversion functions
 int mbsinit(const mbstate_t* ps);
 size_t mbrlen(const char* s, size_t n, mbstate_t* ps);
 size_t mbrtowc(const wchar_t* pwc, const char* s, size_t n, mbstate_t* ps);
 size_t wcrtomb(const char* s, wchar_t wc, mbstate_t* ps);
 size_t mbsrtowcs(const wchar_t* dst, const char** src, size_t len, mbstate_t* ps);
 size_t wcsrtombs(const char* dst, const wchar_t** src, size_t len, mbstate_t* ps);
}
#define NULL see 17.2.3
#define WCHAR_MAX see below
#define WCHAR_MIN see below
#define WEOF see below

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 wcachr, 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]

See also: ISO C 7.29

§ 23.5.4

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23.5.5 Header <cuchar> synopsis

namespace std {
  using mbstate_t = see below;
  using size_t = see 17.2.4;

  size_t mbrtoc8(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 mbrtoc16(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 mbrtoc32(char32_t* pc32, const char* s, size_t n, mbstate_t* ps);
  size_t c32rtomb(char* s, char32_t c32, mbstate_t* ps);
}

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 mbrtoc8 and c8rtomb functions and does not declare types char16_t nor char32_t.

See also: ISO C 7.28

23.5.6 Multibyte / wide string and character conversion functions

[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]

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);

Effects: These functions have the semantics specified in the C standard library.

See also: ISO C 7.22.7.1, 7.22.8, 7.29.6.2.1

int mbtowc(wchar_t* pwc, const char* s, size_t n);
int wctomb(char* s, wchar_t wchar);

Effects: These functions have the semantics specified in the C standard library.

Remarks: Calls to these functions may introduce a data race (16.4.6.10) with other calls to the same function.

See also: ISO C 7.22.7

size_t mbrcat(size_t mbrcat(const char* s, size_t n, mbstate_t* ps);
size_t mbtowc wchar_t* pwc, const char* s, size_t n, mbstate_t* ps);
size_t wcrtomb wchar_t* s, wchar_t wchar, mbstate_t* ps);
size_t mbstowcs wchar_t* dst, const char** src, size_t len, mbstate_t* ps);
size_t wcstombs wchar_t* dst, const wchar_t** src, size_t len, mbstate_t* ps);

Effects: These functions have the semantics specified in the C standard library.

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 C 7.29.6.3

size_t mbrtoc8(char8_t* pc8, const char* s, size_t n, mbstate_t* ps);

Effects: If s is a null pointer, equivalent to mbrtoc8(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 U+0000 NULL, the resulting state described is the initial conversion state.

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 \( \text{u+0000} \) 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) \( \text{size_t}(-3) \), 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) \( \text{size_t}(-2) \), 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) \( \text{size_t}(-1) \), 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 \text{EILSEQ} is stored in \text{errno}, and the conversion state is unspecified.

size_t c8rtomb(char* s, char8_t c8, mbstate_t* ps);

Effects: If \( s \) is a null pointer, equivalent to c8rtomb(buf, u8'\0', ps) where \( \text{buf} \) is an internal buffer. Otherwise, if \( \text{c8} \) 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 \text{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.

Returns: The number of bytes stored in the array object (including any shift sequences). If \( \text{c8} \) does not contribute to a sequence of char8_t corresponding to a valid multibyte character, the value of the macro \text{EILSEQ} is stored in \text{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 78.

Table 78: Containers library summary

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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]

Allocators-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 (20.2.8.3), 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 General

In subclause 24.2.2,

1. X denotes a container class containing objects of type T,
2. a and b denote values of type X,
3. i and j denote values of type (possibly const) X::iterator,
4. u denotes an identifier,
5. r denotes a non-const value of type X, and
6. rv denotes a non-const rvalue of type X.

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(a);
X u = a;
Preconditions: T is Cpp17CopyInsertable into X (see below).
Postconditions: u == a
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 constant for all other standard containers.

a = rv
Result: X&.
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.~X()
Result: void
Effects: Destroys every element of a; any memory obtained is deallocated.
Complexity: Linear.

a.begin()
Result: iterator; const_iterator for constant a.
Returns: An iterator referring to the first element in the container.
Complexity: Constant.
a.end()

Result: iterator; const_iterator for constant a.
Returns: An iterator which is the past-the-end value for the container.
Complexity: Constant.

a.cbegin()

Result: const_iterator.
Returns: const_cast<X const&>(a).begin()
Complexity: Constant.

a.cend()

Result: const_iterator.
Returns: const_cast<X const&>(a).end()
Complexity: Constant.

i <=> j

Result: strong_ordering.
Constraints: X::iterator meets the random access iterator requirements.
Complexity: Constant.

a == b

Preconditions: T meets the Cpp17EqualityComparable requirements.
Result: Convertible to bool.
Returns: equal(a.begin(), a.end(), b.begin(), b.end())
[Note 1: The algorithm equal is defined in 27.6.11. — end note]
Complexity: Constant if a.size() != b.size(), linear otherwise.
Remarks: == is an equivalence relation.

a != b

Effects: Equivalent to !(a == b).

a.swap(b)

Result: void
Effects: Exchanges the contents of a and b.
Complexity: Linear for array and constant for all other standard containers.

swap(a, b)

Effects: Equivalent to a.swap(b).

r = a

Result: X&.
Postconditions: r == a.
Complexity: Linear.

a.size()

Result: size_type.
Returns: distance(a.begin(), a.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.
a.max_size()

*Result:* size_type.
*Returns:* distance(begin(), end()) for the largest possible container.
*Complexity:* Constant.

a.empty()

*Result:* Convertible to bool.
*Returns:* a.begin() == a.end()
*Complexity:* Constant.
*Remarks:* If the container is empty, then a.empty() is 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 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 `pointer_traits<>::template rebind<unspecified>`, where \( P \) is `allocator_traits<>::pointer`.
— end note]

Copy constructors for these container types obtain an allocator by calling `allocator_traits<>::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 `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 `swap()`. Allocators are replaced by copy assignment, move assignment, or swapping of the allocator only if

\[ \text{allocator_traits<>::propagate_on_container_copy_assignment::value} \]
\[ \text{allocator_traits<>::propagate_on_container_move_assignment::value} \]
\[ \text{allocator_traits<>::propagate_on_container_swap::value} \]

is true within the implementation of the corresponding container operation. In all container types defined in this Clause, the member `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.

The expression `a.swap(b)`, for containers \( a \) and \( b \) of a standard container type other than `array`, shall exchange the values of \( a \) and \( b \) without invoking any move, copy, or swap operations on the individual container elements. If values of any `Compare`, `Pred`, or `Hash` types belonging to \( a \) and \( b \) shall be swappable 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 values of type `allocator_type` shall be swappable 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.
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.

```cpp
a.rend()
```

Result: `reverse_iterator; const_reverse_iterator` for constant `a`.

Returns: `reverse_iterator(begin())`

Complexity: Constant.

```cpp
a.crbegin()
```

Result: `const_reverse_iterator`.

Returns: `const_cast<X const&>(a).rbegin()`

Complexity: Constant.

```cpp
a.crend()
```

Result: `const_reverse_iterator`.

Returns: `const_cast<X const&>(a).rend()`

Complexity: Constant.

Unless otherwise specified (see 24.2.7.2, 24.2.8.2, 24.3.8.4, and 24.3.11.5) 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 throws an exception.
6. no `swap()` function invalidates any references, pointers, or iterators referring to the elements of the containers being swapped.

[Note 1: 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).

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.

```cpp
a <=> b
```

2. **Result:** `synth-three-way-result<X::value_type>`.  

3. **Preconditions:** Either `<=>` is defined for values of type (possibly const) `T`, or `<` is defined for values of type (possibly const) `T` and `<` is a total ordering relationship.

4. **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]

5. **Complexity:** Linear.

### 24.2.2.5 Allocator-aware containers

1. All of the containers defined in Clause 24 and in 23.4.3 except `array` meet the additional requirements of an `allocator-aware container`, as described below.

2. 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` of type (possibly 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:

   1. **(2.1)** `T` is `Cpp17DefaultInsertable into X` means that the following expression is well-formed:
      ```cpp
      allocator_traits<A>::construct(m, p)
      ```

   2. **(2.2)** An element of `X` is `default-inserted` if it is initialized by evaluation of the expression
      ```cpp
      allocator_traits<A>::construct(m, p)
      ```
      where `p` is the address of the uninitialized storage for the element allocated within `X`.

   3. **(2.3)** `T` is `Cpp17MoveInsertable into X` means that the following expression is well-formed:
      ```cpp
      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]

   4. **(2.4)** `T` is `Cpp17CopyInsertable into X` means that, in addition to `T` being `Cpp17MoveInsertable` into `X`, the following expression is well-formed:
      ```cpp
      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`.

   5. **(2.5)** `T` is `Cpp17EmplaceConstructible into X from args`, for zero or more arguments `args`, means that the following expression is well-formed:
      ```cpp
      allocator_traits<A>::construct(m, p, args)
      ```

   6. **(2.6)** `T` is `Cpp17Erasable from X` means that the following expression is well-formed:
      ```cpp
      allocator_traits<A>::destroy(m, p)
      ```

   [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 `::new((void*)p) T(args)`, but specialized allocators can choose a different definition. — end note]

3. The following exposition-only concept is used in the definition of containers:

   ```cpp
template<class R, class T>
concept container-compatible-range = // exposition only
   ranges::input_range<R> && convertible_to<ranges::range_reference_t<R>, T>;
```

4. In this subclause,

   1. **(4.1)** `X` denotes an allocator-aware container class with a `value_type` of `T` using an allocator of type `A`,
(4.2) u denotes a variable,
(4.3) a and b denote non-const lvalues of type X,
(4.4) c denotes an lvalue of type const X,
(4.5) t denotes an lvalue or a const rvalue of type X,
(4.6) rv denotes a non-const rvalue of type X, and
(4.7) 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

Preconditions: 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: X&.

Preconditions: T is Cpp17CopyInsertable into X and Cpp17CopyAssignable.

Postconditions: a == t is true.

Complexity: Linear.

a = rv

Result: X&.
Preconditions: If allocator_traits<allocator_type>::propagate_on_container_move_assignment::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.

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:

(34.1) — The qualified-id A::value_type is valid and denotes a type (13.10.3).
(34.2) — The expression declval<A&>().allocate(size_t{}) is well-formed when treated as an unevaluated operand.

24.2.3 Container data races

For purposes of avoiding data races (16.4.6.10), implementations shall consider the following functions to be const: 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 four basic kinds of sequence containers: 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 or queues, out of the basic sequence container kinds (or out of other kinds of sequence containers that the user defines).

[Note 1: The sequence containers offer the programmer different complexity trade-offs. vector is appropriate in most circumstances. array has a fixed size known during translation. list or forward_list support frequent insertions and deletions from the middle of the sequence. deque supports efficient insertions and deletions taking place at the beginning or at the end of the sequence. When choosing a container, remember vector is best; leave a comment to explain if you choose from the rest! — end note]

In this subclause,

(3.1) — X denotes a sequence container class,
(3.2) — a denotes a value of type X containing elements of type T,
(3.3) — u denotes the name of a variable being declared,
(3.4) — 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,
(3.5) — i and j denote iterators that meet the Cpp17InputIterator requirements and refer to elements implicitly convertible to value_type,
(3.6) — [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,

q denotes a valid dereferenceable 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 sized_range nor 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 Cpp17EmplaceConstructible into X from args. For vector and deque, T is also Cpp17MoveInsertable into X and Cpp17MoveAssignable.

Effects: Inserts an object of type T constructed with std::forward<Args>(args)… before p.

[Note 2: args can directly or indirectly refer to a value in a. — end note]

Returns: An iterator that points to the new element constructed from args into a.
a.insert(p, t)
   Result: iterator.
   Preconditions: T is Cpp17CopyInsertable into X. For vector and deque, T is also 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 Cpp17MoveInsertable into X. For vector and deque, T is also Cpp17MoveAssignable.
   Effects: Inserts a copy of rv before p.
   Returns: An iterator that points to the copy of rv inserted into a.

a.insert(p, n, t)
   Result: iterator.
   Preconditions: T is Cpp17CopyInsertable into X and Cpp17CopyAssignable.
   Effects: Inserts n copies of t before p.
   Returns: An iterator that points to the copy of the first element inserted into a, or p if n == 0.

a.insert(p, i, j)
   Result: iterator.
   Preconditions: T is Cpp17EmplaceConstructible into X from *i. For vector and deque, T is also Cpp17MoveInsertable into X, Cpp17MoveConstructible, Cpp17MoveAssignable, and swappable (16.4.4.3). Neither i nor j are iterators into a.
   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 i == j.

a.insert_range(p, rg)
   Result: iterator.
   Preconditions: T is Cpp17EmplaceConstructible into X from *ranges::begin(rg). For vector and deque, T is also Cpp17MoveInsertable into X, Cpp17MoveConstructible, Cpp17MoveAssignable, and swappable (16.4.4.3). rg and a do not overlap.
   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 vector and deque, T is Cpp17MoveAssignable.
   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.

a.erase(q1, q2)
   Result: iterator.
   Preconditions: For 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, \( \texttt{a.end()} \) is returned.

\( \texttt{a.clear()} \)

Result: \( \texttt{void} \)

Effects: Destroys all elements in \( \texttt{a} \). Invalidates all references, pointers, and iterators referring to the elements of \( \texttt{a} \) and may invalidate the past-the-end iterator.

Postconditions: \( \texttt{a.empty()} \) is true.

Complexity: Linear.

\( \texttt{a.assign(i, j)} \)

Result: \( \texttt{void} \)

Preconditions: \( \texttt{T} \) is \( \texttt{Cpp17EmplaceConstructible} \) into \( \texttt{X} \) from \( \texttt{*i} \) and assignable from \( \texttt{*i} \). For \texttt{vector}, if the iterator does not meet the forward iterator requirements (25.3.5.5), \( \texttt{T} \) is also \( \texttt{Cpp17MoveInsertable} \) into \( \texttt{X} \). Neither \( \texttt{i} \) nor \( \texttt{j} \) are iterators into \( \texttt{a} \).

Effects: Replaces elements in \( \texttt{a} \) with a copy of \( \texttt{[i, j)} \). Invalidates all references, pointers and iterators referring to the elements of \( \texttt{a} \). For \texttt{vector} and \texttt{deque}, also invalidates the past-the-end iterator. Each iterator in the range \( \texttt{[i, j)} \) is dereferenced exactly once.

\( \texttt{a.assign\_range(rg)} \)

Result: \( \texttt{void} \)

Mandates: \( \texttt{assignable\_from<T&, ranges::range\_reference\_t<R>}> \) is modeled.

Preconditions: \( \texttt{T} \) is \( \texttt{Cpp17EmplaceConstructible} \) into \( \texttt{X} \) from \( \texttt{ranges::begin(rg)} \). For \texttt{vector}, if \( \texttt{R} \) models neither \texttt{sized\_range} nor \texttt{forward\_range}, \( \texttt{T} \) is also \( \texttt{Cpp17MoveInsertable} \) into \( \texttt{X} \). \( \texttt{rg} \) and \( \texttt{a} \) do not overlap.

Effects: Replaces elements in \( \texttt{a} \) with a copy of each element in \( \texttt{rg} \). Invalidates all references, pointers, and iterators referring to the elements of \( \texttt{a} \). For \texttt{vector} and \texttt{deque}, also invalidates the past-the-end iterator. Each iterator in the range \( \texttt{rg} \) is dereferenced exactly once.

\( \texttt{a.assign(il)} \)

Effects: Equivalent to \( \texttt{a.assign(il.begin(), il.end())} \).

\( \texttt{a.assign(n, t)} \)

Result: \( \texttt{void} \)

Preconditions: \( \texttt{T} \) is \( \texttt{Cpp17CopyInsertable} \) into \( \texttt{X} \) and \( \texttt{Cpp17CopyAssignable} \). \( \texttt{t} \) is not a reference into \( \texttt{a} \).

Effects: Replaces elements in \( \texttt{a} \) with \( \texttt{n} \) copies of \( \texttt{t} \). Invalidates all references, pointers and iterators referring to the elements of \( \texttt{a} \). For \texttt{vector} and \texttt{deque}, also invalidates the past-the-end iterator.

For every sequence container defined in this Clause and in Clause 23:

(68.1) — If the constructor

\[
\text{template<class InputIterator>}
\text{X(InputIterator first, InputIterator last,}
\text{ const allocator\_type& alloc = allocator\_type());}
\]

is called with a type \texttt{InputIterator} that does not qualify as an input iterator, then the constructor shall not participate in overload resolution.

(68.2) — If the member functions of the forms:

\[
\text{template<class InputIterator>}
\text{return\_type F(const\_iterator p,}
\text{ InputIterator first, InputIterator last);} \quad \text{// such as insert}
\]

\[
\text{template<class InputIterator>}
\text{return\_type F(InputIterator first, InputIterator last);} \quad \text{// such as append, assign}
\]
are called with a type 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 InputIterator template parameter and a type that does not qualify as an input iterator is deduced for that parameter, or if it has an 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. An implementation shall implement them so as to take amortized constant time.

a.front()

Result: reference; const_reference for constant a.

Returns: *a.begin()

Remarks: Required for basic_string, array, deque, forward_list, list, and vector.

a.back()

Result: reference; const_reference for constant a.

Effects: Equivalent to:
  auto tmp = a.end();
  --tmp;
  return *tmp;

Remarks: Required for basic_string, array, deque, list, and vector.

a.emplace_front(args)

Result: reference

Preconditions: T is Cpp17EmplaceConstructible into X from args.

Effects: Prepends an object of type T constructed with std::forward<Args>(args)....

Returns: a.front().

Remarks: Required for deque, forward_list, and list.

a.emplace_back(args)

Result: reference

Preconditions: T is Cpp17EmplaceConstructible into X from args. For vector, T is also Cpp17MoveInsertable into X.

Effects: Appends an object of type T constructed with std::forward<Args>(args)....

Returns: a.back().

Remarks: Required for deque, list, and vector.

a.push_front(t)

Result: void

Preconditions: T is Cpp17CopyInsertable into X.

Effects: Prepends a copy of t.

Remarks: Required for deque, forward_list, and list.

a.push_front(rv)

Result: void

Preconditions: T is Cpp17MoveInsertable into X.

Effects: Prepends a copy of rv.

Remarks: Required for deque, forward_list, and list.
a.prepend_range(rg)

Result: void

 Preconditions: T is Cpp17EmplaceConstructible into X from *ranges::begin(rg).

 Effects: Inserts copies of elements in rg before begin(). Each iterator in the range rg is dereferenced exactly once.

 [Note 3: The order of elements in rg is not reversed. — end note]

 Remarks: Required for deque, forward_list, and list.

a.push_back(t)

Result: void

 Preconditions: T is Cpp17CopyInsertable into X.

 Effects: Appends a copy of t.

 Remarks: Required for basic_string, deque, list, and vector.

a.push_back(rv)

Result: void

 Preconditions: T is Cpp17MoveInsertable into X.

 Effects: Appends a copy of rv.

 Remarks: Required for basic_string, deque, list, and vector.

a.append_range(rg)

Result: void

 Preconditions: T is Cpp17EmplaceConstructible into X from *ranges::begin(rg). For vector, T is also Cpp17MoveInsertable into X.

 Effects: Inserts copies of elements in rg before end(). Each iterator in the range rg is dereferenced exactly once.

 Remarks: Required for deque, list, and vector.

a.pop_front()

Result: void

 Preconditions: a.empty() is false.

 Effects: Destroys the first element.

 Remarks: Required for deque, forward_list, and list.

a.pop_back()

Result: void

 Preconditions: a.empty() is false.

 Effects: Destroys the last element.

 Remarks: Required for basic_string, deque, list, and vector.

a[n]

Result: reference; const_reference for constant a

 Returns: *(a.begin() + n)

 Remarks: Required for basic_string, array, deque, 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, 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 79.

Table 79: Container types with compatible nodes

<table>
<thead>
<tr>
<th>Container Type 1</th>
<th>Container Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>map&lt;K, T, C1, A&gt;</td>
<td>map&lt;K, T, C2, A&gt;</td>
</tr>
<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_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.

```cpp
template<unspecialized>
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;

    private:
    using container_node_type = unspecified; // exposition only
    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 : ptr_(), alloc_() {}
    node-handle(node-handle&&) noexcept;
    node-handle& operator=(node-handle&&);

    ~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;
};
```
```cpp
// 24.2.5.5, modifiers
void swap(node-handle&)
    noexcept(ator_traits::propagate_on_container_swap::value ||
              ator_traits::is_always_equal::value);

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
    [container.node.cons]
node-handle(node-handle&& nh) noexcept;
1 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);
2 Preconditions: Either !alloc_, or ator_traits::propagate_on_container_move_assignment::value is true, or alloc_ == nh.alloc_.
3 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_.
4 Returns: *this.
5 Throws: Nothing.

24.2.5.3 Destructor
    [container.node.dtor]
~node-handle();
1 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
    [container.node.observers]
value_type& value() const;
1 Preconditions: empty() == false.
2 Returns: A reference to the value_type subobject in the container_node_type object pointed to by
ptr_.
3 Throws: Nothing.

key_type& key() const;
4 Preconditions: empty() == false.
5 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_.
6 Throws: Nothing.
7 Remarks: Modifying the key through the returned reference is permitted.

mapped_type& mapped() const;
8 Preconditions: empty() == false.
9 Returns: A reference to the mapped_type member of the value_type subobject in the container_node_type object pointed to by ptr_.

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```
10. **Throws**: Nothing.

    allocator_type get_allocator() const;

11. **Preconditions**: empty() == false.

12. **Returns**: *alloc_.

13. **Throws**: Nothing.

    explicit operator bool() const noexcept;


    [[nodiscard]] bool empty() const noexcept;

15. **Returns**: ptr_ == nullptr.

24.2.5.5 **Modifiers**

    //container.node.modifiers

    void swap(node-handle nh)
    noexcept(ator_traits::propagate_on_container_swap::value ||
             ator_traits::is_always_equal::value);

1. **Preconditions**: !alloc_, or !nh.alloc_, or ator_traits::propagate_on_container_swap::value is true, or alloc_ == nh.alloc_.

2. **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**

    //container.insert.return

    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;
    };

1. 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**

    //associative.reqmts

24.2.7.1 **General**

1. Associative containers provide fast retrieval of data based on keys. The library provides four basic kinds of associative containers: set, multiset, map and multimap.

2. 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.

3. 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.

4. 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 79),
- `b` denotes a possibly `const` value of type `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 possibly `const` value of type `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 possibly `const` value of type `X::key_compare`;
- `kl` is a value such that `a` is partitioned (27.8) with respect to `c(x, kl)`, 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 (24.2.2.1) 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`.

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[Note 3: For example, in some cases key_type and mapped_type are required 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.

  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 distance(i, j); linear if [i, j) is sorted with value_comp().

    X(i, j)

    Preconditions: key_compare meets the Cpp17DefaultConstructible requirements. value_type is Cpp17EmplaceConstructible into X from *i.

    Effects: Constructs an empty container and inserts elements from the range [i, j) into it; uses Compare() as a comparison object.

    Complexity: N log N in general, where N has the value distance(i, j); linear if [i, j) is sorted with value_comp().

    X(from_range, rg, c)

    Preconditions: value_type is Cpp17EmplaceConstructible into X from *range::begin(rg).

    Effects: Constructs an empty container and inserts each element from rg into it. Uses c as the comparison object.
Complexity: \(N \log N\) in general, where \(N\) has the value \(\text{ranges}\::\text{distance}(\text{rg})\); linear if \(\text{rg}\) is sorted with \(\text{value\_comp}()\).

\(X(\text{from\_range}, \text{rg})\)

\(\text{Preconditions:}\ \text{key\_comp}()\) meets the \text{Cpp17DefaultConstructible} requirements. \(\text{value\_type}\) is \text{Cpp17EmplaceConstructible} into \(X\) from \(\text{ranges}\::\text{begin}(\text{rg})\).

\(\text{Effects:}\) Constructs an empty container and inserts each element from \(\text{rg}\) into it. Uses \(\text{Compare}()\) as the comparison object.

\(\text{Complexity:}\) Same as \(X(\text{from\_range}, \text{rg}, \text{c})\).

\(X(\text{i1}, \text{c})\)

\(\text{Effects:}\) Equivalent to \(X(\text{i1}.\text{begin()}, \text{i1}.\text{end()}, \text{c})\).

\(X(\text{i1})\)

\(\text{Effects:}\) Equivalent to \(X(\text{i1}.\text{begin()}, \text{i1}.\text{end()})\).

\(a = \text{i1}\)

\(\text{Result:}\ \text{i1}\)

\(\text{Preconditions:}\ \text{value\_type}\) is \text{Cpp17CopyInsertable} into \(X\) and \text{Cpp17CopyAssignable}.

\(\text{Effects:}\) Assigns the range \([\text{i1}.\text{begin()}, \text{i1}.\text{end()})\) into \(a\). All existing elements of \(a\) are either assigned to or destroyed.

\(\text{Complexity:}\ \(N \log N\) in general, where \(N\) has the value \(\text{i1}.\text{size()} + a.\text{size()};\) linear if \([\text{i1}.\text{begin()}, \text{i1}.\text{end()})\) is sorted with \(\text{value\_comp}()\).

\(b.\text{key\_comp()}\)

\(\text{Result:}\ \text{X}::\text{key\_comp}\)

\(\text{Returns:}\) The comparison object out of which \(b\) was constructed.

\(\text{Complexity:}\) Constant.

\(b.\text{value\_comp()}\)

\(\text{Result:}\ \text{X}::\text{value\_compare}\)

\(\text{Returns:}\) An object of \text{value\_compare} constructed out of the comparison object.

\(\text{Complexity:}\) Constant.

\(a.\text{uniq}.\text{emplace}(\text{args})\)

\(\text{Result:}\ \text{pair<iterator, bool>}\)

\(\text{Preconditions:}\ \text{value\_type}\) is \text{Cpp17EmplaceConstructible} into \(X\) from \(\text{args}\).

\(\text{Effects:}\) Inserts a \text{value\_type} object \(t\) constructed with \(\text{std}::\text{forward<Args>}(\text{args})\) if and only if there is no element in the container with key equivalent to the key of \(t\).

\(\text{Returns:}\) The \text{bool} component of the returned pair is \text{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 \(t\).

\(\text{Complexity:}\) Logarithmic.

\(a.\text{eq}.\text{emplace}(\text{args})\)

\(\text{Result:}\ \text{iterator}\)

\(\text{Preconditions:}\ \text{value\_type}\) is \text{Cpp17EmplaceConstructible} into \(X\) from \(\text{args}\).

\(\text{Effects:}\) Inserts a \text{value\_type} object \(t\) constructed with \(\text{std}::\text{forward<Args>}(\text{args})\). If a range containing elements equivalent to \(t\) exists in \(a.\text{eq}\), \(t\) is inserted at the end of that range.

\(\text{Returns:}\) An iterator pointing to the newly inserted element.

\(\text{Complexity:}\) Logarithmic.
```plaintext

a.emplace_hint(p, args)

  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 in general, but amortized constant if the element is inserted right before `p`.

a_uniq.insert(t)

  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.

a_eq.insert(t)

  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` and returns the iterator pointing to the newly inserted element. If a range containing elements equivalent to `t` exists in `a_eq`, `t` is inserted at the end of that range.
  Complexity: Logarithmic.

a.insert(p, t)

  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`.

a.insert(i, j)

  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())

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())

a.extract(q)

Result: node_type

Effects: Removes the element pointed to by q.

Returns: A node_type owning that element.
Complexity: Amortized constant.

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().

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: \( \log(a.size()) + a.count(k) \)

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.end().
Complexity: Amortized constant.

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.

a.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.end() is returned.
Complexity: \( \log(a.size()) + N \), where \( N \) has the value distance(q1, q2).

a.clear()
Effects: Equivalent to a.erase(a.begin(), a.end()).
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 the key equivalent to k, or b.end() if such an element is not found.

**Complexity:** Logarithmic.

```cpp
a_tran.find(ke)
```

**Result:** iterator; const_iterator for constant a_tran.

**Returns:** An iterator pointing to an element with key r such that \( !c(r, ke) \&\& !c(ke, r) \) is true, or a_tran.end() if such an element is not found.

**Complexity:** Logarithmic.

```cpp
b.count(k)
```

**Result:** size_type

**Returns:** The number of elements with key equivalent to k.

**Complexity:** \( \log(b.size()) + b.count(k) \)

```cpp
a_tran.count(ke)
```

**Result:** size_type

**Returns:** The number of elements with key r such that \( !c(r, ke) \&\& !c(ke, r) \).

**Complexity:** \( \log(a_tran.size()) + a_tran.count(ke) \)

```cpp
b.contains(k)
```

**Result:** bool

**Effects:** Equivalent to: return b.find(k) != b.end();

```cpp
a_tran.contains(ke)
```

**Result:** bool

**Effects:** Equivalent to: return a_tran.find(ke) != a_tran.end();

```cpp
b.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.end() if such an element is not found.

**Complexity:** Logarithmic.

```cpp
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.

```cpp
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.

```cpp
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:

(181.1) — It has an InputIterator template parameter and a type that does not qualify as an input iterator is deduced for that parameter.

(181.2) — It has an Allocator template parameter and a type that does not qualify as an allocator is deduced for that parameter.

(181.3) — 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

1 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).

2 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.

3 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

24.2.8.1 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 Cpp17Hash 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:

- X denotes an unordered associative container class,
- a denotes a value of type X,
- a2 denotes a value of a type with nodes compatible with type X (Table 79),
- b denotes a possibly const value of type X,
- a_uniq denotes a value of type X when X supports unique keys,
- a_eq denotes a value of type X when X supports equivalent keys,
- a_tran denotes a possibly const value of type X when the qualified-ids X::key_equal::is_transparent and X::hasher::is_transparent are both valid and denote types (13.10.3),
— i and j denote input iterators that refer 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 and q2 denote valid constant iterators to a,
— q and q1 denote valid dereferenceable constant iterators to a,
— r denotes a valid dereferenceable iterator to a,
— [q1, q2) denotes a valid range in a,
— il denotes a value of type initializer_list<value_type>,
— t denotes a value of type X::value_type,
— k denotes a value of type key_type,
— hf denotes a possibly const value of type hasher,
— eq denotes a possibly const value of type key_equal,
— ke is a value such that
  — eq(r1, ke) == eq(ke, r1),
  — hf(r1) == hf(ke) if eq(r1, ke) is true, and
  — (eq(r1, ke) && eq(r1, r2)) == eq(r2, ke),
  where r1 and r2 are keys of elements in a_tran,
— kx is a value such that
  — eq(r1, kx) == eq(kx, r1),
  — hf(r1) == hf(kx) if eq(r1, kx) is true,
  — (eq(r1, kx) && eq(r1, r2)) == eq(r2, kx), and
  — kx is not convertible to either iterator or const_iterator,
  where r1 and r2 are keys of elements in a_tran,
— n denotes a value of type size_type,
— z denotes a value of type float, and
— nh denotes a non-const 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 (24.2.2.1) 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 are sometimes required 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 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.

§ 24.2.8.1
typedef 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: Θ(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: Θ(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: Θ(n)

X a = X();
X a;

Preconditions: hasher and key_equal meet the Cpp17DefaultConstructible requirements.

Effects: Constructs an empty container with an unspecified number of buckets, using hasher() as the hash function and key_equal() as the key equality predicate.

Complexity: Constant.

X(i, j, n, hf, eq)

Preconditions: value_type is 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 Θ(N) (N is distance(i, j)), worst case Θ(N^2).

X(i, j, n, hf)

Preconditions: key_equal meets the Cpp17DefaultConstructible requirements. value_type is Cpp17-EmplaceConstructible 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 \( \Theta(N) \) \((N = \text{distance}(i, j))\), worst case \( \Theta(N^2) \).

\[
X(i, j, n)
\]

Preconditions: \( \text{hasher} \) and \( \text{key\_equal}() \) meet the Cpp17DefaultConstructible requirements. \( \text{value\_type} \) is 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 \( \Theta(N) \) \((N = \text{distance}(i, j))\), worst case \( \Theta(N^2) \).

\[
X(i, j)
\]

Preconditions: \( \text{hasher} \) and \( \text{key\_equal}() \) meet the Cpp17DefaultConstructible requirements. \( \text{value\_type} \) is Cpp17EmplaceConstructible into \( X \) from \( *i \).

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, and inserts elements from \([i, j)\) into it.

Complexity: Average case \( \Theta(N) \) \((N = \text{distance}(i, j))\), worst case \( \Theta(N^2) \).

\[
X(\text{from\_range}, \text{rg}, n, hf, eq)
\]

Preconditions: \( \text{value\_type} \) is Cpp17EmplaceConstructible into \( X \) from \( \text{*ranges::begin(rg)} \).

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 \( \text{rg} \) into it.

Complexity: Average case \( \Theta(N) \) \((N = \text{ranges::distance(rg)})\), worst case \( \Theta(N^2) \).

\[
X(\text{from\_range}, \text{rg}, n, hf)
\]

Preconditions: \( \text{key\_equal}() \) meets the Cpp17DefaultConstructible requirements. \( \text{value\_type} \) is Cpp17EmplaceConstructible into \( X \) from \( \text{*ranges::begin(rg)} \).

Effects: Constructs an empty container with at least \( n \) buckets, using \( hf \) as the hash function and \( \text{key\_equal}() \) as the key equality predicate, and inserts elements from \( \text{rg} \) into it.

Complexity: Average case \( \Theta(N) \) \((N = \text{ranges::distance(rg)})\), worst case \( \Theta(N^2) \).

\[
X(\text{from\_range}, \text{rg})
\]

Preconditions: \( \text{hasher} \) and \( \text{key\_equal}() \) meet the Cpp17DefaultConstructible requirements. \( \text{value\_type} \) is Cpp17EmplaceConstructible into \( X \) from \( \text{*ranges::begin(rg)} \).

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, and inserts elements from \( \text{rg} \) into it.

Complexity: Average case \( \Theta(N) \) \((N = \text{ranges::distance(rg)})\), worst case \( \Theta(N^2) \).

\[
X(\text{il})
\]

Effects: Equivalent to \( X(\text{il}.\text{begin()}, \text{il}.\text{end()}) \).

\[
X(\text{il}, n)
\]

Effects: Equivalent to \( X(\text{il}.\text{begin()}, \text{il}.\text{end()}, n) \).

\[
X(\text{il}, n, hf)
\]

Effects: Equivalent to \( X(\text{il}.\text{begin()}, \text{il}.\text{end()}, n, hf) \).
X(il, n, hf, eq)

Effects: Equivalent to X(il.begin(), il.end(), n, hf, eq).

X(b)

Effects: In addition to the container requirements (24.2.2.1), copies the hash function, predicate, and maximum load factor.

Complexity: Average case linear in b.size(), worst case quadratic.

a = b

Result: 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 = il

Result: X&

Preconditions: value_type 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.

Complexity: Average case linear in il.size(), worst case quadratic.

b.hash_function()

Result: hasher

Returns: b’s hash function.

Complexity: Constant.

b.key_eq()

Result: key_equal

Returns: b’s key equality predicate.

Complexity: Constant.

a_uniq.emplace(args)

Result: pair<iterator, bool>

Preconditions: value_type is Cpp17EmplaceConstructible into X from 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: Average case $O(1)$, worst case $O(a_uniq.size())$.

a_eq.emplace(args)

Result: iterator

Preconditions: value_type is Cpp17EmplaceConstructible into X from args.

Effects: Inserts a value_type object t constructed with std::forward<Args>(args)... and

Returns: An iterator pointing to the newly inserted element.

Complexity: Average case $O(1)$, worst case $O(a_eq.size())$.

a.emplace_hint(p, args)

Result: iterator

Preconditions: value_type is Cpp17EmplaceConstructible into X from args.

Effects: Equivalent to a.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 $\mathcal{O}(1)$, worst case $\mathcal{O}(a.size())$.

```cpp
a_uniq.insert(t)
```

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 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 $\mathcal{O}(1)$, worst case $\mathcal{O}(a.size())$.

```cpp
a_eq.insert(t)
```

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`.

Returns: An iterator pointing to the newly inserted element.

Complexity: Average case $\mathcal{O}(1)$, worst case $\mathcal{O}(a.size())$.

```cpp
a.insert(p, t)
```

Result: `iterator`

Preconditions: If `t` is a non-const rvalue, `value_type` is `Cpp17MoveInsertable` into `X`; otherwise, `value_type` is `Cpp17CopyInsertable` into `X`.

Effects: Equivalent to `a.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 $\mathcal{O}(1)$, worst case $\mathcal{O}(a.size())$.

```cpp
a.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 $\mathcal{O}(N)$, where $N$ is `distance(i, j)`, worst case $\mathcal{O}(N(a.size() + 1))$.

```cpp
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 $\mathcal{O}(N)$, where $N$ is `ranges::distance(rg)`, worst case $\mathcal{O}(N(a.size() + 1))$.

```cpp
a.insert(il)
```

Effects: Equivalent to `a.insert(il.begin(), il.end())`.

```cpp
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 $\Theta(a_{uniq}.size())$.

\hspace{1em} 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 $\Theta(a_{eq}.size())$.

\hspace{1em} 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 $\Theta(a.size())$.

\hspace{1em} 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 $\Theta(a.size())$.

\hspace{1em} 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 $\Theta(a_{tran}.size())$.

\hspace{1em} 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 $\Theta(a.size())$.

\hspace{1em} 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 \( \text{a2} \) refer to those same elements but as members of \( \text{a} \). Iterators referring to the transferred elements and all iterators referring to \( \text{a} \) will be invalidated, but iterators to elements remaining in \( \text{a2} \) will remain valid.

Complexity: Average case \( \Theta(N) \), where \( N \) is \( \text{a2.size()} \), worst case \( \Theta(N\cdot \text{a.size()} + N) \).

\[
a.\text{erase}(k)
\]

Result: size_type

Effects: Erases all elements with key equivalent to \( k \).

Returns: The number of elements erased.

Complexity: Average case \( \Theta(\text{a.count}(k)) \), worst case \( \Theta(\text{a.size()}) \).

\[
a.\text{erase}(\text{q})
\]

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 \( \Theta(\text{a.size()}) \).

\[
a.\text{erase}(r)
\]

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 \( \Theta(\text{a.size()}) \).

\[
a.\text{erase}([q1, q2))
\]

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 \( \text{distance}(q1, q2) \), worst case \( \Theta(\text{a.size()}) \).

\[
a.\text{clear()}
\]

Result: void

Effects: Erases all elements in the container.

Postconditions: \( \text{a.empty()} \) is true.

Complexity: Linear in \( \text{a.size()} \).

\[
b.\text{find}(k)
\]

Result: iterator; const_iterator for const \( b \).

Returns: An iterator pointing to an element with key equivalent to \( k \), or \( \text{b.end()} \) if no such element exists.

Complexity: Average case \( \Theta(1) \), worst case \( \Theta(\text{b.size()}) \).

\[
a.\text{tran}.\text{find}(\text{ke})
\]

Result: iterator; const_iterator for const \( a.\text{tran} \).

Returns: An iterator pointing to an element with key equivalent to \( \text{ke} \), or \( a.\text{tran}.\text{end()} \) if no such element exists.
Complexity: Average case $O(1)$, worst case $O(a_{\text{tran}}.\text{size()}$).

\texttt{b.count(k)}

\textbf{Result}: \texttt{size_type}

\textbf{Returns}: The number of elements with key equivalent to \texttt{k}.

\textbf{Complexity}: Average case $O(b.\text{count(k)}$, worst case $O(b.\text{size()}$).

\texttt{a_{\text{tran}}.\text{count(ke)}}

\textbf{Result}: \texttt{size_type}

\textbf{Returns}: The number of elements with key equivalent to \texttt{ke}.

\textbf{Complexity}: Average case $O(a_{\text{tran}}.\text{count(ke)}$, worst case $O(a_{\text{tran}}.\text{size()}$).

\texttt{b.contains(k)}

\textbf{Effects}: Equivalent to \texttt{b.find(k) != b.end()}.

\texttt{a_{\text{tran}}.\text{contains(ke)}}

\textbf{Effects}: Equivalent to \texttt{a_{\text{tran}}.find(ke) != a_{\text{tran}}.end()}.

\texttt{b.equal_range(k)}

\textbf{Result}: \texttt{pair<iterator, iterator>; pair<const_iterator, const_iterator> for const b.}

\textbf{Returns}: A range containing all elements with keys equivalent to \texttt{k}. Returns \texttt{make_pair(b.end(), b.end())} if no such elements exist.

\textbf{Complexity}: Average case $O(b.\text{count(k)}$, worst case $O(b.\text{size()}$).

\texttt{a_{\text{tran}}.\text{equal_range(ke)}}

\textbf{Result}: \texttt{pair<iterator, iterator>; pair<const_iterator, const_iterator> for const a_{\text{tran}}.}

\textbf{Returns}: A range containing all elements with keys equivalent to \texttt{ke}. Returns \texttt{make_pair(a_{\text{tran}}.end(), a_{\text{tran}}.end())} if no such elements exist.

\textbf{Complexity}: Average case $O(a_{\text{tran}}.\text{count(ke)}$, worst case $O(a_{\text{tran}}.\text{size()}$).

\texttt{b.bucket_count()}

\textbf{Returns}: The number of buckets that \texttt{b} contains.

\textbf{Complexity}: Constant.

\texttt{b.max_bucket_count()}

\textbf{Returns}: An upper bound on the number of buckets that \texttt{b} can ever contain.

\textbf{Complexity}: Constant.

\texttt{b.bucket(k)}

\textbf{Result}: \texttt{size_type}

\textbf{Preconditions}: \texttt{b.bucket_count()} > 0.

\textbf{Returns}: The index of the bucket in which elements with keys equivalent to \texttt{k} would be found, if any such element existed. The return value is in the range $[0, b.\text{bucket_count()}$).

\textbf{Complexity}: Constant.

\texttt{b.bucket_size(n)}

\textbf{Result}: \texttt{size_type}

\textbf{Preconditions}: \texttt{n} shall be in the range $[0, b.\text{bucket_count()}$).

\textbf{Returns}: The number of elements in the \texttt{n}th bucket.

\textbf{Complexity}: $O(b.\text{bucket_size(n)}$)

\section{24.2.8.1}
b.begin(n)

Result: local_iterator; const_local_iterator for const b.

Preconditions: n is in the range \([0, \text{b.bucket_count()}]\).

Returns: An iterator referring to the first element in the bucket. If the bucket is empty, then \(b\begin{b}(n) == b\end{b}(n)\).

Complexity: Constant.

b.end(n)

Result: local_iterator; const_local_iterator for const b.

Preconditions: n is in the range \([0, \text{b.bucket_count()}]\).

Returns: An iterator which is the past-the-end value for the bucket.

Complexity: Constant.

b.cbegin(n)

Result: const_local_iterator

Preconditions: n shall be in the range \([0, \text{b.bucket_count()}]\).

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.cend(n)

Result: const_local_iterator

Preconditions: n is in the range \([0, \text{b.bucket_count()}]\).

Returns: An iterator which is the past-the-end value for the bucket.

Complexity: Constant.

b.load_factor()

Result: float

Returns: The average number of elements per bucket.

Complexity: Constant.

b.max_load_factor()

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.

a.max_load_factor(z)

Result: void

Preconditions: z is positive. May change the container’s maximum load factor, using z as a hint.

Complexity: Constant.

a.rehash(n)

Result: void

Postconditions: a.bucket_count() >= a.size() / a.max_load_factor() and a.bucket_count() >= n.

Complexity: Average case linear in a.size(), worst case quadratic.

a.reserve(n)

Effects: Equivalent to a.rehash(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 \([Ea1, Ea2] \) obtained from \( a.equal_range(Ea1) \), there exists an equivalent-key group \([Eb1, Eb2] \) obtained from \( b.equal_range(Ea1) \), such that \( \text{is_permutation}(Ea1, Ea2, Eb1, Eb2) \) returns \( \text{true} \). 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 \( N \) is \( a.size() \). 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 \( N \) is \( a.size() \), 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 \( E_a \) and \( E_b \) 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 \texttt{Key} is a refinement\(^{214} \) 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 \( (N+n) <= z \ast B \), 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.

The \texttt{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 \texttt{node_type} is undefined behavior. References and pointers to an element obtained while it is owned by a \texttt{node_type} are invalidated if the element is successfully inserted.

The member function templates \texttt{find}, \texttt{count}, \texttt{equal_range}, \texttt{contains}, \texttt{extract}, and \texttt{erase} shall not participate in overload resolution unless the \texttt{qualified-ids} \texttt{Pred::is_transparent} and \texttt{Hash::is_transparent} are both valid and denote types \((13.10.3)\). Additionally, the member function templates \texttt{extract} and \texttt{erase} shall not participate in overload resolution if \texttt{is_convertible_v<K&&, iterator>} \( \| \) \texttt{is_convertible_v<K&&, const_iterator>} is \( \text{true} \), where \( K \) is the type substituted as the first template argument.

A deduction guide for an unordered associative container shall not participate in overload resolution if any of the following are true:

\begin{itemize}
\item It has an \texttt{InputIterator} template parameter and a type that does not qualify as an input iterator is deduced for that parameter.
\item It has an \texttt{Allocator} template parameter and a type that does not qualify as an allocator is deduced for that parameter.
\item It has a \texttt{Hash} template parameter and an integral type or a type that qualifies as an allocator is deduced for that parameter.
\item It has a \texttt{Pred} template parameter and a type that qualifies as an allocator is deduced for that parameter.
\end{itemize}

\subsection*{24.2.8.2 Exception safety guarantees}

For unordered associative containers, no \texttt{clear()} function throws an exception. \texttt{erase(k)} does not throw an exception unless that exception is thrown by the container’s \texttt{Hash} or \texttt{Pred} object (if any).

For unordered associative containers, if an exception is thrown by any operation other than the container’s hash function from within an \texttt{insert} or \texttt{emplace} function inserting a single element, the insertion has no effect.

For unordered associative containers, no \texttt{swap} function throws an exception unless that exception is thrown by the swap of the container’s \texttt{Hash} or \texttt{Pred} object (if any).

\footnote{Equality comparison is a refinement of partitioning if no two objects that compare equal fall into different partitions.}
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

#### 24.3.1 In general

The headers `<array>` (24.3.2), `<deque>` (24.3.3), `<forward_list>` (24.3.4), `<list>` (24.3.5), and `<vector>` (24.3.6) define class templates that meet the requirements for sequence containers.

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

```cpp
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 24.3.7, class template array
    template<class T, size_t N> struct array;
    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);

    // 24.3.7.4, specialized algorithms
    template<class T, size_t N>
    constexpr void swap(array<T, N>& x, array<T, N>& y) noexcept(noexcept(x.swap(y)));

    // 24.3.7.6, array creation functions
    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]);

    // 24.3.7.7, tuple interface
    template<class T> struct tuple_size;
    template<size_t I, class T> struct tuple_element;
    template<class T, size_t N>
    struct tuple_size<array<T, N>>;
    template<size_t I, class T, size_t N>
    struct 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;
    template<size_t I, class T, size_t N>
    constexpr const T& get(const array<T, N>&) noexcept;
    template<size_t I, class T, size_t N>
    constexpr const T&& get(const array<T, N>&&) noexcept;
}
```

### 24.3.3 Header `<deque>` synopsis

```cpp
#include <compare> // see 17.11.1
#include <initializer_list> // see 17.10.2

namespace std {
    // 24.3.8, class template deque
    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>
type_name deque<T, Allocator>::size_type
erase(deque<T, Allocator>&& c, const U& value);

template<class T, class Allocator, class Predicate>
type_name deque<T, Allocator>::size_type
erase_if(deque<T, Allocator>& c, Predicate pred);

namespace pmr {
  template<class T>
    using deque = std::deque<T, polymorphic_allocator<T>>;
}

24.3.4 Header <forward_list> synopsis
[forward.list.syn]
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
  // 24.3.9, 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, class U>
  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
[list.syn]
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
  // 24.3.10, class template list
  template<class T, class Allocator = allocator<T>> class list;

§ 24.3.5
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)));  

template<class T, class Allocator, class U>  
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

namespace std {  
    // 24.3.11, 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)));  
    
    template<class T, class Allocator, class U>  
    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);  
    
    // 24.3.12, class vector<bool>  
    template<class Allocator> class vector<bool, Allocator>;  
    
    // hash support  
    template<class T> struct hash;  
    template<class Allocator> struct hash<vector<bool, Allocator>>;  
    
    namespace pmr {  
        template<class T>  
        using vector = std::vector<T, polymorphic_allocator<T>>;  
    }  
}
24.3.7 Class template array

24.3.7.1 Overview

The header `<array>` defines a class template for storing fixed-size sequences of objects. An `array` is a contiguous container (24.2.2.1). An instance of `array<T, N>` stores `N` elements of type `T`, so that `size()` == `N` is an invariant.

An `array` is an aggregate (9.4.2) that can be list-initialized with up to `N` elements whose types are convertible to `T`.

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.

`array<T, N>` is a template type (13.2) if `T` is a template argument. 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.

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;
    }
}
```
24.3.7.2 Constructors, copy, and assignment

1 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 Cpp17MoveConstructible or Cpp17MoveAssignable, respectively.

24.3.7.3 Member functions

constexpr size_type size() const noexcept;  

1 Returns: \( N \).

constexpr T* data() noexcept;  
constexpr const T* data() const noexcept;  

2 Returns: A pointer such that \([\text{data()}, \text{data() + size()}]\) is a valid range. For a non-empty array, \( \text{data()} == \text{addressof(front())} \).

constexpr void fill(const T& u);  

3 Effects: As if by \( \text{fill_n(begin(), N, u)} \).

constexpr void swap(array& y) noexcept(noexcept(x.swap(y)));  

4 Effects: Equivalent to \( \text{swap_ranges(begin(), end(), y.begin())} \).

5 [Note 1: Unlike the swap function for other containers, array::swap takes linear time, can exit via an exception, and does not cause iterators to become associated with the other container. — end note]

24.3.7.4 Specialized algorithms

template<class T, size_t N>
constexpr void swap(array<T, N>& x, array<T, N>& y) noexcept(noexcept(x.swap(y)));  

1 Constraints: \( N == 0 \) or \( \text{is_swappable_v<T> is true} \).

2 Effects: As if by \( \text{x.swap(y)} \).

3 Complexity: Linear in \( N \).

24.3.7.5 Zero-sized arrays

array shall provide support for the special case \( N == 0 \).

1 In the case that \( N == 0 \), \( \text{begin()} == \text{end()} == \text{unique value} \). The return value of \( \text{data()} \) is unspecified.

2 The effect of calling \( \text{front()} \) or \( \text{back()} \) for a zero-sized array is undefined.

3 Member function \( \text{swap()} \) shall have a non-throwing exception specification.
24.3.7.6 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]) }`.

24.3.7.7 Tuple interface

```cpp
template<class T, size_t N>
struct tuple_size<array<T, N>> : integral_constant<size_t, N> { };`
```

1. **Mandates:** `I < N` is true.
2. **Returns:** A reference to the `I`th element of `a`, where indexing is zero-based.

24.3.8 Class template `deque`

24.3.8.1 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.

2 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 {
        // 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
    public:
    //
```
using iterating = 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>;

// 24.3.8.2, construct/copy/destroy
deque() : deque(Allocator()) { }
explicit deque(const Allocator&);
explicit deque(size_type n, const Allocator& = Allocator());
deque(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(const_reverse_iterator x);
deque(const & , 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(algorithm_traits<Allocator>::is_always_equal::value);
deque& 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;

// 24.3.8.3, 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();

§ 24.3.8.1
const_reference back() const;

// 24.3.8.4, 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);
void clear() noexcept;

template<class InputIterator, class Allocator = allocator<iter_value_type<InputIterator>>>
  deque(InputIterator, InputIterator, Allocator = Allocator())
  -> deque<iter_value_type<InputIterator>, Allocator>;

template<ranges::input_range R, class Allocator = allocator<ranges::range_value_t<R>>>
  deque(from_range_t, R&&, Allocator = Allocator())
  -> deque<ranges::range_value_t<R>, Allocator>;

24.3.8.2 Constructors, copy, and assignment

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 [first, last), using the specified allocator.

Complexity: Linear in distance(first, 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 rg, using the specified allocator.

Complexity: Linear in ranges::distance(rg).

24.3.8.3 Capacity

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.

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.

void shrink_to_fit();

Preconditions: T is Cpp17MoveInsertable into *this.

Effects: 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.

24.3.8.4 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 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.

2 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.

3 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();

4 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]

5 Throws: Nothing unless an exception is thrown by the assignment operator of T.

6 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.

24.3.8.5 Erasure
[deque.earasure]
template<class T, class Allocator, class U>
type erase(deque<T, Allocator>& 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;

template<class T, class Allocator, class Predicate>
type erase_if(deque<T, Allocator>& 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());
    return r;

24.3.9 Class template forward_list
[forward.list]
24.3.9.1 Overview
[forward.list.overview]
1 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]

2 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.

3 [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

            // 24.3.9.2, 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;
            operator=(allocator_traits<Allocator>::is_always_equal::value);
            forward_list& operator=(initialize_list<T>());
            template<class InputIterator>
            void assign(InputIterator first, InputIterator last);
            template<container-compatible-range<T> R>
            void assign(R&& rg);
            void assign(size_type n, const T& t);
            void assign(initializer_list<T>);

            allocator_type get_allocator() const noexcept;

            // 24.3.9.3, 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;
            const_iterator cbegin() const noexcept;
            const_iterator cbegin() const noexcept;
            const_iterator cend() const noexcept;
        }
    }
}
// capacity
[[nodiscard]] bool empty() const noexcept;
size_type max_size() const noexcept;

// 24.3.9.4, element access
reference front();
const_reference front() const;

// 24.3.9.5, 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);
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(allocator_traits<Allocator>::is_always_equal::value);
void resize(size_type sz);
void resize(size_type sz, const value_type& c);
void clear() noexcept;

// 24.3.9.6, 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, T&& x, const_iterator i);
void splice_after(const_iterator position, forward_list& x, const_iterator first, const_iterator last);
void splice_after(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 cmp);
template<class Compare> void merge(forward_list&& x, Compare cmp);

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.

### 24.3.9.2 Constructors, copy, and assignment

#### [forward.list.cons]

```cpp
explicit forward_list(const Allocator&);
1 Effects: Constructs an empty `forward_list` object using the specified allocator.
2 Complexity: Constant.

explicit forward_list(size_type n, const Allocator& = Allocator());
3 Preconditions: \( T \) is `Cpp17DefaultInsertable` into `*this`.
4 Effects: Constructs a `forward_list` object with \( n \) default-inserted elements using the specified allocator.
5 Complexity: Linear in \( n \).

forward_list(size_type n, const T& value, const Allocator& = Allocator());
6 Preconditions: \( T \) is `Cpp17CopyInsertable` into `*this`.
7 Effects: Constructs a `forward_list` object with \( n \) copies of `value` using the specified allocator.
8 Complexity: Linear in \( n \).

template<class InputIterator>
forward_list(InputIterator first, InputIterator last, const Allocator& = Allocator());
9 Effects: Constructs a `forward_list` object equal to the range `[first, last)`.
10 Complexity: Linear in distance(first, last).

template<container-compatible-range<R> R> forward_list(from_range_t, R&& rg, const Allocator& = Allocator());
11 Effects: Constructs a `forward_list` object with the elements of the range `rg`.
12 Complexity: Linear in ranges::distance(rg).
```

### 24.3.9.3 Iterators

#### [forward.list.iter]

```cpp
iterator before_begin() noexcept;
1 const_iterator before_begin() const noexcept;
const_iterator cbefore_begin() const noexcept;
1 Effects: `cbefore_begin()` is equivalent to `const_cast<forward_list const&>(*this).before_begin()`.
2 Returns: A non-dereferenceable iterator that, when incremented, is equal to the iterator returned by `begin()`.
3 Remarks: `before_begin() == end()` shall equal `false`.
```

### 24.3.9.4 Element access

#### [forward.list.access]

```cpp
reference front();
1 const_reference front() const;
1 Returns: *begin()
```

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24.3.9.5 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`.

```cpp
template<class... Args> reference emplace_front(Args&&... args);
```

**Effects:** Inserts an object of type `value_type` constructed with `value_type(std::forward<Args>(args))...` at the beginning of the list.

```cpp
void push_front(const T& x);
void push_front(T&& x);
```

**Effects:** Inserts a copy of `x` at the beginning of the list.

```cpp
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.

```cpp
[Note 1: The order of elements is not reversed. —end note]
```

```cpp
void pop_front();
```

**Effects:** As if by `erase_after(before_begin())`.

```cpp
iterator insert_after(const_iterator position, const T& x);
iterator insert_after(const_iterator position, T&& x);
```

**Preconditions:** `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`.

```cpp
iterator insert_after(const_iterator position, size_type n, const T& x);
```

**Preconditions:** `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`.

```cpp
template<class InputIterator>
iterator insert_after(const_iterator position, InputIterator first, InputIterator last);
```

**Preconditions:** `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`.

```cpp
template<container-compatible-range<T> R>
iterator insert_range_after(const_iterator position, R&& rg);
```

**Preconditions:** `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`.

**Returns:** An iterator pointing to the last inserted element, or `position` if `rg` is empty.

```cpp
iterator insert_after(const_iterator position, initializer_list<T> il);
```

**Effects:** `insert_after(p, il.begin(), il.end())`.

**Returns:** An iterator pointing to the last inserted element or `position` if `il` is empty.
template<class... Args>
iterator emplace_after(const_iterator position, Args&&... args);

Preconditions: position is before_begin() or is a dereferenceable iterator in the range [begin(), end()).
Effects: Inserts an object of type value_type constructed with value_type(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.

24.3.9.6 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 position, and x becomes empty. 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.
Throws: Nothing.
Complexity: \(O(\text{distance}(x\text{.begin()}, x\text{.end()}))\)

```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:** position is before\_begin() or is a dereferenceable iterator in the range [begin(), end()). The iterator following i is a dereferenceable iterator in x. get\_allocator() == x.get\_-allocator() is true.

**Effects:** Inserts the element following i into \*this, following position, and removes it from x. The result is unchanged if position == i or position == ++i. Pointers and references to +++i continue to refer to the same element but as a member of \*this. Iterators to +++i continue to refer to the same element, but now behave as iterators into \*this, not into x.

**Throws:** Nothing.

**Complexity:** \(O(1)\)

```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:** position is before\_begin() or is a dereferenceable iterator in the range [begin(), end()). (first, last) is a valid range in x, and all iterators in the range (first, last) are dereferenceable. position is not an iterator in the range (first, last). get\_allocator() == x.get\_-allocator() is true.

**Effects:** Inserts elements in the range (first, last) after 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 \*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:** \(O(\text{distance(first, last)})\)

```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()), 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 distance(begin(), 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 binary\_pred be equal\_to<>{} for the first overload.

**Preconditions:** 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 [begin() + 1, end()) for which binary\_pred(*i, *(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.

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).

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.

24.3.9.7 Erasure [forward.list erasure]

template<class T, class Allocator, class U>
    typename forward_list<T, Allocator>::size_type
    erase(forward_list<T, Allocator>& c, const U& value);

Effects: Equivalent to: return erase_if(c, [\&](auto& elem) { return elem == value; });

template<class T, class Allocator, class Predicate>
    typename forward_list<T, Allocator>::size_type
    erase_if(forward_list<T, Allocator>& c, Predicate pred);

Effects: Equivalent to: return c.remove_if(pred);

24.3.10 Class template list [list]

24.3.10.1 Overview [list 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 (24.3.11) and deques (24.3.8), 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.

215 These member functions are only provided by containers whose iterators are random access iterators.
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>;

    // 24.3.10.2, construct/copy/destroy
    list() : list(Allocator()) {};
    explicit list(const Allocator&);
    explicit list(size_type n, const Allocator& = Allocator());
    template<class InputIterator>
    list(InputIterator first, InputIterator last, const Allocator& = Allocator());
    template<container-compatible-range<R> 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) 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<R> 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;

    // 24.3.10.3, capacity
    [[nodiscard]] bool empty() const noexcept;
    size_type size() const noexcept;
    size_type max_size() const noexcept;

§ 24.3.10.1
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;

// 24.3.10.4, 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<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<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<container-compatible-range<T> R>
  iterator insert_range(const_iterator position, R&& rg);
iterator insert_range(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;

// 24.3.10.5, 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);

void reverse() noexcept;

};
template<class InputIterator, class Allocator = allocator<iter-value-type<InputIterator>>>  
list<InputIterator, InputIterator, Allocator = Allocator>();

template<ranges::input_range R, class Allocator = allocator<ranges::range_value_t<R>>>  
list(from_range_t, R&&, Allocator = Allocator());

}  

An incomplete type \( T \) may be used when instantiating \( \text{list} \) 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 \( \text{list} \) is referenced.

### 24.3.10.2 Constructors, copy, and assignment [list.cons]

**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 \( \text{Cpp17DefaultInsertable} \) 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 \( \text{Cpp17CopyInsertable} \) into *this.

Effects: Constructs a list with \( n \) copies of \( value \), using the specified allocator.

Complexity: Linear in \( n \).

**template<class InputIterator>**

list(InputIterator first, InputIterator last, const Allocator& = Allocator());

Effects: Constructs a list equal to the range \([\text{first}, \text{last})\].

Complexity: Linear in \( \text{distance} \)(first, last).

**template<container-compatible-range<T> R>**

list(from_range_t, R&& rg, const Allocator& = Allocator());

Effects: Constructs a list object with the elements of the range \( rg \).

Complexity: Linear in \( \text{ranges::distance} \)(rg).

### 24.3.10.3 Capacity [list.capacity]

**void resize(size_type sz);**

Preconditions: \( T \) is \( \text{Cpp17DefaultInsertable} \) into *this.

Effects: If \( \text{size()} < sz \), appends \( sz - \text{size()} \) default-inserted elements to the sequence. If \( sz \leq \text{size()} \), equivalent to:

\[
\text{list<T>::iterator it} = \text{begin()};  
\text{advance(it, sz);}  
\text{erase(it, end());}
\]

void resize(size_type sz, const T& c);

Preconditions: \( T \) is \( \text{Cpp17CopyInsertable} \) into *this.

Effects: As if by:

\[
\text{if}(sz > \text{size()}) \quad \text{insert(end(), sz-size(), c);}  
\text{else if}(sz < \text{size()}) \quad \text{iterator i} = \text{begin()};  
\text{advance(i, sz);}  
\]

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erase(i, end());

24.3.10.4 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.

4 Throws: Nothing.

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.

24.3.10.5 Operations

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.

1

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);

§ 24.3.10.5
void splice(const_iterator position, list&& x);

Preconditions: addressof(x) != this is true.

Effects: Inserts the contents of x before position and x becomes empty. 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.

Throws: Nothing.

Complexity: Constant time.

void splice(const_iterator position, list& x, const_iterator i);
void splice(const_iterator position, list&& x, const_iterator i);

Preconditions: i is a valid dereferenceable iterator of x.

Effects: Inserts an element pointed to by i from list x before position and removes the element from x. The result is unchanged if position == i or position == ++i. Pointers and references to *i continue to refer to this same element but as a member of *this. Iterators to *i (including i itself) continue to refer to the same element, but now behave as iterators into *this, not into x.

Throws: Nothing.

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);

Preconditions: [first, last) is a valid range in x. position is not an iterator in the range [first, last).

Effects: Inserts elements in the range [first, last) before position and removes the elements from x. Pointers and references to the moved elements of x now refer to those same elements as 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.

Throws: Nothing.

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);

Effects: Erases all the elements in the list referred to by a list iterator i for which the following conditions hold: *i == value, pred(*i) != false. Invalidates only the iterators and references to the erased elements.

Returns: The number of elements erased.

Throws: Nothing unless an exception is thrown by *i == value or pred(*i) != false.

Complexity: Exactly size() applications of the corresponding predicate.

Remarks: Stable (16.4.6.8).

size_type unique();
template<class BinaryPredicate> size_type unique(BinaryPredicate binary_pred);

Let binary_pred be equal_to<>{} for the first overload.

Preconditions: 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 [begin() + 1, end()) for which binary_pred(*i, *(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.
25  Complexity: If empty() is false, exactly size() - 1 applications of the corresponding predicate, otherwise no applications of the predicate.

26  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);

27  Let comp be less<> for the first two overloads.

28  Preconditions: *this and x are both sorted with respect to the comparator comp, and get_allocator() == x.get_allocator() is true.

29  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.

30  Complexity: At most size() + x.size() - 1 comparisons if addressof(x) != this; otherwise, no comparisons are performed.

31  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.

32  void reverse() noexcept;

33  Effects: Reverses the order of the elements in the list. Does not affect the validity of iterators and references.

34  Complexity: Linear time.

35  void sort();
template<class Compare> void sort(Compare comp);

36  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.

37  Complexity: Approximately N log N comparisons, where N == size().

38  Remarks: Stable (16.4.6.8).

24.3.10.6 Erasure  [list.erasure]

39  template<class T, class Allocator, class U>
typename list<T, Allocator>::size_type
erase(list<T, Allocator>& c, const U& value);

40  Effects: Equivalent to: return erase_if(c, [&] (auto& elem) { return elem == value; });

41  template<class T, class Allocator, class Predicate>
typename list<T, Allocator>::size_type
erase_if(list<T, Allocator>& c, Predicate pred);

42  Effects: Equivalent to: return c.remove_if(pred);

24.3.11 Class template vector  [vector]

24.3.11.1 Overview  [vector.overview]

1  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.

2  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 (24.2.2.1). 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 \texttt{iterator} and \texttt{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>;
        // 24.3.11.2, 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;
    }
```
// 24.3.11.3, capacity
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 reference at(size_type n);
constexpr const_reference at(size_type n) const;
constexpr reference front();
constexpr const_reference front() const;
constexpr reference back();
constexpr const_reference back() const;

// 24.3.11.4, data access
constexpr T* data() noexcept;
constexpr const T* data() const noexcept;

// 24.3.11.5, modifiers
template<class... Args> constexpr reference emplace_back(Args&&... args);
constexpr void push_back(const T& x);
constexpr void push_back(T&& x);

// 24.3.11.6, input

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.
24.3.11.2 Constructors

constexpr explicit vector(const Allocator&) noexcept;

Effects: Constructs an empty vector, using the specified allocator.
Complexity: Constant.

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.

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.

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.

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 ranges::distance(rg). Performs no reallocations if R models ranges::forward_range or ranges::sized_range; otherwise, performs order log N reallocations and order N calls to the copy or move constructor of T.

24.3.11.3 Capacity

constexpr size_type capacity() const noexcept;

Returns: The total number of elements that the vector can hold without requiring reallocation.
Complexity: Constant time.

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().\(^{217}\)

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]

\(^{217}\) 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.

### 24.3.11.4 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()).

**Complexity:** Constant time.

### 24.3.11.5 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.

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 in the vector after the erased elements.

24.3.11.6 Erasure

template<class T, class Allocator, class U>
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;

24.3.12 Class vector<bool>

To optimize space allocation, a specialization of vector for bool elements is provided:

namespace std {
    template<class Allocator>
    class vector<bool, Allocator> {
public:
// types
    using value_type = bool;
    using allocator_type = Allocator;
    using pointer = implementation-defined;
    using const_pointer = implementation-defined;
    using const_reference = bool;
    using size_type = implementation-defined; // see 24.2
    using difference_type = implementation-defined; // see 24.2
    using iterator = implementation-defined; // see 24.2
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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() : vector(Allocator()) {}
constexpr explicit vector(const Allocator&);
constexpr explicit vector(size_type n, const Allocator& = Allocator());
constexpr vector(size_type n, const bool& 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);
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);
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<bool> 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<bool> 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&);
constexpr static 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 (20.2.8.3) 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<bool>. 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.

constexpr static 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>>;

7 The specialization is enabled (22.10.19).
24.4 Associative containers

24.4.1 In general

1 The header `<map>` defines the class templates map and multimap; the header `<set>` defines the class templates set and multiset.

2 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<typename iterator_traits<InputIterator>::value_type::first_type>; // exposition only

template<class InputIterator>
using iter-mapped-type = typename iterator_traits<InputIterator>::value_type::second_type; // exposition only

template<class InputIterator>
using iter-to-alloc-type = pair<
    add_const_t<typename iterator_traits<InputIterator>::value_type::first_type>,
    typename iterator_traits<InputIterator>::value_type::second_type>; // 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>,
    typename 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); // 24.4.4.2

    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); // 24.4.4.2

    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)));

    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); // 24.4.4.2

    // 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>*>(
        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)));

namespace pmr {
    template<class Key, class T, class Compare = less<Key>>
        using map = std::map<Key, T, Compare,
                               polymorphic_allocator<pair<const Key, T>>>
    template<class Key, class T, class Compare = less<Key>>
        using multimap = std::multimap<Key, T, Compare,
                                       polymorphic_allocator<pair<const Key, T>>>;
}

24.4.3 Header `<set>` synopsis

```cpp
#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)));
    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);

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```
template<class Key, class Compare, class Allocator>
void swap(multiset<Key, Compare, Allocator>& x,
          multiset<Key, Compare, Allocator>& y)
    noexcept(noexcept(x.swap(y)));

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 (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);
                    }
                }
            } // map
        } // std
} // ISO
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 Compare& comp, const Allocator& = Allocator());

map(const map& x);
map(map&& x);
map(const Allocator&);
map(const Allocator&);
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 P> pair<iterator, bool> 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&&);
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... 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 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);

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
directory_compare key_comp() const;
directory_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<typename InputIterator::key_type>,
class Allocator = allocator<typename InputIterator::mapped_type>>
map(InputIterator, InputIterator, Compare = Compare(), Allocator = Allocator())
-> map<typename InputIterator::key_type, typename InputIterator::mapped_type, Compare, Allocator>;

template<
ranges::input_range R, class Compare = less<typename R::key_type>,
class Allocator = allocator<typename R::mapped_type>>
map(from_range_t, R&&, Compare = Compare(), Allocator = Allocator())
-> map<typename R::key_type, typename R::mapped_type, 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<typename InputIterator::key_type, typename InputIterator::mapped_type, less<typename InputIterator::key_type>, Allocator>;

template<
ranges::input_range R, class Allocator>
map(from_range_t, R&&, Allocator)
-> map<typename R::key_type, typename R::mapped_type, less<typename R::key_type>, Allocator>;

template<class Key, class T, class Allocator>
map(initializer_list<pair<Key, T>>, Allocator) -> map<Key, T, less<Key>, Allocator>;

24.4.4.2 Constructors, copy, and assignment

explicit map(const Compare& comp, const Allocator& = Allocator());

Effects: Constructs an empty map using the specified comparison object and allocator.

Complexity: Constant.
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 using comp and otherwise $N \log N$, where $N$ is last - first.

template<container-compatible-range<value_type> 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 using comp and otherwise $N \log N$, where $N$ is ranges::distance(rg).

### 24.4.4.3 Element 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(move(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.

### 24.4.4.4 Modifiers

```
template<class P>
pair<iterator, bool> insert(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)).

```
template<class... Args>
pair<iterator, bool> try_emplace(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.

```
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(std::move(k)), forward_as_tuple(std::forward<Args>(args)...).

**Effects:** The same as emplace and emplace_hint, respectively.
Effects: If the map already contains an element whose key is equivalent to \( k \), there is no effect. Otherwise inserts an object of type \( \text{value	extunderscore type} \) constructed with \( \text{piecewise	extunderscore construct, forward	extunderscore as	extunderscore tuple} (\text{std}::\text{move}(k)), \text{forward	extunderscore as	extunderscore tuple} (\text{std}::\text{forward}\langle \text{Args} \rangle (\text{args})...) \).

Returns: In the first overload, the \( \text{bool} \) component of the returned pair is \text{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 \text{emplace} and \text{emplace	extunderscore hint}, respectively.

\template{\text{class M}}
\pair{\text{iterator, bool}} \text{insert	extunderscore or	extunderscore assign}(\text{const key	extunderscore type} & k, M &\& obj);
\template{\text{class M}}
\iter\\tor\text{insert	extunderscore or	extunderscore assign}(\text{const\_iterator hint, const key	extunderscore type} & k, M &\& obj);

\text{Mandates:} is\_assignable	extunderscore v<\text{mapped	extunderscore type}, M &\&> is \text{true}.

Preconditions: \text{value	extunderscore type} is \text{Cpp17EmplaceConstructible} into \text{map} from \( k, \text{forward}<M>(\text{obj}) \).

Effects: If the map already contains an element \( e \) whose key is equivalent to \( k \), assigns std::\text{forward}<M>(\text{obj}) to \( e.second \). Otherwise inserts an object of type \text{value	extunderscore type} constructed with \( k, \text{std}::\text{forward}<M>(\text{obj}) \).

Returns: In the first overload, the \text{bool} component of the returned pair is \text{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 \text{emplace} and \text{emplace	extunderscore hint}, respectively.

\template{\text{class M}}
\pair{\text{iterator, bool}} \text{insert	extunderscore or	extunderscore assign}(\text{key	extunderscore type} & k, M &\& obj);
\template{\text{class M}}
\iter\\tor\text{insert	extunderscore or	extunderscore assign}(\text{const\_iterator hint, key	extunderscore type} & k, M &\& obj);

\text{Mandates:} is\_assignable	extunderscore v<\text{mapped	extunderscore type}, M &\&> is \text{true}.

Preconditions: \text{value	extunderscore type} is \text{Cpp17EmplaceConstructible} into \text{map} from \text{move}(k), \text{forward}<M>(\text{obj})

Effects: If the map already contains an element \( e \) whose key is equivalent to \( k \), assigns std::\text{move}<M>(\text{obj}) to \( e.second \). Otherwise inserts an object of type \text{value	extunderscore type} constructed with std::\text{move}(k), std::\text{forward}<M>(\text{obj})

Returns: In the first overload, the \text{bool} component of the returned pair is \text{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 \text{emplace} and \text{emplace	extunderscore hint}, respectively.

\section*{24.4.4.5 Erasure \[\text{map	extunderscore erasure}\]}

\template{\text{class Key, class T, class Compare, class Allocator, class Predicate}}
\text{typename} \text{map<Key, T, Compare, Allocator>::size	extunderscore type}
\text{erase	extunderscore if}(\text{map<Key, T, Compare, Allocator>& c, Predicate pred);}

Effects: Equivalent to:

\begin{verbatim}
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();
\end{verbatim}

\section*{24.4.5 Class template multimap \[\text{multimap}\]}

\subsection*{24.4.5.1 Overview \[\text{multimap\textunderscore overview}\]}

A \text{multimap} is an associative container that supports equivalent keys (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 \text{multimap} class supports bidirectional iterators.

A \text{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 \text{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>`. Descriptions are provided here only for operations on **multimap** that are not described in one of those tables or for operations where there is additional semantic information.

```cpp
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(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>);
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<typename... Args> iterator emplace(Args&&... args);
template<typename... Args> iterator emplace_hint(const_iterator position, Args&&... args);
iterator insert(const value_type& x);
iterator insert(value_type&& x);
template<typename P> iterator insert(P&& x);
iterator insert(const_iterator position, const value_type& x);
iterator insert(const_iterator position, value_type&& x);
template<typename P> iterator insert(const_iterator position, P&& x);
template<typename InputIterator>
  void insert(InputIterator first, InputIterator last);
template<container-compatible-range<br type=“range”> 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<typename 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<typename 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<typename C2>
  void merge(multimap<Key, T, C2, Allocator>& source);
template<class C2>
    void merge(multimap<Key, T, C2, Allocator>&& source);

template<class C2>
    void merge(map<Key, T, C2, Allocator>& source);

template<class C2>
    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::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>>>
    multimap(from_range_t, R&&, Compare = Compare(), Allocator = Allocator())
        -> multimap<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>>>
    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>;

§ 24.4.5.1
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

explicit multimap(const Compare& comp, const Allocator& = Allocator());

1 Effects: Constructs an empty multimap using the specified comparison object and allocator.

2 Complexity: Constant.

template<class InputIterator>
multimap(InputIterator first, InputIterator last,
          const Compare& comp = Compare(),
          const Allocator& = Allocator());

3 Effects: Constructs an empty multimap using the specified comparison object and allocator, and inserts elements from the range [first, last).

4 Complexity: Linear in \( N \) if the range [first, last) is already sorted using 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());

5 Effects: Constructs an empty multimap using the specified comparison object and allocator, and inserts elements from the range rg.

6 Complexity: Linear in \( N \) if rg is already sorted using comp and otherwise \( N \log N \), where \( N \) is ranges::distance(rg).

24.4.5.3 Modifiers

template<class P> iterator insert(P&& x);

1 Constraints: is_constructible_v<value_type, P&&> is true.

2 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

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);

1 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 Class template set

24.4.6.1 Overview

A set is an associative container that supports unique keys (contains at most one of each key value) and provides for fast retrieval of the keys themselves. The set class supports bidirectional iterators.

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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.

```cpp
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) { }
            ~set();
            set& operator=(const set& x);
            set& operator=(set&& x)
                noexcept(allocator_traits<Allocator>::is_always_equal::value &&
                          isnothrow_move_assignable_v<Compare>);
            set& 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> 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);
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);
insert_return_type 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(set&);
noexcept(allocator_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>;

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

explicit set(const Compare& comp, const Allocator& = Allocator());

1 Effects: Constructs an empty set using the specified comparison objects and allocator.

2 Complexity: Constant.
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 using comp and otherwise $N \log N$, where $N$ is last - first.

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 using comp and otherwise $N \log N$, where $N$ is ranges::distance(rg).

24.4.6.3 Erasure

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);

Effects: Equivalent to:

```c++
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();
```

24.4.7 Class template multiset

24.4.7.1 Overview

A multiset is an associative container that supports equivalent keys (possibly contains multiple copies of the same key value) and provides for fast retrieval of the keys themselves. The multiset class supports bidirectional iterators.

A 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 (24.2.5), 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 \texttt{a\_eq} operations in 24.2.7 but not the \texttt{a\_uniq} operations. For a \texttt{multiset<Key>} both the \texttt{key\_type} and \texttt{value\_type} are \texttt{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.

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(const multiset& x);
explicit multiset(const Allocator&);
multiset(const multiset&, const type_identity_t<Allocator>&);
multiset(multiset&& x);

// 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;

// 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);

node_type extract(const_iterator position);

size_type erase(const_iterator position);

size_type erase(const key_type& x);

size_type erase(const key_type& x);

size_type erase(const key_type& x);

size_type erase(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(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;

pair<iterator, iterator> equal_range(const key_type& x);

pair<const_iterator, const_iterator> equal_range(const key_type& 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<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>>>
multiset(InputIterator, InputIterator, 
    Compare = Compare(), Allocator = Allocator()) 
    -> multiset<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>>>
multiset(from_range_t, R&&, Compare = Compare(), Allocator = Allocator()) 
    -> multiset<ranges::range_value_t<R>, Compare, Allocator>;

template<class Key, class Compare = less<Key>, class Allocator = allocator<Key>>
multiset(initializer_list<Key>, Compare = Compare(), Allocator = Allocator()) 
    -> multiset<Key, Compare, Allocator>;

template<class InputIterator, class Allocator>
multiset(InputIterator, InputIterator, Allocator) 
    -> multiset<iter-value-type<InputIterator>, 
        less<iter-value-type<InputIterator>>, Allocator>;

template<ranges::input_range R, class Allocator>
multiset(from_range_t, R&&, Allocator) 
    -> multiset<ranges::range_value_t<R>, less<ranges::range_value_t<R>>, Allocator>;

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 using 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 using 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 In 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`, and `iter-to-alloc-type` defined in 24.4.1 may appear in deduction guides for unordered containers.

24.5.2 Header `<unordered_map>` synopsis

```cpp
#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 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)));

    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);

    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

#include <compare>    // see 17.11.1
#include <initializer_list>    // see 17.10.2

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)));

    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);

    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);

    § 24.5.3 926
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>>;
}

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>;

        // 24.5.4.2, 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());

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(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) { }

unordered_map(initializer_list<value_type> il, size_type n, const allocator_type& a) :
    unordered_map(il, n, hasher(), key_equal(), a) { }
~unordered_map();
unordered_map& operator=(const unordered_map&);
unordered_map& operator=(unordered_map&&);
noexcept(algorithm_traits<Allocator>::is_always_equal::value &&
    is_nothrow_move_assignable_v<Hash> &&
    is_nothrow_move_assignable_v<Pred>);
unordered_map& operator=(initializer_list<value_type> il);
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<... Args> pair<iterator, bool> emplace(Args&... args);
template<... 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<R> 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<... Args>
pair<iterator, bool> try_emplace(const key_type& k, Args&... args);
template<... 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);
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);

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_map&)
   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_map<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_multimap<Key, T, H2, P2, Allocator>& source);
template<class H2, class P2>
void merge(unordered_multimap<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;
template<class K>
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;

// 24.5.4.3, element access
mapped_type& operator[](const key_type& k);
mapped_type& operator[](key_type&& k);
mapped_type& at(const key_type& k);
const mapped_type& at(const key_type& 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-key-type<InputIterator>>,
class Pred = equal_to<iter-key-type<InputIterator>>,
class Allocator = allocator<iter-to-alloc-type<InputIterator>>>
unordered_map(InputIterator, InputIterator, typename
see below::size_type = see below,
Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_map<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_map(from_range_t, R&&, typename
see below::size_type = see below,
Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_map<range-key-type<R>, range-mapped-type<R>, Hash, Pred, Allocator>;

§ 24.5.4.1
template<class Key, class T, class Hash = hash<Key>,
class Pred = equal_to<Key>, class Allocator = allocator<pair<const Key, T>>>
unordered_map(initializer_list<pair<Key, T>>,
typename see below::size_type = see below, Hash = Hash(),
Pred = Pred(), Allocator = Allocator())
-> unordered_map<Key, T, Hash, Pred, Allocator>;

template<class InputIterator, class Allocator>
unordered_map(InputIterator, InputIterator, typename
see below::size_type = see below, 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 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 = see below, Hash = Hash(),
Pred = Pred(), Allocator = Allocator())
-> unordered_map<Key, T, Hash, Pred, Allocator>;

template<ranges::input_range R, class Allocator>
unordered_map(from_range_t, R&&, typename
see below::size_type = see below, 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<ranges::input_range R, class Hash, class Allocator>
unordered_map(from_range_t, R&&, typename
see below::size_type = see below, Hash, Allocator)
-> unordered_map<range-key-type<R>, range-mapped-type<R>,
hash<range-key-type<R>>,
equal_to<range-key-type<R>>, Allocator>;

4 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(),

§ 24.5.4.2 931
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. \( \text{max_load_factor()} \) returns 1.0.

Complexity: Constant.

```cpp
template<typename 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());
```

```cpp
template<typename 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());
```

```cpp
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. \( \text{max_load_factor()} \) returns 1.0.

Complexity: Average case linear, worst case quadratic.

24.5.4.3 Element access

```cpp
mapped_type& operator[](const key_type& k);
```

Effects: Equivalent to: \( \text{return try_emplace(k).first}\rightarrow\text{second}; \)

```cpp
mapped_type& operator[](key_type&& k);
```

Effects: Equivalent to: \( \text{return try_emplace(move(k)).first}\rightarrow\text{second}; \)

```cpp
mapped_type& at(const key_type& k);
cast mapped_type& at(const key_type& k) const;
```

Returns: A reference to \( x.\text{second} \), where \( x \) is the (unique) element whose key is equivalent to \( k \).

Throws: An exception object of type \( \text{out_of_range} \) if no such element is present.

24.5.4.4 Modifiers

```cpp
template<typename P>
pair<iterator, bool> insert(P&& obj);
```

Constraints: \( \text{is_constructible_v<value_type, P&&> is true.} \)

Effects: Equivalent to: \( \text{return emplace(std::forward<P>(obj));} \)

```cpp
template<typename P>
iterator insert(const_iterator hint, P&& obj);
```

Constraints: \( \text{is_constructible_v<value_type, P&&> is true.} \)

Effects: Equivalent to: \( \text{return emplace_hint(hint, std::forward<P>(obj));} \)

```cpp
template<typename... 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)...).

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.

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)...).

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.

template<class M>
pair<iterator, bool> insert_or_assign(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.

template<class M>
pair<iterator, bool> insert_or_assign(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.
24.5.4.5 Erasure

```
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);
```

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();
   ```

24.5.5 Class template unordered_multimap

24.5.5.1 Overview

1. 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.

2. 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, but 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>`.

3. 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.

```
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());

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(initializer_list<value_type> il, size_type n,
    const allocator_type& a)
    : unordered_multimap(il, n, hasher(), key_equal(), a) { }

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, hf, key_equal(), a) { }

unordered_multimap(initializer_list<value_type> il, size_type n,
    const allocator_type& a)
    : unordered_multimap(il, 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) { }

allocator_type get_allocator() const noexcept;

// iterators
iterator begin() noexcept;
const_iterator begin() const noexcept;
iterator end() noexcept;
const_iterator end() const noexcept;

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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(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);
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);
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);

// 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) const;
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 K& k);
    pair<const_iterator, const_iterator> equal_range(const K& 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;
    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-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 Hash = hash<Key>,
    class Pred = equal_to<Key>,
    class Allocator = allocator<pair<const Key, T>>
unordered_multimap(initializer_list<pair<Key, T>>,
    typename see below::size_type = see below,
    Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_multimap<Key, T, Hash, Pred, Allocator>;

template<class InputIterator, class Allocator>
unordered_multimap(InputIterator, InputIterator,
    typename see below::size_type, Allocator)
-> unordered_multimap<
    iter-key-type
    <InputIterator>,
    iter-mapped-type
    <InputIterator>,
    hash<
        iter-key-type
        <InputIterator>>,
    equal_to<
        iter-key-type
        <InputIterator>>,
    Allocator>;

template<class InputIterator, class Allocator>
unordered_multimap(InputIterator, InputIterator, Allocator)
-> unordered_multimap<
    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_multimap(InputIterator, InputIterator, typename see below::size_type, Hash, Allocator)
  -> unordered_multimap<iter-key-type<InputIterator>, iter-mapped-type<InputIterator>, Hash, equal_to<iter-key-type<InputIterator>>, Allocator>;

template<ranges::input_range R, class Allocator>
unordered_multimap(from_range_t, R&&, typename see below::size_type, Hash, Allocator)
  -> unordered_multimap<range-key-type<R>, range-mapped-type<R>, hash<range-key-type<R>>, Allocator>;

template<ranges::input_range R, class Hash, class Allocator>
unordered_multimap(from_range_t, R&&, typename see below::size_type, Hash, Allocator)
  -> unordered_multimap<range-key-type<R>, range-mapped-type<R>, Hash, equal_to<range-key-type<R>>, 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>;

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

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);

Constraints: is_constructible_v<value_type, P&&> is true.

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);

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

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.

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.

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>>

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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) {}
  template<class InputIterator>
  unordered_set(InputIterator f, InputIterator l, size_type n,
                const allocator_type& a)
  : unordered_set(f, l, n, hasher(), key_equal(), a) {}
  template<class InputIterator>
  unordered_set(InputIterator f, InputIterator l, size_type n,
                const hasher& hf, const allocator_type& a)
  : unordered_set(f, l, n, hf, key_equal(), a) {}
  unordered_set(initializer_list<value_type> il, size_type n,
                const allocator_type& a)
  : unordered_set(il, n, hasher(), key_equal(), a) {}
template<container-compatible-range<value_type> R>
unordered_set(from_range_t, R&& rg, size_type n, const allocator_type& a)
  : unordered_set(from_range, std::forward<R>(rg), n, key_equal(), a) { }

template<container-compatible-range<value_type> R>
unordered_set(from_range_t, R&& rg, size_type n, const hasher& hf, const allocator_type& a)
  : unordered_set(from_range, std::forward<R>(rg), n, hf, key_equal(), a) { }
unordered_set(initializer_list<value_type> il, size_type n, const hasher& hf,
  const allocator_type& a)
  : unordered_set(il, n, hf, key_equal(), a) { }
~unordered_set();
unordered_set& operator=(const unordered_set&);
unordered_set& operator=(unordered_set&&)
  noexcept(algorithm_traits<Allocator>::is_always_equal::value &&
    is_nothrow_move_assignable_v<Hash> &&
    is_nothrow_move_assignable_v<Pred>);
unordered_set& 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;

// modifiers
pair<iterator, bool> emplace(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 InputIterator> void insert(InputIterator first, InputIterator last);
void insert_range(R&& rg);
void insert(initializer_list<value_type>);
node_type extract(const_iterator position);
ode_type extract(const key_type& x);
template<class K> node_type extract(K&& x);
insert_return_type insert(node_type&& nh);
iterator erase(const_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 hint, const_iterator last);
void swap(unordered_set&)
  noexcept(algorithm_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_set<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_multiset<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(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 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_set<InputIterator, InputIterator, typename see below::size_type = see below,=
Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_set<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_set(from_range_t, R&&, typename see below::size_type = see below,=
Hash = Hash(), Pred = Pred(), Allocator = Allocator())

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-> unordered_set<ranges::range_value_t<R>, Hash, Pred, Allocator>;

template<class T, class Hash = hash<T>,
  class Pred = equal_to<T>, class Allocator = allocator<T>>
unordered_set(initializer_list<T>, typename see below::size_type = see below,
  Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_set<T, Hash, Pred, Allocator>;

template<class InputIterator, class Allocator>
unordered_set(InputIterator, InputIterator, typename see below::size_type, Allocator)
-> unordered_set<iter_value_type<InputIterator>,
  hash<iter_value_type<InputIterator>>,
  equal_to<iter_value_type<InputIterator>>,
  Allocator>;

template<class InputIterator, class Hash, class Allocator>
unordered_set(InputIterator, InputIterator, typename see below::size_type, Hash, Allocator)
-> unordered_set<iter_value_type<InputIterator>, Hash,
  equal_to<iter_value_type<InputIterator>>,
  Allocator>;

template<ranges::input_range R, class Allocator>
unordered_set(from_range_t, R&&, typename see below::size_type, Allocator)
-> unordered_set<ranges::range_value_t<R>, hash<ranges::range_value_t<R>>,
  equal_to<ranges::range_value_t<R>>, Allocator>;

template<ranges::input_range R, class Hash, class Allocator>
unordered_set(from_range_t, R&&, typename see below::size_type, Hash, Allocator)
-> unordered_set<ranges::range_value_t<R>, Hash,
  equal_to<ranges::range_value_t<R>>, Allocator>;

template<class T, class Allocator>
unordered_set(initializer_list<T>, typename see below::size_type, Allocator)
-> unordered_set<T, hash<T>, equal_to<T>, Allocator>;

template<class T, class Hash, class Allocator>
unordered_set(initializer_list<T>, typename see below::size_type, Hash, Allocator)
-> unordered_set<T, Hash, equal_to<T>, Allocator>;

4 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

unordered_set() : unordered_set(size_type(see below)) {} 
explicit unordered_set(size_type n,
  const hasher& hf = hasher(),
  const key_equal& eqi = key_equal(),
  const allocator_type& a = allocator_type());

1 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.

2 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

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();

24.5.7 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.

namespace std {
  template<class Key,
    class Hash = hash<Key>,
    class Pred = equal_to<Key>,
    class Allocator = allocator<Key>>
class unordered_multiset {
public:

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// 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;

// 24.5.7.2, construct/copy/destroy
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());

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) { }

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<class InputIterator>
unordered_multiset(unordered_multiset f, InputIterator l, size_type n, const allocator_type& a) :
    unordered_multiset(f, l, n, hasher(), key_equal(), a) { }

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, hasher(), 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;
const_iterator 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(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_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, Pred, Allocator>& source);
template<class H2, class P2>
void merge(unordered_multiset<Key, H2, Pred, 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);
const_iterator equal_range(const key_type& k) const;
template<class K>
    pair<iterator, iterator> equal_range(const K& k);
template<class K>
    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())

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-> unordered_multiset<ranges::range_value_t<R>, Hash, Pred, Allocator>;

template<class T, class Hash = hash<T>,
        class Pred = equal_to<T>, class Allocator = allocator<T>>
unordered_multiset(initializer_list<T>, typename see below::size_type = see below,
                   Hash = Hash(), Pred = Pred(), Allocator = Allocator())
-> unordered_multiset<T, Hash, Pred, Allocator>;

template<class InputIterator, class Allocator>
unordered_multiset(InputIterator, InputIterator, typename see below::size_type, Allocator)
-> unordered_multiset<iter-value-type<InputIterator>,
                      hash<iter-value-type<InputIterator>>,
                      equal_to<iter-value-type<InputIterator>>,
                      Allocator>;

template<class InputIterator, class Hash, class Allocator>
unordered_multiset(InputIterator, InputIterator, typename see below::size_type, Hash, Allocator)
-> unordered_multiset<iter-value-type<InputIterator>, Hash,
                      equal_to<iter-value-type<InputIterator>>,
                      Allocator>;

template<ranges::input_range R, class Allocator>
unordered_multiset(from_range_t, R&&, typename see below::size_type, Allocator)
-> unordered_multiset<ranges::range_value_t<R>, Hash<ranges::range_value_t<R>>,
                      equal_to<ranges::range_value_t<R>>, Allocator>;

template<ranges::input_range R, class Hash, class Allocator>
unordered_multiset(from_range_t, R&&, typename see below::size_type, Hash, Allocator)
-> unordered_multiset<ranges::range_value_t<R>, Hash, equal_to<ranges::range_value_t<R>>,
                      Allocator>;

template<class T, class Allocator>
unordered_multiset(initializer_list<T>, typename see below::size_type, Allocator)
-> unordered_multiset<T, hash<T>, equal_to<T>, Allocator>;

template<class T, class Hash, class Allocator>
unordered_multiset(initializer_list<T>, typename see below::size_type, Hash, Allocator)
-> unordered_multiset<T, Hash, equal_to<T>, Allocator>;

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());

1 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.

2 Complexity: Constant.
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(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 [unord.multiset.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 [container.adaptors]

24.6.1 In general [container.adaptors.general]

The headers <queue> and <stack> define the container adaptors queue, priority_queue, and stack.

The container adaptors each take a Container template parameter, and each constructor takes a Container reference argument. This container is copied into the Container member of each adaptor. If the container 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. The first template parameter T of the container adaptors 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 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.

A deduction guide for a container adaptor shall not participate in overload resolution if any of the following are true:

(5.1) — It has an InputIterator template parameter and a type that does not qualify as an input iterator is deduced for that parameter.

(5.2) — It has a Compare template parameter and a type that qualifies as an allocator is deduced for that parameter.
It has a container template parameter and a type that qualifies as an allocator is deduced for that parameter.

— It has no container template parameter, and it has an allocator template parameter, and a type that does not qualify as an allocator is deduced for that parameter.

— It has both container and allocator template parameters, and uses_allocator_v<Container, Allocator> is false.

The exposition-only alias template iter_value_type defined in 24.3.1 may appear in deduction guides for container adaptors.

24.6.2 Header <queue> synopsis

```cpp
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
    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>
    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>;
}
```

§ 24.6.3 Header <stack> synopsis

```cpp
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
    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, 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>;
}
```
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);

// operator<=> for three-way comparison

// swap function

// uses_allocator

24.6.4 Class template queue

24.6.4.1 Definition

Any sequence container supporting operations `front()`, `back()`, `push_back()` and `pop_front()` can be used to instantiate queue. In particular, `list` (24.3.10) and `deque` (24.3.8) can be used.

```cpp
namespace std {
    template<class T, class Container = deque<T>>
    class queue {
        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;

        public:
            using allocator_type = Container::allocator_type;

            queue() : queue(std::move(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<container-compatible-range<T> R, class Alloc>
            void push_range(R&& rg, const Alloc&);
            template<... Args>
            decltype(auto) emplace(Args&&... args) {
                return c.emplace_back(std::forward<Args>(args)...);
            }
            void pop() {
                c.pop_front();
            }
    }
} // namespace std
```
```cpp
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 { };
```

### 24.6.4.2 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))`.

### 24.6.4.3 Constructors with allocators

1. If `uses_allocator_v<container_type, Alloc>` is `false` the constructors in this subclause shall not participate in overload resolution.

- **template<Alloc> explicit queue(const Alloc& a);**
  
  **Effects:** Initializes `c` with `a`.

- **template<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<container_type&& cont, const Alloc& a);**
  
  **Effects:** Initializes `c` with `std::move(cont)` as the first argument and `a` as the second argument.

- **template<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).

24.6.4.4 Modifiers [queue.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)).

24.6.4.5 Operators [queue.ops]

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.

24.6.4.6 Specialized algorithms [queue.special]

template<class T, class Container>
void swap(queue<T, Container>& x, queue<T, Container>& y) noexcept(noexcept(x.swap(y)));
24.6.5 Class template priority_queue

24.6.5.1 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` (24.3.11) and `deque` (24.3.8) 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).

```cpp
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&);
        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<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<class InputIterator, class Alloc>
        priority_queue(InputIterator, InputIterator, const Compare&, Container&&,
                        const Alloc&);
        template<class InputIterator, class Alloc>
        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&);
        [[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);
    }
```

§ 24.6.5.1
void push(value_type&& x);
void push_range(R&& rg);
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<
  iter_value_type<InputIterator>>,
  class Container = vector<
  iter_value_type<InputIterator>>>;
  priority_queue(InputIterator, InputIterator, Compare = Compare(), Container = Container())
  -> priority_queue<
  iter_value_type<InputIterator>, Container, 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<
  iter_value_type<InputIterator>,
  vector<
  iter_value_type<InputIterator>, Allocator>,
  less<
  iter_value_type<InputIterator>>>;

// no equality is provided

template<class T, class Container, class Compare, class Alloc>
  struct uses_allocator<priority_queue<T, Container, Compare>, Alloc>
  : uses_allocator<Container, Alloc>::type { };
Effects: Initializes \( \text{comp} \) with \( x \) and \( c \) with \( y \) (copy constructing or move constructing as appropriate); calls `make_heap(c.begin(), c.end(), \text{comp})`.

```cpp
template<class InputIterator>
priority_queue(InputIterator first, InputIterator last, const Compare& x = Compare());
```  
**Preconditions:** \( x \) defines a strict weak ordering (27.8).

Effects: Initializes \( c \) with \( \text{first} \) as the first argument and \( \text{last} \) as the second argument, and initializes \( \text{comp} \) with \( x \); then calls `make_heap(c.begin(), c.end(), \text{comp})`.

```cpp
template<class InputIterator>
priority_queue(InputIterator first, InputIterator last, const Compare& x, const Container& y);
```

Effects: Initializes \( \text{comp} \) with \( x \) and \( c \) with \( y \) (copy constructing or move constructing as appropriate); calls `c.insert(c.end(), \text{first}, \text{last})`; and finally calls `make_heap(c.begin(), c.end(), \text{comp})`.

```cpp
template<class Container& R>
priority_queue(from_range_t, R&& rg, const Compare& x = Compare());
```

Effects: Initializes \( \text{comp} \) with \( x \) and \( c \) with `ranges::to<Container>(std::forward<R>(rg))` and finally calls `make_heap(c.begin(), c.end(), \text{comp})`.

### 24.6.5.3 Constructors with allocators

If `uses_allocator_{vt}container_type, Alloc` is `false` the constructors in this subclause shall not participate in overload resolution.

```cpp
template<class Alloc> explicit priority_queue(const Alloc& a);
```

Effects: Initializes \( c \) with \( a \) and value-initializes \( \text{comp} \).

```cpp
template<class Alloc> priority_queue(const Compare& compare, const Alloc& a);
```

Effects: Initializes \( c \) with \( a \) and initializes \( \text{comp} \) with \( \text{compare} \).

```cpp
template<class Alloc>
priority_queue(const Compare& compare, const Container& cont, const Alloc& a);
```

Effects: Initializes \( c \) with \( \text{cont} \) as the first argument and \( a \) as the second argument, and initializes \( \text{comp} \) with \( \text{compare} \); calls `make_heap(c.begin(), c.end(), \text{comp})`.

```cpp
template<class Alloc>
priority_queue(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 \( \text{comp} \) with `std::move(\text{compare})`; calls `make_heap(c.begin(), c.end(), \text{comp})`.

```cpp
template<class Alloc>
priority_queue(const priority_queue& q, const Alloc& a);
```

Effects: Initializes \( c \) with \( q.c \) as the first argument and \( a \) as the second argument, and initializes \( \text{comp} \) with \( q.\text{comp} \).

```cpp
template<class Alloc>
priority_queue(priority_queue&& q, const Alloc& a);
```

Effects: Initializes \( c \) with `std::move(q.c)` as the first argument and \( a \) as the second argument, and initializes \( \text{comp} \) with `std::move(q.\text{comp})`.

```cpp
template<class InputIterator, class Alloc>
priority_queue(InputIterator first, InputIterator last, const Alloc& a);
```

Effects: Initializes \( c \) with \( \text{first} \) as the first argument, \( \text{last} \) as the second argument, and \( a \) as the third argument, and value-initializes \( \text{comp} \); calls `make_heap(c.begin(), c.end(), \text{comp})`. 

§ 24.6.5.3 956
template<class InputIterator, class Alloc>
    priority_queue(InputIterator first, InputIterator last, const Compare& compare, const Alloc& a);

Effects: Initializes c with first as the first argument, last as the second argument, and a as the third argument, and initializes comp with compare; calls make_heap(c.begin(), c.end(), comp).

template<class InputIterator, class Alloc>
    priority_queue(InputIterator first, InputIterator last, const Compare& compare, const Container& cont, const Alloc& a);

Effects: Initializes c with 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).

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).

template<container-compatible-range<T> R, class Alloc>
    priority_queue(from_range_t, R&& rg, const Compare& compare, const Alloc& a);

Effects: Initializes comp with compare and c with ranges::to<Container>(std::forward<R>(rg), a); calls make_heap(c.begin(), c.end(), comp).

24.6.5.4 Members

void push(const value_type& x);

Effects: As if by:
    c.push_back(x);
    push_heap(c.begin(), c.end(), comp);

void push(value_type&& x);

Effects: As if by:
    c.push_back(std::move(x));
    push_heap(c.begin(), c.end(), comp);

template<container-compatible-range<T> R>
    void push_range(R&& rg);

Effects: Insert all elements of rg in c.

Postconditions: is_heap(c.begin(), c.end(), comp) is true.

template<class... Args> void emplace(Args&&... args);

Effects: As if by:
    c.emplace_back(std::forward<Args>(args)...);
    push_heap(c.begin(), c.end(), comp);

void pop();

Effects: As if by:
    pop_heap(c.begin(), c.end(), comp);
    c.pop_back();
24.6.5.5 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)));
```

1. Constraints: `is_swappable_v<Container>` is true and `is_swappable_v<Compare>` is true.

2. Effects: As if by `x.swap(y)`.

24.6.6 Class template stack

24.6.6.1 General

Any sequence container supporting operations `back()`, `push_back()` and `pop_back()` can be used to instantiate stack. In particular, `vector (24.3.11)`, `list (24.3.10)` and `deque (24.3.8)` can be used.

24.6.6.2 Definition

```
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&);

    public:
      [[nodiscard]] bool empty() const { return c.empty(); }
      size_type size() const { return c.size(); }
      reference top() const { 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>;
```

§ 24.6.6.2 958
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 { };}

24.6.6.3 Constructors

explicit stack(const Container& cont);
1 Effects: Initializes c with cont.

explicit stack(Container&& cont);
2 Effects: Initializes c with std::move(cont).

template<class InputIterator>
stack(InputIterator first, InputIterator last);
3 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);
4 Effects: Initializes c with ranges::to<Container>(std::forward<R>(rg)).

24.6.6.4 Constructors with allocators

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);
2 Effects: Initializes c with a.

template<class Alloc> stack(const container_type& cont, const Alloc& a);
3 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);
4 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);
5 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);
6 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& a);

    Effects: Initializes $c$ with ranges::to<Container>(std::forward<R>(rg), a).

24.6.6.5 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)).

24.6.6.6 Operators [stack.ops]

    template<class T, class Container>
        bool operator==(const stack<T, Container>& x, const stack<T, Container>& y);

    Returns: $x.c == y.c$.

    template<class T, class Container>
        bool operator!=(const stack<T, Container>& x, const stack<T, Container>& y);

    Returns: $x.c != y.c$.

    template<class T, class Container>
        bool operator<(const stack<T, Container>& x, const stack<T, Container>& y);

    Returns: $x.c < y.c$.

    template<class T, class Container>
        bool operator>(const stack<T, Container>& x, const stack<T, Container>& y);

    Returns: $x.c > y.c$.

    template<class T, class Container>
        bool operator<=(const stack<T, Container>& x, const stack<T, Container>& y);

    Returns: $x.c <= y.c$.

    template<class T, class Container>
        bool operator>=(const stack<T, Container>& x, const stack<T, Container>& y);

    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);

    Returns: $x.c <=> y.c$.

24.6.6.7 Specialized algorithms [stack.special]

    template<class T, class Container>
        void swap(stack<T, Container>& x, stack<T, Container>& y) noexcept(noexcept(x.swap(y)));

    Constraints: is_swappable_v<Container> is true.

    Effects: As if by x.swap(y).

24.7 Views [views]

24.7.1 General [views.general]

1 The header <span> defines the view span.
24.7.2 Header `<span>` synopsis

```cpp
namespace std {
    // constants
    inline constexpr size_t dynamic_extent = numeric_limits<size_t>::max();

    // 24.7.3, class template span
    template<class ElementType, size_t Extent = dynamic_extent>
    class span;

    template<class ElementType, size_t Extent>
    inline constexpr bool ranges::enable_view<span<ElementType, Extent>> = true;
    template<class ElementType, size_t Extent>
    inline constexpr bool ranges::enable_borrowed_range<span<ElementType, Extent>> = true;

    // 24.7.3.8, 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;
}
```

24.7.3 Class template `span` [views.span]

### 24.7.3.1 Overview [span.overview]

1. A `span` is a view over a contiguous sequence of objects, the storage of which is owned by some other object.
2. All member functions of `span` have constant time complexity.

```cpp
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 24.7.3.7
            using reverse_iterator = std::reverse_iterator<iterator>;
            static constexpr size_type extent = Extent;

            // 24.7.3.2, 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 span(const span& other) noexcept = default;
            template<class OtherElementType, size_t OtherExtent>
            constexpr explicit(see below) span(const span<OtherElementType, OtherExtent>& s) noexcept;
```
```cpp
constexpr span() noexcept = default;

constexpr span& operator=(const span& other) noexcept = default;

// 24.7.3.4, subviews
template<size_t Count>
constexpr span<element_type, Count> first() const;

// 24.7.3.4, subviews
template<size_t Count>
constexpr span<element_type, Count> last() const;

// 24.7.3.4, subviews
template<Size Offset, size_t Count = dynamic_extent>
constexpr span<element_type, see below> subspan() const;

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;

// 24.7.3.5, observers
constexpr size_type size() const noexcept;
constexpr size_type size_bytes() const noexcept;

[[nodiscard]] constexpr bool empty() const noexcept;

// 24.7.3.6, element access
constexpr reference operator[](size_type idx) const;
constexpr reference front() const;
constexpr reference back() const;
constexpr pointer data() const noexcept;

// 24.7.3.7, iterator support
constexpr iterator begin() const noexcept;
constexpr iterator end() const noexcept;
constexpr reverse_iterator rbegin() const noexcept;
constexpr reverse_iterator rend() const noexcept;

private:
    pointer data_;   // exposition only
    size_type size_; // exposition only
};
```

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.

### 24.7.3.2 Constructors, copy, and assignment

```cpp
constexpr span() noexcept;
```

1 Constraints: Extent == dynamic_extent || Extent == 0 is true.

2 Postconditions: size() == 0 && data() == nullptr.

```cpp
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>>.
It satisfies contiguous_iterator.

is_convertible_v<
U(*[]),
\text{element_type(*[])}> is true.

[Note 1: The intent is to allow only qualification conversions of the iterator reference type to element_type.
—end note]

Preconditions:

— [first, first + count) is a valid range.
— It models contiguous_iterator.
— If extent is not equal to dynamic_extent, then count is equal to extent.

Effects: Initializes data_ with to_address(first) and size_ with count.

Throws: Nothing.

template<class It, class End>
  constexpr explicit(extent != dynamic_extent) span(It first, End last);

Constraints: Let \( U \) be remove_reference_t<iter_reference_t<It>>.

— is_convertible_v<\U(*[]), \text{element_type(*[])}> is true.

[Note 2: The intent is to allow only qualification conversions of the iterator reference type to element_type.
—end note]

— It satisfies contiguous_iterator.
— End satisfies sized_sentinel_for<It>.
— is_convertible_v<End, size_t> is false.

Preconditions:

— If extent is not equal to dynamic_extent, then last - first is equal to extent.
— [first, last) is a valid range.
— It models contiguous_iterator.
— 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.

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;

Constraints: Let \( U \) be remove_pointer_t<
decltype(data(arr))>.

— extent == dynamic_extent || N == extent is true, and
— is_convertible_v<\U(*[]), \text{element_type(*[])}> is true.

[Note 3: The intent is to allow only qualification conversions of the array element type to element_type.
—end note]

Effects: Constructs a span that is a view over the supplied array.

[Note 4: type_identity_t affects class template argument deduction. —end note]

Postconditions: size() == N \&\& data() == data(arr) is true.

template<class R> constexpr explicit(extent != dynamic_extent) span(R&& r);

Constraints: Let \( U \) be remove_reference_t<branges::range_reference_t<R>>.

— \( R \) satisfies ranges::contiguous_range and ranges::sized_range.
— Either \( R \) satisfies ranges::borrowed_range or is_const_v<element_type> is true.
— remove_cvref_t<R> is not a specialization of span.
— remove_cvref_t<R> is not a specialization of array.
— is_array_v<\text{remove_cvref_t<R>>} is false.
— is_convertible_v<\U(*[]), element_type(*[])> is true.
Preconditions:
— If extent is not equal to dynamic_extent, then ranges::size(r) is equal to extent.
— R models ranges::contiguous_range and ranges::sized_range.
— If is_convertible_v<element_type(*)[], element_type(*)[]> is true.

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.

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:
— extent == dynamic_extent || OtherExtent == dynamic_extent || extent == OtherExtent is true, and
— is_convertible_v<OtherElementType(*)[], element_type(*)[]> is true.

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:

constexpr span& operator=(const span& other) noexcept = default;

Postconditions: size() == other.size() & data() == other.data().

4.7.3.3 Deduction guides

template<class It, class EndOrSize>
span(It, EndOrSize) -> span<remove_reference_t<iter_reference_t<It>>>;

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.

4.7.3.4 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:

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};

24.7.3.5 Observers

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;

24.7.3.6 Element access

constexpr reference operator[](size_type idx) const;
Preconditions: idx < size() is true.
Effects: Equivalent to: return *(data() + idx);

constexpr reference front() const;
Preconditions: empty() is false.
Effects: Equivalent to: return *data();

constexpr reference back() const;
Preconditions: empty() is false.
Effects: Equivalent to: return *(data() + (size() - 1));
constexpr pointer data() const noexcept;

**Effects**: Equivalent to: return data_;  

### 24.7.3.7 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) 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());

### 24.7.3.8 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;
```

2. **Constraints**: is_const_v<ElementType> is false.

3. **Effects**: Equivalent to: return R{reinterpret_cast<byte*>(s.data()), s.size_bytes()}; where R is the return type.
25 Iterators library

25.1 General

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).

The following subclauses describe iterator requirements, and components for iterator primitives, predefined iterators, and stream iterators, as summarized in Table 80.

Table 80: Iterators library summary

<table>
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</table>

25.2 Header <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     // exposition only
        = requires { typename with_reference<T>; };  
    template<class T> concept dereferenceable   // exposition only
        = 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;
    template<class T>
        using iter_difference_t = see below;

    // 25.3.2.2, indirectly readable traits
    template<class> struct indirectly_readable_traits;
    template<class T>
        using iter_value_t = see below;

    // 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&>());

    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
template<
dereferenceable T>
requires requires(T& t) {
  { ranges::iter_move(t) } -> can-reference;
}

using iter_rvalue_reference_t
= decltype(ranges::iter_move(declval<T&>()));

// 25.3.3.2, ranges::iter_swap
inline constexpr
unspecified iter_swap = unspecified;

// 25.3.4, iterator concepts
// 25.3.4.2, concept indirectly_readable
template<class In>
  concept indirectly_readable = see below;

template<indirectly_readable T>
  using iter_common_reference_t
    = common_reference_t<iter_reference_t<T>, iter_value_t<T>&>;

// 25.3.4.3, concept indirectly_writable
template<class Out, class T>
  concept indirectly_writable = see below;

// 25.3.4.4, concept weakly_incrementable
template<class I>
  concept weakly_incrementable = see below;

// 25.3.4.5, concept incrementable
template<class I>
  concept incrementable = see below;

// 25.3.4.6, concept input_or_output_iterator
template<class I>
  concept input_or_output_iterator = see below;

// 25.3.4.7, concept sentinel_for
template<class S, class I>
  concept sentinel_for = see below;

// 25.3.4.8, concept sized_sentinel_for
template<class S, class I>
  inline constexpr bool disable_sized_sentinel_for = false;

// 25.3.4.9, concept input_iterator
template<class I>
  concept input_iterator = see below;

// 25.3.4.10, concept output_iterator
template<class I, class T>
  concept output_iterator = see below;

// 25.3.4.11, concept forward_iterator
template<class I>
  concept forward_iterator = see below;

// 25.3.4.12, concept bidirectional_iterator
template<class I>
  concept bidirectional_iterator = see below;
// 25.3.4.13, concept random_access_iterator
template<class I>
concept random_access_iterator = see below;

// 25.3.4.14, concept contiguous_iterator
template<class I>
concept contiguous_iterator = see below;

// 25.3.6, indirect callable requirements
// 25.3.6.2, indirect callables
template<class F, class I>
concept indirectly_unary_invocable = see below;

template<class F, class I>
concept indirectly_regular_unary_invocable = see below;

template<class F, class I>
concept indirect Unary_predicate = see below;

template<class F, class I1, class I2>
concept indirect_binary_predicate = see below;

template<class F, class I1, class I2 = I1>
concept indirect_equivalence_relation = see below;

template<class F, class I1, class I2 = I1>
concept indirect_strict_weak_order = see below;

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>...>;

// 25.3.6.3, projected
template<indirectly_readable I, indirectly_regular_unary_invocable<I> Proj>
struct projected;

template<weakly_incrementable I, class Proj>
struct incrementable_traits<projected<I, Proj>>;

// 25.3.7, common algorithm requirements
// 25.3.7.2, concept indirectly_movable
template<class In, class Out>
concept indirectly_movable = see below;

template<class In, class Out>
concept indirectly_movable_storable = see below;

// 25.3.7.3, concept indirectly_copyable
template<class In, class Out>
concept indirectly_copyable = see below;

template<class In, class Out>
concept indirectly_copyable_storable = see below;

// 25.3.7.4, concept indirectly_swappable
template<class I1, class I2 = I1>
concept indirectly_swappable = see below;

// 25.3.7.5, concept indirectly_comparable
template<class I1, class I2, class R, class P1 = identity, class P2 = identity>
concept indirectly_comparable = see below;
// 25.3.7.6, concept permutable
template<class I>
concept permutable = see below;

// 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;

// 25.3.7.8, concept sortable
template<class I, class R = ranges::less, class P = identity>
concept sortable = see below;

// 25.4, primitives
// 25.4.2, iterator tags
struct input_iterator_tag { };
struct output_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 { };

// 25.4.3, iterator operations
template<class InputIterator, class Distance>
constexpr void
advance(InputIterator& i, Distance n);

template<class InputIterator>
constexpr typename iterator_traits<InputIterator>::difference_type
distance(InputIterator first, InputIterator last);

template<class InputIterator>
constexpr InputIterator
next(InputIterator x,
typename iterator_traits<InputIterator>::difference_type n = 1);

template<class BidirectionalIterator>
constexpr BidirectionalIterator
prev(BidirectionalIterator x,
typename iterator_traits<BidirectionalIterator>::difference_type n = 1);

// 25.4.4, range iterator operations
namespace ranges {
// 25.4.4.2, ranges::advance
template<input_or_output_iterator I>
constexpr void advance(I& i, iter_difference_t<I> n);

template<input_or_output_iterator I, sentinel_for<I> S>
constexpr void advance(I& i, S bound);

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);

// 25.4.4.3, ranges::distance
template<input_or_output_iterator I, sentinel_for<I> S>
requires (!sized_sentinel_for<S, I>)
constexpr iter_difference_t<I> distance(I first, S last);

template<input_or_output_iterator I, sized_sentinel_for<I> S>
constexpr iter_difference_t<I> distance(I first, const S& last);

template<range R>
constexpr range_difference_t<R> distance(R&& r);

// 25.4.4.4, ranges::next
template<input_or_output_iterator I>
constexpr I next(I x);

template<input_or_output_iterator I>
constexpr I next(I x, iter_difference_t<I> n);

template<input_or_output_iterator I, sentinel_for<I> S>
constexpr I next(I x, S bound);

}
template<input_or_output_iterator I, sentinel_for<I> S>
constexpr I next(I x, iter_difference_t<I> n, S bound);

// 25.4.4.5, ranges::prev
template<bidirectional_iterator I>
constexpr I prev(I x);
template<bidirectional_iterator I>
constexpr I prev(I x, iter_difference_t<I> n);
template<bidirectional_iterator I>
constexpr I prev(I x, iter_difference_t<I> n, I bound);
}

// 25.5, predefined iterators and sentinels
// 25.5.1, reverse iterators
template<class Iterator> class reverse_iterator;

template<class Iterator1, class Iterator2>
constexpr bool operator==(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y);
template<class Iterator1, class Iterator2>
constexpr bool operator!=(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y);
template<class Iterator1, class Iterator2>
constexpr bool operator<(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y);
template<class Iterator1, class Iterator2>
constexpr bool operator>(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y);
template<class Iterator1, class Iterator2>
constexpr bool operator<=(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y);
template<class Iterator1, class Iterator2>
constexpr bool operator>=(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y);

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);

template<class Iterator1, class Iterator2>
constexpr auto operator-(const reverse_iterator<Iterator1>& x, const reverse_iterator<Iterator2>& y) -> decltype(y.base() - x.base());

template<class Iterator1>
constexpr reverse_iterator<Iterator1> operator+(iter_difference_t<Iterator1> n, const reverse_iterator<Iterator1>& x);

template<class Iterator1, class Iterator2>
requires (!sized_sentinel_for<Iterator1, Iterator2>)
inline 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;

§ 25.2
template<class Container>
    constexpr back_insert_iterator<Container> back_inserter(Container& x);

template<class Container> class front_insert_iterator;
template<class Container>
    constexpr front_insert_iterator<Container> front_inserter(Container& x);

template<class Container> class insert_iterator;
template<class Container>
    constexpr insert_iterator<Container> inserter(Container& x, ranges::iterator_t<Container> i);

// 25.5.3, move iterators and sentinels
template<class Iterator> class move_iterator;

    template<class Iterator1, class Iterator2>
    constexpr bool operator==(
        const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

    template<class Iterator1, class Iterator2>
    constexpr bool operator<(
        const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

    template<class Iterator1, class Iterator2>
    constexpr bool operator>(
        const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

    template<class Iterator1, class Iterator2>
    constexpr bool operator<=
        (const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

    template<class Iterator1, class Iterator2>
    constexpr bool operator>=
        (const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);

    template<class Iterator1, three_way_comparable_with<Iterator1> Iterator2>
    constexpr compare_three_way_result_t<Iterator1, Iterator2>
        operator<=>(const move_iterator<Iterator1>& x, 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());

    template<class Iterator>
    constexpr move_iterator<Iterator> operator+(iter_difference_t<Iterator> n, const move_iterator<Iterator>& x);

    template<class Iterator>
    constexpr move_iterator<Iterator> make_move_iterator(Iterator i);

    template<semiregular S> class move_sentinel;

// 25.5.4, common iterators
template<input_or_output_iterator I, sentinel_for<I> S>
    requires (!same_as<I, S> && copyable<I>)
    class common_iterator;

    template<class I, class S>
    struct incrementable_traits<common_iterator<I, S>>;

    template<input_iterator I, class S>
    struct iterator_traits<common_iterator<I, S>>;

// 25.5.5, default sentinel
struct default_sentinel_t;
inline constexpr default_sentinel_t default_sentinel{};
// 25.5.6, counted iterators
template<input_or_output_iterator I> class counted_iterator;

template<input_iterator I>
    requires see below
    struct iterator_traits<counted_iterator<I>>;

// 25.5.7, unreachable sentinel
struct unreachable_sentinel_t;
inline constexpr unreachable_sentinel_t unreachable_sentinel{};

// 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());
template<class C> constexpr auto begin(const C& c) -> decltype(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());
template<class T, size_t N> constexpr T* begin(T (&array)[N]) noexcept;
template<class T, size_t N> constexpr T* end(T (&array)[N]) noexcept;
template<class C> constexpr auto cbegin(const C& c) noexcept(noexcept(std::begin(c)))
    -> decltype(std::begin(c));
template<class C> constexpr auto cend(const C& c) noexcept(noexcept(std::end(c)))
    -> decltype(std::end(c));
template<class C> constexpr auto rbegin(C& c) -> decltype(c.rbegin());
template<class C> constexpr auto rend(const C& c) -> decltype(c.rend());
template<class C> constexpr auto rbegin(initializer_list<typename C::value_type>& il);
template<class C> constexpr auto rend(initializer_list<typename C::value_type>& il);
template<class C> constexpr auto crbegin(const C& c) -> decltype(std::rbegin(c));
template<class C> constexpr auto crend(const C& c) -> decltype(std::rend(c));
template<class C> constexpr auto auto size(const C& c) noexcept;
template<class T, size_t N> constexpr size_t size(const T (&array)[N]) noexcept;
template<class C> [[nodiscard]] constexpr auto empty(const C& c) noexcept;
template<class T, size_t N> [[nodiscard]] constexpr bool empty(const T (&array)[N]) noexcept;
template<class E> [[nodiscard]] constexpr bool empty(initializer_list<E> il) noexcept;
template<class C> constexpr auto data(C& c) -> decltype(c.data());
template<class C> constexpr auto data(const C& c) -> decltype(c.data());
template<class T, size_t N> constexpr T* data(T (&array)[N]);
template<class E> constexpr const E* data(initializer_list<E> il) noexcept;}

25.3 Iterator requirements

25.3.1 In 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 indirectlyritable 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 81.

Table 81: 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

(3.1) — input_iterator (25.3.4.9),
(3.2) — output_iterator (25.3.4.10),
(3.3) — forward_iterator (25.3.4.11),
(3.4) — bidirectional_iterator (25.3.4.12),
(3.5) — random_access_iterator (25.3.4.13), and
(3.6) — 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.

8 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.

9 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 \(j == s\).

10 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.

11 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.

12 The result of the application of library functions to invalid ranges is undefined.

13 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.

14 Destruction of a non-forward iterator may invalidate pointers and references previously obtained from that iterator.

15 An invalid iterator is an iterator that may be singular.

16 Iterators are called constexpr iterators 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*> are constexpr iterators. — end note]

25.3.2 Associated types [iterator.assoc.types]

25.3.2.1 Incrementable traits [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 \(WI\) is the name of a type that models the weakly_incrementable concept (25.3.4.4), the type

\[
\text{iter_difference_t<}WI>\]

be defined as the incrementable type's difference type.

```cpp
namespace std {
    template<class> struct incrementable_traits { };  
    template<class T>  
        requires is_object_v<T>  
    struct incrementable_traits<T> {            
        using difference_type = ptrdiff_t; 
    };  
    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 [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

iter_value_t$<R>$

be defined as the indirectly readable type's value type.

template<class> struct cond_value_type { }; // exposition only

template<class T>  
    requires is_object_v<T>
struct cond_value_type<T> {  
    using value_type = remove_cv_t<T>;
};

template<class T>  
    concept has_member_value_type = requires { typename T::value_type; }; // exposition only

template<class T>  
    concept has_member_element_type = requires { typename T::element_type; }; // exposition only

template<class> struct indirectly_readable_traits { };  

// exposition only

template<class T>  
    struct indirectly_readable_traits<T*>  
        : cond_value_type<T> { };  

// exposition only

template<class I>  
    requires is_array_v<I>
struct indirectly_readable_traits<I> {  
    using value_type = remove_cv_t<remove_extent_t<I>>;
};

// exposition only

template<class I>  
    struct indirectly_readable_traits<const I>  
        : indirectly_readable_traits<I> { };  

// exposition only

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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

(2.1) — indirectly_readable_traits<\( R_I \)>::value_type if iterator_traits<\( R_I \)> names a specialization
generated from the primary template, and

(2.2) — 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

iterator_traits<I>::iterator_category

be defined as the iterator’s iterator category. In addition, the types

iterator_traits<I>::pointer
iterator_traits<I>::reference

shall be defined as the iterator’s pointer and reference types; that is, for an iterator object \( a \) of class
type, the same type as decrype(a.operator->()) and decrype(*a), respectively. The type iterator_traits<\( I \)>::pointer shall be void for an iterator of class type \( I \) that does not support operator->. Additionally, in the case of an output iterator, the types

iterator_traits<\( I \)>::value_type
iterator_traits<\( I \)>::difference_type
iterator_traits<\( I \)>::reference

may be defined as void.

The definitions in this subclause make use of the following exposition-only concepts:

template<class I>
concept cpp17-iterator =

requires(I i) {
{ *i } -> can-reference;
{ ++i } -> same_as<I&>;
{ i++ } -> can-reference;
} && copyable<I>;

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&>;}
template<class I>
concept cpp17-forward-iterator =
cpp17-input-iterator<I> && constructible_from<I> &&
is_lvalue_reference_v<iter_reference_t<I>> &&
same_as<remove_cvref_t<iter_reference_t<I>>>,
type_name 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&>;
  { n + i } -> same_as<I&>;
  { i - i } -> same_as<decay_type(n)>;
  { i[n] } -> convertible_to<iter_reference_t<I>>;
};

3 The members of a specialization iterator_traits<I> generated from the iterator_traits primary tem-
plate 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 = typename I::reference;

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;

(3.2.1) — If the qualified-id I::pointer is valid and denotes a type, pointer names that type. Other-
wise, if decltype(declval<I&>().operator->()) is well-formed, then pointer names that type.
Otherwise, pointer names void.

(3.2.2) — If the qualified-id I::reference is valid and denotes a type, reference names that type. Otherwise, reference names iter_reference_t<I>.

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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
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

### 25.3.3 Customization point objects

#### 25.3.3.1 ranges::iter_move

The name `ranges::iter_move` denotes a customization point object (16.3.3.3.6). The expression `ranges::iter_move(E)` for a subexpression `E` is expression-equivalent to:

---
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, with overload resolution performed in a context that does not include a declaration of ranges::iter_move but does include the declaration

```
void iter_move();
```

(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

The name ranges::iter_swap denotes a customization point object (16.3.3.3.6) that exchanges the values (18.4.9) denoted by its arguments.

Let iter-exchange-move be the exposition-only function:

```
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)));
```

Effects: Equivalent to:

```
iter_value_t<X> old_value(iter_move(x));
*x = iter_move(y);
return old_value;
```

2 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

```
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.

(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 1: 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

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.

(1.2) — Otherwise, if the qualified-id ITER_TRAITS(I)::iterator_category is valid and names a type, then ITER_CONCEPT(I) denotes that type.

(1.3) — Otherwise, if iterator_traits<I> names a specialization generated from the primary template, then ITER_CONCEPT(I) denotes random_access_iterator_tag.

(1.4) — Otherwise, ITER_CONCEPT(I) does not denote a type.
[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

[iterator.concept.readable]

1 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 =
    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>&>;
```

```cpp
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.

[Note 1: The expression `*i` is indirectly required to be valid via the exposition-only `dereferenceable` concept (25.2). — end note]

25.3.4.3 Concept indirectly_writable

[iterator.concept.writable]

1 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) { // not required to be equality-preserving
        *o = std::forward<T>(t); // not required to be equality-preserving
        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

(2.1) — If `Out` and `T` model `indirectly_readable<Out> && same_as<iter_value_t<Out>, decay_t<T>>`, then `o` after any above assignment is equal to the value of `E` before the assignment.

3 After evaluating any above assignment expression, `o` is not required to be dereferenceable.
If \( E \) is an xvalue (7.2.1), the resulting state of the object it denotes is valid but unspecified (16.4.6.15).

[Note 1: The only valid use of an operator* is on the left side of the assignment statement. Assignment through the same value of the indirectly writable type happens only once. — end note]

[Note 2: indirectly_writable has the awkward const_cast expressions to reject iterators with prvalue non-proxy reference types that permit rvalue assignment but do not also permit const rvalue assignment. Consequently, an iterator type \( I \) that returns std::string by value does not model indirectly_writable\( I, \) std::string>. — end note]

25.3.4.4 Concept weakly_incrementable

The weakly_incrementable concept specifies the requirements on types that can be incremented with the pre- and post-increment operators. The increment operations are not required to be equality-preserving, nor is the type required to be equality_comparable.

```cpp
template<class T>
inline constexpr bool is_integer_like = see below;  // exposition only

template<class T>
inline constexpr bool is_signed_integer_like = see below;  // exposition only

template<class I>
concept weakly_incrementable = movable<I> &&
requires(I i) {
  typename iter_difference_t<I>;
  requires is_signed_integer_like<iter_difference_t<I>>;
  { ++i } -> same_as<I&>;  // not required to be equality-preserving
  i++;
  // not required to be equality-preserving
};
```

A type \( I \) is an integer-class type if it is in a set of implementation-defined types that behave as integer types do, as defined below.

[Note 1: An integer-class type is not necessarily a class type. — end note]

The range of representable values of an integer-class type is the continuous set of values over which it is defined. For any integer-class type, its range of representable values is either \(-2^{N-1} \) to \( 2^{N-1} - 1 \) (inclusive) for some integer \( N \), in which case it is a signed_integer-class type, or \( 0 \) to \( 2^N - 1 \) (inclusive) for some integer \( N \), in which case it is an unsigned_integer-class type. In both cases, \( N \) is called the width of the integer-class type. The width of an integer-class type is greater than that of every integral type of the same signedness.

A type \( I \) other than cv bool is integer-like if it models integral\( I \) or if it is an integer-class type. An integer-like type \( I \) is signed_integer-like if it models signed_integral\( I \) or if it is a signed_integer-class type. An integer-like type \( I \) is unsigned_integer-like if it models unsigned_integral\( I \) or if it is an unsigned_integer-class type.

For every integer-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 \( I \).

[Note 2: The corresponding hypothetical specialization numeric_limits\( B(I) \) meets the requirements on numeric_limits specializations for integral types (17.3.5). — end note]

For every integral type \( J \), let B(\( J \)) be the same type as \( J \).

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 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(I)`, 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 implementaton 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) {
        { i++ } -> same_as<I>;
    };
```
Let \( a \) and \( b \) be incrementable objects of type \( I \). \( I \) models incrementable only if

\[
(2.1) \quad \text{If } \text{bool}(a == b) \text{ then } \text{bool}(\text{a}++ == \text{b}).
\]

\[
(2.2) \quad \text{If } \text{bool}(a == b) \text{ then } \text{bool}((\text{void})\text{a}++, a) == ++b).
\]

[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 incrementable. — end note]

### 25.3.4.6 Concept input_or_output_iterator

The \textit{input_or_output_iterator} concept forms the basis of the iterator concept taxonomy; every iterator models \textit{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{C++17Iterator} requirements, the \textit{input_or_output_iterator} concept does not require copyability. — end note]

### 25.3.4.7 Concept sentinel_for

The \textit{sentinel_for} concept specifies the relationship between an \textit{input_or_output_iterator} type and a \textit{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 \textit{sentinel_for} only if

\[
(2.1) \quad i == s \text{ is well-defined.}
\]

\[
(2.2) \quad \text{If bool}(i != s) \text{ then } i \text{ is dereferenceable and } [+i, s) \text{ denotes a range.}
\]

\[
(2.3) \quad \text{assignable_from}<I&, S> \text{ is either modeled or not satisfied.}
\]

[Note 2: 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 sized_sentinel_for

The \textit{sized_sentinel_for} concept specifies requirements on an \textit{input_or_output_iterator} type \( I \) and a corresponding \textit{sentinel_for} that allow the use of the \texttt{-} 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) \text{ be true}. \( S \) and \( I \) model \textit{sized_sentinel_for} only if

\[
(2.1) \quad \text{If } N \text{ is representable by iterator_difference_t}<I>, \text{ then } s - i \text{ is well-defined and equals } N.
\]

\[
(2.2) \quad \text{If } -N \text{ is representable by iterator_difference_t}<I>, \text{ then } i - s \text{ is well-defined and equals } -N.
\]
template<class S, class I>
inline 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 `S` and `I` if `S` and/or `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 (25.5.6.1). — end example]

25.3.4.9 Concept `input_iterator` [iterator.concept.input]

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]

template<class I>
concept input_iterator =
input_or_output_iterator<I> &&
indirectly_readable<I> &&
requires { typename ITER_CONCEPT(I); } &&
derived_from<ITER_CONCEPT(I), input_iterator_tag>;

25.3.4.10 Concept `output_iterator` [iterator.concept.output]

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]

template<class I, class T>
concept output_iterator =
input_or_output_iterator<I> &&
indirectly_writable<I, 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 `T`, and let `i` be a dereferenceable object of type `I`. `I` and `T` model `output_iterator<I, T>` only if `*i++ = E`; has effects equivalent to:

`*i = E;
++i;`

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` [iterator.concept.forward]

The `forward_iterator` concept adds copyability, equality comparison, and the multi-pass guarantee, specified below.

template<class I>
concept forward_iterator =
input_iterator<I> &&
derived_from<ITER_CONCEPT(I), forward_iterator_tag> &&
incrementable<I> &&
sentinel_for<I, 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:
— a == b implies ++a == ++b and

the expression ((void)[X x]{++x;}(a), *a) 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`  

The `bidirectional_iterator` concept adds the ability to move an iterator backward as well as forward.

```cpp
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:

1. If a and b are decrementable, then all of the following are true:
   1.1. addressof(--a) == addressof(a)
   1.2. bool(a-- == b)
   1.3. after evaluating both a-- and --b, bool(a == b) is still true
   1.4. bool(++(--a) == b)

2. 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. (a += n) is equal to b.
   2.2. addressof(a += n) is equal to addressof(a).
   2.3. (a + n) is equal to (a += n).
   2.4. For any two positive values x and y of type D, if (a + D(x + y)) is valid, then (a + D(x + y)) is equal to ((a + x) + y).
   2.5. (a + D(0)) is equal to a.
   2.6. If (a + D(n - 1)) is valid, then (a + n) is equal to [](I c){ return ++c; })(a + D(n - 1)).
(2.7) \((b += D(-n))\) is equal to \(a\).
(2.8) \((b -= n)\) is equal to \(a\).
(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.

```cpp
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>> &&
    same_as<iter_value_t<I>, remove_cvref_t<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 \(\text{iter_difference_t}<I>\). The type \(I\) models contiguous_iterator only if

- (2.1) \(\text{to_address}(a) == \text{addressof}(\ast a)\),
- (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 \(\text{std::move}(\ast a)\), and
- (2.5) if \(\text{ranges::iter_swap}(a, b)\) is well-formed, it has effects equivalent to \(\text{ranges::swap}(\ast a, \ast b)\).

25.3.5 C++17 iterator requirements

25.3.5.1 General

The Cpp17Iterator requirements form the basis of the iterator taxonomy; every iterator meets the Cpp17-Iterator 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).

Let \(a\) and \(b\) denote values of type \(X\) or const \(X\), \(\text{difference_type}\) and \(\text{reference}\) refer to the types \(\text{iterator_traits}<X>::\text{difference_type}\) and \(\text{iterator_traits}<X>::\text{reference}\), respectively, \(n\) denotes a value of \(\text{difference_type}\), \(u\), \(\text{tmp}\), and \(m\) denote identifiers, \(r\) denotes a value of \(X\), \(t\) 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 \(\text{iterator_traits}<X>\) (25.3.2.3). — end note]

25.3.5.2 Cpp17Iterator

A type \(X\) meets the Cpp17Iterator requirements if:

- (2.1) \(X\) meets the \(\text{Cpp17CopyConstructible}, \text{Cpp17CopyAssignable}, \text{and Cpp17Destructible}\) requirements (16.4.4.2) and lvalues of type \(X\) are swappable (16.4.4.3), and
- (2.2) \(\text{iterator_traits}<X>::\text{difference_type}\) is a signed integer type or void, and
- (2.3) the expressions in Table 82 are valid and have the indicated semantics.

25.3.5.3 Input iterators

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 27) requirements and the expressions in Table 83 are valid and have the indicated semantics.

In Table 83, 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
Table 82: *Cpp17Iterator* requirements  [tab:iterator]

<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>unspecified</td>
<td></td>
<td>Preconditions: r is dereferenceable.</td>
</tr>
<tr>
<td>++r</td>
<td>X&amp;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 83: *Cpp17InputIterator* requirements (in addition to *Cpp17Iterator*)  [tab:inputiterator]

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td>a != b</td>
<td>contextually convertible to bool</td>
<td>!(a == b)</td>
<td>Preconditions: (a, b) is in the domain of <code>==</code>.</td>
</tr>
<tr>
<td>*a</td>
<td>reference, convertible to T</td>
<td></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 <code>==</code> then *a is equivalent to *b.</td>
</tr>
<tr>
<td>a-&gt;m</td>
<td>(*a).m</td>
<td></td>
<td>Preconditions: a is dereferenceable.</td>
</tr>
<tr>
<td>++r</td>
<td>X&amp;</td>
<td></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 <code>==</code>.</td>
</tr>
<tr>
<td>(void)r++</td>
<td></td>
<td></td>
<td>equivalent to (void)++r</td>
</tr>
<tr>
<td>*r++</td>
<td>convertible to T</td>
<td>{ T tmp = *r; ++r; return tmp; }</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.
[Note 1: 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 \textit{Cpp17CopyAssignable} type (Table 33). Such an algorithm can be used with streams as the source of the input data through the \texttt{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 \textit{Cpp17Iterator} requirements (25.3.5.2) and the expressions in Table 84 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>(\ast r = o)</td>
<td>result is not used</td>
<td></td>
<td>Remarks: After this operation (r) is not required to be dereferenceable. Postconditions: (r) is incremental.</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 incremental.</td>
<td></td>
</tr>
<tr>
<td>(r++)</td>
<td>convertible to (\text{const } X&amp;)</td>
<td>{ (X) tmp = (r); ++(r); return tmp; }</td>
<td>Remarks: After this operation (r) is not required to be dereferenceable. Postconditions: (r) is incremental.</td>
</tr>
<tr>
<td>(\ast r++ = o)</td>
<td>result is not used</td>
<td></td>
<td>Remarks: After this operation (r) is not required to be dereferenceable. Postconditions: (r) is incremental.</td>
</tr>
</tbody>
</table>

2 \textit{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 \texttt{operator\textasciitilde} 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 requirements of a forward iterator if

1. \(X\) meets the \textit{Cpp17InputIterator} requirements (25.3.5.3),
2. \(X\) meets the \textit{Cpp17DefaultConstructible} requirements (16.4.4.2),
3. if \(X\) is a mutable iterator, \texttt{reference} is a reference to \(T\); if \(X\) is a constant iterator, \texttt{reference} is a reference to \texttt{const }\(T\),
4. the expressions in Table 85 are valid and have the indicated semantics, and
5. objects of type \(X\) offer the multi-pass guarantee, described below.

2 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]

### 25.3.5.6 Random-access iterators

A class or pointer type \(X\) meets the requirements of a random-access iterator if

1. \(X\) meets the \textit{Cpp17InputIterator} requirements (25.3.5.3),
2. \(X\) meets the \textit{Cpp17DefaultConstructible} requirements (16.4.4.2),
3. \(X\) meets the \textit{Cpp17CopyAssignable} requirements (Table 33),
4. if \(X\) is a mutable iterator, \texttt{reference} is a reference to \(T\); if \(X\) is a constant iterator, \texttt{reference} is a reference to \texttt{const }\(T\),
5. the expressions in Table 85 are valid and have the indicated semantics, and
6. objects of type \(X\) offer the multi-pass guarantee, described below.

3 Two dereferenceable iterators \(a\) and \(b\) of type \(X\) offer the \textit{multi-pass guarantee} if:

1. \(a == b\) implies \(++a == ++b\)

\section*{§ 25.3.5.5}
— \( X \) is a pointer type or the expression \((\text{void})++X(a)\), \(*a\) is equivalent to the expression \(*a\).

\[\text{(Note 2): The requirement that } a == b \text{ implies } ++a == ++b \text{ (which is not true for input and output iterators) and the removal of the restrictions on the number of the assignments through a mutable iterator (which applies to output iterators) allows the use of multi-pass one-directional algorithms with forward iterators. — end note}\]

**Table 85: Ccpp17ForwardIterator requirements (in addition to Ccpp17InputIterator)**  
<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 (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>

\[\text{Note 2:} \text{ If } a \text{ and } b \text{ are equal, then either } a \text{ and } b \text{ are both dereferenceable or else neither is dereferenceable.}\]

\[\text{Note 3:} \text{ If } a \text{ and } b \text{ are both dereferenceable, then } a == b \text{ if and only if } *a \text{ and } *b \text{ are bound to the same object.}\]

### 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 Ccpp17ForwardIterator requirements, the following expressions are valid as shown in Table 86.

**Table 86: Ccpp17BidirectionalIterator requirements (in addition to Ccpp17ForwardIterator)**

<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). addressof((r)) == addressof((--r)).</td>
<td></td>
</tr>
<tr>
<td>(r--)</td>
<td>convertible to (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>

**Table 87: Ccpp17RandomAccessIterator requirements (in addition to Ccpp17BidirectionalIterator)**

<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). addressof((r)) == addressof((--r)).</td>
<td></td>
</tr>
<tr>
<td>(r--)</td>
<td>convertible to (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>

\[\text{Note 1:} \text{ Bidirectional iterators allow algorithms to move iterators backward as well as forward. — end note}\]

### 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 Ccpp17BidirectionalIterator requirements, the following expressions are valid as shown in Table 87.
Table 87: `Cpp17RandomAccessIterator` requirements (in addition to `Cpp17BidirectionalIterator`)

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
<th>Assertion/note</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>r += n</code></td>
<td><code>X&amp;</code></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><code>a + n</code></td>
<td><code>X</code></td>
<td><code>{ X tmp = a; return tmp += n; }</code></td>
<td><code>a + n == n + a. </code></td>
</tr>
<tr>
<td><code>n + a</code></td>
<td></td>
<td><code>Preconditions: the absolute value of n is in the range of representable values of difference_type.</code></td>
<td></td>
</tr>
<tr>
<td><code>r -= n</code></td>
<td><code>X&amp;</code></td>
<td><code>return r += -n;</code></td>
<td></td>
</tr>
<tr>
<td><code>a - n</code></td>
<td><code>X</code></td>
<td><code>{ X tmp = a; return tmp -= n; }</code></td>
<td></td>
</tr>
<tr>
<td><code>b - a</code></td>
<td><code>difference_type</code></td>
<td><code>return n</code></td>
<td><code>Preconditions: there exists a value n of type difference_type such that a + n == b. b == a + (b - a).</code></td>
</tr>
<tr>
<td><code>a[n]</code></td>
<td>convertible to reference</td>
<td><code>*(a + n)</code></td>
<td></td>
</tr>
<tr>
<td><code>a &lt; b</code></td>
<td>contextually convertible to bool</td>
<td><code>Effects: Equivalent to: return b - a &gt; 0;</code></td>
<td><code>&lt;</code> is a total ordering relation</td>
</tr>
<tr>
<td><code>a &gt; b</code></td>
<td>contextually convertible to bool</td>
<td><code>b &lt; a</code></td>
<td><code>&gt;</code> is a total ordering relation opposite to <code>&lt;.</code></td>
</tr>
<tr>
<td><code>a &gt;= b</code></td>
<td>contextually convertible to bool</td>
<td><code>!(a &lt; b)</code></td>
<td></td>
</tr>
<tr>
<td><code>a &lt;= b</code></td>
<td>contextually convertible to bool</td>
<td><code>!(a &gt; b)</code></td>
<td></td>
</tr>
</tbody>
</table>

25.3.6 Indirect callable requirements

25.3.6.1 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 callables

1 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_unary_invocable =
        indirectly_readable<I> &&
        copy_constructible<F> &&
        invocable<F&, iter_value_t<I>&> &&
        invocable<F&, iter_reference_t<I>> &&
        invocable<F&, iter_common_reference_t<I>> &&
        common_reference_with<
```
invoke_result_t<F&, iter_value_t<I>&>,
invoke_result_t<F&, iter_reference_t<I>>&;

template<class F, class I>
concept indirectly_regular_unary_invocable =
indirectly_readable<I> &&
copy_constructible<F> &&
regular_invocable<F&, iter_value_t<I>&> &&
regular_invocable<F&, iter_reference_t<I>>& &&
regular_invocable<F&, iter_common_reference_t<I>>& &&
common_reference_with<
invoke_result_t<F&, iter_value_t<I>&>,
invoke_result_t<F&, iter_reference_t<I>>;
25.3.7 Common algorithm requirements

25.3.7.1 General

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`.

[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`

The `indirectly_movable` concept specifies the relationship between a `indirectly_readable` type and a `indirectly_writable` type between which values may be moved.

```cpp
template<class In, class Out>
concept indirectly_movable =
  indirectly_readable<In> &&
  indirectly_writable<Out, iter_rvalue_reference_t<In>>;
```

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.

```cpp
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>>;
```

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

```cpp
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`

The `indirectly_copyable` concept specifies the relationship between a `indirectly_readable` type and a `indirectly_writable` type between which values may be copied.

```cpp
template<class In, class Out>
concept indirectly_copyable =
  indirectly_readable<In> &&
  indirectly_writable<Out, iter_reference_t<In>>;
```

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, const iter_value_t<In>&&> &&
```
Let \( i \) be a dereferenceable value of type \( \text{In} \). \( \text{In} \) and \( \text{Out} \) model `indirectly_copyable_storable<\text{In}, \text{Out}>` only if after the initialization of the object \( \text{obj} \) in
\[
\text{iter\_value\_t<\text{In> obj(*i));}
\]
\( \text{obj} \) is equal to the value previously denoted by \(*i\). If `iter\_reference\_t<\text{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  
**[alg.req.ind.swap]**

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  
**[alg.req.ind.cmp]**

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  
**[alg.req.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  
**[alg.req.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<I1, Out> &&
    indirectly_copyable<I2, Out> &&
    indirect_strict_weak_order<R, projected<I1, P1>, projected<I2, P2>>;
```

### 25.3.7.8 Concept sortable  
**[alg.req.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>>;
```
To simplify the use of iterators, the library provides several classes and functions.

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).

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:]

    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&;
    };
    —end example]

[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:]

    template<class BidirectionalIterator>
    inline void
    evolve(BidirectionalIterator first, BidirectionalIterator last) {
        evolve(first, last,
               typename iterator_traits<BidirectionalIterator>::iterator_category());
    }

    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]

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 § 25.4.4.2.1

template<input_or_output_iterator I>
constexpr void ranges::advance(I& i, iter_difference_t<I> n);

Preconditions: If I does not model bidirectional_iterator, n is not negative.
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 S and I 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.

7 Returns: n - M, where M is the difference between the ending and starting positions of i.

25.4.4.3 ranges::distance

template<input_or_output_iterator 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<input_or_output_iterator I, sized_sentinel_for<I> S>
constexpr iter_difference_t<I> ranges::distance(const I& first, const S& last);

3 Effects: Equivalent to: return last - 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:
   return ranges::distance(ranges::begin(r), ranges::end(r)); // 26.3

25.4.4.4 ranges::next

template<input_or_output_iterator I>
constexpr I ranges::next(I x);

1 Effects: Equivalent to: ++x; return x;

template<input_or_output_iterator I>
constexpr I ranges::next(I x, iter_difference_t<I> n);

2 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;

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

template<bidirectional_iterator I>
constexpr I ranges::prev(I x);

Effects: Equivalent to: --x; return x;

template<bidirectional_iterator I>
constexpr I ranges::prev(I x, iter_difference_t<I> n);

Effects: Equivalent to: ranges::advance(x, -n); return x;

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

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
   — random_access_iterator_tag if Iterator models random_access_iterator, and
   — bidirectional_iterator_tag otherwise.

2 The member typedef-name iterator_category denotes
   — random_access_iterator_tag if the type iterator_traits<Iterator>::iterator_category models derived_from<random_access_iterator_tag>, and
   — 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
   — operator+, operator-, operator+=, operator-= (25.5.1.7), or
   — operator[] (25.5.1.6),
   or the non-member operators (25.5.1.8)
   — 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);
3 Constraints: is_same_v<U, Iterator> is false and const U& models convertible_to<Iterator>.
4 Effects: Initializes current with u.current.

template<class U>
constexpr reverse_iterator& operator=(const reverse_iterator<U>& u);
5 Constraints: is_same_v<U, Iterator> is false, const U& models convertible_to<Iterator>, and assignable_from<Iterator&, const U&> is modeled.
6 Effects: Assigns u.current to current.
7 Returns: *this.
25.5.1.5 Conversion

```cpp
constexpr Iterator base() const;  // explicit

Returns: current.
```

25.5.1.6 Element access

```cpp
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->();
```

```cpp
constexpr unspecified operator[](difference_type n) const;

Returns: current[-n-1].
```

25.5.1.7 Navigation

```cpp
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.
```

§ 25.5.1.7
25.5.1.8 Comparisons

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator==(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y);  

Constraints: \( x.\text{base}() == y.\text{base}() \) is well-formed and convertible to \( \text{bool} \).

Returns: \( x.\text{base}() == y.\text{base}() \).
```

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator!=(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y);  

Constraints: \( x.\text{base}() \neq y.\text{base}() \) is well-formed and convertible to \( \text{bool} \).

Returns: \( x.\text{base}() \neq y.\text{base}() \).
```

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator<(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y);  

Constraints: \( x.\text{base}() > y.\text{base}() \) is well-formed and convertible to \( \text{bool} \).

Returns: \( x.\text{base}() > y.\text{base}() \).
```

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator>(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y);  

Constraints: \( x.\text{base}() < y.\text{base}() \) is well-formed and convertible to \( \text{bool} \).

Returns: \( x.\text{base}() < y.\text{base}() \).
```

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator<=(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y);  

Constraints: \( x.\text{base}() \geq y.\text{base}() \) is well-formed and convertible to \( \text{bool} \).

Returns: \( x.\text{base}() \geq y.\text{base}() \).
```

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator>=(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y);  

Constraints: \( x.\text{base}() \leq y.\text{base}() \) is well-formed and convertible to \( \text{bool} \).

Returns: \( x.\text{base}() \leq y.\text{base}() \).
```

```cpp
template<class Iterator1, class Iterator2>
constexpr compare_three_way_result_t<Iterator1, Iterator2>  
operator<=>(const reverse_iterator<Iterator1>& x,  
             const reverse_iterator<Iterator2>& y);  

Returns: \( y.\text{base}() \leftrightarrow x.\text{base}() \).
[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

```cpp
template<class Iterator1, class Iterator2>
constexpr auto operator-(  
    const reverse_iterator<Iterator1>& x,  
    const reverse_iterator<Iterator2>& y) -> decltype(y.base() - x.base());  

Returns: \( y.\text{base}() - x.\text{base}() \).
```
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(see below);

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&>()))

template<indirectly_swappable<Iterator> Iterator2>
friend constexpr void iter_swap(const reverse_iterator& x, 
    const reverse_iterator<Iterator2>& y) noexcept(see below);

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 to work 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. operator* returns the insert iterator itself. The assignment operator=(const T& x) is defined on insert iterators to allow writing into them, it inserts 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. back_insert_iterator inserts elements at the end of a container, front_insert_iterator inserts elements at the beginning of a container, and insert_iterator inserts elements where the iterator points to in a container. back_inserter, front_inserter, and inserter are three functions making the insert iterators out of a 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);

25.5.2.2.1 Operations [back.insert.iter.ops]

constexpr explicit back_insert_iterator(Container& x);
1
Effects: Initializes container with addressof(x).

constexpr back_insert_iterator& operator=(const typename Container::value_type& value);
2
Effects: As if by: container->push_back(value);
Returns: *this.

constexpr back_insert_iterator& operator=(typename Container::value_type&& value);
3
Effects: As if by: container->push_back(std::move(value));
Returns: *this.

constexpr back_insert_iterator& operator*();
Returns: *this.

constexpr back_insert_iterator& operator++();
4
constexpr back_insert_iterator operator++(int);
Returns: *this.

25.5.2.2 back_inserter [back.inserter]

template<class Container>
constexpr back_insert_iterator<Container> back_inserter(Container& x);

Returns: back_insert_iterator<Container>(x).

25.5.2.3 Class template front_insert_iterator [front.insert.iterator]

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);

§ 25.5.2.3
1003
constexpr front_insert_iterator& operator*();
constexpr front_insert_iterator& operator++();
constexpr front_insert_iterator operator++(int);
}

25.5.2.3.1 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.

constexpr front_insert_iterator& operator++(int);

25.5.2.3.2 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

namespace std {
  template<class Container>
  class insert_iterator {
    protected:
    Container* container;
    ranges::iterator_t<Container> iter;

    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 insert_iterator(Container& x, ranges::iterator_t<Container> i);
    constexpr insert_iterator& operator=(const typename Container::value_type& value);
    constexpr insert_iterator& operator=(typename Container::value_type&& value);
    constexpr insert_iterator& operator*();
    constexpr insert_iterator& operator++();
    constexpr insert_iterator& operator++(int);
  };
}

25.5.2.4.1 Operations

constexpr insert_iterator(Container& x, ranges::iterator_t<Container> i);
1 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.

25.5.2.4.2 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 Move iterators and sentinels

25.5.3.1 General

Class template move_iterator is an iterator adaptor with the same behavior as the underlying iterator except that its indirect operator implicitly converts the value returned by the underlying iterator's indirect operator to an rvalue. Some generic algorithms can be called with move iterators to replace copying with moving.

[Example 1:

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]

25.5.3.2 Class template move_iterator

namespace std {

template<class Iterator>
class move_iterator {

public:
using iterator_type = Iterator;
using iterator_concept = input_iterator_tag;
using iterator_category = see below;  // not always present
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);

§ 25.5.3.2
```cpp
cconstexpr const Iterator& base() const & noexcept;
cconstexpr Iterator base() &&;
cconstexpr reference operator*() const;
cconstexpr move_iterator& operator++();
cconstexpr auto operator++(int);
cconstexpr move_iterator& operator--();
cconstexpr move_iterator operator--(int);
cconstexpr move_iterator operator+(difference_type n) const;
cconstexpr move_iterator& operator+=(difference_type n);
cconstexpr move_iterator operator-(difference_type n) const;
cconstexpr move_iterator& operator-=(difference_type n);
cconstexpr reference operator[](difference_type n) const;

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);

friend constexpr iter_rvalue_reference_t<Iterator>
iter_move(const move_iterator& i)
noexcept(noexcept(ranges::iter_move(i.current)));

template<indirectly_swappable<Iterator> Iterator2>
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_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

(1.1) — `random_access_iterator_tag` if the type `iterator_traits<Iterator>::iterator_category` models derived from `random_access_iterator_tag`, and

(1.2) — `iterator_traits<Iterator>::iterator_category` otherwise.

### 25.5.3.3 Requirements

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).

### 25.5.3.4 Construction and assignment

1 `constexpr move_iterator();`

   **Effects:** Value-initializes `current`.

2 `constexpr explicit move_iterator(Iterator i);`

   **Effects:** Initializes `current` with `std::move(i)`.

   ```cpp
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`. 

§ 25.5.3.4
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.

25.5.3.5 Conversion [move.iter.op.conv]

constexpr const Iterator& base() const & noexcept;

Returns: current.

constexpr Iterator base() &&;

Returns: std::move(current).

25.5.3.6 Element access [move.iter.elem]

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);

25.5.3.7 Navigation [move.iter.nav]

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.
25.5.3.8 Comparisons

```cpp
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);
```

1. Constraints: `x.base() == y.base()` is well-formed and convertible to `bool`.
2. Returns: `x.base() == y.base()`.

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator<(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);
```

3. Constraints: `x.base() < y.base()` is well-formed and convertible to `bool`.
4. Returns: `x.base() < y.base()`.

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator>(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);
```

5. Constraints: `y.base() < x.base()` is well-formed and convertible to `bool`.
6. Returns: `y < x`.

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator<=(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);
```

7. Constraints: `y.base() < x.base()` is well-formed and convertible to `bool`.
8. Returns: `!(y < x)`.

```cpp
template<class Iterator1, class Iterator2>
constexpr bool operator>=(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);
```

9. Constraints: `x.base() < y.base()` is well-formed and convertible to `bool`.
10. Returns: `!(x < y)`.

```cpp
template<class Iterator1, three_way_comparable_with<Iterator1> Iterator2>
constexpr compare_three_way_result_t<Iterator1, Iterator2>
operator<=>(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y);
```

11. Returns: `x.base() <=> y.base()`.

25.5.3.9 Non-member functions

```cpp
template<class Iterator1, class Iterator2>
constexpr auto operator-(const move_iterator<Iterator1>& x, const move_iterator<Iterator2>& y)
-> decltype(x.base() - y.base());
```

1. Returns: `x.base() - y.base()`.

```cpp
template<class Iterator>
constexpr move_iterator<Iterator>
operator+(iter_difference_t<Iterator> n, const move_iterator<Iterator>& x);
```

2. Constraints: `x.base() + n` is well-formed and has type `Iterator`.
3. Returns: `x + n`.

§ 25.5.3.9
friend constexpr iter_rvalue_reference_t<Iterator>
iter_move(const move_iterator& i)
noexcept(noexcept(ranges::iter_move(i.current)));

Effects: Equivalent to: return ranges::iter_move(i.current);

 template<indirectly_swappable<Iterator> Iterator2>
friend constexpr void
iter_swap(const move_iterator& x, const move_iterator<Iterator2>& y)
noexcept(noexcept(ranges::iter_swap(x.current, y.current)));

Effects: Equivalent to: ranges::iter_swap(x.current, y.current).

template<class Iterator>
constexpr move_iterator<Iterator> make_move_iterator(Iterator i);

Returns: move_iterator<Iterator>(std::move(i)).

25.5.3.10 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) {
  std::ranges::copy_if(move_iterator<I>{first}, move_sentinel<S>{last}, out, pred);
}
```
—end example]

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
        };
    }

25.5.3.11 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.

25.5.4 Common iterators

25.5.4.1 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 s
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 decltype(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);
    }

§ 25.5.4.1
template<
  sized_sentinel_for<I> I2,
  sized_sentinel_for<S> 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 iter_rvalue_reference_t<I> 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;
  using value_type = iter_value_t<I>;
  using difference_type = iter_difference_t<I>;
  using pointer = see below;
  using reference = iter_reference_t<I>;
};

§ 25.5.4.2  Associated types
The nested typedef-names of the specialization of iterator_traits for common_iterator<I, S> are defined
as follows.

(1.1) — iterator_concept denotes forward_iterator_tag if I models forward_iterator; otherwise it
denotes input_iterator_tag.

(1.2) — iterator_category denotes forward_iterator_tag if the qualified-id iterator_traits<I>::iter-
ator_category is valid and denotes a type that models derived_from<forward_iterator_tag>;
otherwise it denotes input_iterator_tag.

(1.3) — 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.

§ 25.5.4.3  Constructors and conversions

castexpr common_iterator(I i);
  Effects: Initializes v_ as if by v_{in_place_type<I>, std::move(i)}.

castexpr 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>
  castexpr 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&> && assignable_from<S&, 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_.index().

Returns: *this

25.5.4.4 Accessors

constexpr decltype(auto) operator*();
constexpr decltype(auto) operator*() const
requires dereferenceable<const I>;

Preconditions: holds_alternative<I>(v_) is true.

Effects: Equivalent to: return *get<I>(v_);

constexpr decltype(auto) operator->() const
requires see below;

The expression in the requires-clause is equivalent to:

indirectly_readable<const I> &&
(requires(const I& i) { i.operator->(); } ||
is_reference_v<ioperator_reference_t<I>> ||
constructible_from<ioperator_value_t<I>, ioperator_reference_t<I>>)

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 ioperator_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:

class proxy {
  ioperator_value_t<I> keep_;  
  constexpr proxy(ioperator_reference_t<I>&& x) : keep_(std::move(x)) {}
  public:
    constexpr const ioperator_value_t<I>* operator->() const noexcept {
      return addressof(keep_);
    }
};

25.5.4.5 Navigation

constexpr common_iterator& operator++();

Preconditions: holds_alternative<I>(v_) is true.

Effects: Equivalent to ++get<I>(v_).

Returns: *this

constexpr decltype(auto) operator++(int);

Preconditions: holds_alternative<I>(v_) is true.

Effects: If I models forward_iterator, equivalent to:
common_iterator tmp = *this;
++*this;
return tmp;

Otherwise, if requires(I& i) { { *i++ } -> can-reference; } is true or
indirectly_readable<I> && constructible_from<iter_value_t<I>, iter_reference_t<I>> &&
move_constructible<iter_value_t<I>>
is false, equivalent to:
return get<I>(v_++)++;

Otherwise, equivalent to:
postfix-proxy p(**this);
++*this;
return p;

where postfix-proxy is the exposition-only class:
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_; 
    }
};

25.5.4.6 Comparisons
[common.iter.cmp]

```cpp
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);
```

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().

```cpp
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);
```

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().

```cpp
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);
```

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().

25.5.4.7 Customizations
[common.iter.cust]

```cpp
friend constexpr iter_rvalue_reference_t<I> iter_move(const common_iterator& i)
oxcept(noexcept(ranges::iter_move(declval<const I&>())))
requires input_iterator<I>;
```

1 Preconditions: holds_alternative<I>(i.v_) is true.
Effects: Equivalent to: `return ranges::iter_move(get<I>(i.v_));`

```cpp
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&>())))
```

Preconditions: `holds_alternative<I>(x.v_)` and `holds_alternative<I2>(y.v_)` are each true.

Effects: Equivalent to `ranges::iter_swap(get<I>(x.v_), get<I2>(y.v_));`

### 25.5.5 Default sentinel

```cpp
namespace std {
    struct default_sentinel_t {};
}
```

1. 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` (25.5.6.1)).

### 25.5.6 Counted iterators

#### 25.5.6.1 Class template counted_iterator

1. 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.

2. [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]

3. Two values `i1` and `i2` 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);
            template<class I2>
                requires assignable_from<I&, const I2&>
            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>;
        }
```
```cpp
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>;
constexpr counted_iterator operator--();
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>;

template<common_with<I> I2>
  friend constexpr bool operator==(const counted_iterator& x, const counted_iterator<I2>& y);
friend constexpr bool operator==(const counted_iterator& x, default_sentinel_t);

template<common_with<I> I2>
  friend constexpr strong_ordering operator<=>(const counted_iterator& x, const counted_iterator<I2>& y);

friend constexpr iter_rvalue_reference_t<I> iter_move(const counted_iterator& i)
  noexcept(noexcept(ranges::iter_move(i.current)))
  requires input_iterator<I>;

template<indirectly_swappable<I> I2>
  friend constexpr void iter_swap(const counted_iterator& x, const counted_iterator<I2>& y)
  noexcept(noexcept(ranges::iter_swap(x.current, y.current)));

private:
  I current = I();                // exposition only
  iter_difference_t<I> length = 0; // exposition only
};

template<input_iterator I>
  requires same_as<ITER_TRAITS(I), iterator_traits<I>> // see 25.3.4.1
struct iterator_traits<counted_iterator<I>> : iterator_traits<I> {
  using pointer = conditional_t<counted_iterator<I>,
    add_pointer_t<iterator_traits<I>::add_pointer_t<I>>, void>;
};
```
25.5.6.2 Constructors and conversions

```cpp
constexpr counted_iterator(I i, iter_difference_t<I> n);
```

1. **Preconditions**: \( n \geq 0 \).
2. **Effects**: Initializes `current` with `std::move(i)` and `length` with `n`.

```cpp
template<class I2>
requires convertible_to<const I2&, I>
constexpr counted_iterator(const counted_iterator<I2>& x);
```

3. **Effects**: Initializes `current` with `x.current` and `length` with `x.length`.

```cpp
template<class I2>
requires assignable_from<I&, const I2&>
constexpr counted_iterator& operator=(const counted_iterator<I2>& x);
```

4. **Effects**: Assigns `x.current` to `current` and `x.length` to `length`.
5. **Returns**: `*this`.

25.5.6.3 Accessors

```cpp
constexpr const I& base() const & noexcept;
```

1. **Effects**: Equivalent to: `return current;`

```cpp
constexpr I& base() &&;
```

2. **Returns**: `std::move(current)`.

```cpp
constexpr iter_difference_t<I> count() const noexcept;
```

3. **Effects**: Equivalent to: `return length;`

25.5.6.4 Element access

```cpp
constexpr decltype(auto) operator*();
```

1. **Effects**: Equivalent to: `return *current;`

```cpp
constexpr decltype(auto) operator*() const
requires dereferenceable<const I>;
```

2. **Preconditions**: `length > 0` is true.
3. **Effects**: Equivalent to: `return to_address(current);`

```cpp
constexpr decltype(auto) operator[](iter_difference_t<I> n) const
requires random_access_iterator<I>;
```

4. **Preconditions**: \( n < \text{length} \).
5. **Effects**: Equivalent to: `return current[n];`

25.5.6.5 Navigation

```cpp
constexpr counted_iterator& operator++();
```

1. **Preconditions**: `length > 0`.
2. **Effects**: Equivalent to:
   ```cpp
   ++current;
   --length;
   return *this;
   ```

```cpp
constexpr decltype(auto) operator++(int);
```

3. **Preconditions**: `length > 0`.
4. **Effects**: Equivalent to:
   ```cpp
   --length;
   ```
```cpp
try { return current++; }
catch(...) { ++length; throw; }

castexpr counted_iterator operator++(int)
requires forward_iterator<I>;

**Effects**: Equivalent to:

```cpp
counted_iterator tmp = *this;
++*this;
return tmp;
```

```cpp
castexpr counted_iterator& operator--()
requires bidirectional_iterator<I>;

**Effects**: Equivalent to:

```cpp
--current;
++length;
return *this;
```

```cpp
castexpr counted_iterator operator--(int)
requires bidirectional_iterator<I>;

**Effects**: Equivalent to:

```cpp
counted_iterator tmp = *this;
--*this;
return tmp;
```

```cpp
castexpr counted_iterator operator+(iter_difference_t<I> n) const
requires random_access_iterator<I>;

**Effects**: Equivalent to:

```cpp
return counted_iterator(current + n, length - n);
```

```cpp
friend castexpr counted_iterator operator+(iter_difference_t<I> n, const counted_iterator& x)
requires random_access_iterator<I>;

**Effects**: Equivalent to: return x + n;

```cpp
castexpr counted_iterator& operator+=(iter_difference_t<I> n)
requires random_access_iterator<I>;

**Preconditions**: n <= length.

**Effects**: Equivalent to:

```cpp
current += n;
length -= n;
return *this;
```

```cpp
castexpr counted_iterator operator-(iter_difference_t<I> n) const
requires random_access_iterator<I>;

**Effects**: Equivalent to: return counted_iterator(current - n, length + n);

```cpp
template<common_with<I> I2>
castexpr 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 (25.5.6.1).

**Effects**: Equivalent to: return y.length - x.length;

```cpp
friend castexpr iter_difference_t<I> operator-(
const counted_iterator& x, default_sentinel_t);

**Effects**: Equivalent to: return -x.length;

```cpp
friend castexpr iter_difference_t<I> operator-(
default_sentinel_t, const counted_iterator& y);

**Effects**: Equivalent to: return y.length;
```

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constexpr counted_iterator& operator-=(iter_difference_t<I> n)
    requires random_access_iterator<I>;

Preconditions: \( -n \leq \text{length} \).

Effects: Equivalent to:
    current -= n;
    length += n;
    return *this;

25.5.6.6 Comparisons

template<common_with<I> I2>
    friend constexpr bool operator==(const counted_iterator& x, const counted_iterator<I2>& y);

Preconditions: \( x \) and \( y \) refer to elements of the same sequence (25.5.6.1).

Effects: Equivalent to: \( \text{return } x.\text{length} = y.\text{length} \);

friend constexpr bool operator==(const counted_iterator& x, default_sentinel_t);

Effects: Equivalent to: \( \text{return } x.\text{length} = 0 \);

template<common_with<I> I2>
    friend constexpr strong_ordering operator<=>(const counted_iterator& x, const counted_iterator<I2>& y);

Preconditions: \( x \) and \( y \) refer to elements of the same sequence (25.5.6.1).

Effects: Equivalent to: \( \text{return } y.\text{length} <=> x.\text{length} \);

[Note 1: The argument order in the Effects: element is reversed because \( \text{length} \) counts down, not up. — end note]

25.5.6.7 Customizations

friend constexpr iter_rvalue_reference_t<I>
    iter_move(const counted_iterator& i)
    noexcept(noexcept(ranges::iter_move(i.current)))
    requires input_iterator<I>;

Preconditions: \( i.\text{length} > 0 \) is true.

Effects: Equivalent to: \( \text{return } \text{ranges::iter_move}(i.\text{current}) \);

template<indirectly_swappable<I> I2>
    friend constexpr void
    iter_swap(const counted_iterator& x, const counted_iterator<I2>& y)
    noexcept(noexcept(ranges::iter_swap(x.current, y.current)));

Preconditions: Both \( x.\text{length} > 0 \) and \( y.\text{length} > 0 \) are true.

Effects: Equivalent to \( \text{ranges::iter_swap}(x.\text{current}, y.\text{current}) \).

25.5.7 Unreachable sentinel

Class unreachable_sentinel_t can be used with any weakly_incrementable type to denote the “upper bound” of an unbounded interval.

[Example 1:
    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]
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:
    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.

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);
        ~istream_iterator() = default;
        istream_iterator& operator=(const istream_iterator& x) = default;
        istream_iterator& operator=(const istream_iterator& x) = 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
    }
}

2 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.

```cpp
istream_iterator(istream_type& s);
```

**Effects**: Initializes `in_stream` with `addressof(s)`, value-initializes `value`, and then calls `operator++()`.

**Postconditions**: `in_stream == x.in_stream` is true.

**Remarks**: If `is_trivially_copy_constructible_v<T>` is true, then this constructor is trivial.

```cpp
~istream_iterator() = default;
```

**Remarks**: If `is_trivially_destructible_v<T>` is true, then this destructor is trivial.

25.6.2.3 Operations

```cpp
const T& operator*() const;
```

**Preconditions**: `in_stream != nullptr` is true.

**Returns**: `value`.

```cpp
const T* operator->() const;
```

**Preconditions**: `in_stream != nullptr` is true.

**Returns**: `addressof(value)`.

```cpp
istream_iterator& operator++();
```

**Preconditions**: `in_stream != nullptr` is true.

**Effects**: Equivalent to:

```
if (!(*in_stream >> value))
in_stream = nullptr;
```

**Returns**: `*this`.

```cpp
istream_iterator operator++(int);
```

**Preconditions**: `in_stream != nullptr` is true.

**Effects**: Equivalent to:

```
istream_iterator tmp = *this;
++*this;
return tmp;
```

```cpp
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);
```

**Returns**: `x.in_stream == y.in_stream`.

```cpp
friend bool operator==(const istream_iterator& i, default_sentinel_t);
```

**Returns**: `!i.in_stream`.

25.6.3 Class template ostream_iterator

### 25.6.3.1 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.
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;
    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(const ostream_iterator& x);
    ~ostream_iterator();
    
    ostream_iterator& operator=(const ostream_iterator&);
    ostream_iterator& operator=(const T& value);
    
    ostream_iterator& operator*();
    ostream_iterator& operator++();
    ostream_iterator& operator++(int);
};

25.6.3.2 Constructors and destructor

ostream_iterator(ostream_type& s);

1 Effects: Initializes out_stream with addressof(s) and delim with nullptr.

ostream_iterator(ostream_type& s, const charT* delimiter);

2 Effects: Initializes out_stream with addressof(s) and delim with delimiter.

25.6.3.3 Operations

ostream_iterator& operator=(const T& value);

1 Effects: As if by:
    *out_stream << value;
    if (delim)
        *out_stream << delim;
    return *this;

ostream_iterator& operator*();

2 Returns: *this.

ostream_iterator& operator++();
ostream_iterator& operator++(int);

3 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.

2 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>;
                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 [istreambuf.iterator.proxy]

1 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
            charT keep_;  
            basic_streambuf<charT,traits>* sbuf_;  
            proxy(charT c, basic_streambuf<charT,traits>* sbuf)
                : keep_(c), sbuf_(sbuf) { }
            public:
                charT operator*() { return keep_; }  
            }
        }

§ 25.6.4.2
25.6.4.3 Constructors [istreambuf.iterator.cons]

1 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.

```cpp
constexpr istreambuf_iterator() noexcept;
constexpr istreambuf_iterator(default_sentinel_t) noexcept;
```

2 **Effects**: Initializes `sbuf_` with `nullptr`.

```cpp
istreambuf_iterator(istream_type& s) noexcept;
```

3 **Effects**: Initializes `sbuf_` with `s.rdbuf()`.

```cpp
istreambuf_iterator(streambuf_type* s) noexcept;
```

4 **Effects**: Initializes `sbuf_` with `s`.

```cpp
istreambuf_iterator(const proxy& p) noexcept;
```

5 **Effects**: Initializes `sbuf_` with `p.sbuf_`.

25.6.4.4 Operations [istreambuf.iterator.ops]

```cpp
charT operator*() const;
```

1 **Returns**: The character obtained via the `streambuf` member `sbuf_->sgetc()`.

```cpp
istreambuf_iterator& operator++();
```

2 **Effects**: As if by `sbuf_->sbumpc()`.

3 **Returns**: `*this`.

```cpp
proxy operator++(int);
```

4 **Returns**: `proxy(sbuf_->sbumpc(), sbuf_)`.

```cpp
bool equal(const istreambuf_iterator& b) const;
```

5 **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);
```

6 **Returns**: `a.equal(b)`.

```cpp
friend bool operator==(const istreambuf_iterator& i, default_sentinel_t s);
```

7 **Returns**: `i.equal(s)`.

25.6.5 Class template ostreambuf_iterator [ostreambuf.iterator]

25.6.5.1 General [ostreambuf.iterator.general]

1 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_iterator(ostream_type& s) noexcept;
1  Preconditions: s.rdbuf() is not a null pointer.
2  Effects: Initializes sbuf_ with s.rdbuf().

ostreambuf_iterator(streambuf_type* s) noexcept;
3  Preconditions: s is not a null pointer.
4  Effects: Initializes sbuf_ with s.

25.6.5.3 Operations

ostreambuf_iterator& operator=(charT c);
1  Effects: If failed() yields false, calls sbuf_->sputc(c); otherwise has no effect.
2  Returns: *this.

ostreambuf_iterator& operator*();
3  Returns: *this.

ostreambuf_iterator& operator++();
ostreambuf_iterator& operator++(int);
4  Returns: *this.

bool failed() const noexcept;
5  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

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), <forward_list> (24.3.4), <list> (24.3.5), <map> (24.4.2), <regex> (32.3), <set> (24.4.3), <span> (24.7.2), <string> (23.4.2), <string_view> (23.3.2), <unordered_map> (24.5.2), <unordered_set> (24.5.3), and <vector> (24.3.6). Each of these templates is a designated customization point (16.4.5.2.1).

template<class C> constexpr auto begin(C& c) -> decltype(c.begin());
template<class C> constexpr auto begin(const C& c) -> decltype(c.begin());
1  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());
2  Returns: c.end().

template<class T, size_t N> constexpr T* begin(T (&array)[N]) noexcept;
3  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(C& c) -> decltype(c.rbegin());
template<class C> constexpr auto rbegin(const C& c) -> decltype(c.rbegin());

Returns: c.rbegin().

template<class T, size_t N> constexpr reverse_iterator<T*> rbegin(T (&array)[N]);

Returns: reverse_iterator<T*>(array + N).

template<class T, size_t N> constexpr reverse_iterator<T*> rend(T (&array)[N]);

Returns: reverse_iterator<T*>(array).

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 T, size_t N> constexpr size_t size(const T (&array)[N]) noexcept;

Returns: N.

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 T, ptrdiff_t N> constexpr ptrdiff_t ssize(const T (&array)[N]) noexcept;

Returns: N.

template<class C> [[nodiscard]] constexpr auto empty(const C& c) -> decltype(c.empty());

Returns: c.empty().

template<class T, size_t N> [[nodiscard]] constexpr bool empty(const T (&array)[N]) noexcept;

Returns: false.
template<class E> [[nodiscard]] constexpr bool empty(initializer_list<E> il) noexcept;

Returns: il.size() == 0.

template<class C> constexpr auto data(C& c) -> decltype(c.data());
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 as summarized in Table 88.

Table 88: Ranges library summary

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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;
        inline constexpr unspecified end = unspecified;
        inline constexpr unspecified cbegin = unspecified;
        inline constexpr unspecified cend = unspecified;
        inline constexpr unspecified rbegin = unspecified;
        inline constexpr unspecified rend = unspecified;
        inline constexpr unspecified crbegin = unspecified;
        inline constexpr unspecified crend = unspecified;
        inline constexpr unspecified size = unspecified;
        inline constexpr unspecified ssize = unspecified;
        inline constexpr unspecified empty = unspecified;
        inline constexpr unspecified data = unspecified;
        inline constexpr unspecified cdata = unspecified;
    }

    // 26.4, ranges
    template<class T> concept range = see below;

    template<class T> inline constexpr bool enable_borrowed_range = false;

    template<class T> concept borrowed_range = see below;

    template<class T> using iterator_t = decltype(ranges::begin(declval<T &>()));
    template<class R> using sentinel_t = decltype(ranges::end(declval<R &>()));
    template<class R> using range_difference_t = iter_difference_t<iterator_t<R>>;
```
template<sized_range R>
  using range_size_t = decltype(ranges::size(declval<R&>()));

template<sized_range R>
  using range_value_t = iter_value_t<iterator_t<R>>;

template<sized_range R>
  using range_reference_t = iter_reference_t<iterator_t<R>>;

template<sized_range R>
  using range_rvalue_reference_t = iter_rvalue_reference_t<iterator_t<R>>;

// 26.4.3, sized ranges
template<class>
  inline constexpr bool disable_sized_range = false;

template<class T>
  concept sized_range = see below;

// 26.4.4, views
template<class T>
  inline constexpr bool enable_view = see below;

struct view_base {};

template<class T>
  concept view = see below;

// 26.4.5, other range refinements
template<class R, class T>
  concept output_range = see below;

template<class T>
  concept input_range = see below;

template<class T>
  concept forward_range = see below;

template<class T>
  concept bidirectional_range = see below;

template<class T>
  concept random_access_range = see below;

template<class T>
  concept contiguous_range = see below;

template<class T>
  concept common_range = see below;

template<class T>
  concept viewable_range = see below;

// 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;

// 26.5.4, sub-ranges
enum class subrange_kind : bool { unsized, sized };

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;

template<class I, class S, subrange_kind K>
  inline constexpr bool enable_borrowed_range<subrange<I, S, K>> = true;

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// 26.5.5, dangling iterator handling
struct dangling;

template<range R>
    using borrowed_iterator_t = see below;

template<range R>
    using borrowed_subrange_t = see below;

// 26.5.6, range conversions
template<class C, input_range R, class... Args> requires (!view<C>)
    constexpr C to(R&& r, Args&&... args);

template<template<class...> class C, input_range R, class... Args>
    constexpr auto to(R&& r, Args&&... args) -> see below;

template<class C, class... Args> requires (!view<C>)
    constexpr auto to(Args&&... args) -> see below;

// 26.6.2, empty view
template<class T>
    requires is_object_v<T>
    class empty_view;

namespace views {
    template<class T>
        inline constexpr empty_view<T> empty{};
}

// 26.6.3, single view
template<copy_constructible T>
    requires is_object_v<T>
    class single_view;

namespace views { inline constexpr unspecified single = unspecified; }

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;

namespace views {
    template<class W, class Bound>
        inline constexpr iota_view<iota_view<W, Bound>> = true;
}

// 26.6.5, istream view
template<movable Val, class CharT, class Traits = char_traits<CharT>>
    requires see below
    class basic_istream_view;

namespace views {
    template<class T> inline 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 { };

// 26.7.5, all view
namespace views {
    inline constexpr unspecified all = unspecified;

    template<viewable_range R>
        using all_t = decltype(all(declval<R>()));
}

template<range R>
    requires is_object_v<R>
class ref_view;

template<class T>
    inline constexpr bool enable_borrowed_range<ref_view<T>> = true;

// 26.7.5.3, owning view
template<range R>
    requires see below
class owning_view;

template<class T>
    inline constexpr bool enable_borrowed_range<owning_view<T>> = enable_borrowed_range<T>;

// 26.7.6, 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; }

// 26.7.7, transform view
template<input_range V, copy_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; }

// 26.7.8, take view
template<class T>
    inline constexpr bool enable_borrowed_range<take_view<T>> = enable_borrowed_range<T>;

namespace views { inline constexpr unspecified take = unspecified; }

// 26.7.9,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; }

// 26.7.10, drop view
template<class V>
    class drop_view;

§ 26.2
template<class T>
    inline constexpr bool enable_borrowed_range<drop_view<T>> = enable_borrowed_range<T>;

namespace views { inline constexpr unspecified drop = unspecified; }

// 26.7.11, drop while view
template<input_range V, class Pred>
    requires input_range<V> && is_object_v<Pred> &&
        indirect_unary_predicate<const Pred, iterator_t<V>>
    class drop_while_view;

template<class T, class Pred>
    inline constexpr bool enable_borrowed_range<drop_while_view<T, Pred>> =
    enable_borrowed_range<T>;

namespace views { inline constexpr unspecified drop_while = unspecified; }

// 26.7.12, 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; }

// 26.7.13, join with view
template<class R, class P>
    concept compatible_joinable_ranges = see below; // exposition only
template<input_range V, forward_range Pattern>
    requires view<V> && input_range<range_reference_t<V>>
        && view<Pattern>
        && compatible_joinable_ranges<range_reference_t<V>, Pattern>
    class join_with_view;

namespace views { inline constexpr unspecified join_with = unspecified; }

// 26.7.14, 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;

// 26.7.15, split view
template<formal_range V, formal_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 lazy_split = unspecified;
inline constexpr unspecified split = unspecified;
}

// 26.7.16, counted view
namespace views { inline constexpr unspecified counted = unspecified; }

// 26.7.17, common view
template<input_view V>
    requires (!common_range<V> && copyable<iterator_t<V>>)
    class common_view;

§ 26.2
```cpp
// 26.7.18, reverse view
template<class T>
inline constexpr bool enable_borrowed_range<common_view<T>> = enable_borrowed_range<T>;
namespace views { inline constexpr unspecified common = unspecified; }

// 26.7.19, elements view
template<input_range V, size_t N>
requires see below
class elements_view;

template<class T, size_t N>
inline constexpr bool enable_borrowed_range<elements_view<T, N>> = enable_borrowed_range<T>;

template<class R>
using keys_view = elements_view<R, 0>;
template<class R>
using values_view = elements_view<R, 1>;

namespace views {
  template<size_t N>
  inline constexpr unspecified elements = unspecified;
  inline constexpr auto keys = elements<0>;
  inline constexpr auto values = elements<1>;
}

// 26.7.20, zip view
template<input_range... Views>
requires (view<Views> && ...) && (sizeof...(Views) > 0)
class zip_view;

template<class... Views>
inline constexpr bool enable_borrowed_range<zip_view<Views...>> =
  (enable_borrowed_range<Views> && ...);

namespace views { inline constexpr unspecified zip = unspecified; }

// 26.7.21, zip transform view
template<copy_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;

namespace views { inline constexpr unspecified zip_transform = unspecified; }

// 26.7.22, adjacent view
template<forward_range V, size_t N>
requires view<V> && (N > 0)
class adjacent_view;

template<class V, size_t N>
inline constexpr bool enable_borrowed_range<adjacent_view<V, N>> =
  enable_borrowed_range<V>;
```
namespace views {
    template<size_t N>
    inline constexpr unspecified adjacent = unspecified;
    inline constexpr auto pairwise = adjacent<2>;
}

// 26.7.23, adjacent transform view
template<forward_range V, copy_constructible F, size_t N>
requires see below
class adjacent_transform_view;

namespace views {
    template<size_t N>
    inline constexpr unspecified adjacent_transform = unspecified;
    inline constexpr auto pairwise_transform = adjacent_transform<2>;
}

// 26.7.24, chunk view
template<view V>
requires input_range<V>
class chunk_view;

template<view V>
requires forward_range<V>
class chunk_view<V>;

template<class V>
inline constexpr bool enable_borrowed_range<chunk_view<V>> =
    forward_range<V> && enable_borrowed_range<V>;

namespace views { inline constexpr unspecified chunk = unspecified; }

// 26.7.25, slide view
template<view V>
requires forward_range<V>
class slide_view;

template<class V>
inline constexpr bool enable_borrowed_range<slide_view<V>> =
    enable_borrowed_range<V>;

namespace views { inline constexpr unspecified slide = unspecified; }

// 26.7.26, 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;

namespace views { inline constexpr unspecified chunk_by = unspecified; }

namespace std {
    namespace views = ranges::views;

template<class T> struct tuple_size;
    template<size_t I, class T> struct tuple_element;

    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; }; inline constexpr from_range_t from_range{};

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 <iterator> (25.2) is included.

Within 26.3, the reified object of a subexpression E denotes

(2.1) — the same object as E if E is a glvalue, or
(2.2) — 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 (16.3.3.3.6).

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 an rvalue and enable_borrowed_range<remove_cv_t<T>> is false, ranges::begin(E) is ill-formed.
(2.2) — 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 expression-equivalent to t + 0.
(2.3) — Otherwise, if T is an array type, ranges::begin(E) is expression-equivalent to t.begin() 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()).
(2.4) — Otherwise, if T is a class or enumeration type and auto(begin(t)) is a valid expression whose type models input_or_output_iterator with overload resolution performed in a context in which unqualified lookup for begin finds only the declarations

    void begin(auto&) = delete;
    void begin(const auto&) = delete;

    then ranges::begin(E) is expression-equivalent to auto(begin(t)) with overload resolution performed in the above context.
(2.5) — 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]

(2.6) — Otherwise, ranges::begin(E) is ill-formed.

[Note 2: Whenever ranges::begin(E) is a valid expression, its type models input_or_output_iterator. — end note]
26.3.3  `ranges::end` [range.access.end]

1 The name `ranges::end` denotes a customization point object (16.3.3.3.6).
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 an rvalue and `enable_borrowed_range<remove_cv_t<T>>` is false, `ranges::end(E)` is ill-formed.
   (2.2) — 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.
   (2.3) — Otherwise, if T is an array of unknown bound, `ranges::end(E)` is ill-formed.
   (2.4) — Otherwise, if T is an array, `ranges::end(E)` is expression-equivalent to `t + extent_v<T>.
   (2.5) — 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())`.
   (2.6) — Otherwise, `ranges::end(E)` is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when `ranges::end(E)` appears in the immediate context of a template instantiation. — end note]

4 [Note 2: Whenever `ranges::end(E)` is a valid expression, the types S and I of the expressions `ranges::end(E)` and `ranges::begin(E)` model `sentinel_for<S, I>`. — end note]

26.3.4  `ranges::cbegin` [range.access.cbegin]

1 The name `ranges::cbegin` denotes a customization point object (16.3.3.3.6). The expression `ranges::cbegin(E)` for a subexpression E of type T is expression-equivalent to:
   (1.1) — `ranges::begin(static_cast<const T&>(E))` if E is an lvalue.
   (1.2) — Otherwise, `ranges::begin(static_cast<const T&&>(E))`.

2 [Note 1: Whenever `ranges::cbegin(E)` is a valid expression, its type models `input_or_output_iterator`. — end note]

26.3.5  `ranges::cend` [range.access.cend]

1 The name `ranges::cend` denotes a customization point object (16.3.3.3.6). The expression `ranges::cend(E)` for a subexpression E of type T is expression-equivalent to:
   (1.1) — `ranges::end(static_cast<const T&>(E))` if E is an lvalue.
   (1.2) — Otherwise, `ranges::end(static_cast<const T&&>(E))`.

2 [Note 1: Whenever `ranges::cend(E)` is a valid expression, the types S and I of the expressions `ranges::cend(E)` and `ranges::cbegin(E)` model `sentinel_for<S, I>`. — end note]

26.3.6  `ranges::rbegin` [range.access.rbegine]

1 The name `ranges::rbegin` denotes a customization point object (16.3.3.3.6).
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 an rvalue and `enable_borrowed_range<remove_cv_t<T>>` is false, `ranges::rbegin(E)` is ill-formed.
   (2.2) — Otherwise, if T is an array type (9.3.4.5) and `remove_all_extents_t<T>` is an incomplete type, `ranges::rbegin(E)` is ill-formed with no diagnostic required.
   (2.3) — Otherwise, if `auto(t.rbegin())` is a valid expression whose type models `input_or_output_iterator`, `ranges::rbegin(E)` is expression-equivalent to `auto(t.rbegin())`.

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Otherwise, if $T$ is a class or enumeration type and $\text{auto}(\text{rbegin}(t))$ is a valid expression whose type models `input_or_output_iterator` with overload resolution performed in a context in which unqualified lookup for `rbegin` finds only the declarations

```c++
void rbegin(auto&) = delete;
void rbegin(const auto&) = delete;
```

then `ranges::rbegin(E)` is expression-equivalent to $\text{auto}(\text{rbegin}(t))$ with overload resolution performed in the above context.

Otherwise, if both `ranges::begin(t)` and `ranges::end(t)` are valid expressions of the same type which models `bidirectional_iterator` (25.3.4.12), `ranges::rbegin(E)` is expression-equivalent to `make_reverse_iterator(ranges::end(t))`.

Otherwise, `ranges::rbegin(E)` is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when `ranges::rbegin(E)` appears in the immediate context of a template instantiation. — end note]

4 [Note 2: Whenever `ranges::rbegin(E)` is a valid expression, its type models `input_or_output_iterator`. — end note]

### 26.3.7 ranges::rend

The name `ranges::rend` denotes a customization point object (16.3.3.3.6).

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::rend(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::rend(E)` is ill-formed with no diagnostic required.

3

- Otherwise, if `auto(t.rend())` is a valid expression whose type models `sentinel_for<decltype(ranges::rbegin(E))>` then `ranges::rend(E)` is expression-equivalent to `auto(t.rend())`.

4

- Otherwise, if $T$ is a class or enumeration type and `auto(rend(t))` is a valid expression whose type models `sentinel_for<decltype(ranges::rbegin(E))>` with overload resolution performed in a context in which unqualified lookup for `rend` finds only the declarations

```c++
void rend(auto&) = delete;
void rend(const auto&) = delete;
```

then `ranges::rend(E)` is expression-equivalent to `auto(rend(t))` with overload resolution performed in the above context.

Otherwise, `ranges::rend(E)` is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when `ranges::rend(E)` appears in the immediate context of a template instantiation. — end note]

4 [Note 2: Whenever `ranges::rend(E)` is a valid expression, the types $S$ and $I$ of the expressions `ranges::rend(E)` and `ranges::rbegin(E)` model `sentinel_for<S, I>`. — end note]

### 26.3.8 ranges::crbegin

The name `ranges::crbegin` denotes a customization point object (16.3.3.3.6). The expression `ranges::crbegin(E)` for a subexpression $E$ of type $T$ is expression-equivalent to:

1

- `ranges::rbegin(static_cast<const T&>(E))` if $E$ is an lvalue.

2

- Otherwise, `ranges::rbegin(static_cast<const T&&>(E))`.

3 [Note 1: Whenever `ranges::crbegin(E)` is a valid expression, the types $S$ and $I$ of the expressions `ranges::rend(E)` and `ranges::rbegin(E)` model `sentinel_for<S, I>`. — end note]

### 26.3.9 ranges::crend

The name `ranges::crend` denotes a customization point object (16.3.3.3.6). The expression `ranges::crend(E)` for a subexpression $E$ of type $T$ is expression-equivalent to:
ranges::rend(static_cast<const T&>(E)) if E is an lvalue.

Otherwise, ranges::rend(static_cast<const T&&>(E)).

[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>. — end note]

26.3.10 ranges::size

The name ranges::size denotes a customization point object (16.3.3.3.6).

Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. Then:

— If T is an array of unknown bound (9.3.4.5), ranges::size(E) is ill-formed.

— Otherwise, if T is an array type, ranges::size(E) is expression-equivalent to auto(extent_v<T>).

— 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()).

— Otherwise, if T is a class or enumeration type, disable_sized_range<remove_cv_t<T>> is false and auto(size(t)) is a valid expression of integer-like type with overload resolution performed in a context in which unqualified lookup for size finds only the declarations

```cpp
void size(auto&) = delete;
void size(const auto&) = delete;
```

then ranges::size(E) is expression-equivalent to auto(size(t)) with overload resolution performed in the above context.

— Otherwise, if to_unsigned-like(ranges::end(t) - ranges::begin(t)) (26.2) is a valid expression and the types I and S of ranges::begin(t) and ranges::end(t) (respectively) model both sized_sentinel_for<S, I> (25.3.4.8) and forward_iterator<I>, then ranges::size(E) is expression-equivalent to to_unsigned-like(ranges::end(t) - ranges::begin(t)).

— Otherwise, ranges::size(E) is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when ranges::size(E) appears in the immediate context of a template instantiation. — end note]

4 [Note 2: Whenever ranges::size(E) is a valid expression, its type is integer-like. — end note]

26.3.11 ranges::ssize

The name ranges::ssize denotes a customization point object (16.3.3.3.6).

Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. If ranges::size(t) is ill-formed, ranges::ssize(E) is ill-formed. Otherwise let D be make_signed-like-t<decltype(ranges::size(t))>, or ptrdiff_t if it is wider than that type; ranges::ssize(E) is expression-equivalent to static_cast<D>(ranges::size(t)).

26.3.12 ranges::empty

The name ranges::empty denotes a customization point object (16.3.3.3.6).

Given a subexpression E with type T, let t be an lvalue that denotes the reified object for E. Then:

— If T is an array of unknown bound (9.3.4.5), ranges::empty(E) is ill-formed.

— Otherwise, if bool(t.empty()) is a valid expression, ranges::empty(E) is expression-equivalent to bool(t.empty()).

— Otherwise, if (ranges::size(t) == 0) is a valid expression, ranges::empty(E) is expression-equivalent to (ranges::size(t) == 0).

— Otherwise, if bool(ranges::begin(t) == ranges::end(t)) is a valid expression and the type of ranges::begin(t) models forward_iterator, ranges::empty(E) is expression-equivalent to bool(ranges::begin(t) == ranges::end(t)).

— Otherwise, ranges::empty(E) is ill-formed.

3 [Note 1: Diagnosable ill-formed cases above result in substitution failure when ranges::empty(E) appears in the immediate context of a template instantiation. — end note]

4 [Note 2: Whenever ranges::empty(E) is a valid expression, it has type bool. — end note]
26.3.13 ranges::data

The name ranges::data denotes a customization point object (16.3.3.6).

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::data(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::data(E) is ill-formed with no diagnostic required.
3. Otherwise, if auto(t.data()) is a valid expression of pointer to object type, ranges::data(E) is expression-equivalent to auto(t.data()).
4. Otherwise, ranges::data(E) is ill-formed.

[Note 1: Diagnosable ill-formed cases above result in substitution failure when ranges::data(E) appears in the immediate context of a template instantiation. —end note]

26.3.14 ranges::cdata

The name ranges::cdata denotes a customization point object (16.3.3.6). The expression ranges::cdata(E) for a subexpression E of type T is expression-equivalent to:

1. ranges::data(static_cast<const T&>(E)) if E is an lvalue.
2. Otherwise, ranges::data(static_cast<const T&&>(E)).

[Note 1: Whenever ranges::cdata(E) is a valid expression, it has pointer to object type. —end note]

26.4 Range requirements

26.4.1 General

Ranges are an abstraction that allow 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.

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 O(1). The view concept specifies requirements on a range type to provide operations with predictable complexity.

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

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);
    };
```

The required expressions ranges::begin(t) and ranges::end(t) of the range concept do not require implicit expression variations (18.2).

Given an expression t such that decltype((t)) is T& T models range only if
— [ranges::begin(t), ranges::end(t)] denotes a range (25.3.1),
— both ranges::begin(t) and ranges::end(t) are amortized constant time and non-modifying, and
— if the type of ranges::begin(t) models forward_iterator, ranges::begin(t) is equality-preserving.

[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]

```cpp
template<class>
inline 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.

```cpp
[Example 1: Each specialization S of class template subrange (26.5.4) models borrowed_range because
(8.1) — enable_borrowed_range<S> is specialized to have the value true, and
(8.2) — 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.

```cpp
template<class T>
concept sized_range =
  range<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]

```cpp
template<class>
inline 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.

```cpp
[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 [range.view]

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).

```cpp
template<class T>
concept view =
    range<T> && movable<T> && enable_view<T>;
```

1. **T models view only if:**

   - T has O(1) move construction; and
   - 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 O(N + M) destruction; and
   - copy_constructible<T> is false, or T has O(1) copy construction; and
   - copyable<T> is false, or copy assignment of an object of type T is no more complex than destruction followed by copy construction.

2. [Note 1: The constraints on copying and moving imply that a moved-from object of type T has O(1) destruction. — end note]

3. [Example 1: Examples of views are:

   - A range type that wraps a pair of iterators.
   - A range type that holds its elements by shared_ptr and shares ownership with all its copies.
   - A range type that generates its elements on demand.

A container such as vector<string> does not meet the semantic requirements of view since copying the container copies all of the elements, which cannot be done in constant time. — end example]

4. Since the difference between range and view is largely semantic, the two are differentiated with the help of enable_view.

5. Remarks: Pursuant to 16.4.5.2.1, users may specialize enable_view to true for cv-unqualified program-defined types which model view, and false for types which do not. Such specializations shall be usable in constant expressions (7.7) and have type const bool.

26.4.5 Other range refinements [range.refinements]

1. The output_range concept specifies requirements of a range type for which ranges::begin returns a model of output_iterator (25.3.4.10). input_range, forward_range, bidirectional_range, and random_access_range are defined similarly.

```cpp
template<class R, class T>
concept output_range =
    range<R> && output_iterator<iterator_t<R>, T>;

template<class T>
concept input_range =
    range<T> && input_iterator<iterator_t<T>>;

template<class T>
concept forward_range =
    range<T> && forward_iterator<iterator_t<T>>;
```
template<class T>
concept bidirectional_range =
  forward_range<T> && bidirectional_iterator<iterator_t<T>>;

template<class T>
concept random_access_range =
  bidirectional_range<T> && random_access_iterator<iterator_t<T>>;

2 contiguous_range additionally requires that the 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>>>;
  };

3 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.

4 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>>;

5 For a type R, is-initializer-list<R> is true if and only if remove_cvref_t<R> is a specialization of initializer_list.

6 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>))));

26.5 Range utilities [range.utility]
26.5.1 General [range.utility.general]
1 The components in 26.5 are general utilities for representing and manipulating ranges.

26.5.2 Helper concepts [range.utility.helpers]
1 Many of the types in subclause 26.5 are specified in terms of the following exposition-only concepts:

template<class R>
concept simple-view =
  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 =
  input_iterator<I> && (is_pointer_v<I> || requires(I i) { i.operator->(); });

template<class T, class U>
concept different-from =
  !same_as<remove_cvref_t<T>, remove_cvref_t<U>>;
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 forward_range<D> {
        return ranges::begin(derived()) == ranges::end(derived());
      }
      constexpr bool empty() const requires forward_range<const D> {
        return ranges::begin(derived()) == ranges::end(derived());
      }

      constexpr explicit operator bool() requires requires { ranges::empty(derived()); } {
        return !ranges::empty(derived());
      }
      constexpr explicit operator bool() const requires requires { ranges::empty(derived()); } {
        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 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 ranges::end(derived()) - ranges::begin(derived());
      }

      constexpr decltype(auto) front() requires forward_range<D>; // bidirectional_range<D>;
      constexpr decltype(auto) front() const requires forward_range<const D>; // bidirectional_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];
      // }
  }
}
```
The template parameter \( D \) for \view_interface\ may be an incomplete type. Before any member of the resulting specialization of \view_interface\ other than special member functions is referenced, \( D \) shall be complete, and model both \derived_from<\view_interface<D>>\ and \view\.

### 26.5.3.2 Members

[view.interface.members]

```cpp
constexpr decltype(auto) front() requires forward_range<D>; // Preconditions: !empty() is true.
constexpr decltype(auto) front() const requires forward_range<const D>;
```

```cpp
constexpr decltype(auto) back() requires bidirectional_range<D> && common_range<D>; // Preconditions: !empty() is true.
constexpr decltype(auto) back() const requires bidirectional_range<const D> && common_range<const D>;
```

### 26.5.4 Sub-ranges

[range.subrange]

#### 26.5.4.1 General

[range.subrange.general]

The \subrange\ class template combines together an iterator and a sentinel into a single object that models the \view\ concept. Additionally, it models the \sized_range\ concept when the final template parameter is \subrange_kind::sized\.

```cpp
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_non_slicing<From, To> &&
        !uses-nonqualification-pointer-conversion<decay_t<From>, decay_t<To>>;

    template<class T>
    concept pair-like = // exposition only
        !is_reference_v<T> && requires(T t) {
            typename tuple_size<T>::type; // ensures tuple_size<T> is complete
            requires derived_from<tuple_size<T>, integral_constant<size_t, 2>>;
            typename tuple_element_t<0, remove_const_t<T>>;
            typename tuple_element_t<1, remove_const_t<T>>;
            { std::get<0>(t) } -> convertible_to<const tuple_element_t<0, T>>&;
            { std::get<1>(t) } -> convertible_to<const tuple_element_t<1, T>>&;
        };

    template<class T, class U, class V>
    concept pair-like-convertible-from = // exposition only
        !range<T> && pair-like<T> &&
        constructible_from<T, U, V> &&
        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
    // when 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 = 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
    // when 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);
};

§ 26.5.4.1 1044
? 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>;
```

```
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);
```

```
template<size_t N, class I, class S, subrange_kind K>
requires (N < 2)
constexpr auto get(subrange<I, S, K>&& r);
```

```
namespace std {
  using ranges::get;
}
```

### 26.5.4.2 Constructors and conversions

**constructor**

```
constexpr subrange(convertible-to-non-slicing<I> auto i, S s) requires (!StoreSize);
```

1. **Preconditions:** \([i, s)\) is a valid range.
2. **Effects:** Initializes `\(\text{begin}_i\)` with `std::move(i)` and `\(\text{end}_s\)` with `s`.

```
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);
```

3. **Preconditions:** \([i, s)\) is a valid range, and \(n == \text{to-unsigned-like(ranges::distance}(i, s))\) is true.
4. **Effects:** Initializes `\(\text{begin}_i\)` with `std::move(i)` and `\(\text{end}_s\)` with `s`. If `StoreSize` is true, initializes `\(\text{size}_s\)` 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>);
```

6. **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;
```

7. **Effects:** Equivalent to: `return PairLike(begin_, end_)`;

### 26.5.4.3 Accessors

```
constexpr I begin() const requires copyable<I>;
```

1. **Effects:** Equivalent to: `return begin_;`

2. **Effects:** Equivalent to: `return std::move(begin_)`;

```
constexpr S end() const;
```

3. **Effects:** Equivalent to: `return end_;`
constexpr bool empty() const;

Effects: Equivalent to: return begin_ == end_

constexpr make-unsigned-like-t<iter_difference_t<I>> size() const
requires (K == subrange_kind::sized);

Effects:
- If StoreSize is true, equivalent to: return size_
- Otherwise, equivalent to: return to-unsigned-like(end_ - begin_)

[[nodiscard]] constexpr subrange next(iter_difference_t<I> n = 1) const &
requires forward_iterator<I>

Effects: Equivalent to:
auto tmp = *this;
tmp.advance(n);
return tmp;

[[nodiscard]] constexpr subrange next(iter_difference_t<I> n = 1) &&
requires bidirectional_iterator<I>

Effects: Equivalent to:
auto tmp = *this;
tmp.advance(-n);
return tmp;

constexpr subrange& advance(iter_difference_t<I> n);

Effects: Equivalent to:
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;

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);

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:
if constexpr (N == 0)
  return r.begin();
else
  return r.end();
26.5.5 Dangling iterator handling

The tag 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 tag type **dangling** is returned instead of an iterator or subrange.

```cpp
namespace std::ranges {
    struct dangling {
        constexpr dangling() noexcept = default;
        constexpr dangling(auto&&...) noexcept {};
    };
}
```

**Example 1:**

```cpp
vector<int> f();
auto result1 = ranges::find(f(), 42); // #1
static_assert(same_as<decltype(result1), ranges::dangling>);
auto vec = f();
auto result2 = ranges::find(vec, 42); // #2
static_assert(same_as<decltype(result2), vector<int>::iterator>);
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]

26.5.6 Range conversions

26.5.6.1 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.

**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"\}
```

—end example]

3 For a type `R` that models `range`:

- if `R` models `borrowed_range`, then `borrowed_iterator_t<R>` denotes `iterator_t<R>`, and `borrowed_subrange_t<R>` denotes `subrange<iterator_t<R>>`;
- otherwise, both `borrowed_iterator_t<R>` and `borrowed_subrange_t<R>` denote `dangling`.

### § 26.5.6.1 1047
Let *container-inserter* be defined as follows:

```cpp
template<typename Ref>
auto container-inserter(C& c) {
  // exposition only
  if constexpr (requires { c.push_back(declval<Ref>()); })
    return back_inserter(c);
  else
    return inserter(c, c.end());
}
```

### 26.5.6.2 ranges::to

`template<class C, input_range R, class... Args> requires (!view<C>)
constexpr C to(R&& r, Args&&... args);`

1 Returns: An object of type C constructed from the elements of r in the following manner:

   (1.1) If convertible_to<range_reference_t<R>, range_value_t<C>> is true:
       (1.1.1) If constructible_from<C, R, Args...> is true:
       C(std::forward<R>(r), std::forward<Args>(args)...)  
       (1.1.2) Otherwise, if constructible_from<C, from_range_t, R, Args...> is true:
       C(from_range, std::forward<R>(r), std::forward<Args>(args)...)  
       (1.1.3) Otherwise, if
       (1.1.3.1) common_range<R> is true,
       (1.1.3.2) cpp17-input-iterator<iterator_t<R>> is true, and
       (1.1.3.3) constructible_from<C, iterator_t<R>, sentinel_t<R>, Args...> is true:
       C(ranges::begin(r), ranges::end(r), std::forward<Args>(args)...)  
       (1.1.4) Otherwise, if
       (1.1.4.1) constructible_from<C, Args...> is true, and
       (1.1.4.2) container-insertable<C, range_reference_t<R>> is true:
       C r(std::forward<Args>(args)...);  
       if constexpr (sized_range<R> && reservable-container<C>)
       c.reserve(ranges::size(r));
       ranges::copy(r, container-inserter<range_reference_t<R>>(c));  
   (1.2) Otherwise, if input_range<range_reference_t<R>> is true:
      to<C>(r | views::transform([](auto&& elem) {
        return to<range_value_t<C>>(std::forward<decltype(elem)>(elem));  
      }), std::forward<Args>(args)...)  
   (1.3) Otherwise, the program is ill-formed.
```

2 Let *input-iterator* be an exposition-only type:

```cpp
struct input-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;
};
```

[Note 1: *input-iterator* meets the syntactic requirements of Cpp17InputIterator. — end note]

3 Let *DEDUCE_EXPR* be defined as follows:

---

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§ 26.5.6.2 1048
3.1 — C(declval<R>(), declval<Args>()...) if that is a valid expression,

3.2 — otherwise, C(from_range, declval<R>(), declval<Args>()...) if that is a valid expression,

3.3 — otherwise,

C(declval<input_iterator>()(), declval<input_iterator>()(), declval<Args>()...)

if that is a valid expression,

3.4 — otherwise, the program is ill-formed.

Returns: to<decltype(DEDUCE_EXPR)>(std::forward<R>(r), std::forward<Args>(args)...).

26.5.6.3 ranges::to adaptors

template<class C, class... Args> requires (!view<C>)
constexpr auto to(Args&&... args);

template<template<class...> class C, class... Args>
constexpr auto to(Args&&... args);

Returns: A range adaptor closure object (26.7.2) f that is a perfect forwarding call wrapper (22.10.4) with the following properties:

1. It has no target object.

2. Its bound argument entities bound_args consist of objects of types decay_t<Args>... direction-non-list-initialized with std::forward<Args>(args)..., respectively.

3. Its call pattern is to<C>(r, bound_args...), where r is the argument used in a function call expression of f.

26.6 Range factories

26.6.1 General

Subclause 26.6 defines range factories, which are utilities to create a view.

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());

— end example]

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.
The name `views::single` denotes a customization point object (16.3.3.3.6). Given a subexpression `E`, the expression `views::single(E)` is expression-equivalent to `single_view<decay_t<decltype(E)>> (E)`.

**Example 1:**
```cpp
for (int i : views::single(4))
    cout << i;  // prints 4
```

---

### 26.6.3.2 Class template `single_view`

```cpp
namespace std::ranges {
    template<copy_constructible T>
    requires is_object_v<T>
    class single_view : public view_interface<single_view<T>> {
        private:
            copyable-box<T> value_;
            // exposition only (see 26.7.3)

        public:
            single_view() requires default_initializable<T> = default;
            constexpr explicit single_view(const T& 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 size_t size() noexcept;
            constexpr T* data() noexcept;
            constexpr const T* data() const noexcept;
    }
}
```

**Effects:**

1. Initializes `value_` with `t`.
2. Initializes `value_` with `std::move(t)`.
3. Initializes `value_` as if by `value_(in_place, std::forward<Args>(args)...)`.

```cpp
constexpr explicit single_view(T) -> single_view<T>;
```

**Effects:** Equivalent to:`data()`.

```cpp
template<class T>
    single_view(T) -> single_view<T>;
```

**Effects:** Equivalent to:`data()`.

```cpp
constexpr explicit single_view(const T& t);
```

**Effects:** Equivalent to:`data()`.

```cpp
constexpr explicit single_view(T&& t);
```

**Effects:** Equivalent to:`data()`.

```cpp
template<class... Args>
    requires constructible_from<T, Args...>
    constexpr explicit single_view(in_place_t, Args&&... args);
```

**Effects:** Equivalent to:`data()`.

```cpp
constexpr T* begin() noexcept;
```

**Effects:** Equivalent to:`return data()`.

```cpp
constexpr const T* begin() const noexcept;
```

**Effects:** Equivalent to:`return data() + 1`.

```cpp
constexpr T* end() noexcept;
```

**Effects:** Equivalent to:`return 1`.

```cpp
constexpr const T* end() const noexcept;
```

**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 (16.3.3.3.6). Given subexpressions `E` and `F`, the expressions `views::iota(E)` and `views::iota(E, F)` are expression-equivalent to `iota_view(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

```cpp
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
            struct iterator;
                // exposition only

            // 26.6.4.4, class iota_view::sentinel
            struct sentinel;
                // exposition only

        W value_ = W();  // exposition only
        Bound bound_ = Bound();  // exposition only

        public:
            iota_view() requires default_initializable< W> = default;
            constexpr explicit iota_view(W value);
            constexpr iota_view(type_identity_t< W> value, type_identity_t<Bound> bound);
            constexpr iota_view(iterator first, see below last);

            constexpr iterator begin() const;
            constexpr auto end() const requires same_as< W, Bound>;
            constexpr iterator end() const requires same_as< W, Bound>;

            constexpr auto size() const requires see below;
    };

template<class W, class Bound>
    requires (!is_integer_like< W> || !is_integer_like<Bound> ||
        (is_signed_integer_like< W> == is_signed_integer_like<Bound>))
    iota_view(W,Bound) -> iota_view< W, Bound>;
}
```

1. Let `IOTA-DIFF-T(W)` be defined as follows:

(1.1) — If `W` is not an integral type, or if it is an integral type and `sizeof(iter_difference_t< W>)` is greater than `sizeof(W)`, then `IOTA-DIFF-T(W)` denotes `iter_difference_t< W>.`

(1.2) — Otherwise, `IOTA-DIFF-T(W)` is a signed integer type of width greater than the width of `W` if such a type exists.

(1.3) — Otherwise, `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:

```cpp
template<class I>
concept decrementable =
    // exposition only
    incrementalable<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

- If a and b are decrementable, then the following are all true:
  1. `addressof(--a) == addressof(a)`
  2. `bool(a-- == b)`
  3. `bool(((void)a--, a) == --b)`
  4. `bool(++(--a) == b)`. (4.2)

The exposition-only advanceable concept is equivalent to:

```cpp
template<class I>
concept advanceable =
    // exposition only
    decrementable<I> && totally_ordered<I> && requires(I i, const I j, const IOTA-DIFF-T(I) n) {
        { i += n } -> same_as<I&>;
        { i -= n } -> same_as<I&>;
        I(j + n);
        I(n + j);
        I(j - n);
        { j - j } -> convertible_to<IOTA-DIFF-T(I)>;
    };
```

Let D be 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

- (a += n) is equal to b. (5.1)
- addressof(a += n) is equal to addressof(a). (5.2)
- I(a + n) is equal to (a += n). (5.3)
- For any two positive values x and y of type D, if I(a + D(x + y)) is well-defined, then I(a + D(x + y)) is equal to I(I(a + x) + y). (5.4)
- I(a + D(0)) is equal to a. (5.5)
- If I(a + D(n - 1)) is well-defined, then I(a + n) is equal to \( (I(i) \{ \text{return ++c; } \}(a + D(n - 1))) \). (5.6)
- (b += -n) is equal to a. (5.7)
- (b -= n) is equal to a. (5.8)
- addressof(b -= n) is equal to addressof(b). (5.9)
- I(b - n) is equal to (b -= n). (5.10)
- D(b - a) is equal to n. (5.11)
- D(a - b) is equal to D(-n). (5.12)
- bool(a <= b) is true. (5.13)

```cpp
constexpr explicit iota_view(W value);
```

**Preconditions:** Bound denotes unreachable_sentinel_t or Bound() is reachable from value.

**Effects:** Initializes value_ with value.
constexpr iota_view(type_identity_t<W> value, type_identity_t<Bound> bound);

**Preconditions:** Bound denotes unreachable_sentinel_t or bound is reachable from value. When W and Bound model totally_ordered_with, then bool(value <= bound) is true.

**Effects:** Initializes value_ with value and bound_ with bound.

constexpr iota_view(iterator first, see below last);

**Effects:** Equivalent to:

- If same_as=W, Bound> is true, iota_view(first.value_, last.value_).
- Otherwise, if Bound denotes unreachable_sentinel_t, iota_view(first.value_, last).
- Otherwise, iota_view(first.value_, last.bound_).

**Remarks:** The type of last is:

- If same_as=W, Bound> is true, iterator.
- Otherwise, if Bound denotes unreachable_sentinel_t, Bound.
- Otherwise, sentinel.

constexpr iterator begin() const;

**Effects:** Equivalent to: return iterator{value_};

constexpr auto end() const;

**Effects:** Equivalent to:

\[
\text{if constexpr (same_as<Bound, unreachable_sentinel_t>)}
\]
\[
\text{return unreachable_sentinel;}
\]
\[
\text{else}
\]
\[
\text{return sentinel{bound_};}
\]

constexpr iterator end() const requires same_as<W, Bound>;

**Effects:** Equivalent to: return iterator{bound_};

constexpr auto size() const requires see below;

**Effects:** Equivalent to:

\[
\text{if constexpr (is-integer-like<W> \&\& is-integer-like<Bound>)}
\]
\[
\text{return (value_ < 0)}
\]
\[
\text{? ((bound_ < 0)}
\]
\[
\text{? to-unsigned-like(-value_) - to-unsigned-like(-bound_)}
\]
\[
\text{: to-unsigned-like(bound_) + to-unsigned-like(-value_)}
\]
\[
\text{: to-unsigned-like(bound_) - to-unsigned-like(value_))}
\]
\[
\text{else}
\]
\[
\text{return to-unsigned-like(bound_ - value_);}
\]

**Remarks:** The expression in the requires-clause is equivalent to:

\[
\text{(same_as=W, Bound> \&\& advanceable<W>) || (is-integer-like<W> \&\& is-integer-like<Bound>) || sized_sentinel_for<Bound, W>}
\]

### 26.6.4.3 Class iota_view::iterator

```cpp
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;
            using iterator_category = input_iterator_tag; // present only if W models incrementable
            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>);
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>;
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_;

4
5 [Note 2: The noexcept clause is needed by the default iter_move implementation. — end note]

constexpr iterator& operator++();

Effects: Equivalent to:

§ 26.6.4.3
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 bool operator>(const iterator& x, const iterator& y)  
requires totally_ordered<W> && three_way_comparable<W>;

Effects: Equivalent to: return y < x;  

friend constexpr bool operator<=(const iterator& x, const iterator& y)  
requires totally_ordered<W> && three_way_comparable<W>;

Effects: Equivalent to: return !(y < x);  

friend constexpr bool operator>=(const iterator& x, const iterator& y)  
requires totally_ordered<W> && three_way_comparable<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_;  

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 sentinel(Bound bound);
friend constexpr bool operator==(const iterator x, const sentinel& y);
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);  

1 Effects: Initializes bound_ with bound.

friend constexpr bool operator==(const iterator x, const sentinel& y);

2 Effects: Equivalent to: return x.value_ == y.bound_; 

friend constexpr iter_difference_t<W> operator-(const iterator x, const sentinel& y)
  requires sized_sentinel_for<Bound, W>;

3 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>;

4 Effects: Equivalent to: return -(y - x); 

26.6.5 Istream view [range.istream]

26.6.5.1 Overview [range.istream.overview] 

1 basic_istream_view models input_range and reads (using operator>>) successive elements from its corresponding input stream.

2 The name views::istream<T> denotes a customization point object (16.3.3.3.6). 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.

3 [Example 1]:

```cpp
auto ints = istringstream{"0 1 2 3 4"};
ranges::copy(ranges::istream_view<int>(ints), ostream_iterator<int>{cout, "-"});
// prints 0-1-2-3-4-
```

— end example]

26.6.5.2 Class template basic_istream_view [range.istream.view] 

namespace std::ranges {
  template<class Val, class CharT, class Traits>
  concept stream-extractable =
    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;

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private:
    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;

26.6.5.3 Class template 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_;

§ 26.6.5.3
26.7 Range adaptors

26.7.1 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));
```

26.7.2 Range adaptor objects

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 (16.3.3.6) 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<decay_t<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 Copyable wrapper

Many types in this subclause are specified in terms of an exposition-only class template `copyable-box<T>` behaves exactly like `optional<T>` with the following differences:

1. `copyable-box<T>` constrains its type parameter `T` with `copy_constructible<T> && is_object_v<T>`.
2. The default constructor of `copyable-box<T>` is equivalent to:
   ```cpp
   constexpr copyable-box() noexcept(is_nothrow_default_constructible_v<T>)
   requires default_initializable<T>
   : copyable-box{in_place} {}  
   ```
3. If `copyable<T>` is not modeled, the copy assignment operator is equivalent to:
   ```cpp
   constexpr copyable-box& operator=(const copyable-box& that)
   noexcept(is_nothrow_copy_constructible_v<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
   constexpr copyable-box& operator=(copyable-box&& that)
   noexcept(is_nothrow_move_constructible_v<T>) {
     if (this != addressof(that)) {
       if (that) emplace(std::move(*that));
       else reset();
     }
     return *this;
   }  
   ```

2. **Recommended practice:** `copyable-box<T>` should store only a `T` if either `T` models `copyable` or `is_nothrow_move_constructible_v<T>` is true.

### 26.7.4 Non-propagating cache

Some types in subclause 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>`.
2. The copy constructor is equivalent to:
   ```cpp
   constexpr non-propagating-cache(const non-propagating-cache&) noexcept {}
   ```
3. The move constructor is equivalent to:
   ```cpp
   constexpr non-propagating-cache(non-propagating-cache&& other) noexcept {
     other.reset();
   }
   ```
4. The copy assignment operator is equivalent to:
   ```cpp
   constexpr non-propagating-cache& operator=(const non-propagating-cache& other) noexcept {
     if (addressof(other) != this)
     reset();
   }
   ```
— 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 All view

#### 26.7.5.1 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:

1. `decay-copy(E)` if the decayed type of `E` models `view`.
2. Otherwise, `ref_view{E}` if that expression is well-formed.
3. Otherwise, `owning_view{E}`.

#### 26.7.5.2 Class template `ref_view`

`ref_view` is a `view` of the elements of some other `range`.

```cpp
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
cconstexpr 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_); }

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```
```cpp
constexpr auto data() const requires contiguous_range<R>
    { return ranges::data(*r_); }
};

template<class R>
    ref_view(R&) -> ref_view<R>;
}

```
26.7.6 Filter view

26.7.6.1 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
```
—end example]

26.7.6.2 Class template filter_view

```cpp
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
            copyable-box<Pred> pred_; // exposition only

        // 26.7.6.3, class filter_view::iterator
class iterator;
        // exposition only

        // 26.7.6.4, class filter_view::sentinel
class sentinel; // exposition only

        public:
            filter_view() requires default_initializable<V> && default_initializable<Pred> = default;
            constexpr filter_view(V base, Pred pred);

            constexpr V base() const & requires copy_constructible<V> { return base_; } // exposition only
            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>
        filter_view(R&&, Pred) -> filter_view<views::all_t<R>, Pred>;
}
```

`constexpr filter_view(V base, Pred pred);`

1 *Effects:* Initializes `base_` with `std::move(base)` and initializes `pred_` with `std::move(pred)`.

`constexpr const Pred& pred() const;`

2 *Effects:* Equivalent to: `return *pred_;`
constexpr iterator begin();

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.

26.7.6.3 Class filter_view::iterator

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;
      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.
— If \( C \) models \( \text{derived_from}\langle \text{bidirectional\_iterator\_tag} \rangle \), then \( \text{iterator\_category} \) denotes \( \text{bidirectional\_iterator\_tag} \).

— Otherwise, if \( C \) models \( \text{derived_from}\langle \text{forward\_iterator\_tag} \rangle \), then \( \text{iterator\_category} \) denotes \( \text{forward\_iterator\_tag} \).

— Otherwise, \( \text{iterator\_category} \) denotes \( C \).

```cpp
cconstexpr iterator(filter_view& parent, iterator_t<V> current);
```

**Effects:** Initializes \( \text{current\_} \) with \( \text{std::move}(\text{current}) \) and \( \text{parent\_} \) with \( \text{addressof}(\text{parent}) \).

```cpp
cconstexpr const iterator_t<V>& base() const & noexcept;
```

**Effects:** Equivalent to: \( \text{return \ current\_} \).  

```cpp
cconstexpr iterator_t<V> base() &&;
```

**Effects:** Equivalent to: \( \text{return std::move}(\text{current\_}) \).

```cpp
cconstexpr range_reference_t<V> operator*() const;
```

**Effects:** Equivalent to: \( \text{return \*}\text{current\_} \).

```cpp
cconstexpr iterator_t<V> operator->() const
requires has\_arrow<iterator_t<V>> && copyable<iterator_t<V>>;
```

**Effects:** Equivalent to: \( \text{return \ current\_} \).

```cpp
cconstexpr iterator& operator++();
```

**Effects:** Equivalent to:

```cpp
\text{current\_} = \text{ranges::find\_if}(\text{std::move}(++\text{current\_}), \text{ranges::end}(...\text{base}\_),
\text{ref}(...\text{pred}\_));
\text{return \*this;}
```

```cpp
cconstexpr void operator++(int);
```

**Effects:** Equivalent to \(++\*this\).

```cpp
cconstexpr iterator operator++(int) requires forward\_range<V>;
```

**Effects:** Equivalent to:

```cpp
\text{auto tmp = \*this; \;++this; \;return tmp;}
```

```cpp
cconstexpr iterator& operator--() requires bidirectional\_range<V>;
```

**Effects:** Equivalent to:

```cpp
\text{do \;--\current\_; \;while (!\text{invoke}(...\text{pred}\_, \;\text{current}\_;)) \;return \*\text{this;}}
```

```cpp
cconstexpr iterator operator--(int) requires bidirectional\_range<V>;
```

**Effects:** Equivalent to:

```cpp
\text{auto tmp = \*\text{this; \;--\*this; \;return tmp;}
```

```cpp
\text{friend constexpr bool operator==(const iterator\& x, const iterator\& y)
\text{requires equality\_comparable<iterator\_t<V>>; \;return x.\text{current\_} \;== \;y.\text{current\_;}}
```

```cpp
\text{friend constexpr range\_rvalue\_reference\_t<V> iter\_move(const iterator\& i)
\text{noexcept(noexcept(\text{ranges::iter\_move}(i.\text{current}\_)))};
```

**Effects:** Equivalent to: \( \text{return ranges::iter\_move}(i.\text{current\_}) \);
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<V>>;

Effects: Equivalent to ranges::iter_swap(x.current_, y.current_).

26.7.6.4 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_;

26.7.7 Transform view

26.7.7.1 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]

26.7.7.2 Class template transform_view

namespace std::ranges {
    template<input_range V, copy 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:
    // 26.7.7.3, class template transform view::iterator
    template<bool> struct iterator;
    // exposition only

    // 26.7.7.4, class template transform view::sentinel
    template<bool> struct sentinel;
    // exposition only

§ 26.7.7.2
V base_ = V(); // exposition only
copyable-box<F> fun_; // exposition only

public:
    transform_view() requires default_initializable<V> && default_initializable<F> = default;
    constexpr 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 common_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 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_)};
```cpp
constexpr iterator<true> end() const
  requires common_range<const V> &&
    regular_invocable<Const F, range_reference_t<const V>>;

Effects: Equivalent to:

    return iterator<true>{*this, ranges::end(base_)};

26.7.7.3 Class template transform_view::iterator

namespace std::ranges {
  template<input_range V, copy_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;
      using iterator_category = see below;                     // not always present
      using value_type = remove_cvref_t<invoke_result_t<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--() requires bidirectional_range<Base>;
      constexpr iterator 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>;
  }
}  // namespace std::ranges
```
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_lvalue_reference_v<invoke_result_t<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).

constexpr 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_.

constexpr const iterator_t<Base>& base() const & noexcept;
5 Effects: Equivalent to: return current_;

constexpr iterator_t<Base> base() &&;
6 Effects: Equivalent to: return std::move(current_);

constexpr iterator& operator++();
7 Effects: Equivalent to:
   ++current_
   return *this;

constexpr void operator++(int);
8 Effects: Equivalent to ++current_.

§ 26.7.7.3
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:
--current_;
return *this;

constexpr iterator operator--(int) requires bidirectional_range<Base>;

Effects: Equivalent to:
auto tmp = *this;
--*this;
return tmp;

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<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_;

26.7.7.4 Class template transform_view::sentinel

namespace std::ranges {
  template<input_range V, copy_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);
    }

    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_).

    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_;

26.7.8 Take view

26.7.8.1 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:

1. If \( T \) is a specialization of ranges::empty_view (26.6.2.2), then ((void) F, decay-copy(E)), except that the evaluations of \( E \) and \( F \) are indeterminately sequenced.
2. Otherwise, if \( T \) models random_access_range and sized_range and is a specialization of span (24.7.3), basic_string_view (23.3), or ranges::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:
   1. If \( T \) is a specialization of span, then \( U \) is span<typename T::element_type>;
   2. otherwise, if \( T \) is a specialization of basic_string_view, then \( U \) is \( T \);
   3. otherwise, \( T \) is a specialization of ranges::subrange, and \( U \) is ranges::subrange_iterator_t<T>;
   4. otherwise, if \( T \) is a specialization of ranges::iota_view (26.6.4.2) that models random_access_range and sized_range, then ranges::iota_view(*ranges::begin(E), *(ranges::begin(E) + std::min<D>(ranges::distance(E), F)))

— Otherwise, ranges::take_view(E, F).

3 [Example 1:

```cpp
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]

26.7.8.2 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

    // 26.7.8.3, class template take_view::sentinel
    template<bool> struct sentinel; // exposition only

public:
    take_view() requires default_initializable<V> = default;
    constexpr 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 {  
        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 {  
        return counted_iterator(ranges::begin(base_), count_);  
    }  
}  

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 {  
        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 {  
        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 take_view(V base, range_difference_t<V> count);
1
   Effects: Initializes base_ with std::move(base) and count_ with count.

26.7.8.3 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>>>;
         sentinel_t<Base> end_ = sentinel_t<Base>();
      public:
         sentinel() = default;
         constexpr explicit sentinel(sentinel_t<Base> end);
         constexpr sentinel(sentinel<!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(sentinel_t<Base> end);
1
   Effects: Initializes end_ with end.

constexpr sentinel(sentinel<!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);
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);
4
   Effects: Equivalent to: return y.count() == 0 || y.base() == x.end_;

26.7.9 Take while view
26.7.9.1 Overview
1
   Given a unary predicate pred and a view r, take_while_view produces a view of the range [begin(r),
   ranges::find_if_not(r, pred)).

2
   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:]
   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 = istream_view<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
— end example]

26.7.9.2 Class template take_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 take_while_view : public view_interface<take_while_view<V, Pred>> {
        // 26.7.9.3, class template take_while_view::sentinel
        template<bool> class sentinel;  // exposition only
        V base_ = V();  // exposition only
        copyable-box<Pred> pred_;  // exposition only
    public:
        take_while_view() requires default_initializable<V> && default_initializable<Pred> = default;
        constexpr take_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() 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 take_while_view(V base, Pred pred);
1 Effects: Initializes base_ with std::move(base) and pred_ with std::move(pred).

constexpr const Pred& pred() const;
2 Effects: Equivalent to: return *pred_;

26.7.9.3 Class template take_while_view::sentinel

namespace std::ranges {
    template<view V, class Pred>
        requires input_range<V> && is_object_v<Pred> &&
            indirect_unary_predicate<const Pred, iterator_t<V>>
    template<bool Const>
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<!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);

1 Effects: Initializes end_ with end and pred_ with pred.

constexpr sentinel(sentinel<!Const> s) requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

2 Effects: Initializes end_ with 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);

3 Effects: Equivalent to: return y.end_ == x || !invoke(*y.pred_, *x);

26.7.10 Drop view [range.drop]
26.7.10.1 Overview [range.drop.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.

(2.1) If \( T \) is a specialization of ranges::empty_view (26.6.2.2), then \((\text{void}) F, \text{decay}-\text{copy}(E))\), 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 (24.7.3),

(2.2.2) a specialization of basic_string_view (23.3),

(2.2.3) a specialization of ranges::iota_view (26.6.4.2), or

(2.2.4) a specialization of ranges::subrange (26.5.4) where \( T::\text{StoreSize} \) is false, then \( U(\text{ranges}::\text{begin}(E) + \text{std}::\text{min}<D>(\text{ranges}::\text{distance}(E), F), \text{ranges}::\text{end}(E))\), except that \( E \) is evaluated only once, where \( U \) is \text{span<typename } T::\text{element_type}> if \( T \) is a specialization of span and \( T \) otherwise.
— Otherwise, if \( T \) is a specialization of `ranges::subrange` (26.5.4) that models `random_access_range` and `sized_range`, then

\[
T(\text{\texttt{ranges::begin}}(E) + \text{\texttt{std::min}}<D>(\text{\texttt{ranges::distance}}(E), F), \text{\texttt{ranges::end}}(E), \text{\texttt{to-unsigned-like}}(\text{\texttt{ranges::distance}}(E) - \text{\texttt{std::min}}<D>(\text{\texttt{ranges::distance}}(E), F)));
\]

except that \( E \) and \( F \) are each evaluated only once.

— Otherwise, \`ranges::drop_view\( (E, F) \).

3

[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]

### 26.7.10.2 Class template `drop_view` [range.drop.view]

```cpp
namespace std::ranges {

    template<class V>
    class drop_view : public view_interface<drop_view<V>> {
    public:
        drop_view() requires default_initializable<V> = default;
        constexpr drop_view(V base, range_difference_t<V> count);

        constexpr V base() const & requires copy_constructible<V> { return base_; }
        constexpr V base() && { return std::move(base_); }

        constexpr auto begin() requires (!\((\text{\texttt{simple-view}}<V> && 
            \text{\texttt{random_access_range}}<\text{\texttt{const V}}> && \text{\texttt{sized_range}}<\text{\texttt{const V}}>)\));
        constexpr auto begin() const requires \text{\texttt{range}}<\text{\texttt{const V}}>
        { return ranges::begin(base_); }

        constexpr auto end() requires (!\((\text{\texttt{simple-view}}<V>)\))
        { return ranges::end(base_); }
        constexpr auto end() const requires \text{\texttt{range}}<\text{\texttt{const V}}>
        { return ranges::end(base_); }

        constexpr auto size() requires sized_range<V> {
            const auto s = ranges::size(base_);
            const auto c = static_cast<decltype(s)>\((\text{\texttt{count}}\_);\)
            return s < c ? 0 : s - c;
        }
        constexpr auto size() const requires sized_range<\text{\texttt{const V}}>
        { const auto s = ranges::size(base_);
            const auto c = static_cast<decltype(s)>\((\text{\texttt{count}}\_);\)
            return s < c ? 0 : s - c;
        }

    private:
        V base_ = V();  
        range_difference_t<V> count_ = 0;  
    };

    template<class R>
    drop_view(R&&, range_difference_t<R>) -> drop_view<views::all_t<R>>;
}
```

1

**Preconditions:** \text{\texttt{count}} >= 0 is true.

2

**Effects:** Initializes `base_` with `std::move(base)` and `count_` with `count`.

§ 26.7.10.2
constexpr 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]

§ 26.7.11 Drop while view  [range.drop.while]
26.7.11 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]:

```cpp
constexpr auto source = " \t \t \t hello there";
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

§ 26.7.11.2 Class template drop_while_view  [range.drop.while.view]

```cpp
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 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
    copyable_box<Pred> pred_; // exposition only
};
```

```cpp
    template<class R, class Pred>
    drop_while_view(R&&, Pred) -> drop_while_view<views::all_t<R>, Pred>;
}
```

constexpr 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_

constexpr auto begin();

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]

26.7.12 Join view

26.7.12.1 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]

26.7.12.2 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

            // 26.7.12.3, class template join_view::iterator
            template<bool Const>
            struct iterator;
                // exposition only

            // 26.7.12.4, class template join_view::sentinel
            template<bool Const>
            struct sentinel;
                // exposition only

        V base_ = V(); // exposition only

        non-propagating-cache<remove_cv_t<InnerRng>> inner_; // exposition only, present only
            // when !is_reference_v<InnerRng>

        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() {
                constexpr bool use_const = simple_view<V> &&
                    is_reference_v<range_reference_t<V>>;
                return iterator<use_const>{*this, ranges::begin(base_)};
            }
        }
    }
}
constexpr auto begin() const  
__requires,input_range<const V> &&
   is_reference_v<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,input_range<const V> &&
   is_reference_v<range_reference_t<const V>> {
if constexpr (forward_range<const V> &&
   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).

template<class R>
explicit join_view(R&&) -> join_view<views::all_t<R>>;

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>;
            using Base    = maybe-const<Const, V>;
            using OuterIter = iterator_t<Base>;
            using InnerIter = iterator_t<range_reference_t<Base>>;

            static constexpr bool ref_is_glvalue =
                is_reference_v<range_reference_t<Base>>;

            OuterIter outer_ = OuterIter();
            InnerIter inner_ = InnerIter();
            Parent* parent_ = nullptr;

            constexpr void satisfy();

        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() requires default_initializable<OuterIter> &&
                default_initializable<InnerIter> = default;
    }

§ 26.7.12.3
constexpr iterator(Parent& parent, OuterIter outer);
constexpr iterator(iterator<!Const> i)
    requires Const &&
    convertible_to<iterator_t<V>, OuterIter> &&
    convertible_to<iterator_t<InnerRng>, InnerIter>;

cconstexpr decltype(auto) operator*() const { return *inner_; }

cconstexpr InnerIter operator->() const
    requires has_arrow<InnerIter> && copyable<InnerIter>;

cconstexpr iterator& operator++();
cconstexpr void operator++(int);

cconstexpr iterator& operator++(int)
    requires ref-is-glvalue && forward_range<Base> &&
    forward_range<range_reference_t<Base>>;

cconstexpr iterator operator--();

cconstexpr iterator operator--(int)
    requires ref-is-glvalue && bidirectional_range<Base> &&
    bidirectional_range<range_reference_t<Base>> &&
    common_range<range_reference_t<Base>>;

cconstexpr iterator operator--(int)
    requires ref-is-glvalue && bidirectional_range<Base> &&
    bidirectional_range<range_reference_t<Base>> &&
    common_range<range_reference_t<Base>>;

friend constexpr bool operator==(const iterator x, const iterator y)
    requires ref-is-glvalue && equality_comparable<iterator_t<Base>> &&
    equality_comparable<iterator_t<range_reference_t<Base>>>;
iterator::difference_type denotes the type:

common_type_t<
  range_difference_t<Base>,
  range_difference_t<range_reference_t<Base>>>

join_view iterators use the satisfy function to skip over empty inner ranges.

constexpr void satisfy();  // exposition only

Effects: Equivalent to:

auto update_inner = [this](const iterator_t<Base>& x) -> auto&& {
  if constexpr (ref-is-glvalue) // *x is a reference
    return *x;
  else
    return parent_->inner_.emplace_deref(x);
};

for (; outer_ != ranges::end(parent_->base_); ++outer_) {
  auto&& inner = update_inner(outer_);
  inner_ = ranges::begin(inner);
  if (inner_ != ranges::end(inner))
    return;
}

if constexpr (ref-is-glvalue)
  inner_ = InnerIter();

constexpr iterator(Parent& parent, OuterIter outer);

Effects: Initializes outer_ with std::move(outer) and 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_.

constexpr InnerIter operator->() const
  requires has-arrow<InnerIter> && copyable<InnerIter>;

Effects: Equivalent to return inner_.

constexpr iterator& operator++();

Effects: Equivalent to:

Let inner-range be:

- If ref-is-glvalue is true, *outer_.
- Otherwise, *parent_->inner_.

Effects: Equivalent to:

auto&& inner_rng = inner-range;
if (++inner_ == ranges::end(inner_rng)) {
  ++outer_;  
  satisfy();
}

return *this;

constexpr void operator++(int);

Effects: Equivalent to: +++this.

constexpr iterator 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 iterator& operator--() const
    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(*--outer_);
while (inner_ == ranges::begin(*outer_))
    inner_ = ranges::end(*--outer_);
--inner_;
return *this;

constexpr iterator operator--(int) const
    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 && equality_comparable<iterator_t<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_);

26.7.12.4 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>>;

            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_;

26.7.13 Join with view

26.7.13.1 Overview

1 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.

2 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).

3 [Example 1:
  vector<string> vs = {"the", "quick", "brown", "fox"};
  for (char c : vs | join_with(‘-‘)) {
    cout << c;
  }
  
The above prints: the-quick-brown-fox — end example]

26.7.13.2 Class template join_with_view

namespace std::ranges {
    template<class R, class P>
    concept compatible_joinable_ranges =
        // exposition only
        common_with<range_value_t<R>, range_value_t<P>> &&
        common_reference_with<range_reference_t<R>, range_reference_t<P>> &&
        common_reference_with<range_rvalue_reference_t<R>, range_rvalue_reference_t<P>>;

    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>
        && compatible_joinable_ranges<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<remove_cv_t<InnerRng>> inner_;
            // exposition only, present only
        // when !is_reference_v<InnerRng>
        Pattern pattern_ = Pattern();
            // exposition only

        // 26.7.13.3, class template join_with_view::iterator
        template<bool Const> struct iterator;
            // exposition only

        // 26.7.13.4, 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 join_with_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<InnerRng>>>
constexpr 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() {
  constexpr bool use_const =
    simple_view<V> && is_reference_v<InnerRng> && simple_view<Pattern>;
  return iterator{*this, ranges::begin(base_);};
}
constexpr auto begin() const
requires input_range<const V> &&
  forward_range<const Pattern> &&
  is_reference_v<range_reference_t<const V>> { return iterator{*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 input_range<const V> && forward_range<const Pattern> &&
  is_reference_v<range_reference_t<const V>> { using InnerConstRng = range_reference_t<const V>;
if constexpr (forward_range<const V> && forward_range<InnerConstRng> &&
  common_range<InnerConstRng>)
  return iterator<true>{*this, ranges::end(base_);};
else
  return sentinel<true>{*this};
};

join_with_view(R&&, P&&) -> join_with_view<views::all_t<R>, views::all_t<P>>;

join_with_view(R&&, range_value_t<range_reference_t<R>>)
  -> join_with_view<views::all_t<R>, single_view<range_value_t<range_reference_t<R>>>;
}

constexpr join_with_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<InnerRng>>>
constexpr join_with_view(R&& r, range_value_t<InnerRng> e);
  Effects: Initializes base_ with views::all(std::forward<R>(r)) and pattern_ with views::single(std::move(e)).

26.7.13.3 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> && compatible-joinable-ranges<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
    variant<PatternIter, InnerIter> inner_it_;                   // exposition only

    constexpr iterator(Parent& parent, iterator_t<Base> outer);   // exposition only
    constexpr auto&& update-inner(const OuterIter&);            // exposition only
    constexpr auto&& get-inner(const OuterIter&);               // exposition only
    constexpr void satisfy();                                   // exposition only

public:
    using iterator_concept = see below;                         // not always present
    using iterator_category = see below;
    using value_type = see below;
    using difference_type = see below;

    iterator() requires default_initializable<OuterIter> = default;
    constexpr iterator(=Const i)                                // exposition only
        requires Const && convertible_to<iterator_t<V>, OuterIter> &&
            convertible_to<iterator_t<InnerBase>, InnerIter> &&
            convertible_to<iterator_t<Pattern>, PatternIter>;

    constexpr decltype(auto) operator*() const;

    constexpr iterator& operator++();                           // exposition only
    constexpr void operator++(int);                             // exposition only
    constexpr iterator& operator++(int) requires ref-is-glvalue &&
        forward_iterator<OuterIter> &&
        forward_iterator<InnerIter>;

    constexpr iterator& operator--() requires ref-is-glvalue &&
        bidirectional_range<OuterIter> &&
        bidirectional-common<InnerIter> &&
        bidirectional-common<PatternIter>;

    constexpr iterator& operator--(int) requires ref-is-glvalue &&
        bidirectional_range<OuterIter> &&
        bidirectional-common<InnerIter> &&
        bidirectional-common<PatternIter>;

    friend constexpr bool operator==(const iterator& x, const iterator& y) // exposition only
        requires ref-is-glvalue && equality_comparable<OuterIter> &&
            equality_comparable<InnerIter>;

    friend constexpr decltype(auto) iter_move(const iterator& x) { // exposition only
        using rvalue_reference = common_reference_t<
            iterator_rvalue_reference_t<InnerIter>,
            iterator_rvalue_reference_t<PatternIter>>;
        return visit<rvalue_reference>(ranges::iter_move, x.inner_it_);
    }

    friend constexpr void iter_swap(const iterator& x, const iterator& y) // exposition only
        requires indirectly_swappable<InnerIter, PatternIter> {
            visit(ranges::iter_swap, x.inner_it_, y.inner_it_);
        }
}

§ 26.7.13.3
iterator::iterator_concept is defined as follows:

(1.1) If \( \text{ref-is-glvalue} \) is true, \( \text{Base} \) models \text{bidirectional\_range}, and \( \text{InnerBase} \) and \( \text{PatternBase} \) each model \text{bidirectional\_common}, then \text{iterator\_concept} denotes \text{bidirectional\_iterator\_tag}.

(1.2) Otherwise, if \( \text{ref-is-glvalue} \) is true and \( \text{Base} \) and \( \text{InnerBase} \) each model \text{forward\_range}, then \text{iterator\_concept} denotes \text{forward\_iterator\_tag}.

(1.3) Otherwise, \text{iterator\_concept} denotes \text{input\_iterator\_tag}.

The member typedef-name \text{iterator\_category} is defined if and only if \( \text{ref-is-glvalue} \) is true, and \( \text{Base} \) and \( \text{InnerBase} \) each model \text{forward\_range}. In that case, \text{iterator\_concept} is defined as follows:

(2.1) Let \( \text{OUTERC} \) denote \text{iterator\_traits<OuterIter>::iterator\_category}, let \( \text{INNERC} \) denote \text{iterator\_traits<InnerIter>::iterator\_category}, and let \( \text{PATTERNC} \) denote \text{iterator\_traits<PatternIter>::iterator\_category}.

(2.2) If

\[
\text{is\_lvalue\_reference\_v<common\_reference\_t<iter\_reference\_t<InnerIter>, iter\_reference\_t<PatternIter>>>}
\]

is false, \text{iterator\_category} denotes \text{input\_iterator\_tag}.

(2.3) Otherwise, if \( \text{OUTERC}, \text{INNERC}, \) and \( \text{PATTERNC} \) each model \text{derived\_from<bidirectional\_iterator\_category>} and \( \text{InnerBase} \) and \( \text{PatternBase} \) each model \text{common\_range}, \text{iterator\_category} denotes \text{bidirectional\_iterator\_tag}.

(2.4) Otherwise, if \( \text{OUTERC}, \text{INNERC}, \) and \( \text{PATTERNC} \) each model \text{derived\_from<forward\_iterator\_tag>}, \text{iterator\_category} denotes \text{forward\_iterator\_tag}.

(2.5) Otherwise, \text{iterator\_category} denotes \text{input\_iterator\_tag}.

\text{iterator\_::value\_type} denotes the type:

\[
\text{common\_type\_t<iter\_value\_t<InnerIter>, iter\_value\_t<PatternIter>>}
\]

\text{iterator\_::difference\_type} denotes the type:

\[
\text{common\_type\_t<}
\quad \text{iter\_difference\_t<OuterIter>,}
\quad \text{iter\_difference\_t<InnerIter>,}
\quad \text{iter\_difference\_t<PatternIter>>}
\]

\text{constexpr auto&&} update-inner(const OuterIter& x);

\text{Effects:} Equivalent to:

\[
\begin{align*}
\text{if constexpr (ref-is-glvalue)} & \quad \text{return } *x; \\
& \quad \text{else} \\
& \quad \text{return } \parent\_\to inner\_.emplace\_deref(x);
\end{align*}
\]

\text{constexpr auto&&} get-inner(const OuterIter& x);

\text{Effects:} Equivalent to:

\[
\begin{align*}
\text{if constexpr (ref-is-glvalue)} & \quad \text{return } *x; \\
& \quad \text{else} \\
& \quad \text{return } *\parent\_\to inner\_;
\end{align*}
\]

\text{constexpr void} satisfy();

\text{Effects:} Equivalent to:

\[
\text{while (true) } \{
\text{if (inner\_it\_.index() == 0) } \{
\text{if (std::get<0>(inner\_it_) != ranges::end(\parent\_\to pattern_)) break;}
\text{auto&& inner = update-inner(outer\_it_);}
\text{inner\_it\_.emplace<1>(ranges::begin(inner));}
\text{\}}
\text{\}}
\]

§ 26.7.13.3
else {
    auto&& inner = get-inner(outer_it_);
    if (std::get<1>(inner_it_) != ranges::end(inner))
        break;
    if (++outer_it_ == ranges::end(parent_->base_)) {
        if constexpr (ref-is-glvalue)
            inner_it_.emplace<0>();
        break;
    }
    inner_it_.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, iterator_t<Parent> outer);

Effects: Initializes parent_ with addressof(parent) and outer_it_ with std::move(outer). Then, equivalent to:

if (outer_it_ != ranges::end(parent_->base_)) {
    auto&& inner = update-inner(outer_it_);
    inner_it_.emplace<1>(ranges::begin(inner));
    satisfy();
}

constexpr iterator(iterator<Const> i)
requires Const & convertible_to<iterator_t<OuterIter>, OuterIter> &&
convertible_to<iterator_t<InnerIter>, InnerIter> &&
convertible_to<iterator_t<Pattern>, PatternIter>;

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_.emplace<0>(std::get<0>(std::move(i.inner_it_)));
else
    inner_it_.emplace<1>(std::get<1>(std::move(i.inner_it_)));

constexpr decltype(auto) operator*() const;

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++();

Effects: Equivalent to:

visit([](auto& it){ ++it; }, inner_it_);
return *this;

constexpr void operator++(int);

Effects: Equivalent to +++this.

constexpr iterator operator++(int)
requires ref-is-glvalue && forward_iterator<OuterIter> && forward_iterator<InnerIter>;

Effects: Equivalent to:

    iterator tmp = *this;
    +++this;
    return tmp;

constexpr iterator& operator--();

Effects: Equivalent to --*this.

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_.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_.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_.emplace<0>(ranges::end(parent_->pattern_));
        } else {
            break;
        }
    }
    visit([](auto& it){ --it; }, inner_it_);
    return *this;
}

constexpr iterator operator--(int)
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 && equality_comparable<OuterIter> &&
    equality_comparable<InnerIter>;

Effects: Equivalent to:

return x.outer_it_ == y.outer_it_ && x.inner_it_ == y.inner_it_;

26.7.13.4 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> && compatible-joinable-ranges
        <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>;  // exposition only
        sentinel_t<Base> end_ = sentinel_t<Base>();  // exposition only

        constexpr explicit sentinel(Parent& parent);  // exposition only

    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);
1 Effects: Initializes end_ with ranges::end(parent.base_).
constexpr sentinel(s sentinel<Const> s)
requires Const && convertible_to<sentinel_t<Base>, sentinel_t<V>>;
2 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>);
3 Effects: Equivalent to: return x.outer_it_ == y.end_;

26.7.14 Lazy split view
[range.lazy.split]

26.7.14.1 Overview
[range.lazy.split.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.

2 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).

3 [Example 1:

```c++
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]
```

26.7.14.2 Class template lazy_split_view
[range.lazy.split.view]
namespace std::ranges {
    template<auto> struct require-constant; // exposition only

template<class R>
concept tiny-range = // exposition only
    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>

    // 26.7.14.3, class template lazy_split_view::outer_iterator
    template<bool> struct outer_iterator;
    // exposition only

    // 26.7.14.5, class template lazy_split_view::inner_iterator
    template<bool> struct inner_iterator;
    // exposition only

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public:

    lazy_split_view()
        requires default_initializable<V> && default_initializable<Pattern> = default;
    constexpr 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>>> = default;
    constexpr lazy_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 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};
        }
    }

    constexpr auto begin() const requires forward_range<V> && forward_range<const V> {
        return
            outer_iterator<true>*{this, ranges::begin(base_)};
    }

    constexpr auto end() requires forward_range<V> && common_range<V> {
        return
            outer_iterator<simple_view<V> && simple_view<Pattern>>
            {*this, ranges::end(base_)};
    }

    constexpr 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>
        requires constructible_from<V, views::all_t<R>> &&
            constructible_from<Pattern, single_view<range_value_t<R>>> = default;
    lazy_split_view(R&& r, range_value_t<R> e);

    template<input_range R>
        requires constructible_from<V, views::all_t<R>> &&
            constructible_from<Pattern, single_view<range_value_t<R>>> = default;
    lazy_split_view(R&& r, range_value_t<R> e);

constexpr lazy_split_view(V base, Pattern pattern);

    Effects: Initializes \texttt{base} with std::move(base), and \texttt{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>>> = default;
    lazy_split_view(R&& r, range_value_t<R> e);

    Effects: Initializes \texttt{base} with views::all(std::forward<R>(r)), and \texttt{pattern} with views::
        single(std::move(e)).

26.7.14.3 Class template lazy_split_view::outer_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> &&

§ 26.7.14.3
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

  // 26.7.14.4, 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 26.7.14 refer to the notional member current of outer_iterator. current is equivalent to current_ if V models forward_range, and *parent_ -> current_ otherwise.

2 Effects: Initializes parent_ with addressof(parent).

3 Effects: Initializes parent_ with addressof(parent) and current_ with std::move(current).
constexpr outer-iterator(outer-iterator<!Const> i)
  requires Const && convertible_to<iterator_t<V>, iterator_t<Base>>;
4
  Effects: Initializes parent_ with i.parent_ and current_ with std::move(i.current_).

constexpr value_type operator*() const;
5
  Effects: Equivalent to: return value_type{*this};

constexpr outer-iterator& operator++();
6
  Effects: Equivalent to:
    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;
        if (current == end)
          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>;
7
  Effects: Equivalent to:
    return x.current_ == y.current_ && x.trailing_empty_ == y.trailing_empty_;

friend constexpr bool operator==(const outer-iterator& x, default_sentinel_t);
8
  Effects: Equivalent to:
    return x.current == ranges::end(x.parent_->base_) && !x.trailing_empty_;
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;

26.7.14.5 Class template lazy_split_view::inner-iterator [range.lazy.split.inner]

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;
        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);
        }

    } // struct lazy_split_view<V, Pattern>::inner-iterator

} // namespace std::ranges
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.

cconstexpr explicit inner_iterator(outer_iterator<Const> i);
2 Effects: Initializes i_ with std::move(i).

cconstexpr const iterator_t<Base>& base() const & noexcept;
3 Effects: Equivalent to: return i_.current;

cconstexpr iterator_t<Base> base() && requires forward_range<V>;
4 Effects: Equivalent to: return std::move(i_.current);

cconstexpr inner_iterator& operator++();
5 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>;
6 Effects: Equivalent to: return x.i_.current == y.i_.current;

friend constexpr bool operator==(const inner_iterator& x, default_sentinel_t);
7 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;
   }

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).
26.7.15 Split view

26.7.15.1 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:]

```cpp
string str{"the quick brown fox");
for (string_view word : split(str, ' ')) {
    cout << word << ' ';
}
// The above prints: the quick brown fox
```

--- end example

26.7.15.2 Class template split_view

```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>
    class split_view : public view_interface<split_view<V, Pattern>> {

        private:
            V base_ = V(); // exposition only
            Pattern pattern_ = Pattern(); // exposition only

        // 26.7.15.3, class split_view::iterator
        struct iterator;
        // exposition only

        // 26.7.15.4, class split_view::sentinel
        struct sentinel;
        // exposition only

        public:

            split_view()
                requires default_initializable<V> && default_initializable<Pattern> = default;
                constexpr 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 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
        }

    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 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 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); // exposition only

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};

26.7.15.3 Class split_view::iterator
        [range.split.iterator]

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<V, Pattern>::iterator {
        private:
            split_view* parent_ = nullptr; // exposition only
            iterator_t<V> cur_ = iterator_t<V>(); // exposition only
            subrange<iterator_t<V>> next_ = subrange<iterator_t<V>>(); // exposition only
            bool trailing_empty_ = false; // exposition only

        public:
            using iterator_concept = forward_iterator_tag;
            using iterator_category = input_iterator_tag;
            using value_type = subrange<iterator_t<V>>;
            using difference_type = range_difference_t<V>;

            iterator() = default;
            constexpr iterator(split_view& parent, iterator_t<V> current, subrange<iterator_t<V>>& next);

            constexpr iterator_t<V> base() const;
            constexpr value_type operator*() const;

            constexpr iterator& operator++();
            constexpr iterator operator++(int);

            friend constexpr bool operator==(const iterator& x, const iterator& y);  
};

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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 return {cur_, next_.begin()};

constexpr iterator& operator++();

Effects: Equivalent to:

    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:

    auto tmp = *this;
    ++*this;
    return tmp;

friend constexpr bool operator==(const iterator& x, const iterator& y);

Effects: Equivalent to:

    return x.cur_ == y.cur_ && x.trailing_empty_ == y.trailing_empty_;

26.7.15.4 Class split_view::sentinel

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);
        }
    }

constexpr explicit sentinel(split_view& parent);

Effects: Initializes end_ with ranges::end(parent.base_).

friend constexpr bool operator==(const iterator& x, const sentinel& y);

Effects: Equivalent to: return x.cur_ == y.end_ && !x.trailing_empty_;
26.7.16 Counted view

1 A counted view presents a view of the elements of the counted range \( i + [0, n] \) for an iterator \( i \) and non-negative integer \( n \).

2 The name \( \text{views}::\text{counted} \) denotes a customization point object (16.3.3.6). Let \( E \) and \( F \) be expressions, let \( T \) be \( \text{decay_t< decltype((E))>} \), and let \( D \) be \( \text{iter_difference_t<T>} \). If \( \text{decltype}((F)) \) does not model \( \text{convertible_to<D>} \), \( \text{views}::\text{counted}(E, F) \) is ill-formed.

[Note 1: This case can result in substitution failure when \( \text{views}::\text{counted}(E, F) \) appears in the immediate context of a template instantiation. — end note]

Otherwise, \( \text{views}::\text{counted}(E, F) \) is expression-equivalent to:

1. If \( T \) models \( \text{contiguous_iterator} \), then \( \text{span(to_address}(E), \text{static_cast< size_t>}(\text{static_cast< D>(F)})) \).
2. Otherwise, if \( T \) models \( \text{random_access_iterator} \), then \( \text{subrange}(E, E + \text{static_cast< D>(F)}) \), except that \( E \) is evaluated only once.
3. Otherwise, \( \text{subrange(counted_iterator}(E, F), \text{default_sentinel}) \).

26.7.17 Common view

26.7.17.1 Overview

1 \( \text{common_view} \) 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.

2 [Note 1: \( \text{common_view} \) is useful for calling legacy algorithms that expect a range's iterator and sentinel types to be the same. — end note]

3 The name \( \text{views}::\text{common} \) denotes a range adaptor object (26.7.2). Given a subexpression \( E \), the expression \( \text{views}::\text{common}(E) \) is expression-equivalent to:

1. If \( \text{decltype}((E)) \) models \( \text{common_range} \) and \( \text{views}::\text{all}(E) \) is a well-formed expression.
2. Otherwise, \( \text{common_view}(E) \).

[Example 1:

```
// 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());
    // ...
}
```
—end example]

26.7.17.2 Class template \texttt{common\_view}

namespace std::ranges {
    template<typename V>
    requires (!std::ranges::common_range<V> && std::copyable<iterator_t<V>>)
    class common_view : public std::view_interface<common_view<V>> { 
        private:
        V base_ = V(); // exposition only
        public:
        common_view() requires std::default_initializable<V> = default;
        constexpr explicit common_view(V r);
        constexpr V base() const & requires std::copy_constructible<V> { return base_; }
        constexpr V base() && { return std::move(base_); }
    }
}
constexpr auto begin() {
    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() {
    if constexpr (random_access_range<V> && sized_range<V>)
        return ranges::begin(base_) + ranges::size(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::size(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).

26.7.18 Reverse view

26.7.18.1 Overview

reverse_view takes a bidirectional view and produces another view that iterates the same elements in reverse order.

1 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:

(2.1) — If the type of E is a (possibly cv-qualified) specialization of reverse_view, equivalent to E.base().

(2.2) — 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,

(2.2.1) — if K is subrange_kind::sized, equivalent to:

    subrange<I, I, K>(E.end().base(), E.begin().base(), E.size())

(2.2.2) — otherwise, equivalent to:

    subrange<I, I, K>(E.end().base(), E.begin().base())

However, in either case E is evaluated only once.

(2.3) — Otherwise, equivalent to reverse_view(E).
3 [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]

26.7.18.2 Class template reverse_view

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 reverse_iterator<iterator_t<V>> begin() requires common_range<V>;
        constexpr auto begin() const requires common_range<const V>;

        constexpr reverse_iterator<iterator_t<V>> end();
        constexpr auto end() const requires common_range<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>
        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>> begin() requires common_range<V>;
    constexpr auto begin() const requires common_range<const V>;
    Effects: Equivalent to: return make_reverse_iterator(ranges::end(base_));

    constexpr reverse_iterator<iterator_t<V>> end();
    constexpr auto end() const requires common_range<const V>;
    Effects: Equivalent to: return make_reverse_iterator(ranges::begin(base_));
26.7.19 Elements view

26.7.19.1 Overview

1 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.

2 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:]
```
auto 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
}
```

—end example]

3 keys_view is an alias for elements_view<R, 0>, and is useful for extracting keys from associative containers.

[Example 2:]
```
auto names = historical_figures | views::keys;
for (auto&& name : names) {
  cout << name << ' ' << // prints Babbage Hamilton Lovelace Turing
}
```

—end example]

4 values_view is an alias for elements_view<R, 1>, and is useful for extracting values from associative containers.

[Example 3:]
```
auto is_even = [](const auto x) { return x % 2 == 0; }
cout << ranges::count_if(historical_figures | views::values, is_even); // prints 2
```

—end example]

26.7.19.2 Class template elements_view

```cpp
define<
```
```cpp
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:

  constexpr explicit elements_view(V base) 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 iterator<false>(ranges::begin(base_)); }
  constexpr auto begin() const requires range<const V>
  { return iterator<true>(ranges::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 sentinel<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:
  // 26.7.19.3, class template elements_view::iterator
template<bool> struct iterator;
  // exposition only

  // 26.7.19.4, class template elements_view::sentinel
template<bool> struct sentinel;
  // exposition only

  V base_ = V();
  // exposition only
};

constexpr explicit elements_view(V base);

Effects: Initializes base_ with std::move(base).

26.7.19.3 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<Const>
class elements_view<V, N>::iterator {
using Base = maybe-const<Const, V>;
  // exposition only

  iterator<Base> current_ = iterator<Base>();
  // exposition only

  static constexpr decltype(auto) get_element(const iterator_t<Base>& i);
  // exposition only

};
```
The member typedef-name iterator_concept is defined as follows:

1. If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
2. Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
— Otherwise, if `Base` models `forward_range`, then `iterator_concept` denotes `forward_iterator_tag`.

— 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`.

— If `std::get<N>(*i)` is an rvalue, `iterator_category` denotes `input_iterator_tag`.

— Otherwise, if `C` models `derived_from<random_access_iterator_tag>`, `iterator_category` denotes `random_access_iterator_tag`.

— Otherwise, `iterator_category` denotes `C`.

```cpp
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));
}
```

```cpp
constexpr explicit iterator(iterator_t<Base> current);

Effects: Initializes `current_` with `std::move(current)`.
```

```cpp
constexpr iterator(iterator_t<Base> current);

Effects: Equivalent to: `++current_`.
```

```cpp
constexpr iterator operator++();

Effects: Equivalent to: `auto temp = *this; ++current_; return temp;`
```

```cpp
constexpr iterator operator++(int);

Effects: Equivalent to: `++current_`.
```

```cpp
constexpr iterator operator++(int) requires forward_range<Base>;

Effects: Equivalent to:
auto temp = *this;
++current_; return temp;
```

```cpp
constexpr iterator operator--() requires bidirectional_range<Base>;

Effects: Equivalent to:
--current_; return *this;
```

```cpp
constexpr iterator operator--(int) requires bidirectional_range<Base>;

Effects: Equivalent to:
auto temp = *this;
--current_; return temp;
```
constexpr iterator& operator+=(difference_type n);
  
  **Effects:** Equivalent to:
  
  current_ += n;
  return *this;

constexpr iterator& operator-=(difference_type n);
  
  **Effects:** Equivalent to:
  
  current_ -= n;
  return *this;

friend constexpr bool operator==(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return x.current_ == y.current_;

friend constexpr bool operator<(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return x.current_ < y.current_;

friend constexpr bool operator>(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return y < x;

friend constexpr bool operator<=(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return !(y < x);

friend constexpr bool operator>=(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return !(x < y);

friend constexpr auto operator<=>(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return x.current_ <=> y.current_;

friend constexpr iterator operator+(const iterator& x, difference_type y);
  
  **Effects:** Equivalent to:
  
  return iterator{x} += y;

friend constexpr iterator operator+(difference_type x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return y + x;

friend constexpr iterator operator-(const iterator& x, difference_type y);
  
  **Effects:** Equivalent to:
  
  return iterator{x} -= y;

friend constexpr difference_type operator-(const iterator& x, const iterator& y);
  
  **Effects:** Equivalent to:
  
  return sized_sentinel_for<iterator_t<Base>, iterator_t<Base>>;

### 26.7.19.4 Class template `elements_view::sentinel` [range.elements.sentinel]

```cpp
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);
    constexpr sentinel(sentinel<!Const> other)
        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 sentinel& x, const iterator<OtherConst>& 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);

1 Effects: Initializes end_ with end.

constexpr sentinel(sentinel<!Const> other)
    requires Const && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

2 Effects: Initializes end_ with std::move(other.end_).

constexpr sentinel_t<Base> base() const;

3 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);

4 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);

5 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);

6 Effects: Equivalent to: return x.end_ - y.current_;

26.7.20 Zip view

26.7.20.1 Overview

1 zip_view takes any number of views and produces a view of tuples of references to the corresponding elements of the constituent views.

2 The name views::zip denotes a customization point object (16.3.3.3.6). Given a pack of subexpressions Es..., the expression views::zip(Es...) is expression-equivalent to
(2.1) — auto(views::empty<tuple<>>()) if Es is an empty pack,
(2.2) — otherwise, zip_view<views::all<decltype((Es...))>>(Es...).

[Example 1]

```cpp
vector v = {1, 2};
list l = {'a', 'b', 'c'};
auto z = views::zip(v, l);
range_reference_t<decltype(z)> f = z.front(); // f is a pair<int&, char&>
// that refers to the first element of v and l

for (auto& [x, y] : z) {
    cout << '(' << x << ' ' << y << ')' << endl; // prints: (1, a) (2, b)
}
```

—end example]

26.7.20.2 Class template zip_view

```cpp
namespace std::ranges {
    template<class... Rs>
    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> && ...));

    template<class... Ts>
    using tuple-or-pair = see below; // exposition only

    template<class F, class Tuple>
    constexpr auto tuple-transform(F&& f, Tuple&& tuple) { // exposition only
        return apply([&]<class... Ts>(Ts&&... elements) {
            return tuple-or-pair<invoke_result_t<F&, Ts>...>(
                invoke(f, std::forward<Ts>(elements))...);
        }, std::forward<Tuple>(tuple));
    }

    template<class F, class Tuple>
    constexpr void tuple-for-each(F&& f, Tuple&& tuple) { // exposition only
        apply([&]<class... Ts>(Ts&&... elements) {
            invoke(f, std::forward<Ts>(elements), ...);
        }, std::forward<Tuple>(tuple));
    }

    template<input_range... Views>
    requires (view<Views> && ... && (sizeof...(Views) > 0))
    class zip_view : public view_interface<zip_view<Views...>> {
        tuple<Views...> views_; // exposition only

        // 26.7.20.3, class template zip_view::iterator
        template<bool> class iterator;
        // exposition only

        // 26.7.20.4, 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 (!is_simple_view<View>) {
            return iterator<false>(tuple-transform(ranges::begin, views_));
        }
        constexpr auto begin() const requires (ranges::begin) {
            return iterator<true>(tuple-transform(ranges::begin, views_));
        }
```
Given some pack of types \( Ts \), the alias template \( \text{tuple-or-pair} \) is defined as follows:

1. If \( \text{sizeof}(...) (Ts) \) is 2, \( \text{tuple-or-pair<}Ts\ldots\text{>} \) denotes \( \text{pair<}Ts\ldots\text{>} \).
2. Otherwise, \( \text{tuple-or-pair<}Ts\ldots\text{>} \) denotes \( \text{tuple<}Ts\ldots\text{>} \).

Two \( \text{zip_view} \) objects have the same underlying sequence if and only if the corresponding elements of \( \text{views} \) are equal (18.2) and have the same underlying sequence.

\[
\text{constexpr explicit zip_view(Views... views);}
\]

**Effects:** Initializes \( \text{views}_\text{with std::move}(\text{views}) \ldots \).

\[
\text{constexpr auto size() requires (sized_range<Views> \&\& ...) const requires (sized_range<const Views> \&\& ...);}
\]

**Effects:** Equivalent to:

\[
\text{return apply(\{\text{auto... sizes}\) }
\]

\[
\text{\quad using CT = make_unsigned_like_t<common_type_t<\text{decltype(sizes)\ldots}>>;}
\]

\[
\text{return ranges::min({CT(sizes)\ldots});}
\]

\[
\text{, tuple-transform(ranges::size, \text{views}_\text{with std::move}(\text{views})\ldots);}
\]

### 26.7.20.3 Class template \( \text{zip_view::iterator} \)

**name space std::ranges {**

**template<auto Const, class... Views>**

**concept all_random_access =**

\[
\text{\quad (random_access_range<\text{maybe-const}<Const, Views>> \&\& ...);}
\]

**template<auto Const, class... Views>**

**concept all_bidirectional =**

\[
\text{\quad (bidirectional_range<\text{maybe-const}<Const, Views>> \&\& ...);}
\]

**template<auto Const, class... Views>**

**concept all_forward =**

\[
\text{\quad (forward_range<\text{maybe-const}<Const, Views>> \&\& ...);}
\]}
template<input_range... Views>
  requires (view<Views> && ... && (sizeof...(Views) > 0))
#endif
template<bool Const>
class zip_view<Views...>::
  iterator
{
  tuple-or-pair<iterator_t<
    maybe-const<Const, Views>>>... current;
  // exposition only
  constexpr explicit iterator(tuple-or-pair<iterator_t<
    maybe-const<Const, Views>>>...);
  // exposition only
public:
  using iterator_category = input_iterator_tag;
  // not always present
  using iterator_concept = see below;
  using value_type = tuple-or-pair<
    range_value_t<
      maybe-const<Const, Views>>...>;
  using difference_type = common_type_t<
    range_difference_t<
      maybe-const<Const, Views>>...>;
  iterator() = default;
  constexpr iterator(iterator<
    Const> i)
    requires Const && ( convertible_to<
      iterator_t<
        Views>,
      iterator_t<
        maybe-const<
          Const, Views>>> && ...);
  constexpr auto operator*() const;
  constexpr iterator& operator++();
  constexpr void operator++(int);
  constexpr iterator& operator++(int) requires
    all-forward<
      Const, Views...>;
  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>>> && ...);
  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...> &&
    (three_way_comparable<
      iterator_t<
        maybe-const<
          Const, Views>>> && ...);
  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...>;
  friend constexpr iterator operator-(const
    iterator& i, difference_type n)
    requires all-random-access<
      Const, Views...>;
  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>>> && ...);
  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, Views>>> && ...);
iterator::iterator_concept is defined as follows:

1. If all-random-access<Const, Views...> is modeled, then iterator_concept denotes random-access_iterator_tag.
2. Otherwise, if all-bidirectional<Const, Views...> is modeled, then iterator_concept denotes bidirectional_iterator_tag.
3. Otherwise, if all-forward<Const, Views...> is modeled, then iterator_concept denotes forward_iterator_tag.
4. 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-or-pair<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<maybe-const<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_);
```cpp
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
    requires all-random-access<Const, Views...>;

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:
    — x.current_ == y.current_ if all-bidirectional<Const, Views...> is true.
    — Otherwise, true if there exists an integer 0 ≤ i < sizeof...(Views) such that bool(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]
    — Otherwise, false.

friend constexpr bool operator<(const iterator& x, const iterator& y)
    requires all-random-access<Const, Views...>;

Returns: x.current_ < y.current_.

friend constexpr bool operator>(const iterator& x, const iterator& y)
    requires all-random-access<Const, Views...>;

Effects: Equivalent to: return y < x;

friend constexpr bool operator<=(const iterator& x, const iterator& y)
    requires all-random-access<Const, Views...>;

Effects: Equivalent to: return !(y < x);

friend constexpr bool operator>=(const iterator& x, const iterator& y)
    requires all-random-access<Const, Views...>;

Effects: Equivalent to: return !(x < y);

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 iterator operator-(const iterator& i, difference_type n)
    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<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).

26.7.20.4 Class template zip_view::sentinel
[range.zip.sentinel]
namespace std::ranges {
    template<input_range... Views>
    requires (view<Views> && ...) && (sizeof...(Views) > 0)
    template<bool Const>
    class zip_view<Views...>::sentinel
    {
        tuple-or-pair<sentinel_t<maybe-const<Const, Views>>>... end_; // exposition only
        constexpr explicit sentinel(tuple-or-pair<sentinel_t<maybe-const<Const, Views>>>...> end);
        // exposition only
    public:
        sentinel() = default;
        constexpr sentinel(sentinels<i>Constar i)
            requires Const &&
            (convertible_to<sentinel_t<Views>, sentinel_t<maybe-const<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> 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 iterator<OtherConst>& x, const sentinel<y> 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);

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```cpp
constexpr explicit sentinel((tuple-or-pair<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<maybe-const<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 iterator<OtherConst>& x, const sentinel& y);

Effects: Equivalent to return -(x - y);
```

### 26.7.21 Zip transform view

#### 26.7.21.1 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 (16.3.3.3.6). Let \( F \) be a subexpression, and let \( E_s... \) be a pack of subexpressions.

1. If \( E_s \) is an empty pack, let \( FD \) be \( \text{decay}_t<\text{decltype}(F)> \).
2. If \( \text{copy_constructible<FD> \&\& regular_invocable<FD\&> \text{ is false, or if } \text{decay}_t<\text{invoke_result_t<FD\&>}> \text{ is not an object type, views::zip_transform(F, Es...) is ill-formed.} \)
3. Otherwise, the expression views::zip_transform(F, Es...) is expression-equivalent to

\[
((\text{void})F, \text{auto(views::empty<\text{decay}_t<\text{invoke_result_t<FD\&>}})})
\]

— 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
}
```
26.7.21.2 Class template `zip_transform_view`

```cpp
namespace std::ranges {
    template<copy_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 : public view_interface<zip_transform_view<F, Views...>> {
        copyable-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

        // 26.7.21.3, class template `zip_transform_view`::iterator
        template<bool> class iterator;
        // exposition only

        // 26.7.21.4, 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()); }
        constexpr auto begin() const requires range<const InnerView> &&
            regular_invocable<const F, range_reference_t<const Views>...> {
            return iterator<true>(*this, zip_.begin());
        }
        constexpr auto end() if constexpr (common_range<InnerView>) {
            return iterator<false>(*this, zip_.end());
        } else {
            return sentinel<false>(zip_.end());
        }
        constexpr 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());
            }
        }
        constexpr auto size() requires sized_range<InnerView> {
            return zip_.size();
        }
        constexpr 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)....

### 26.7.21.3 Class template zip_transform_view::iterator

```cpp
namespace std::ranges {

    template<copy_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...>::iterator {

        using Parent = maybe-const<Const, zip_transform_view>; // exposition only
        using Base = maybe-const<Const, InnerView>; // exposition only
        Parent* parent_ = nullptr; // exposition only
        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>&,
                inner_>>::range_reference_t<maybe-const<Const, Views>...>;
            using difference_type = range_difference_t<Base>;

            iterator() = default;
            constexpr iterator(iterator<!Const> i)
                requires Const && convertible_to<zierator<false>, ziperator<Const>>;

            constexpr decltype(auto) operator*() const noexcept(see below);
            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
                requires random_access_range<Base>;

            friend constexpr bool operator==(const iterator& x, const iterator& y)
                requires equality_comparable<zierator<Const>>;

            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<zierator<Const>>;
```
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<typename iterator<Const, ziperator<Const>>>;  
};

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:

(1.1) — If

   invoke_result_t<
      maybe-const<Const, F>&, range_reference_t<
      maybe-const<Const, Views>>&...>

   is not an lvalue reference, iterator_category denotes input_iterator_tag.

(1.2) — Otherwise, let Cs denote the pack of types iterator_traits<

   iterator_t<
      maybe-const<Proto, Views>>>::iterator_category...

(1.2.1) — If (derived_from<Cs, random_access_iterator_tag> && ...) is true, iterator_category denotes random_access_iterator_tag.

(1.2.2) — Otherwise, if (derived_from<Cs, bidirectional_iterator_tag> && ...) is true, iterator_category denotes bidirectional_iterator_tag.

(1.2.3) — Otherwise, if (derived_from<Cs, forward_iterator_tag> && ...) is true, iterator_category denotes forward_iterator_tag.

(1.2.4) — 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<Proto> 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:

   return apply([&](const auto&... iters) -> decltype(auto) {
      return invoke(*parent_->fun_, *iters...);
   }, inner_.current_);

Remarks: Let Is be the pack 0, 1, ..., (size...(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;

castexpr 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([&]<class... Is>(const Is&... 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 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<ziperator<Const>>;

**Effects**: Equivalent to:

```
return x.inner_ op y.inner_;  
```

friend constexpr auto operator+(const iterator& i, difference_type n) requires random_access_range<Base>;

**Effects**: Equivalent to:

```
return iterator(*i.parent_, i.inner_ + n);
```

friend constexpr auto operator+(difference_type n, const iterator& i) 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_;  
```
26.7.21.4 Class template `zip_transform_view::sentinel` [range.zip.transform.sentinel]

namespace std::ranges {
    template<
copy_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<F, Views...>::sentinel {
        sentinel<Const> inner; // exposition only
        constexpr explicit sentinel(sentinellConst i) :
            requires Const && convertible_to<sentinel<false>, sentinel<Const>>;
    
public:
        sentinel() = default;
        constexpr explicit sentinel(sentinell Const i) :
            requires Const && convertible_to<sentinel<false>, sentinel<Const>>;
        sentinel(sentinell 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 sentinel& x, const iterator<OtherConst>& 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);
    }
}

1 Effects: Initializes `inner_` with `inner`.
2 ```
constexpr explicit sentinel(sentinell Const i) :
    requires Const && convertible_to<sentinel<false>, sentinel<Const>>;
2 Effects: Initializes `inner_` with `std::move(i. inner_)`.
```  
3 Effects: Equivalent to: return x. inner_ == y. inner_;  
4 Effects: Equivalent to: return x. inner_ - y. inner_;  

26.7.22 Adjacent view [range.adjacent]

26.7.22.1 Overview [range.adjacent.overview]

1 `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.

2 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
— if $N$ is equal to 0,
— otherwise, adjacent_view<views::all_t<decltype((E))>, N>(E).

[Example 1]:
vector v = {1, 2, 3, 4};
for (auto i : v | views::adjacent<2>) {
  cout << "(" << i.first << ", " << i.second << ")" << endl; // prints: (1, 2) (2, 3) (3, 4)
}
—end example]

3 Define $\texttt{REPEAT}(T, N)$ as a pack of $N$ types, each of which denotes the same type as $T$.

### 26.7.22.2 Class template adjacent_view

```cpp
namespace std::ranges {
  template<forward_range V, size_t N>
  requires view<V> && (N > 0)
  class adjacent_view : public view_interface<adjacent_view<V, N>> {
    V base_ = V(); // exposition only
    // 26.7.22.3, class template adjacent_view::iterator
    template<bool> class iterator; // exposition only
    // 26.7.22.4, class template adjacent_view::sentinel
    template<bool> class sentinel; // exposition only
    struct as_sentinel{}; // exposition only
  }

  public:
    adjacent_view() requires default_initializable<V> = default;
    constexpr explicit adjacent_view(V base);
    constexpr auto begin() requires (!simple_view<V>) {
      return iterator<false>(ranges::begin(base_), ranges::end(base_));
    }
    constexpr auto begin() const requires range<const V> {
      return iterator<true>(ranges::begin(base_), ranges::end(base_));
    }
    constexpr auto end() requires (!simple_view<V>) {
      if constexpr (common_range<V>) {
        return iterator<false>(as_sentinel{}, ranges::begin(base_), ranges::end(base_));
      } else {
        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 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);

26.7.22.3 Class template adjacent_view::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>;
    array<iterator_t<Base>, N> current_ = array<iterator_t<Base>, N>();
    constexpr iterator(iterator_t<Base> first, sentinel_t<Base> last);
    constexpr iterator(as sentinel, iterator_t<Base> first, iterator_t<Base> last);

public:
  using iterator_category = input_iterator_tag;
  using iterator_concept = see below;
  using value_type = tuple-or-pair<REPEAT(range_value_t<Base>, N)...>;
  using difference_type = range_difference_t<Base>;
  iterator() = default;
  constexpr iterator(iterator_t<!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--() 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>;

  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<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>;

  // exposition only
}

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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>>;
}

iterator::iterator_concept is defined as follows:

— If Base models random_access_range, then iterator_concept denotes random_access_iterator_tag.
— Otherwise, if Base models bidirectional_range, then iterator_concept denotes bidirectional_iterator_tag.
— Otherwise, iterator_concept denotes forward_iterator_tag.

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.

constexpr iterator& operator++(int);  
 Preconditions: Equivalent to:
  auto tmp = *this;
  ***this;
  return tmp;

constexpr iterator& operator--() requires bidirectional_range<Base>;  
 Preconditions: current_.front() is decrementable.
Postconditions: Each element of current_ is equal to ranges::prev(i), where i is the value of that element before the call.
Returns: *this.
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>;

**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.

customexpr 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.

customexpr 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_);
```

friend constexpr bool operator==(const iterator& x, const iterator& y);

**Returns:** x.current_.back() == y.current_.back().

friend constexpr bool operator<(const iterator& x, const iterator& y) requires random_access_range<Base>;

**Returns:** x.current_.back() < y.current_.back().

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_.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:

```cpp
    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>>;

    Effects: Equivalent to: return x.current_.back() - y.current_.back();

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>>()))

§ 26.7.22.4  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>;
        sentinel_t<Base> end_ = sentinel_t<Base>();
        constexpr explicit sentinel(sentinel_t<Base> end);
    }

public:
    sentinel() = default;
    constexpr sentinel(sentinel<!Const> i)
        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);

    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.

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constexpr sentinel(sentinel<NotConst> i)
    requires NotConst && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

2 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);

3 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);

4 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);

5 Effects: Equivalent to: return y.end_ - x.current_.back();

26.7.23 Adjacent transform view

26.7.23.1 Overview

1 adjacent_transform_view takes an invocable object and a view and produces a view whose Mth element is the result of applying the invocable object to the Mth 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::adjacent_transform<N> denotes a range adaptor object (26.7.2). Given subexpressions E and F and a constant expression N:

(2.1) If N is equal to 0, views::adjacent_transform<N>(E, F) is expression-equivalent to ((void)E, views::zip_transform(F)), except that the evaluations of E and F are indeterminately sequenced.

(2.2) Otherwise, the expression views::adjacent_transform<N>(E, F) is expression-equivalent to adjacent_transform_view<views::all_t<decltype((E))>, decay_t<decltype((F))>, N>(E, F).

3 [Example 1:]

```
vector v = {1, 2, 3, 4};

for (auto i : v | views::adjacent_transform<2>(std::multiplies())) {
    cout << i << ' ';  // prints: 2 6 12
}
```

—end example]

26.7.23.2 Class template adjacent_transform_view

```
namespace std::ranges {

template<forward_range V, copy_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>> {
    copyable-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

    // 26.7.23.3, class template adjacent_transform_view::iterator

template<bool> class iterator;  // exposition only

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```
// 26.7.23.4, 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 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).

26.7.23.3 Class template adjacent_transform_view::iterator
[range.adjacent.transform.iterator]

namespace std::ranges {
    template<forward_range V, copy_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<F, V...>::iterator {
        using Parent = maybe-const<Const, adjacent_transform_view>;
        using Base = maybe-const<Const, V>;
        Parent* parent_ = nullptr;
        inner_iterator<Const> inner_;

        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*() const noexcept;
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 decltype(auto) operator[](difference_type n) const 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>;
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<inner_iterator<Const>>;
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<inner_iterator<Const>, inner_iterator<Const>>;

1 The member typedef-name iterator::iterator_category is defined as follows:
(1.1) If invoke_result_t<maybe-const<Const, F>&, 
REPEAT(range_reference_t<Base>, N)...> is not an lvalue reference, iterator_category denotes input_iterator_tag.
(1.2) Otherwise, let C denote the type iterator_traits<iterator_t<Base>>::iterator_category.
(1.2.1) If derived_from<C, random_access_iterator_tag> is true, iterator_category denotes random_access_iterator_tag.
(1.2.2) Otherwise, if derived_from<C, bidirectional_iterator_tag> is true, iterator_category denotes bidirectional_iterator_tag.
(1.2.3) Otherwise, if derived_from<C, forward_iterator_tag> is true, iterator_category denotes forward_iterator_tag.
(1.2.4) Otherwise, iterator_category denotes input_iterator_tag.

constexpr iterator(Parent& parent, inner_iterator<Const> inner);

2 Effects: Initializes parent_ with addressof(parent) and inner_ with std::move(inner).
constexpr iterator<iterator<!Const> i)  
requires Const && convertible_to<inner-iterator<false>, inner-iterator<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:
    return apply([&](const auto&... iters) -> decltype(auto) {
        return invoke(*parent_->fun_, *iters...);
    }, inner_.current_);

Remarks: Let Is be the pack 0, 1, ..., (N-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 iterator operator++(int);

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[n]...);
    }, inner_.current_);

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>;

§ 26.7.23.3
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<inner_iterator<Const>>;

Let \textit{op} be the operator.

**Effects:** Equivalent to: \( \text{return } x.\text{inner}_. \text{op} y.\text{inner}_. \)

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: \( \text{return } \text{iterator}(*i.\text{parent}_., i.\text{inner}_.+ n); \)

friend constexpr iterator operator-(const iterator& i, difference_type n) requires random_access_range<Base>;

**Effects:** Equivalent to: \( \text{return } \text{iterator}(*i.\text{parent}_., i.\text{inner}_.- n); \)

friend constexpr difference_type operator-(const iterator& x, const iterator& y) requires sized_sentinel_for<inner_iterator<Const>, inner_iterator<Const>>;

**Effects:** Equivalent to: \( \text{return } x.\text{inner}_.- y.\text{inner}_. \)

### 26.7.23.4 Class template adjacent_transform_view::sentinel

```cpp
namespace std::ranges {
    template<forward_range V, copy_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>
    requires sentinel_for<inner_iterator<Const>, inner_iterator<Const>>
    friend constexpr bool operator==(const iterator<OtherConst>& x, const sentinel& y);
    template<bool OtherConst>
    requires sized_sentinel_for<inner_iterator<Const>, inner_iterator<OtherConst>>
    friend constexpr range_difference_t<maybe_const<OtherConst, InnerView>>
    operator-(const iterator<OtherConst>& x, const sentinel& y);
}
```

**Effects:** Initializes \( \text{inner}_. \) with \( \text{inner}_. \).
constexpr sentinel(sentinel<!Const> i)
  requires Const && convertible_to<inner-sentinel<false>, inner-sentinel<Const>>;

Effects: Initializes inner_ with std::move(i.inner_).

template<bool OtherConst>
  requires sentinel_for<inner-sentinel<Const>, inner-iterator<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<inner-sentinel<Const>, inner-iterator<OtherConst>>
  friend constexpr range_difference_t<maybe-const<OtherConst, InnerView>>
    operator-(const iterator<OtherConst>& x, const sentinel& y);

Effects: Equivalent to return x.inner_ - y.inner_

26.7.24 Chunk view

26.7.24.1 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:

```cpp
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 << "]";
}
```

The above prints: [1, 2] [3, 4] [5] — end example]

26.7.24.2 chunk_view for input ranges

namespace std::ranges {
  template<class I>
   constexpr I div-ceil(I num, I denom) {
      I r = num / denom;
      if (num % denom)
        ++r;
      return r;
    }

template<class V>
  requires input_range<V>
  class chunk_view : public view_interface<chunk_view<V>> {
    V base_ = V();
    range_difference_t<V> n_ = 0;
    range_difference_t<V> remainder_ = 0;
    non-propagating-cache<iterator_t<V>> current_;
// 26.7.24.3, class chunk_view::outer-iterator
class outer-iterator;     // exposition only

// 26.7.24.5, class chunk_view::inner-iterator
class inner-iterator;     // exposition only

public:
chunk_view() requires default_initializable<V> = default;
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() noexcept;

constexpr auto size() requires sized_range<V>;
constexpr auto size() const requires sized_range<const V>;
};

template<class R>
chunk_view(R&& r, range_difference_t<R>) -> chunk_view<views::all_t<R>>;

constexpr explicit chunk_view(V base, range_difference_t<V> n);

Preconditions: n > 0 is true.

Effects: Initializes base_ with std::move(base) and n_ with n.

constexpr outer-iterator begin();

Effects: Equivalent to:
    current_ = ranges::begin(base_);
    remainder_ = n_;
    return outer-iterator(*this);

constexpr default_sentinel_t end() noexcept;

Returns: default_sentinel.

constexpr auto size() requires sized_range<V>;
constexpr auto size() const requires sized_range<const V>;

Effects: Equivalent to:
    return to_unsigned_like(div ceil(ranges::distance(base_), n_));

26.7.24.3 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>;

        // 26.7.24.4, class chunk_view::outer-iterator::value_type
        struct value_type;

        outer-iterator(outer-iterator&&) = default;
        outer-iterator& operator=(outer-iterator&&) = default;

    } // chunk_view::outer-iterator
};
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:

ranges::advance(*parent_->current_, parent_->remainder_, ranges::end(parent_->base));
parent_->remainder_ = parent_->n_;
return *this;

constexpr void operator++(int);
Effects: Equivalent to ++*this.

friend constexpr bool operator==(const outer_iterator& x, default_sentinel_t);
Effects: Equivalent to:

return *x.parent_->current_ == ranges::end(x.parent_->base) && x.parent_->remainder_ != 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);

26.7.24.4 Class chunk_view::outer_iterator::value_type
[range.chunk.outer.value]

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;

§ 26.7.24.4
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 ranges::min(parent_->remainder_, ranges::end(parent_->base_) - *parent_->current_);

26.7.24.5 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>;
        
        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>>;
    };

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_;

§ 26.7.24.5
constexpr inner-iterator& operator++();

5  Preconditions: *this == default_sentinel is false.
6  Effects: Equivalent to:
   
   ***parent_->current_;  
   if (*parent_->current_ == ranges::end(parent_->base_))  
     parent_->remainder_ = 0;  
   else  
     --parent_->remainder_;  
   return *this;

constexpr void operator++(int);
7  Effects: Equivalent to +++this.

friend constexpr bool operator==(const inner-iterator& x, default_sentinel_t);
8  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>>;
9  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>>;
10 Effects: Equivalent to: return -(y - x);

26.7.24.6 chunk_view for forward ranges  [range.chunk.view.fwd]

namespace std::ranges {
   template<typename V>  
   requires forward_range<V>
   class chunk_view<V> : public view_interface<chunk_view<V>> {
      V base_ = V(); // exposition only
      range_difference_t<V> n_ = 0; // exposition only
   }

   // 26.7.24.7, class template chunk_view::iterator  
   template<bool> class iterator; // exposition only

public:
   chunk_view() requires default_initializable<V> = default;
   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;
      }
   }

§ 26.7.24.6
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_, ranges::end(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.
2 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>;

3 Effects: Equivalent to:
    return to_unsigned_like(div_ceil(ranges::distance(base_, n_));

26.7.24.7 Class template chunk_view<V>::iterator for forward ranges [range.chunk.fwd.iter]

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>>
                && convertible_to<sentinel_t<V>, sentinel_t<Base>>;

            constexpr iterator_t<Base> base() const;

            constexpr value_type operator*() const;
            constexpr iterator& operator++();
            constexpr iterator operator++(int);

    § 26.7.24.7 1135
constexpr iterator& operator--() requires bidirectional_range<Base>;
constexpr iterator operator--(int) requires bidirectional_range<Base>;

c媪expr iterator& operator+=(difference_type x)
    requires random_access_range<Base>;
constexpr iterator& operator-=(difference_type x)
    requires random_access_range<Base>;

cxFFenexpr 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, 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 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);

2  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>>;

3  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;

4  Returns: current_.

§ 26.7.24.7 1136
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:
  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) {
    missing_ = ranges::advance(current_, n_ * x, 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>;

Effects: Equivalent to: return *this += -x;

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_.

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: (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>>;

  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>>;

  Effects: Equivalent to: return -(y - x);

26.7.25 Slide view

26.7.25.1 Overview

slide_view takes a view and a number N and produces a view whose Mth element is a view over the Mth 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 view::slide denotes a range adaptor object (26.7.2). Given subexpressions E and N, the expression view::slide(E, N) is expression-equivalent to slide_view(E, N).

[Example 1]:
  vector v = {1, 2, 3, 4};
N4910

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for (auto i : v | views::slide(2)) {
cout << '[' << i[0] << ", " << i[1] << "] ";
}

// prints: [1, 2] [2, 3] [3, 4]

— end example]

26.7.25.2

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>;

// exposition only

template<forward_range V>
requires view<V>
class slide_view : public view_interface<slide_view<V>> {
V base_ = V();
// exposition only
range_difference_t<V> n_ = 0;
// exposition only
// 26.7.25.3, class template slide_view::iterator
template<bool> class iterator ;
// exposition only
// 26.7.25.4, class slide_view::sentinel
class sentinel ;
// exposition only
public:
slide_view() requires default_initializable<V> = default;
constexpr explicit slide_view(V base, range_difference_t<V> n);
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&& r, range_difference_t<R>) -> slide_view<views::all_t<R>>;
}
constexpr explicit slide_view(V base, range_difference_t<V> n);
1

Effects: Initializes base_ with std::move(base) and n_ with n.
constexpr auto begin()
requires (!(simple-view <V> && slide-caches-nothing <const V>));

2
(2.1)

Returns:
— If V models slide-caches-first ,
iterator <false>(ranges::begin(base_),
ranges::next(ranges::begin(base_), n_ - 1, ranges::end(base_)), n_)

(2.2)

— Otherwise, iterator <false>(ranges::begin(base_), n_).

§ 26.7.25.2

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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-first.

```cpp
conestexpr auto begin() const requires slide-caches-nothing<const V>;
```

Returns: iterator<true>(ranges::begin(base_), n_).

```cpp
conestexpr auto end()
    requires (!((simple-view<V> && slide-caches-nothing<const V>));
```

Returns: (5.1) If V models slide-caches-nothing,
        iterator<false>(ranges::begin(base_) + range_difference_t<V>(size()), n_)
(5.2) Otherwise, if V models slide-caches-last,
        iterator<false>(ranges::prev(ranges::end(base_), n_ - 1, ranges::begin(base_)), n_)
(5.3) Otherwise, if V models common_range,
        iterator<false>(ranges::end(base_), ranges::end(base_), n_)
(5.4) Otherwise, sentinel(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 slide_view for use on subsequent calls when V models slide-caches-last.

```cpp
conestexpr auto end() const requires slide-caches-nothing<const V>;
```

Returns: begin() + range_difference_t<const V>(size()).

```cpp
conestexpr auto size() requires sized_range<V>;
conestexpr auto size() const requires sized_range<const V>;
```

Effects: Equivalent to:
```cpp
auto sz = ranges::distance(base_) - n_ + 1;
if (sz < 0) sz = 0;
return to-unsigned-like(sz);
```

26.7.25.3 Class template slide_view::iterator

```cpp
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 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;
    }
}```
```cpp
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--() 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>;

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>>;
```

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.

3. `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`.

4. `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`.

§ 26.7.25.3
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);

Effects: Equivalent to:
  auto tmp = *this;
  +++*this;
  return tmp;

constexpr iterator& operator--() requires bidirectional_range<Base>;

Preconditions: current_ and last_ele_ (if present) are decrementable.

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.

Returns: *this.

constexpr iterator operator--(int) requires bidirectional_range<Base>;

Preconditions: current_ and last_ele_ (if present) have well-defined behavior.

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.

Returns: *this.

constexpr iterator& operator+=(difference_type x)
  requires random_access_range<Base>;

Preconditions: current_ + x and last_ele_ + x (if last_ele_ is present) have well-defined behavior.

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.

Returns: *this.

constexpr iterator& operator-=(difference_type x)
  requires random_access_range<Base>;

Preconditions: current_ - x and last_ele_ - x (if last_ele_ is present) have well-defined behavior.

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.

Returns: *this.

constexpr auto operator[](difference_type n) const
  requires random_access_range<Base>;

Effects: Equivalent to: return views::counted(current_ + n, n_);

friend constexpr bool operator==(const iterator& x, const iterator& y);

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>;

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_.

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 \texttt{last\_ele\_} is present, x.last\_ele\_ - y.last\_ele\_; otherwise, x.current_ - y.current_.

### 26.7.25.4 Class \texttt{slide\_view::sentinel} [range.slide.sentinel]

```cpp
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<sentinel_t<V>, iterator_t<V>>;
    }
}
```
friend constexpr 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);

**Returns:** x.last_ele_ - y.end_.

friend constexpr range_difference_t<V> operator-(const sentinel& y, const iterator<false>& x);

**Returns:** y.end_ - x.last_ele_.

### 26.7.26 Chunk by view

#### 26.7.26.1 Overview

`chunk_by_view` takes a `view` and a predicate, and splits the `view` into subranges 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:**

```cpp
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]" — end example"

#### 26.7.26.2 Class template `chunk_by_view`

```cpp
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>> {
        V base_; // exposition only
copyable-box<Pred> pred_ = Pred(); // exposition only
    }
}
```

**Public:**

```cpp
chunk_by_view() requires default_initializable<V> && default_initializable<Pred> = default;
constexpr explicit chunk_by_view(V base, Pred pred);

constexpr V base() const && { return base_; }
constexpr V base() const { return std::move(base_); }
```
chunk_by_view(base, pred);

Effects: Initializes base_ with std::move(base) and pred_ with std::move(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(chunk_by_view& parent, iterator_t<V> current, // exposition only
                iterator_t<V> next);

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);
    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);

2 Effects: Initializes parent_ with addressof(parent), current_ with current, and next_ with next.

constexpr value_type operator*() const;
3 Preconditions: current_ is not equal to next_.
4 Returns: subrange(current_, next_).

constexpr iterator& operator++();
5 Preconditions: current_ is not equal to next_.
6 Effects: Equivalent to:
    current_ = next_;
    next_ = parent_->find-next(current_); return *this;

constexpr iterator& operator++(int);
7 Effects: Equivalent to:
    auto tmp = *this;
    +++this;
    return tmp;

constexpr iterator& operator--() requires bidirectional_range<V>;
8 Effects: Equivalent to:
    next_ = current_; current_ = parent_->find-prev(next_);
    return *this;

constexpr iterator operator--(int) requires bidirectional_range<V>;
9 Effects: Equivalent to:
    auto tmp = *this;
    --*this;
    return tmp;
friend constexpr bool operator==(const iterator& x, const iterator& y);

Returns: \( x.\text{current} == y.\text{current} \).

friend constexpr bool operator==(const iterator& x, default_sentinel_t);

Returns: \( x.\text{current} == x.\text{next} \).
27 Algorithms library

27.1 General

1 This Clause describes components that C++ programs may use to perform algorithmic operations on containers (Clause 24) and other sequences.

2 The following subclauses describe components for non-modifying sequence operations, mutating sequence operations, sorting and related operations, and algorithms from the ISO C library, as summarized in Table 89.

Table 89: Algorithms library summary

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27.2 Algorithms requirements

1 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.

2 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.

[Example 1:]

```c++
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

3 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.

4 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 template parameter is named InputIterator, InputIterator1, or InputIterator2, the template argument shall meet the Cpp17InputIterator requirements (25.3.5.3).

(4.2) — If an algorithm’s template parameter is named OutputIterator, OutputIterator1, or OutputIterator2, the template argument shall meet the Cpp17OutputIterator requirements (25.3.5.4).

(4.3) — If an algorithm’s template parameter is named ForwardIterator, ForwardIterator1, or ForwardIterator2, the template argument shall meet the Cpp17ForwardIterator requirements (25.3.5.5).

(4.4) — If an algorithm’s template parameter is named NoThrowForwardIterator, the template argument shall meet the Cpp17ForwardIterator requirements (25.3.5.5), and is required to have the property that no
exceptions are thrown from increment, assignment, or comparison of, or indirection through, valid iterators.

(4.5) If an algorithm’s template parameter is named BidirectionalIterator, BidirectionalIterator1, or BidirectionalIterator2, the template argument shall meet the Cpp17BidirectionalIterator requirements (25.3.5.6).

(4.6) If an algorithm’s template parameter is named RandomAccessIterator, RandomAccessIterator1, or RandomAccessIterator2, the template argument shall meet the Cpp17RandomAccessIterator requirements (25.3.5.7).

5 If an algorithm’s Effects element specifies that a value pointed to by any iterator passed as an argument is modified, then that algorithm has an additional type requirement: The type of that argument shall meet the requirements of a mutable iterator (25.3).

[Note 1: This requirement does not affect arguments that are named OutputIterator, OutputIterator1, or OutputIterator2, because output iterators must always be mutable, nor does it affect arguments that are constrained, for which mutability requirements are expressed explicitly. —end note]

6 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).

7 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. In other words, if an algorithm takes Predicate pred as its argument and first as its iterator argument with value type T, it should work correctly in the construct pred(*first) contextually converted to bool (7.3). The function object pred shall not apply any non-constant function through the dereferenced iterator. 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).

8 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. In other words, if an algorithm takes BinaryPredicate binary_pred as its argument and first1 and first2 as its iterator arguments with respective value types T1 and T2, it should work correctly in the construct binary_pred(*first1, *first2) contextually converted to bool (7.3). 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, it should work correctly in the construct binary_pred(*first1, value) contextually converted to bool (7.3). binary_pred shall not apply any non-constant function through the dereferenced iterators. 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).

9 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 noncopied implementation object such as reference_wrapper<T> (22.10.6), or some equivalent solution, can be used. —end note]

10 When the description of an algorithm gives an expression such as *first == value as a condition, the expression shall evaluate to either true or false in boolean contexts.

11 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;
for (; n > 0; --n) ++tmp;
return tmp;
```

220 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.
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

\[
\text{iter_difference_t<typename(a)> } n = 0;
\]

\[
\text{for (auto tmp = a; tmp != b; ++tmp) } ++n;
\]

\[
\text{return } n;
\]

and if \([b, a)\) denotes a range, the same as those of

\[
\text{iter_difference_t<typename(b)> } n = 0;
\]

\[
\text{for (auto tmp = b; tmp != a; ++tmp) } --n;
\]

\[
\text{return } n;
\]

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 \(a - D(n)\).

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 \(\text{ranges::next}(i, s)\).

Overloads of algorithms that take \(\text{range}\) arguments \((26.4.2)\) behave as if they are implemented by calling \(\text{ranges::begin}\) and \(\text{ranges::end}\) on the \(\text{range}(s)\) and dispatching to the overload in namespace \(\text{ranges}\) that takes separate iterator and sentinel arguments.

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.

[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 parallel algorithm is a function template listed in this document with a template parameter named \(\text{ExecutionPolicy}\).

Parallel algorithms access objects indirectly accessible via their arguments by invoking the following functions:

1. All operations of the categories of the iterators that the algorithm is instantiated with.
2. Operations on those sequence elements that are required by its specification.
3. User-provided function objects to be applied during the execution of the algorithm, if required by the specification.
4. Operations on those function objects required by the specification.

[Note 1: See 27.2. — end note]

These functions are herein called element access functions.

[Example 1: The \text{sort}\ function may invoke the following element access functions:

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 \(\text{RandomAccessIterator}\).
2. The \text{swap}\ function on the elements of the sequence (as per the preconditions specified in 27.8.2.1).
3. The user-provided \text{Compare}\ function object.

— end example]

A standard library function is \text{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.

[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:

\[
\text{int } x = 0;
\]

§ 27.3.1
std::mutex m;
void f() {
    int a[] = {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, BinaryOperation, BinaryOperation1, BinaryOperation2, 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]

1 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.

2 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]

3 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]

4 The invocations of element access functions in parallel algorithms invoked with an execution policy object of type std::execution::sequenced_policy all occur in the calling thread of execution.

[Note 3: The invocations are not interleaved; see 6.9.1. —end note]

5 The invocations of element access functions in parallel algorithms invoked with an execution policy object of type std::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 a 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]

6 The invocations of element access functions in parallel algorithms invoked with an execution policy object of type std::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:
```
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:
```
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:
```
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 a `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]

9 If an invocation of a parallel algorithm uses threads of execution implicitly created by the library, then the invoking thread of execution will either

(9.1) temporarily block with forward progress guarantee delegation (6.9.2.3) on the completion of these library-managed threads of execution, or

(9.2) 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]
27.3.4 Parallel algorithm exceptions

1 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.

2 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

1 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]

2 Unless otherwise specified, the semantics of ExecutionPolicy algorithm overloads are identical to their overloads without.

3 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 $O(expr)$.

4 Parallel algorithms shall not participate in overload resolution unless is_execution_policy_v<remove_cvref_t<ExecutionPolicy>> is true.

27.4 Header <algorithm> synopsis

#include <initializer_list>

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 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, Proj 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, Proj pred, Proj proj = {});
}

// 27.6.2, 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,
                // 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 any_of(I first, S last, Proj 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, Proj pred, Proj proj = {});
}

// 27.6.3, 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,
                 // 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 none_of(I first, S last, Proj 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, Proj pred, Proj proj = {});
}

// 27.6.4, 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 = {});
}

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);

namespace ranges {
    template<class I, class F>
    using for_each_n_result = in_fun_result<I, F>;

    template<input_iterator I, class Proj = identity,
        indirectly_unary_invocable<projected<I, Proj>> Fun>
    constexpr for_each_n_result<I, Fun>
        for_each_n(I first, iter_difference_t<I> n, Fun f, Proj proj = {});
}

// 27.6.5, find
template<class InputIterator, class T>
constexpr InputIterator find(InputIterator first, InputIterator last,
    const T& value);

template<class ExecutionPolicy, class ForwardIterator, class T>
ForwardIterator find(ExecutionPolicy&& exec,
    // see 27.3.5
    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 Predicate>
ForwardIterator find_if(ExecutionPolicy&& exec,
    // see 27.3.5
    ForwardIterator first, ForwardIterator last,
    Predicate pred);

namespace ranges {
    template<input_iterator I, sentinel_for<I> S, class T, class Proj = identity>
        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 T, class Proj = identity>
        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>> Pred>
    constexpr borrowed_iterator_t<R>
        find_if(R&& r, Pred pred, Proj proj = {});

    template<input_iterator I, sentinel_for<I> S, class Proj = identity,
                indirect_unary_predicate<projected<I, Proj>> Pred>
    constexpr I find_if_not(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 borrowed_iterator_t<R>
        find_if_not(R&& r, Pred pred, Proj proj = {});
}
// 27.6.6, 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,
        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 = {});

    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>
    find_end(R1&& r1, R2&& r2, Pred pred = {}),
              Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.7, find first

namespace ranges {
    template<class InputIterator, class ForwardIterator>
    constexpr InputIterator
    find_first_of(InputIterator first1, InputIterator last1,
                  ForwardIterator first2, ForwardIterator last2);

    template<class InputIterator, class ForwardIterator, class BinaryPredicate>
    constexpr InputIterator
    find_first_of(InputIterator first1, InputIterator last1,
                  ForwardIterator first2, ForwardIterator last2,
                  BinaryPredicate pred);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
    ForwardIterator1
    find_first_of(ExecutionPolicy&& exec,
                  ForwardIterator1 first1, ForwardIterator1 last1,
                  ForwardIterator2 first2, ForwardIterator2 last2);

    template<class ExecutionPolicy, class ForwardIterator1,
             class ForwardIterator2, class BinaryPredicate>
    ForwardIterator1
    find_first_of(ExecutionPolicy&& exec,
                  ForwardIterator1 first1, ForwardIterator1 last1,
                  ForwardIterator2 first2, ForwardIterator2 last2,
                  BinaryPredicate pred);
}
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 = {});
    template<input_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_iterator_t<R1> find_first_of(R1&& r1, R2&& r2, Pred pred = {}, 
            Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.8, adjacent find
namespace ranges {
    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);
}

// 27.6.9, count
namespace ranges {
    template<class InputIterator, class T>
    constexpr typename iterator_traits<InputIterator>::difference_type
    count(InputIterator first, InputIterator last, const T& value);
    template<class ExecutionPolicy, class ForwardIterator, class T>
    typename iterator_traits<ForwardIterator>::difference_type
        // see 27.3.5
    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
        // see 27.3.5
    count_if(ExecutionPolicy&& exec, 
        ForwardIterator first, ForwardIterator last, Predicate pred);
}
namespace ranges {

template<input_iterator I, sentinel_for<I> S, class T, class Proj = identity>
    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 T, class Proj = identity>
    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<projected<iterator_t<R>, Proj>> Pred>
    constexpr range_difference_t<R>
        count_if(R&& r, Pred pred, Proj proj = {});

} // 27.6.10, 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);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
    pair<ForwardIterator1, ForwardIterator2>
        mismatch(ExecutionPolicy&& exec,
            ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
    pair<ForwardIterator1, ForwardIterator2>
        mismatch(ExecutionPolicy&& exec,
            ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2,
            BinaryPredicate pred);

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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 = {});
}

// 27.6.11, equal
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 = {});
  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 equal(R1&& r1, R2&& r2, Pred pred = {},
                       Proj1 proj1 = {}, Proj2 proj2 = {});
}

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// 27.6.12, is permutation

```cpp
template<class ForwardIterator1, class ForwardIterator2>
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,
                               ForwardIterator2 first2);

template<class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,
                               ForwardIterator2 first2, BinaryPredicate pred);

namespace ranges {

    template<class ForwardIterator1, sentinel_for<ForwardIterator1> S1, forward_iterator ForwardIterator2, sentinel_for<ForwardIterator2> S2, class Proj1 = identity, class Proj2 = identity, indirect_equivalence_relation<projected<ForwardIterator1, Proj1>, projected<ForwardIterator2, Proj2>> Pred = ranges::equal_to>
    constexpr bool is_permutation(ForwardIterator1 first1, S1 last1, ForwardIterator2 first2, S2 last2,
                                   Pred pred = {},
                                   Proj1 proj1 = {}, Proj2 proj2 = {});

    template<class ForwardIterator1, forward_range ForwardRange1, forward_iterator ForwardIterator2, class Proj1 = identity, class Proj2 = identity, indirect_equivalence_relation<projected<iterator_t<ForwardRange1>, Proj1>, projected<iterator_t<ForwardIterator2>, Proj2>> Pred = ranges::equal_to>
    constexpr bool is_permutation(ForwardRange1&& r1, ForwardIterator2 first2, S2 last2,
                                   Pred pred = {},
                                   Proj1 proj1 = {}, Proj2 proj2 = {});
}

// 27.6.13, search

```cpp
```
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>
    search(R1&& r1, R2&& r2, Pred pred = {},
           Proj1 proj1 = {}, Proj2 proj2 = {});

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 subrange_t<I1>
    search_n(I1 first1, S1 last1, iter_difference_t<I1> count,
              const T& value, Pred pred = {}, Proj1 proj = {});

    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 borrowed_subrange_t<R1>
    search_n(R1&& r1, R2&& r2, Pred pred = {},
              Proj1 proj1 = {}, Proj2 proj2 = {});
}

namespace ranges {
    template<ForwardIterator first, ForwardIterator last, class Size, class T, 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, class BinaryPredicate>
ForwardIterator
    search_n(ExecutionPolicy&& exec,
             ForwardIterator first, ForwardIterator last,
             Size count, const T& value,
             BinaryPredicate pred);
}

namespace ranges {
    template<class ExecutionPolicy, class ForwardIterator, class Size, class T, class BinaryPredicate>
    ForwardIterator
        search_n(ExecutionPolicy&& exec,
                 ForwardIterator first, ForwardIterator last,
                 Size count, const T& value,
                 BinaryPredicate pred);
}

namespace ranges {
    template<class ExecutionPolicy, class ForwardIterator, class Size, class T, class BinaryPredicate>
    ForwardIterator
        search_n(ExecutionPolicy&& exec,
                 ForwardIterator first, ForwardIterator last,
                 Size count, const T& value,
                 BinaryPredicate pred);
}

namespace ranges {
    template<class ForwardIterator, class Searcher>
    constexpr ForwardIterator
        search(ForwardIterator first, ForwardIterator last, const Searcher& searcher);
}

namespace ranges {
    // 27.6.14, starts with
    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 starts_with(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {},
                           Proj1 proj1 = {}, Proj2 proj2 = {});
}

namespace ranges {
    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 starts_with(R1&& r1, R2&& r2, Pred pred = {},
                           Proj1 proj1 = {}, Proj2 proj2 = {});
}

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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 ends_with(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 (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 = {});

namespace ranges {
    template<class I, class O>
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,
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result);

    template<class I, class O>
    using copy_result = in_out_result<I, O>;
    template<input_iterator I, weakly_incrementable O>
    using copy_result = in_out_result<input_iterator_t<I>, weakly_incrementable_t<O>>;
    template<input_range R, weakly_incrementable O>
    using copy_result = in_out_result<borrowed_iterator_t<R>, weakly_incrementable_t<O>>;

    template<class I, class O>
    constexpr copy_result<I, O> copy(I first, I last, O result);
    template<class ExecutionPolicy, class ForwardIterator1, class Size,
    class ForwardIterator2>
    ForwardIterator2 copy_n(ExecutionPolicy&& exec,
    ForwardIterator1 first, Size n,
    ForwardIterator2 result);

    namespace ranges {
    template<class I, class O>
    using copy_n_result = in_out_result<I, O>;
    template<input_iterator I, weakly_incrementable O>
    using copy_n_result = in_out_result<input_iterator_t<I>, weakly_incrementable_t<O>>;
    template<input_range R, weakly_incrementable O>
    using copy_n_result = in_out_result<borrowed_iterator_t<R>, weakly_incrementable_t<O>>;

    template<class I, class O>
    constexpr copy_n_result<I, O> copy_n(I first, iter_difference_t<I> n, O result);
    }

    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 I, class O>
    using copy_if_result = in_out_result<I, O>;

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 copy_if_result<I, O> 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 copy_if_result<borrowed_iterator_t<R>, O> copy_if(R&& r, O result, Pred pred, Proj proj = {});
}

template<class BidirectionalIterator1, class BidirectionalIterator2>
constexpr BidirectionalIterator2 copy_backward(BidirectionalIterator1 first, BidirectionalIterator1 last, BidirectionalIterator2 result);

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
template<class InputIterator, class OutputIterator>
constexpr OutputIterator move(InputIterator first, InputIterator last, OutputIterator result);

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<iterator_t<R>, O>
    constexpr move_result<borrowed_iterator_t<R>, O> move(R&& r, O result);
}
template<class BidirectionalIterator1, class BidirectionalIterator2>
constexpr BidirectionalIterator2
move_backward(BidirectionalIterator1 first, BidirectionalIterator1 last,
BidirectionalIterator2 result);

namespace ranges {
    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<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<iterator_t<R1>, iterator_t<R2>>
    constexpr swap_ranges_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
    swap_ranges(R1&& r1, R2&& r2);
}

template<class ForwardIterator1, class ForwardIterator2>
constexpr void iter_swap(ForwardIterator1 a, ForwardIterator2 b);

// 27.7.4, transform
template<class InputIterator, class OutputIterator, class UnaryOperation>
constexpr OutputIterator
transform(InputIterator first1, InputIterator last1,
OutputIterator 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);

// 27.7.5, swap
template<class ForwardIterator1, class ForwardIterator2>
constexpr ForwardIterator2
swap_ranges(ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2 swap_ranges(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2);

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<iterator_t<R1>, iterator_t<R2>>
constexpr swap_ranges_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
swap_ranges(R1&& r1, R2&& r2);
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
   class ForwardIterator, class BinaryOperation>
ForwardIterator
transform(ExecutionPolicy&& exec,
   // see 27.3.5
   ForwardIterator1 first1, ForwardIterator1 last1,
   ForwardIterator2 first2, ForwardIterator 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>
        // see indirectly_writable0, 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 Proj = identity>
        // see indirectly_writable0, indirect_result_t<F&, projected<iterator_t<R>, Proj>>
    constexpr unary_transform_result<borrowed_iterator_t<R>, O>
    transform(R&& r, O result, F op, Proj proj = {});

    template<class I1, class I2, class O>
    using binary_transform_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, copy_constructible F, class Proj1 = identity, 
        class Proj2 = identity>
        // see indirectly_writable0, indirect_result_t<F&, projected<I1, Proj1>, 
        // projected<I2, Proj2>>
    constexpr binary_transform_result<I1, I2, O>
    transform(I1 first1, S1 last1, I2 first2, S2 last2, O result,
        F binary_op, Proj1 proj1 = {}, Proj2 proj2 = {});
replace(I first, S last, const T1& old_value, const T2& new_value, Proj proj = {});

template<input_range R, class T1, class T2, class Proj = identity>
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 T, class Proj = identity, 
    indirect_unary_predicate<projected<I>, Proj>> Pred
constexpr I replace_if(I first, S last, Pred pred, const T& new_value, Proj proj = {});

template<input_range R, class T, class Proj = identity, 
    indirect_unary_predicate<projected<iterator_t<R>>, Proj>> Pred
constexpr borrowed_iterator_t<R>
    replace_if(R&& r, Pred pred, const T& new_value, Proj proj = {});

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 T1, class T2, 
        output_iterator<const T2&> O, class Proj = identity>
    requires indirectly_copyable<I, O> &&
        indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T1*>
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 T1, class T2, output_iterator<const T2&> 0, 
        class Proj = identity>
    requires indirectly_copyable<iterator_t<R>, O> &&
        indirect_binary_predicate<ranges::equal_to, 
            projected<iterator_t<R>, Proj>, const T1*>
constexpr replace_copy_result<borrowed_iterator_t<R>, O>
    replace_copy(R&& r, 0 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<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class T>
    ForwardIterator2 replace_copy_if(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first, ForwardIterator1 last, 
        ForwardIterator2 result, 
        const T& old_value, const T& new_value);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, 
        class Predicate, class T>
    ForwardIterator2 replace_copy_if(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first, ForwardIterator1 last, 
        ForwardIterator2 result, 
        Predicate pred, const T& new_value);
}
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template<input_iterator I, sentinel_for<I> S, class T, output_iterator<const T&> O, class Proj = identity, indirect_unary_predicate<projected<I, Proj>> Pred>
  requires indirectly_copyable<I, O>
  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 T, output_iterator<const T&> O, class Proj = identity, indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
  requires indirectly_copyable<iterator_t<R>, O>
  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>
  constexpr void fill(ForwardIterator first, ForwardIterator last, const T& value);

template<class ExecutionPolicy, class ForwardIterator, class T>
  void fill(ExecutionPolicy&& exec, // see 27.3.5
             ForwardIterator first, ForwardIterator last, const T& value);

template<class OutputIterator, class Size, class T>
  constexpr OutputIterator fill_n(OutputIterator first, Size n, const T& value);
	namespace ranges {
    template<class T, output_iterator<const T&> O, sentinel_for<O> S>
      constexpr O fill(O first, S last, const T& value);
    template<class T, output_range<const T&> R>
      constexpr borrowed_iterator_t<R> fill(R&& r, const T& value);
    template<class T, output_iterator<const T&> O>
      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, // see 27.3.5
                ForwardIterator first, ForwardIterator last, Generator gen);

template<class OutputIterator, class Size, class Generator>
  OutputIterator generate_n(OutputIterator 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

```cpp
// 27.7.8, remove

template<class ForwardIterator, class T>
constexpr ForwardIterator remove(ForwardIterator first, ForwardIterator last,
    const T& value);

template<class ExecutionPolicy, class ForwardIterator, class T>
ForwardIterator remove(ExecutionPolicy&& exec, // see 27.3.5
    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, // see 27.3.5
    ForwardIterator first, ForwardIterator last,
    Predicate pred);

namespace ranges {

    template<permutable I, sentinel_for<I> S, class T, class Proj = identity>
    requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*> // see 27.3.5
    constexpr subrange<I> remove(I first, S last, const T& value, Proj proj = {});

    template<forward_range R, class T, class Proj = identity>
    requires permutable<iterator_t<R>> && indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T*> // see 27.3.5
    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>
    requires indirect_unary_predicate<projected<I, Proj>> // see 27.3.5
    constexpr subrange<I> remove_if(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>> // see 27.3.5
    constexpr borrowed_subrange_t<R> remove_if(R&& r, Pred pred, Proj proj = {});

} // namespace ranges

namespace ranges {

    template<class InputIterator, class OutputIterator, class T>
    constexpr OutputIterator remove_copy(InputIterator first, InputIterator last,
        OutputIterator result, const T& value);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
        class T>
    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);

    template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
        class Predicate>
    ForwardIterator2 remove_copy_if(ExecutionPolicy&& exec, // see 27.3.5
        ForwardIterator1 first, ForwardIterator1 last,
        ForwardIterator2 result, Predicate pred);

} // namespace ranges

namespace ranges {

    template<class I, class O>
    using remove_copy_result = in_out_result<I, O>;

} // namespace ranges

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template<input_iterator I, sentinel_for<I> S, weakly_incrementable O, class T, class Proj = identity> 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_incrementable O, class T, class Proj = identity> 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_incrementable 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_incrementable O, class Proj = identity, 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);

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<formal_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> 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

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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,
inirect_equivalence_relation<projected<I>, Proj>> C = ranges::equal_to>
  requires indirectly_copyable<I, O> &&
    (forward_iterator<I> ||
     (input_iterator<O> && same_as<iter_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,
inirect_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
template<class BidirectionalIterator>
constexpr void reverse(BidirectionalIterator first, BidirectionalIterator last);

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);
}

template<class BidirectionalIterator, class OutputIterator>
constexpr OutputIterator
reverse_copy(BidirectionalIterator first, BidirectionalIterator last,
OutputIterator result);

namespace ranges {
  template<class I, class O>
    using reverse_copy_result = in_out_result<I, O>;

  template<class I, class O>
    using reverse_copy_result = in_out_result<I, O>;

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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, 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,
                                 ForwardIterator first,
                                 ForwardIterator middle,
                                 ForwardIterator last);
    }

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);
    }

namespace ranges {

    template<class PopulationIterator, class SampleIterator,
             class Distance, class UniformRandomBitGenerator>
        SampleIterator sample(PopulationIterator first, PopulationIterator last,
                               SampleIterator out, Distance n,
                               UniformRandomBitGenerator& g);
    }

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indirectly_copyable<I, O> && uniform_random_bit_generator<remove_reference_t<Gen>>
0 sample(I first, S last, 0 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>>
0 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);
}

// 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, // see 27.3.5
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, // see 27.3.5
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, sorting and related operations
// 27.8.2, sorting

template<class RandomAccessIterator>
constexpr void sort(RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr void sort(RandomAccessIterator first, RandomAccessIterator last, Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator>
void sort(ExecutionPolicy&& exec, // see 27.3.5
RandomAccessIterator first, RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void 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
  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>
void stable_sort(RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
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);
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 = {});

namespace ranges {

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 = {});
}

namespace ranges {

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);

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 = {});

namespace ranges {

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 = {});
}

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template<class ForwardIterator>
constexpr bool is_sorted(ForwardIterator first, ForwardIterator last);

template<class ForwardIterator, class Compare>
constexpr bool is_sorted(ForwardIterator first, ForwardIterator last, Compare comp);

template<class ExecutionPolicy, class ForwardIterator>
bool is_sorted(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last); // see 27.3.5

template<class ExecutionPolicy, class ForwardIterator, class Compare>
bool is_sorted(ExecutionPolicy&& exec, 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 bool 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 borrowed_iterator_t<R> is_sorted_until(R&& r, Comp comp = {}, Proj proj = {});
}

template<class ForwardIterator>
constexpr ForwardIterator
is_sorted_until(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>
ForwardIterator
is_sorted_until(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last); // see 27.3.5

template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator
is_sorted_until(ExecutionPolicy&& exec, 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 is_sorted_until(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 borrowed_iterator_t<R> is_sorted_until(R&& r, Comp comp = {}, Proj proj = {});
}

// 27.8.3, Nth element

template<class RandomAccessIterator>
constexpr void nth_element(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>
void nth_element(ExecutionPolicy&& exec, RandomAccessIterator first, RandomAccessIterator nth, RandomAccessIterator last); // see 27.3.5

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void nth_element(ExecutionPolicy&& exec, RandomAccessIterator first, RandomAccessIterator nth, 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 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
namespace ranges {
    template<class ForwardIterator, class T>
    constexpr ForwardIterator lower_bound(ForwardIterator first, ForwardIterator last, const T& value);
    template<class ForwardIterator, class T, class Compare>
    constexpr ForwardIterator lower_bound(ForwardIterator first, ForwardIterator last, const T& value, Compare comp);
    template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity, 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 T, class Proj = identity, 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 = {});
}

namespace ranges {
    template<class ForwardIterator, class T>
    constexpr ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last, const T& value);
    template<class ForwardIterator, class T, class Compare>
    constexpr ForwardIterator upper_bound(ForwardIterator first, ForwardIterator last, const T& value, Compare comp);
    template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity, indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
    constexpr I upper_bound(I first, S last, const T& value, Comp comp = {}, Proj proj = {});
    template<forward_range R, class T, class Proj = identity, indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr borrowed_iterator_t<R> upper_bound(R&& r, const T& value, Comp comp = {}, Proj proj = {});
}

namespace ranges {
    template<class ForwardIterator, class T>
    constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, ForwardIterator last, const T& value);
    template<class ForwardIterator, class T, 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 T, class Proj = identity,
             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 T, class Proj = identity,
             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>
constexpr bool
binary_search(ForwardIterator first, ForwardIterator last, const T& value);

namespace ranges {
    template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity,
             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 T, class Proj = identity,
             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);

namespace ranges {
    template<input_iterator 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<input_range R, class Proj = identity,
             indirect_unary_predicate<projected<iterator_t<R>, Proj>> Pred>
    constexpr subrange<R>
    partition(R&& r, Pred pred, Proj proj = {});
}

template<class ForwardIterator, class Predicate>
constexpr ForwardIterator partition(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 subrange<I>
    partition(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 subrange<R>
    partition(R&& r, 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 = {});
}

template<class BidirectionalIterator, class Predicate>
BidirectionalIterator stable_partition(BidirectionalIterator first,
  BidirectionalIterator last,
  Predicate pred);
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, 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);

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 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 merge_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
merge(R1&& r1, R2&& r2, O result,
   Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
}

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template<class BidirectionalIterator>
void inplace_merge(BidirectionalIterator first,
                  BidirectionalIterator middle,
                  BidirectionalIterator last);

template<class BidirectionalIterator, class Compare>
void inplace_merge(BidirectionalIterator first,
                  BidirectionalIterator middle,
                  BidirectionalIterator last, Compare comp);

template<class ExecutionPolicy, class BidirectionalIterator>
void inplace_merge(ExecutionPolicy&& exec, // see 27.3.5
                  BidirectionalIterator first,
                  BidirectionalIterator middle,
                  BidirectionalIterator last);

template<class ExecutionPolicy, class BidirectionalIterator, class Compare>
void inplace_merge(ExecutionPolicy&& exec, // see 27.3.5
                  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>
    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>
    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>
bool includes(ExecutionPolicy&& exec, // see 27.3.5
              ForwardIterator1 first1, ForwardIterator1 last1,
              ForwardIterator2 first2, ForwardIterator2 last2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class Compare>
bool includes(ExecutionPolicy&& exec, // see 27.3.5
              ForwardIterator1 first1, ForwardIterator1 last1,
              ForwardIterator2 first2, ForwardIterator2 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 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 includes(R1&& r1, R2&& r2, Comp comp = {},
                            Proj1 proj1 = {}, Proj2 proj2 = {});
}

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template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
set_union(InputIterator1 first1, InputIterator1 last1,
         InputIterator2 first2, InputIterator2 last2,
         OutputIterator result);

template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
set_union(InputIterator1 first1, InputIterator1 last1,
         InputIterator2 first2, InputIterator2 last2,
         OutputIterator result, Compare comp);

namespace ranges {

    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<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<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 = {});
}

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namespace ranges {

    template<class I1, class I2, class O>
    using set_intersection_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>
    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>
    constexpr set_difference_result<borrowed_iterator_t<R1>, O> set_difference(R1&& r1, R2&& r2, O result, Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
}

namespace ranges {

    template<class I1, class I2, class O>
    using set_difference_result = in_out_result<I1, 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>
    constexpr set_difference_result<I1, O> 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>
    constexpr set_difference_result<borrowed_iterator_t<R1>, O> set_difference(R1&& r1, R2&& r2, O result, Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
}

namespace ranges {

    template<class I, class O>
    using set_difference_result = in_out_result<I, 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>
    constexpr set_difference_result<I1, O> 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>
    constexpr set_difference_result<borrowed_iterator_t<R1>, O> set_difference(R1&& r1, R2&& r2, O result, Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
}
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 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>;

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 ranges {

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 = {});
}

namespace ranges {

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 = {});
}

namespace ranges {

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);

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 = {});
}

namespace ranges {

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);

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 = {});
}

namespace ranges {

template<class RandomAccessIterator>
constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last);
}
template<class RandomAccessIterator, class Compare>
constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last,
                   Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator>
bool is_heap(ExecutionPolicy&& exec, // see 27.3.5
             RandomAccessIterator first, RandomAccessIterator last);

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_iterator R, class Proj = identity,
             indirect_strict_weak_order<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);

template<class RandomAccessIterator, class Compare>
constexpr RandomAccessIterator
is_heap_until(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 I is_heap_until(I first, S last, Comp comp = {}, Proj proj = {});
    template<random_access_iterator R, class Proj = identity,
             indirect_strict_weak_order<iterator_t<R>, Proj>> Comp = ranges::less>
    constexpr borrowed_iterator_t<R>
    is_heap_until(R&& r, Comp comp = {}, Proj proj = {});
}

// 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>
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);
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);

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 {
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 ForwardIterator, class Compare>
constexpr ForwardIterator min_element(ForwardIterator first, ForwardIterator last, Compare comp);
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator min_element(ExecutionPolicy&& exec, // see 27.3.5
   ForwardIterator first, ForwardIterator last);}
template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator min_element(ExecutionPolicy&& exec,  // see 27.3.5
  ForwardIterator first, ForwardIterator last,
  Compare comp);

namespace ranges {
  template<typename I, sentinel_for<I> S, class Proj = identity,
           indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
  constexpr I min_element(I first, S last, Comp comp = {}, Proj proj = {});
  template<typename R, class Proj = identity,
           indirect_strict_weak_order<iterator_t<R>, Proj>> Comp = ranges::less>
  constexpr borrowed_iterator_t<R> 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);

namespace ranges {
  template<typename 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<typename 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 = {});
}

template<class ForwardIterator>
constexpr pair<ForwardIterator, ForwardIterator>
minmax_element(ForwardIterator first, ForwardIterator last);

namespace ranges {
  template<class I>
  using minmax_element_result = min_max_result<I>;
  template<typename 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<typename 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 = {});

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minmax_element(R&& r, Comp comp = {}, Proj proj = {});

// 27.8.10, bounded value
template<class T>
constexpr T clamp(const T& v, const T& lo, const T& hi);

template<class T, class Compare>
constexpr T clamp(const T& v, const T& lo, const T& hi, Compare comp);

namespace ranges {
    template<class T, class Proj = identity, class Compare = ranges::less>
    constexpr T clamp(const T& v, const T& lo, const T& hi, Proj proj = {});
}

// 27.8.11, lexicographical comparison

namespace ranges {
    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2, class Proj1 = identity, class Proj2 = identity, class Compare = ranges::less>
    constexpr bool lexicographical_compare(I1 first1, S1 last1, I2 first2, S2 last2);
    template<input_range R1, input_range R2, class Proj1 = identity, class Proj2 = identity, class Compare = ranges::less>
    constexpr bool lexicographical_compare(R1&& r1, R2&& r2, Compare comp = {});
}

// 27.8.12, three-way comparison algorithms

namespace ranges {
    template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2, class Proj1 = identity, class Proj2 = identity, class Compare = ranges::less>
    constexpr bool lexicographical_compare_three_way(I1 first1, S1 last1, I2 first2, S2 last2, Compare comp = {});
}

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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);

namespace ranges {
    constexpr bool  next_permutation(BidirectionalIterator first,
                                      BidirectionalIterator last, Compare comp);
}

namespace ranges {
    template<class I>
    using next_permutation_result = in_found_result<I>;

template<class BidirectionalIterator I, sentinel_for<I> S, class Comp = ranges::less,
         class Proj = identity>
    constexpr next_permutation_result<I>  
        next_permutation(I first, S last, Comp comp = {}, Proj proj = {});

template<class BidirectionalRange R, class Comp = ranges::less,
         class Proj = identity>
    constexpr next_permutation_result<borrowed_iterator_t<R>>
        next_permutation(R&& r, Comp comp = {}, Proj proj = {});
}

namespace ranges {
    constexpr bool  prev_permutation(BidirectionalIterator first,
                                      BidirectionalIterator last);

namespace ranges {
    template<class I>
    using prev_permutation_result = in_found_result<I>;

template<class BidirectionalIterator I, sentinel_for<I> S, class Comp = ranges::less,
         class Proj = identity>
    constexpr prev_permutation_result<I>  
        prev_permutation(I first, S last, Comp comp = {}, Proj proj = {});

template<class BidirectionalRange R, class Comp = ranges::less,
         class Proj = identity>
    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 I2, class F2>
    requires convertible_to<const I&, I2> && convertible_to<const F&, F2>
constexpr operator in_fun_result<I2, F2>() const & {
    return {in, fun};
}

template<class I2, class F2>
    requires convertible_to<I, I2> && convertible_to<F, F2>
constexpr operator in_fun_result<I2, F2>() && {
    return {std::move(in), std::move(fun)};
};

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<II1, II1> && convertible_to<II2, 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<I, II> &&
convertible_to<O1, OO1> &&
convertible_to<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<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<I, I2>
constexpr operator in_found_result<I2>() && {
    return {std::move(in), found};
};
template<class O, class T>
struct out_value_result {
    [[no_unique_address]] O out;
    [[no_unique_address]] T value;

template<class O2, class T2>
    requires convertible_to<const O&, O2> && convertible_to<const T&, T2>
    constexpr operator out_value_result<O2, T2>() const & {
        return {out, value};
    }

template<class O2, class T2>
    requires convertible_to<O, O2> && convertible_to<T, T2>
    constexpr operator out_value_result<O2, T2>() && {
        return {std::move(out), std::move(value)};
    }
};

27.6 Non-modifying sequence operations [alg.nonmodifying]
27.6.1 All of [alg.all.of]

Let \(E\) be:

1. (1.1) \(\text{pred}(*i)\) for the overloads in namespace \(\text{std}\);
2. (1.2) \(\text{invoke(pred, invoke(proj, *i))}\) for the overloads in namespace \(\text{ranges}\).

Returns: \(\text{false}\) if \(E\) is \(\text{false}\) for some iterator \(i\) in the range \([\text{first}, \text{last})\), and \(\text{true}\) otherwise.

Complexity: At most \(\text{last} - \text{first}\) applications of the predicate and any projection.

27.6.2 Any of [alg.any.of]

Let \(E\) be:

1. (1.1) \(\text{pred}(*i)\) for the overloads in namespace \(\text{std}\);
2. (1.2) \(\text{invoke(pred, invoke(proj, *i))}\) for the overloads in namespace \(\text{ranges}\).
Returns: true if \( E \) is true for some iterator \( i \) in the range \([\texttt{first}, \texttt{last}]\), and false otherwise.

Complexity: At most \( \texttt{last} - \texttt{first} \) applications of the predicate and any projection.

### 27.6.3 None of

\[ \text{alg.none.of} \]

```cpp
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);
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
           indirectly_unary_predicate<projected<I, Proj>> Pred>
constexpr bool ranges::none_of(I first, S last, Pred pred, Proj proj = {});
template<input_range R, class Proj = identity,
           indirectly_unary_predicate<iterator_t<R>, Proj>> Pred>
constexpr bool ranges::none_of(R&& r, Pred pred, Proj proj = {});
```

Let \( E \) be:

1. \( \texttt{pred}(*\texttt{i}) \) for the overloads in namespace \texttt{std};
2. \( \texttt{invoke} \left( \texttt{pred}, \texttt{invoke} \left( \texttt{proj}, *\texttt{i} \right) \right) \) for the overloads in namespace \texttt{ranges}.

Returns: false if \( E \) is true for some iterator \( i \) in the range \([\texttt{first}, \texttt{last}]\), and true otherwise.

Complexity: At most \( \texttt{last} - \texttt{first} \) applications of the predicate and any projection.

### 27.6.4 For each

\[ \text{alg.foreach} \]

```cpp
template<class InputIterator, class Function>
constexpr Function for_each(InputIterator first, InputIterator last, Function f);
```

Preconditions: Function meets the \texttt{Cpp17MoveConstructible} requirements (Table 30).

[Note 1: Function need not meet the requirements of \texttt{Cpp17CopyConstructible} (Table 31). — end note]

Effects: Applies \( f \) to the result of dereferencing every iterator in the range \([\texttt{first}, \texttt{last}]\), starting from \texttt{first} and proceeding to \texttt{last} - 1.

[Note 2: If the type of \texttt{first} meets the requirements of a mutable iterator, \( f \) can apply non-constant functions through the dereferenced iterator. — end note]

Returns: \( f \).

Complexity: Applies \( f \) exactly \( \texttt{last} - \texttt{first} \) times.

Remarks: If \( f \) returns a result, the result is ignored.

```cpp
template<class ExecutionPolicy, class ForwardIterator, class Function>
void for_each(ExecutionPolicy&& exec,
             ForwardIterator first, ForwardIterator last,
             Function f);
```

Preconditions: Function meets the \texttt{Cpp17CopyConstructible} requirements.

Effects: Applies \( f \) to the result of dereferencing every iterator in the range \([\texttt{first}, \texttt{last}]\).

[Note 3: If the type of \texttt{first} meets the requirements of a mutable iterator, \( f \) can apply non-constant functions through the dereferenced iterator. — end note]

Complexity: Applies \( f \) exactly \( \texttt{last} - \texttt{first} \) times.

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]

```cpp
template<input_iterator I, sentinel_for<I> S, class Proj = identity,
           indirectly_unary_invocable<projected<I, Proj>> Fun>
constexpr ranges::for_each_result<I, Fun>
ranges::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 ranges::for_each_result<borrowed_iterator_t<R>, Fun>
ranges::for_each(R&& r, Fun f, Proj proj = {});

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]

Returns: {last, std::move(f)}.

Complexity: Applies f and proj exactly last - first times.

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>
constexpr InputIterator for_each_n(InputIterator 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 Cpp17MoveConstructible requirements.

[Note 7: Function need not meet the requirements of Cpp17CopyConstructible. — end note]

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]

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.

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]

27.6.5 Find

template<class InputIterator, class T>
constexpr InputIterator find(InputIterator first, InputIterator last, T)
Let \( E \) be:

1. \( \ast i == \text{value for find} \)  
2. \( \text{pred}(\ast i) != \text{false for find_if} \)  
3. \( \text{pred}(\ast i) == \text{false for find_if_not} \)  
4. \( \text{bool}(\text{invoke}(\text{proj}, \ast i)) == \text{value for ranges::find} \)  
5. \( \text{bool}(\text{invoke}(\text{pred, invoke}(\text{proj}, \ast i))) \) for ranges::find_if  
6. \( \text{bool}(!\text{invoke}(\text{pred, invoke}(\text{proj}, \ast i))) \) for ranges::find_if_not.

Let \( E \) be:

- \( \ast i == \text{value for find} \)
- \( \text{pred}(\ast i) != \text{false for find_if} \)
- \( \text{pred}(\ast i) == \text{false for find_if_not} \)
- \( \text{bool}(\text{invoke}(\text{proj}, \ast i)) == \text{value for ranges::find} \)
- \( \text{bool}(\text{invoke}(\text{pred, invoke}(\text{proj}, \ast i))) \) for ranges::find_if
- \( \text{bool}(!\text{invoke}(\text{pred, invoke}(\text{proj}, \ast i))) \) for ranges::find_if_not.

Returns: The first iterator \( i \) in the range \([\text{first, last})\) for which \( E \) is true. Returns \( \text{last} \) if no such iterator is found.

**Complexity:** At most \( \text{last} - \text{first} \) applications of the corresponding predicate and any projection.

### 27.6.6 Find end

#### algorithm 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:
(1.1) — pred be equal_to{} for the overloads with no parameter pred;
(1.2) — E be:
(1.2.1) — invoke(pred, invoke(proj1, *(i + n)), invoke(proj2, *(first2 + n))) for the overloads in namespace std;
(1.2.2) — invoke(pred, invoke(proj1, *(i + n)), invoke(proj2, *(first2 + n))) for the overloads in namespace ranges;
(1.3) — i be last1 if [first2, last2) is empty, or if (last2 - first2) > (last1 - first1) is true,
or if there is no iterator in the range [first1, last1 - (last2 - first2)) such that for every non-negative integer n < (last2 - first2), E is true. Otherwise i is the last such iterator in
[first1, last1 - (last2 - first2)].

Returns:
(2.1) — i for the overloads in namespace std.
(2.2) — {i, i + (i == last1 ? 0 : last2 - first2)} for the overloads in namespace ranges.

Complexity: At most (last2 - first2) * (last1 - first1 - (last2 - first2) + 1) applications of the corresponding predicate and any projections.

27.6.7 Find first [alg.find.first.of]
template<class InputIterator, class ForwardIterator,
         class BinaryPredicate>
constexpr InputIterator
    find_first_of(InputIterator first1, InputIterator last1,
                  ForwardIterator first2, ForwardIterator last2,
                  BinaryPredicate pred);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryPredicate>
ForwardIterator1
    find_first_of(ExecutionPolicy&& exec,
                  ForwardIterator1 first1, ForwardIterator1 last1,
                  ForwardIterator2 first2, ForwardIterator2 last2,
                  BinaryPredicate pred);

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 ranges::find_first_of(I1 first1, S1 last1, I2 first2, S2 last2,
                                   Pred pred = {},
                                   Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_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_iterator_t<R1>
    ranges::find_first_of(R1&& r1, R2&& r2,
                          Pred pred = {},
                          Proj1 proj1 = {}, Proj2 proj2 = {});

1 Let $E$ be:
   
   (1.1) $i == j$ for the overloads with no parameter $pred$;
   
   (1.2) $\text{pred}(i, j) \neq false$ for the overloads with a parameter $pred$ and no parameter $proj$;
   
   (1.3) $\text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj1}, i), \text{invoke}(\text{proj2}, j)))$ for the overloads with parameters $pred$ and $proj$.

2 **Effects**: Finds an element that matches one of a set of values.

3 **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 last1 if $[\text{first2}, \text{last2})$ is empty or if no such iterator is found.

4 **Complexity**: At most $(\text{last1}-\text{first1}) \times (\text{last2}-\text{first2})$ applications of the corresponding predicate and any projections.

### § 27.6.8 Adjacent find

[alg.adjacent.find]
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 ranges::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> ranges::adjacent_find(R&& r, Pred pred = {}, Proj proj = {});

Let $E$ be:

(1.1) $\ast i == \ast(i + 1)$ for the overloads with no parameter $\text{pred}$;
(1.2) $\text{pred}(\ast i, \ast(i + 1)) \neq \text{false}$ for the overloads with a parameter $\text{pred}$ and no parameter $\text{proj}$;
(1.3) $\text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, \ast i), \text{invoke}(\text{proj}, \ast(i + 1))))$ for the overloads with both parameters $\text{pred}$ and $\text{proj}$.

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 last if no such iterator is found.

Complexity: For the overloads with no ExecutionPolicy, exactly

$$\min((i - \text{first}) + 1, (\text{last} - \text{first}) - 1)$$

applications of the corresponding predicate, where $i$ is adjacent_find’s return value. For the overloads
with an ExecutionPolicy, $O(\text{last} - \text{first})$ applications of the corresponding predicate, and no more than twice as many applications of any projection.

## 27.6.9 Count

### [alg.count]

```cpp
template<class InputIterator, class T>
constexpr typename iterator_traits<InputIterator>::difference_type
count(InputIterator first, InputIterator last, const T& value);

template<class ExecutionPolicy, class ForwardIterator, class T>
constexpr 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>
constexpr typename iterator_traits<ForwardIterator>::difference_type
count_if(ExecutionPolicy&& exec,
         ForwardIterator first, ForwardIterator last, Predicate pred);
```

Let $E$ be:

(1.1) $\ast i == \text{value}$ for the overloads with no parameter $\text{pred}$ or $\text{proj}$;
(1.2) $\text{pred}(\ast i) \neq \text{false}$ for the overloads with a parameter $\text{pred}$ but no parameter $\text{proj}$;
(1.3) \[ \text{invoke(proj, *i) == value for the overloads with a parameter proj but no parameter pred}; \]

(1.4) \[ \text{bool(invoke(pred, invoke(proj, *i))) for the overloads with both parameters proj and pred.} \]

\[ \frac{2}{E\text{ffects: Returns the number of iterators } i \text{ in the range } \text{[first, last)} \text{ for which } E \text{ holds.}} \]

\[ \frac{3}{\text{Complexity: Exactly last - first applications of the corresponding predicate and any projection.}} \]

### 27.6.10 Mismatch

**mismatch**

```cpp
template<class InputIterator1, class InputIterator2>
constexpr pair<InputIterator1, InputIterator2> mismatch(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
pair<ForwardIterator1, ForwardIterator2> mismatch(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2);
```

```cpp
template<class InputIterator1, class InputIterator2, class BinaryPredicate>
constexpr pair<InputIterator1, InputIterator2> mismatch(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, BinaryPredicate pred);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class BinaryPredicate>
pair<ForwardIterator1, ForwardIterator2> mismatch(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2, BinaryPredicate pred);
```

```cpp
template<class InputIterator1, class InputIterator2>
constexpr pair<InputIterator1, InputIterator2> mismatch(InputIterator1 first1, InputIterator1 last1, InputIterator2 first2, InputIterator2 last2);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
pair<ForwardIterator1, ForwardIterator2> mismatch(ExecutionPolicy&& exec, ForwardIterator1 first1, ForwardIterator1 last1, ForwardIterator2 first2, ForwardIterator2 last2);
```

```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>
requires indirectly_comparable<I1, I2, Pred, Proj1, Proj2>
constexpr ranges::mismatch_result<I1, I2> ranges::mismatch_result<I1, I2, Pred, Proj1, Proj2>
ranges::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 ranges::mismatch_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
   ranges::mismatch(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.
2. Let E be:
   - !(*(first1 + n) == *(first2 + n)) for the overloads with no parameter pred;
   - pred(*(first1 + n), *(first2 + n)) == false for the overloads with a parameter pred and
     no parameter proj1;
   - !invoke(pred, invoke(proj1, *(first1 + n)), invoke(proj2, *(first2 + n))) for the
     overloads with both parameters pred and proj1.
3. Let N be min(last1 - first1, last2 - first2).
4. 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.
5. Complexity: At most N applications of the corresponding predicate and any projections.

27.6.11 Equal

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, BinaryPredicate pred);
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:  
   (1.1) last2 be first2 + (last1 - first1) for the overloads with no parameter last2 or r2;  
   (1.2) pred be equal_to{} for the overloads with no parameter pred;  
   (1.3) 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.

Complexity: If  
   (3.1) the types of first1, last1, first2, and last2 meet the Cpp17RandomAccessIterator require-  
            ments (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.

27.6.12 Is permutation  

[alg.is.permutation]

template<class ForwardIterator1, class ForwardIterator2>  
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,  
    ForwardIterator2 first2);  

template<class ForwardIterator1, class ForwardIterator2,  
class BinaryPredicate>  
constexpr bool is_permutation(ForwardIterator1 first1, ForwardIterator1 last1,  
    ForwardIterator2 first2, BinaryPredicate pred);  

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);  

1 Let last2 be first2 + (last1 - first1) for the overloads with no parameter named last2, and  
   let pred be equal_to{} for the overloads with no parameter pred.

2 Mandates: ForwardIterator1 and ForwardIterator2 have the same value type.

3 Preconditions: The comparison function is an equivalence relation.
Returns: If last1 - first1 != last2 - first2, return false. Otherwise return true if there exists a permutation of the elements in the range [first2, last2), beginning with ForwardIterator2 begin, such that equal(first1, last1, begin, pred) returns true; otherwise, returns false.

Complexity: No applications of the corresponding predicate if ForwardIterator1 and ForwardIterator2 meet the requirements of random access iterators and last1 - first1 != last2 - first2. Otherwise, exactly last1 - first1 applications of the corresponding predicate if equal(first1, last1, first2, last2, pred) would return true; otherwise, at worst \(O(N^2)\), where \(N\) has the value last1 - first1.

27.6.13 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);
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2, ForwardIterator2 last2,
BinaryPredicate pred);

Returns: The first iterator \( i \) in the range \([first1, last1 - (last2-first2))\) such that for every non-negative integer \( n \) less than \( last2 - first2 \) the following corresponding conditions hold: \( *(i + n) == *(first2 + n) \), \( \text{pred}(*(i + n), *(first2 + n)) != false \). Returns \( first1 \) if \([first2, last2)\) is empty, otherwise returns \( last1 \) if no such iterator is found.

Complexity: At most \((last1 - first1) \times (last2 - first2)\) applications of the corresponding predicate.

\[
\begin{align*}
\text{template}<\text{forward_iterator I1, sentinel_for<I1> S1, forward_iterator I2, sentinel_for<I2> S2, class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity> &
\text{ranges::search}(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {}); &
\text{template}<\text{forward_range R1, forward_range R2, class Pred = ranges::equal_to, class Proj1 = identity, class Proj2 = identity> &
\text{ranges::search}(R1&& r1, R2&& r2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});
\end{align*}
\]

Returns:

1. \( \{i, i + (last2 - first2)) \), where \( i \) is the first iterator in the range \([first1, last1 - (last2 - first2))\) such that for every non-negative integer \( n \) less than \( last2 - first2 \) the condition
   \[
   \text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj1}, *(i + n)), \text{invoke}(\text{proj2}, *(first2 + n))))
   \]
   is true.

2. Returns \( \{last1, last1\} \) if no such iterator exists.

Complexity: At most \((last1 - first1) \times (last2 - first2)\) applications of the corresponding predicate and projections.

\[
\begin{align*}
\text{template}<\text{class ForwardIterator, class Size, class T}> &
\text{constexpr ForwardIterator search_n(ForwardIterator first, ForwardIterator last, Size count, const T& value);} &
\text{template}<\text{class ExecutionPolicy, class ForwardIterator, class Size, class T}> &
\text{ForwardIterator search_n(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Size count, const T& value);} &
\text{template}<\text{class ForwardIterator, class Size, class T, class BinaryPredicate}> &
\text{constexpr ForwardIterator search_n(ForwardIterator first, ForwardIterator last, Size count, const T& value, BinaryPredicate pred);} &
\text{template}<\text{class ExecutionPolicy, class ForwardIterator, class Size, class T, class BinaryPredicate}> &
\text{ForwardIterator search_n(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Size count, const T& value, BinaryPredicate pred);} &
\end{align*}
\]

Mandates: The type \( \text{Size} \) 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 \( \text{count} \) the following corresponding conditions hold: \( *(i + n) == \text{value}, \text{pred}(*(i + n), \text{value}) != false \). 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 T, class Pred = ranges::equal_to, class Proj = identity>
  requires indirectly_comparable<I, const T*, Pred, Proj>
  constexpr subrange<I>
  ranges::search_n(I first, S last, iter_difference_t<I> count,
  const T& value, Pred pred = {}, Proj proj = {});

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::starts_with(R1&& r1, R2&& r2, Pred pred = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

1 Returns:
  ranges::mismatch(std::move(first1), last1, std::move(first2), last2, pred, proj1, proj2).in2 == last2
```

27.6.15 Ends 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>
  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 = {});

1 Let N1 be last1 - first1 and N2 be last2 - first2.

2 Returns: false if N1 < N2, otherwise
  ranges::equal(std::move(first1) + (N1 - N2), last1, std::move(first2), last2, pred, proj1, proj2)
```

27.6.14 Starts with

```
```
Proj1 proj1 = {}, Proj2 proj2 = {};

Let N1 be ranges::distance(r1) and N2 be ranges::distance(r2).

Returns: false if N1 < N2, otherwise
ranges::equal(ranges::drop_view(ranges::ref_view(r1), N1 - N2), r2, pred, proj1, proj2)

27.7 Mutating sequence operations [alg.modifying.operations]

27.7.1 Copy [alg.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 last - first.

Preconditions: result is not in the range [first, last).

Effects: Copies elements in the range [first, last) into the range [result, result + N) starting from first and proceeding to last. For each non-negative integer n < N, performs *(result + n) = *(first + n).

Returns:

(4.1) result + N for the overload in namespace std.
(4.2) {last, 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 [first, last) and [result, result + (last - first)) do not overlap.

Effects: Copies elements in the range [first, last) into the range [result, result + (last - first)). For each non-negative integer n < (last - first), performs *(result + n) = *(first + n).

Returns: result + (last - first).

Complexity: Exactly last - 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 Size is convertible to an integral type (7.3.9, 11.4.8).

Effects: For each non-negative integer i < N, performs *(result + i) = *(first + i).

Returns:

(13.1) result + N for the overloads in namespace std.
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>
constexpr ranges::copy_if_result<I, O> ranges::copy_if(I first, S last, O result, Pred pred, Proj proj = {});  

Let E be:
- bool(pred(*i)) for the overloads in namespace std;
- bool(invoke(pred, invoke(proj, *i))) for the overloads in namespace ranges,

and N be the number of iterators i in the range [first, last) for which the condition E holds.

**Preconditions:** The ranges [first, last) and [result.result + (last - first)) do not overlap.

**Note 1:** For the overload with an ExecutionPolicy, there might be a performance cost if `iterator_traits<ForwardIterator1>::value_type` is not `Cpp17MoveConstructible` (Table 30). — end note

**Effects:** Copies all of the elements referred to by the iterator i in the range [first, last) for which E is true.

**Returns:**
- result + N for the overloads in namespace std.
- {last, result + N} for the overloads in namespace ranges.

**Complexity:** Exactly last - first applications of the corresponding predicate and any projection.

**Remarks:** Stable (16.4.6.8).

template<class BidirectionalIterator1, class BidirectionalIterator2>
constexpr BidirectionalIterator2 copy_backward(BidirectionalIterator1 first, BidirectionalIterator1 last, BidirectionalIterator2 result);

template<bidirectional_iterator I1, sentinel_for<I1> S1, bidirectional_iterator I2>
requires indirectly_copyable<I1, I2>
constexpr ranges::copy_backward_result<I1, I2> ranges::copy_backward(I1 first, S1 last, I2 result);

template<bidirectional_iterator I1, sentinel_for<I1> S1, bidirectional_iterator I2>
requires indirectly_copyable<I1, I2>
constexpr ranges::copy_backward_result<I1, I2> ranges::copy_backward(I1 first, S1 last, I2 result);

Let N be last - first.

**Preconditions:** result is not in the range [first, last).

**Effects:** Copies elements in the range [first, last) into the range [result - N, result) starting from last - 1 and proceeding to first.221 For each positive integer n ≤ N, performs *(result - n) =
Returns:

(24.1) \( \text{result} - N \) for the overload in namespace \( \text{std} \).

(24.2) \( \{\text{last}, \text{result} - N\} \) for the overloads in namespace \( \text{ranges} \).

Complexity: Exactly \( N \) assignments.

27.7.2 Move

```
template<class InputIterator, class OutputIterator>
constexpr OutputIterator move(InputIterator first, InputIterator last,
                                OutputIterator result);
```

```
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);
```

```
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);
```

1. Let \( E \) be

(1.1) \( \text{std}::\text{move}(*\text{(first} + n)) \) for the overload in namespace \( \text{std} \);

(1.2) \( \text{ranges}::\text{iter}\_\text{move}(\text{first} + n) \) for the overloads in namespace \( \text{ranges} \).

Let \( N \) be \( \text{last} - \text{first} \).

2. Preconditions: result is not in the range \( [\text{first}, \text{last}) \).

3. Effects: Moves 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 \( *(\text{result} + n) = E \).

4. Returns:

(4.1) \( \text{result} + N \) for the overload in namespace \( \text{std} \).

(4.2) \( \{\text{last}, \text{result} + N\} \) for the overloads in namespace \( \text{ranges} \).

Complexity: Exactly \( N \) assignments.

```
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2 move(ExecutionPolicy&& policy,
                       ForwardIterator1 first, ForwardIterator1 last,
                       ForwardIterator2 result);
```

```
template<bidirectional_iterator I1, sentinel_for<I1> S1, bidirectional_iterator I2>
requires indirectly_movable<I1, I2>
constexpr ranges::move_backward_result<I1, I2>
ranges::move_backward(I1 first, S1 last, I2 result);
```

§ 27.7.2
template<bidirectional_range R, bidirectional_iterator I>
requires indirectly_movable<iterator_t<R>, I>
ranges::move_backward_result<borrowed_iterator_t<R>, I>
ranges::move_backward(R&& r, I result);

Let \( E \) be
\[(1.1) \quad \text{std::move(*((last - n)) \ for \ the \ overload \ in \ namespace \ std;}
\]
\[(1.2) \quad \text{ranges::iter_move(last - n) \ for \ the \ overloads \ in \ namespace \ ranges.}
\]
Let \( N \) be \( \text{last - first} \).

\[\text{Preconditions: result is not in the range } \text{[first, last].}\]

\[\text{Effects: Moves elements in the range } \text{[first, last)} \text{ into the range } \text{[result - N, result)} \text{ starting from last - 1 and proceeding to first.}\]

\[\text{For each positive integer } n \leq N, \text{performs } *\text{(result - n)} = E.\]

\[\text{Returns:}
\]
\[(1.1) \quad \text{result - N \ for \ the \ overload \ in \ namespace \ std.}
\]
\[(1.2) \quad \text{[last, result - N) \ for \ the \ overloads \ in \ namespace \ ranges.}
\]

\[\text{Complexity: Exactly } N \text{ assignments.}\]

\[\text{§ 27.7.3 Swap} \quad [\text{alg.swap}]
\]
template<class ForwardIterator1, class ForwardIterator2>
constexpr ForwardIterator2
swap_ranges(ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
swap_ranges(ExecutionPolicy&& exec,
ForwardIterator1 first1, ForwardIterator1 last1,
ForwardIterator2 first2);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2>
requires indirectly_swappable<I1, I2>
ranges::swap_ranges_result<I1, I2>
ranges::swap_ranges(I1 first1, S1 last1, I2 first2, S2 last2);

template<input_range R1, input_range R2>
requires indirectly_swappable<iterator_t<R1>, iterator_t<R2>>
ranges::swap_ranges_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>>
ranges::swap_ranges(R1&& r1, R2&& r2);

Let:
\[(1.1) \quad \text{last2 be first2 + (last1 - first1) \ for \ the \ overloads \ with \ no \ parameter \ named \ last2;}
\]
\[(1.2) \quad \text{M be min(last1 - first1, last2 - first2).}
\]

\[\text{Preconditions: The two ranges } \text{[first1, last1)} \text{ and } \text{[first2, last2)} \text{ do not overlap. For the overloads in namespace std, *[(first1 + n)] is swappable with (16.4.4.3) *[(first2 + n)].}
\]

\[\text{Effects: For each non-negative integer } n < M \text{ performs:}
\]
\[(3.1) \quad \text{swap(*[(first1 + n)], *[(first2 + n)]) \ for \ the \ overloads \ in \ namespace \ std;}
\]
\[(3.2) \quad \text{ranges::iter_swap(first1 + n, first2 + n) \ for \ the \ overloads \ in \ namespace \ ranges.}
\]

\[\text{Returns:}
\]
\[(4.1) \quad \text{last2 \ for \ the \ overloads \ in \ namespace \ std.}
\]
\[(4.2) \quad \text{[first1 + M, first2 + M) \ for \ the \ overloads \ in \ namespace \ ranges.}
\]

\[\text{Complexity: Exactly } M \text{ swaps.}\]

\[\text{move\_backward \ can \ be \ used \ instead \ of \ move \ when \ last \ is \ in \ the \ range } \text{[result - N, result).}\]
template<class ForwardIterator1, class ForwardIterator2>
constexpr void iter_swap(ForwardIterator1 a, ForwardIterator2 b);

Preconditions: a and b are dereferenceable. *a is swappable with (16.4.4.3) *b.

Effects: As if by swap(*a, *b).

27.7.4  Transform

Let:
  —  (1.1)  last2 be first2 + (last1 - first1) for the overloads with parameter first2 but no parameter last2;
(1.2) — let \( N \) be \( \text{last1} - \text{first1} \) for unary transforms, or \( \min(\text{last1} - \text{first1}, \text{last2} - \text{first2}) \) for binary transforms;

(1.3) — let \( E \) be

(1.3.1) — \( \text{op}(*\text{(first1 + (i - result)})) \) for unary transforms defined in namespace std;

(1.3.2) — \( \text{binary_op}(*\text{(first1 + (i - result)}), *\text{(first2 + (i - result)}) \) for binary transforms defined in namespace std;

(1.3.3) — \( \text{invoke} \text{op, invoke(proj, *\text{(first1 + (i - result)})} \) for unary transforms defined in namespace ranges;

(1.3.4) — \( \text{invoke(binary_op, invoke(proj1, *\text{(first1 + (i - result)})}, \text{invoke(proj2, *\text{(first2 + (i - result)})} \) for binary transforms defined in namespace ranges.

2 Preconditions: \text{op} and \text{binary_op} do not invalidate iterators or subranges, nor modify elements in the ranges

(2.1) — \([\text{first1},\text{first1} + N] \),

(2.2) — \([\text{first2},\text{first2} + N] \), and

(2.3) — \([\text{result},\text{result} + N] \). 223

3 Effects: Assigns through every iterator \( i \) in the range \([\text{result},\text{result} + N] \) a new corresponding value equal to \( E \).

4 Returns:

(4.1) — \( \text{result} + N \) for the overloads defined in namespace std.

(4.2) — \( \{\text{first1} + N, \text{result} + N\} \) for unary transforms defined in namespace ranges.

(4.3) — \( \{\text{first1} + N, \text{first2} + N, \text{result} + N\} \) for binary transforms defined in namespace ranges.

5 Complexity: Exactly \( N \) applications of \text{op} or \text{binary_op}, and any projections. This requirement also applies to the overload with an ExecutionPolicy.

6 Remarks: \text{result} may be equal to \text{first1} or \text{first2}.

27.7.5 Replace [alg.replace]

```cpp
template<class ForwardIterator, class T>
  constexpr void replace(ForwardIterator first, ForwardIterator last, const T& old_value, const T& new_value);

template<class ExecutionPolicy, class ForwardIterator, class T>
  void replace(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, const T& old_value, const T& new_value);

template<class ForwardIterator, class Predicate, class T>
  constexpr void replace_if(ForwardIterator first, ForwardIterator last, Predicate pred, const T& new_value);

template<class ExecutionPolicy, class ForwardIterator, class Predicate, class T>
  void replace_if(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, Predicate pred, const T& new_value);

template<input_iterator I, sentinel_for<I> S, class T1, class T2, class Proj = identity>
  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 T1, class T2, class Proj = identity>
  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 = {});
```

223) The use of fully closed ranges is intentional.
template<
input_iterator I, sentinel_for<I> S, class T, class Proj = identity,
    indirect unary predicate<Projected<I, Proj>> Pred
>constexpr I ranges::replace_if(I first, S last, Pred pred, const T& new_value, Proj proj = {});

template<input_range R, class T, class Proj = identity,
    indirect unary predicate<Projected<iterator_t<R>, Proj>> Pred>
constexpr borrowed_iterator_t<R>
ranges::replace_if(R&& r, Pred pred, const T& new_value, Proj proj = {});

Let \( E \) be

1. \( \text{bool}(\*i == \text{old\_value}) \) for replace;
2. \( \text{bool}(\text{pred}(\*i)) \) for replace\_if;
3. \( \text{bool}((\text{invoke})(\text{proj}, \*i) == \text{old\_value}) \) for ranges::replace;
4. \( \text{bool}((\text{invoke})(\text{pred}, (\text{invoke})(\text{proj}, \*i))) \) for ranges::replace\_if.

**Mandates:** \( \text{new\_value} \) is writable (25.3.1) to \( \text{first} \).

**Effects:** Substitutes elements referred by the iterator \( i \) in the range \([\text{first}, \text{last})\) with \( \text{new\_value} \), when \( E \) is true.

**Returns:** \( \text{last} \) for the overloads in namespace ranges.

**Complexity:** Exactly \( \text{last} - \text{first} \) applications of the corresponding predicate and any projection.
Let \( E \) be

\[ \begin{align*}
(6.1) & \quad \text{bool}(\ast(first + (i - result)) == old_value) \quad \text{for replace_copy}; \\
(6.2) & \quad \text{bool}(pred(\ast(first + (i - result)))) \quad \text{for replace_copy_if}; \\
(6.3) & \quad \text{bool}(\text{invoke(proj, } \ast(first + (i - result))) == old_value) \quad \text{for ranges::replace_copy}; \\
(6.4) & \quad \text{bool}(\text{invoke(pred, invoke(proj, } \ast(first + (i - result)))) \quad \text{for ranges::replace_copy_if}.
\end{align*} \]

Mandates: The results of the expressions *first and new_value are writable (25.3.1) to result.

Preconditions: The ranges \([first, last)\) and \([result, result + (last - first))\) do not overlap.

Effects: Assigns through every iterator \( i \) in the range \([result, result + (last - first))\) a new corresponding value

\[ \begin{align*}
(9.1) & \quad \text{new_value if } E \text{ is true or} \\
(9.2) & \quad \ast(first + (i - result)) \text{ otherwise.}
\end{align*} \]

Returns:

\[ \begin{align*}
(10.1) & \quad \text{result + (last - first) for the overloads in namespace std.} \\
(10.2) & \quad \{last, result + (last - first)} \text{ for the overloads in namespace ranges.}
\end{align*} \]

Complexity: Exactly \( last - first \) applications of the corresponding predicate and any projection.

### 27.7.6 Fill

\[ \text{[alg.fill]} \]

```
template<class ForwardIterator, class T>
    constexpr void fill(ForwardIterator first, ForwardIterator last, const T& value);
template<class ExecutionPolicy, class ForwardIterator, class T>
    void fill(ExecutionPolicy&& exec, 
              ForwardIterator first, ForwardIterator last, const T& value);

template<class OutputIterator, class Size, class T>
    constexpr OutputIterator fill_n(OutputIterator first, Size n, const T& value);
template<class ExecutionPolicy, class ForwardIterator, class Size, class T>
    ForwardIterator fill_n(ExecutionPolicy&& exec, 
                           ForwardIterator first, Size 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);

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 generate_n algorithms, and $\text{last} - \text{first}$ for the generate algorithms.

Mandates: $\text{Size}$ is convertible to an integral type (7.3.9, 11.4.8).

Effects: Assigns the result of successive evaluations of $\text{gen}()$ through each iterator in the range
$[\text{first}, \text{first} + N)$.

Returns: $\text{first} + N$.

Complexity: Exactly $N$ evaluations of $\text{gen}()$ and assignments.

27.7.8 Remove

template<class ForwardIterator, class T>
constexpr ForwardIterator remove(ForwardIterator first, ForwardIterator last,
                                const T& value);
template<class ExecutionPolicy, class ForwardIterator, class T>
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 T, class Proj = identity>
requires indirect_binary_predicate<ranges::equal_to, projected<I, Proj>, const T*>>
constexpr subrange<I> ranges::remove(I first, S last, const T& value, Proj proj = {});
template<forward_range R, class T, class Proj = identity>
requires permutable<iterator_t<R>>
&& indirect_binary_predicate<ranges::equal_to, projected<iterator_t<R>, Proj>, const T*>(
ranges::borrowed_subrange_t<R> ranges::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> ranges::remove_if(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>
ranges::remove_if(R&& r, Pred pred, Proj proj = {});

Let \( E \) be
1. \( \text{bool(*i == value)} \) for \text{remove};
2. \( \text{bool(pred(*i))} \) for \text{remove_if};
3. \( \text{bool(invoke(proj, *i) == value)} \) for \text{ranges::remove};
4. \( \text{bool(invoke(pred, invoke(proj, *i)))} \) for \text{ranges::remove_if}.

Preconditions: For the algorithms in namespace \text{std}, the type of \*first meets the \text{Cpp17MoveAssignable} requirements (Table 32).

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:
1. \( j \) for the overloads in namespace \text{std}.
2. \( \{j, \text{last}\} \) for the overloads in namespace \text{ranges}.

Complexity: Exactly \( \text{last - first} \) applications of the corresponding predicate and any projection.

Remarks: Stable (16.4.6.8).

[Note 1: Each element in the range \([\text{ret}, \text{last})\), where \text{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. — end note]
Let $E$ be

\begin{align*}
\text{(8.1)} & \quad \text{bool(*)i == value) for remove_copy;} \\
\text{(8.2)} & \quad \text{bool(pred(*i)) for remove_copy_if;} \\
\text{(8.3)} & \quad \text{bool(invoke(proj, *i) == value) for ranges::remove_copy;} \\
\text{(8.4)} & \quad \text{bool(invoke(pred, invoke(proj, *i)) for ranges::remove_copy_if.}
\end{align*}

Let $N$ be the number of elements in $[\text{first, last})$ for which $E$ is false.

Mandates: $\text{first}$ is writable (25.3.1) to result.

Preconditions: The ranges $[\text{first, last})$ and $[\text{result, result + (last - first})$ do not overlap.

[Note 2: For the overloads with an ExecutionPolicy, there might be a performance cost if iterator_traits<ForwardIterator>::value_type does not meet the Cpp17MoveConstructible (Table 30) requirements.
—end note]

Effects: Copies all the elements referred to by the iterator $i$ in the range $[\text{first, last})$ for which $E$ is false.

Returns:

\begin{align*}
\text{(13.1)} & \quad \text{result + N, for the algorithms in namespace std.} \\
\text{(13.2)} & \quad \text{\{last, result + N\}, for the algorithms in namespace ranges.}
\end{align*}

Complexity: Exactly $\text{last - first}$ applications of the corresponding predicate and any projection.

Remarks: Stable (16.4.6.8).

### 27.7.9 Unique

[alg.unique]

\begin{verbatim}
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<iterator_t<R>, Proj>> C = ranges::equal_to>
requires permutable<iterator_t<R>>
ranges::unique(R&& r, C comp = {}, Proj proj = {});

Let $\text{pred}$ be equal_to{} for the overloads with no parameter $\text{pred}$, and let $E$ be

\begin{align*}
\text{(1.1)} & \quad \text{bool(pred(*(i - 1), *i)) for the overloads in namespace std;}
\end{align*}
\end{verbatim}
— \( \text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *(\text{i} - 1)), \text{invoke}(\text{proj}, *\text{i}))) \) for the overloads in namespace ranges.

**Preconditions:** For the overloads in namespace std, \( \text{pred} \) is an equivalence relation and the type of 
*first meets the Cpp17MoveAssignable requirements (Table 32).

**Effects:** For a nonempty range, eliminates all but the first element from every consecutive group of equivalent elements referred to by the iterator \( \text{i} \) in the range \([\text{first} + 1, \text{last})\) for which \( E \) is true.

**Returns:** Let \( j \) be the end of the resulting range. Returns:
— \( j \) for the overloads in namespace std.
— \{\( j \), last\} for the overloads in namespace ranges.

**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.

```cpp
template<class InputIterator, class OutputIterator>
constexpr OutputIterator
unique_copy(InputIterator first, InputIterator last,
            OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
unique_copy(ExecutionPolicy&& exec,
            ForwardIterator1 first, ForwardIterator1 last,
            ForwardIterator2 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,
         class BinaryPredicate>
ForwardIterator2
unique_copy(ExecutionPolicy&& exec,
            ForwardIterator1 first, ForwardIterator1 last,
            ForwardIterator2 result, BinaryPredicate pred);
```

Let \( \text{pred} \) be \text{equal_to}\{\} for the overloads in namespace std with no parameter \( \text{pred} \), and let \( E \) be

— \( \text{bool}(\text{pred}(*\text{i}, *(\text{i} - 1))) \) for the overloads in namespace std;
— \( \text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *\text{i}), \text{invoke}(\text{proj}, *(\text{i} - 1)))) \) for the overloads in namespace ranges.

**Mandates:** *first is writable (25.3.1) to result.

**Preconditions:**
— The ranges \([\text{first}, \text{last})\) and \([\text{result}, \text{result} + (\text{last} - \text{first}))\) 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` meets the `Cpp17ForwardIterator` requirements, then there are no additional requirements for T. Otherwise, if `OutputIterator` meets the `Cpp17ForwardIterator` requirements and its value type is the same as T, then T meets the `Cpp17CopyAssignable` (Table 33) requirements. Otherwise, T meets both the `Cpp17CopyConstructible` (Table 31) 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

```cpp
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-Swappable` 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 `(last - first)/2` swaps.

```cpp
template<class BidirectionalIterator, class OutputIterator>
constexpr OutputIterator reverse_copy(BidirectionalIterator first, BidirectionalIterator last,
                                       OutputIterator result);

template<class ExecutionPolicy, class BidirectionalIterator, class ForwardIterator>
ForwardIterator reverse_copy(ExecutionPolicy&& exec,
                             BidirectionalIterator first, BidirectionalIterator last,
                             ForwardIterator result);

template<bidirectional_iterator I, sentinel_for<I> S, weakly_incrementable O>
requires indirectly_copyable<I, O>
constexpr ranges::reverse_copy_result<I, O> ranges::reverse_copy(I first, S last, O result);
```
template<bidirectional_range R, weakly_incrementable O>
requires indirectly_copyable<iterator_t<R>, O>
constexpr ranges::reverse_copy_result<borrowed_iterator_t<R>, O>
ranges::reverse_copy(R&& r, O result);

Let \( N \) be \( \text{last} - \text{first} \).

Preconditions: 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 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}, \text{result} + N\} for the overloads in namespace \text{ranges}.

Complexity: Exactly \( N \) assignments.

27.7.11 Rotate

template<class ForwardIterator>
constexpr ForwardIterator
rotate(ForwardIterator first, ForwardIterator middle, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
rotate(ExecutionPolicy&& exec,
        ForwardIterator first, ForwardIterator middle, ForwardIterator last);

template<permutable I, sentinel_for<I> S>
constexpr subrange<I> ranges::rotate(I first, I middle, S last);

Preconditions: \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\) are valid ranges. For the overloads in namespace \text{std}, \text{ForwardIterator} meets the \text{Cpp17ValueSwappable} requirements (16.4.4.3), and the type of \(*\text{first}\) meets the \text{Cpp17MoveConstructible} (Table 30) and \text{Cpp17MoveAssignable} (Table 32) 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.

template<forward_range R>
requires permutable<iterator_t<R>>
constexpr borrowed_subrange_t<R> ranges::rotate(R&& r, iterator_t<R> middle);

Effects: Equivalent to: 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 $last - first$.

Preconditions: $[first, middle]$ and $[middle, last)$ are valid ranges. The ranges $[first, last)$ and $[result, result + N)$ do not overlap.

Effects: Copies the range $[first, last)$ to the range $[result, result + N)$ such that for each non-negative integer $i < N$ the following assignment takes place: *(result + i) = *(first + (i + (middle - first)) % N).

Returns:

(9.1) — result + $N$ for the overloads in namespace std.
(9.2) — {last, result + $N$} for the overload in namespace 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:

  return ranges::rotate_copy(ranges::begin(r), middle, ranges::end(r), 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 std, Distance is an integer type and *first is writable (25.3.1) to out.

Preconditions: out is not in the range $[first, last)$. For the overload in namespace std:

(2.1) — PopulationIterator meets the Cpp17InputIterator requirements (25.3.5.3).
(2.2) — SampleIterator meets the Cpp17OutputIterator requirements (25.3.5.4).
(2.3) — SampleIterator meets the Cpp17RandomAccessIterator requirements (25.3.5.7) unless PopulationIterator meets the Cpp17ForwardIterator requirements (25.3.5.5).
(2.4) — remove_reference_t<UniformRandomBitGenerator> meets the requirements of a uniform random bit generator type (28.5.3.3).

Effects: Copies min(last - first, n) elements (the sample) from $[first, last)$ (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: $O(last - first)$.

Remarks:
For the overload in namespace `std`, stable if and only if `PopulationIterator` meets the `Cpp17ForwardIterator` requirements. 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

[alg.random.shuffle]

```cpp
template<class RandomAccessIterator, class UniformRandomBitGenerator>
void shuffle(RandomAccessIterator first,
             RandomAccessIterator last,
             UniformRandomBitGenerator&& g);
```

```cpp
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);
```

```cpp
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);
```

1 **Preconditions:** For the overload in namespace `std`:

   1.1 RandomAccessIterator meets the `Cpp17ValueSwappable` requirements (16.4.4.3).
   1.2 The type remove_reference_t<UniformRandomBitGenerator> meets the uniform random bit generator (28.5.3.3) requirements.

2 **Effects:** Permutes the elements in the range `[first, last)` such that each possible permutation of those elements has equal probability of appearance.

3 **Returns:** last for the overloads in namespace `ranges`.

4 **Complexity:** Exactly `(last - first) - 1` swaps.

5 **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

[alg.shift]

```cpp
template<class ForwardIterator>
constexpr ForwardIterator
shift_left(ForwardIterator first, ForwardIterator last,
           typename iterator_traits<ForwardIterator>::difference_type n);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
shift_left(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,
           typename iterator_traits<ForwardIterator>::difference_type n);
```

```cpp
template<permutable I, sentinel_for<I> S>
constexpr subrange<I> ranges::shift_left(I first, S last, iter_difference_t<I> n);
```

```cpp
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 + n + 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`.

(3.1) **NEW_LAST** for the overloads in namespace `std`.

(3.2) `{first, NEW_LAST}` for the overloads in namespace `ranges`. 

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Complexity: At most \((last - first) - n\) assignments.

```cpp
template<class ForwardIterator>
constexpr ForwardIterator
shift_right(ForwardIterator first, ForwardIterator last,
          typename iterator_traits<ForwardIterator>::difference_type n);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator
shift_right(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last,
          typename iterator_traits<ForwardIterator>::difference_type n);
```

```cpp
template<permutable I, sentinel_for<I> S>
constexpr subrange<I> ranges::shift_right(I first, S last, iter_difference_t<I> n);
```

```cpp
template<forward_range R>
requires permutable<iterator_t<R>>
constexpr borrowed_subrange_t<R> ranges::shift_right(R&& r, range_difference_t<R> n);
```

Preconditions: \(n \geq 0\) 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.

Effects: If \(n = 0\) or \(n \geq last - first\), 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:

1. For the overload in namespace `std` without an `ExecutionPolicy` template parameter, `ForwardIterator` meets the `Cpp17BidirectionalIterator` requirements,
2. For the overloads in namespace `ranges`, `I` models `bidirectional_iterator`.

Returns: Let `NEW_FIRST` be `first + n` if \(n < last - first\), otherwise `last`.

1. `NEW_FIRST` for the overloads in namespace `std`.
2. `{NEW_FIRST, last}` for the overloads in namespace `ranges`.

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 contextually converted to `bool` (7.3), 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 (\(!comp(x, x)\) 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:

1. `comp(a, b) && comp(b, c)` implies `comp(a, c)`
2. `equiv(a, b) && equiv(b, c)` implies `equiv(a, c)`

[Note I: Under these conditions, it can be shown that]

3. `equiv` is an equivalence relation,
4. `comp` induces a well-defined relation on the equivalence classes determined by `equiv`, and
5. the induced relation is a strict total ordering.

---

§ 27.8.1
A sequence is sorted with respect to a \texttt{comp} and \texttt{proj} for a comparator and projection \texttt{comp} and \texttt{proj} if for every iterator \texttt{i} pointing to the sequence and every non-negative integer \texttt{n} such that \texttt{i + n} is a valid iterator pointing to an element of the sequence,

\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *(\text{i + n})), \text{invoke}(\text{proj}, *\text{i})))
\]
is false.

A sequence \([\text{start,finish}]\) is partitioned with respect to an expression \(f(e)\) if there exists an integer \(n\) such that for all \(0 \leq i < (\text{finish - start})\), \(f(\text{*(start + i)})\) 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 \texttt{operator==}, 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

\[\text{sort}\]

\begin{verbatim}
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 = {});
\end{verbatim}

Let \texttt{comp} be \texttt{less{}} and \texttt{proj} be \texttt{identity{}} for the overloads with no parameters by those names.

\textbf{Preconditions:} For the overloads in namespace \texttt{std, RandomAccessIterator} meets the \texttt{Cpp17Value-Swappable} requirements (16.4.4.3) and the type of \texttt{*first} meets the \texttt{Cpp17MoveConstructible} (Table 30) and \texttt{Cpp17MoveAssignable} (Table 32) requirements.

\textbf{Effects:} Sorts the elements in the range \([\text{first, last}]\) with respect to \texttt{comp} and \texttt{proj}.

\textbf{Returns:} last for the overloads in namespace \texttt{ranges}.

\textbf{Complexity:} Let \(N\) be \texttt{last - first}. \(\Theta(N \log N)\) comparisons and projections.

#### 27.8.2.2 stable_sort

\[\text{stable_sort}\]

\begin{verbatim}
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>
void stable_sort(RandomAccessIterator first, RandomAccessIterator last, Compare comp);
\end{verbatim}
template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
void stable_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>
I ranges::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>
borrowed_iterator_t<R>
ranges::stable_sort(R&& r, Comp comp = {}, Proj proj = {});

Let \texttt{comp} be \texttt{less\{} and \texttt{proj} be \texttt{identity\{} for the overloads with no parameters by those names.

2 Preconditions: For the overloads in namespace \texttt{std}, \texttt{RandomAccessIterator} meets the \texttt{Cpp17ValueSwappable} requirements (16.4.4.3) and the type of \texttt{*first} meets the \texttt{Cpp17MoveConstructible} (Table 30) and \texttt{Cpp17MoveAssignable} (Table 32) requirements.

3 Effects: Sorts the elements in the range \([\texttt{first}, \texttt{last})\) with respect to \texttt{comp} and \texttt{proj}.

4 Returns: \texttt{last} for the overloads in namespace \texttt{ranges}.

5 Complexity: Let \(N\) be \texttt{last} - \texttt{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.

6 Remarks: Stable (16.4.6.8).

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>
ranges::partial_sort(I first, I middle, S last, Comp comp = {}, Proj proj = {});

1 Let \texttt{comp} be \texttt{less\{} and \texttt{proj} be \texttt{identity\{} for the overloads with no parameters by those names.

2 Preconditions: \texttt{[first, middle)} and \texttt{[middle, last)} are valid ranges. For the overloads in namespace \texttt{std}, \texttt{RandomAccessIterator} meets the \texttt{Cpp17ValueSwappable} requirements (16.4.4.3) and the type of \texttt{*first} meets the \texttt{Cpp17MoveConstructible} (Table 30) and \texttt{Cpp17MoveAssignable} (Table 32) 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.

```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::partial_sort(R&& r, iterator_t<R> middle, Comp comp = {}, Proj proj = {});
```

Effects: Equivalent to:

```cpp
return ranges::partial_sort(ranges::begin(r), middle, ranges::end(r), comp, proj);
```

### 27.8.2.4 partial_sort_copy

```cpp
template<class InputIterator, class RandomAccessIterator>
constexpr RandomAccessIterator
partial_sort_copy(InputIterator first, InputIterator last, 
RandomAccessIterator result_first, RandomAccessIterator result_last);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator, class RandomAccessIterator>
RandomAccessIterator
partial_sort_copy(ExecutionPolicy&& exec, ForwardIterator first, ForwardIterator last, 
RandomAccessIterator result_first, RandomAccessIterator result_last);
```

```cpp
template<class InputIterator, class RandomAccessIterator, class Compare>
constexpr RandomAccessIterator
partial_sort_copy(InputIterator first, InputIterator last, 
RandomAccessIterator result_first, RandomAccessIterator result_last, 
Compare comp);
```

```cpp
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);
```

```cpp
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 = {});
```

```cpp
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&& r1, R2&& r2, result_r, Comp comp = {}, 
Proj1 proj1 = {}, Proj2 proj2 = {});
```

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.

§ 27.8.2.4 1224
Mandates: For the overloads in namespace std, the expression \*first is writable (25.3.1) to result_first.

Preconditions: For the overloads in namespace std, RandomAccessIterator meets the Cpp17ValueSwappable requirements (16.4.4.3), the type of \*result_first meets the Cpp17MoveConstructible (Table 30) and Cpp17MoveAssignable (Table 32) requirements.

For iterators \texttt{a1} and \texttt{b1} in \([\texttt{first}, \texttt{last})\), and iterators \texttt{x2} and \texttt{y2} in \([\texttt{result_first}, \texttt{result_last})\), after evaluating the assignment \texttt{*y2 = *b1}, let \(E\) be the value of
\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj1}, \*\texttt{a1}), \text{invoke}(\text{proj2}, \*\texttt{y2}))).
\]
Then, after evaluating the assignment \texttt{*x2 = *a1}, \(E\) is equal to
\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj2}, \*\texttt{x2}), \text{invoke}(\text{proj2}, \*\texttt{y2}))).
\]
[Note 1: Writing a value from the input range into the output range does not affect how it is ordered by \texttt{comp} and \texttt{proj1} or \texttt{proj2}. — end note]

Effects: Places the first \(N\) elements as sorted with respect to \texttt{comp} and \texttt{proj2} into the range \([\texttt{result_first}, \texttt{result_first} + N)\).

Returns:
\[
\begin{align*}
& \text{(6.1) } \texttt{result_first} + N \text{ for the overloads in namespace std.} \\
& \text{(6.2) } \{\texttt{last}, \texttt{result_first} + N\} \text{ for the overloads in namespace ranges.}
\end{align*}
\]

Complexity: Approximately \((\texttt{last} - \texttt{first}) \ast \log N\) comparisons, and twice as many projections.

27.8.2.5 \texttt{is_sorted} \[is.sorted\]

\begin{verbatim}
template<class ForwardIterator>
constexpr bool is_sorted(ForwardIterator first, ForwardIterator last);

Effects: Equivalent to: return is_sorted_until(first, last) == last;

template<class ExecutionPolicy, class ForwardIterator>
bool is_sorted(ExecutionPolicy&& exec,
              ForwardIterator first, ForwardIterator last);

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);

Effects: Equivalent to: return is_sorted_until(first, last, comp) == last;

template<class ExecutionPolicy, class Compare, class ForwardIterator>
bool is_sorted(ExecutionPolicy&& exec,
               ForwardIterator first, ForwardIterator last,
               Compare comp);

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 = {});

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);
\end{verbatim}
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, S last, Comp comp = {}, Proj proj = {});

template<forward_range R, class Proj = identity,
indirect_strict_weak_order<iterator_t<R>, Proj>>
ranges::is_sorted_until(R&& r, Comp comp = {}, Proj proj = {});

Let comp be \texttt{less{}} and proj be \texttt{identity{}} for the overloads with no parameters by those names.

Returns: The last iterator \(i\) in \([\text{first}, \text{last}]\) for which the range \([\text{first}, i)\) is sorted with respect to \(\text{comp}\) and \(\text{proj}\).

Complexity: Linear.

27.8.3 Nth element

§ 27.8.3 1226
Complexity: For the overloads with no \texttt{ExecutionPolicy}, linear on average. For the overloads with an \texttt{ExecutionPolicy}, $\Theta(N)$ applications of the predicate, and $\Theta(N \log N)$ swaps, where $N = \text{last} - \text{first}$.

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:

\[
\text{return ranges::nth_element(ranges::begin(r), nth, ranges::end(r), comp, proj);}
\]

27.8.4 Binary search

27.8.4.1 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

\[
\text{template<class ForwardIterator, class T>}
\text{constexpr ForwardIterator}
\text{lower_bound(ForwardIterator first, ForwardIterator last, const T\& value);}
\]

\[
\text{template<class ForwardIterator, class T, class Compare>}
\text{constexpr ForwardIterator}
\text{lower_bound(ForwardIterator first, ForwardIterator last, const T\& value, Compare comp);}
\]

\[
\text{template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity,}
\text{indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>}
\text{constexpr I}
\text{ranges::lower_bound(I first, S last, const T\& value, Comp comp = {}, Proj proj = {});}
\]

\[
\text{template<forward_range R, class T, class Proj = identity,}
\text{indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>}
\text{constexpr borrowed_iterator_t<R>}
\text{ranges::lower_bound(R&& r, const T\& value, Comp comp = {}, Proj proj = {});}
\]

1 Let \texttt{comp} be \texttt{less{}} and \texttt{proj} be \texttt{identity{}} for overloads with no parameters by those names.

2 Preconditions: The elements \texttt{e} of \texttt{[first, last]} are partitioned with respect to the expression \texttt{bool(invoke(comp, invoke(proj, e), value))}.

3 Returns: The furthermost iterator \texttt{i} in the range \texttt{[first, last]} such that for every iterator \texttt{j} in the range \texttt{[first, i)}, \texttt{bool(invoke(comp, invoke(proj, *j), value))} is true.

4 Complexity: At most $\log_2(\text{last} - \text{first}) + \Theta(1)$ comparisons and projections.

27.8.4.3 upper_bound

\[
\text{template<class ForwardIterator, class T>}
\text{constexpr ForwardIterator}
\text{upper_bound(ForwardIterator first, ForwardIterator last, const T\& value);}
\]

\[
\text{template<class ForwardIterator, class T, class Compare>}
\text{constexpr ForwardIterator}
\text{upper_bound(ForwardIterator first, ForwardIterator last, const T\& value, Compare comp);}
\]
template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity, 
  indirect_strict_weak_order<const T*, projected<I, Proj>> Comp = ranges::less>
constexpr I ranges::upper_bound(I first, S last, const T& value, Comp comp = {}, Proj proj = {});

template<forward_range R, class T, class Proj = identity, 
  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 = {});

1 Let comp be less{} and proj be identity{} for overloads with no parameters by those names.
2 Preconditions: The elements e of [first, last) are partitioned with respect to the expression !bool(invoke(comp, value, invoke(proj, e))).
3 Returns: The furthermost iterator i in the range [first, last] such that for every iterator j in the range [first, i), !bool(invoke(comp, value, invoke(proj, *j))) is true.
4 Complexity: At most log₂(last - first) + O(1) comparisons and projections.

27.8.4.4 equal_range [equal.range]

template<class ForwardIterator, class T>
  constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, 
  ForwardIterator last, const T& value);

template<class ForwardIterator, class T, class Compare>
  constexpr pair<ForwardIterator, ForwardIterator> equal_range(ForwardIterator first, 
  ForwardIterator last, const T& value, 
  Compare comp);

1 Let comp be less{} and proj be identity{} for overloads with no parameters by those names.
2 Preconditions: The elements e of [first, 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 [first, last), bool(comp(e, value)) implies !bool(comp(value, e)) for the overloads in namespace std.
3 Returns:
(3.1) — For the overloads in namespace std:
  {lower_bound(first, last, value, comp),
   upper_bound(first, last, value, comp)}
(3.2) — For the overloads in namespace ranges:
  {ranges::lower_bound(first, last, value, comp, proj),
   ranges::upper_bound(first, last, value, comp, proj)}
4 Complexity: At most 2 * log₂(last - first) + O(1) comparisons and projections.

27.8.4.5 binary_search [binary.search]

template<class ForwardIterator, class T>
  constexpr bool binary_search(ForwardIterator first, ForwardIterator last, 
  const T& value);
template<class ForwardIterator, class T, class Compare>
constexpr bool
binary_search(ForwardIterator first, ForwardIterator last,  
const T& value, Compare comp);

template<forward_iterator I, sentinel_for<I> S, class T, class Proj = identity,  
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 = {});

template<forward_range R, class T, class Proj = identity,  
indirect_strict_weak_order<const T*, projected<iterator_t<R>, Proj>> Comp = ranges::less>
constexpr bool ranges::binary_search(R&& r, const T& value, Comp comp = {},  
Proj proj = {});

Let \( \text{comp} \) be \( \text{less}{} \) and \( \text{proj} \) be \( \text{identity}{} \) 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 \( \neg \text{bool}(\text{invoke}(\text{comp}, \text{value, invoke}(\text{proj}, e))) \). Also, for all elements \( e \) of \([\text{first}, \text{last})\), \( \text{bool}(\text{comp}(e, \text{value})) \) implies \( \neg \text{bool}(\text{comp}(\text{value, e})) \) for the overloads in namespace std.

Returns: true if and only if for some iterator \( i \) in the range \([\text{first}, \text{last})\), \( \neg \text{bool}(\text{invoke}(\text{comp, invoke}(\text{proj}, *i), \text{value})) \) \&\& \( \neg \text{bool}(\text{invoke}(\text{comp, value, invoke}(\text{proj}, *i))) \) is true.

Complexity: At most \( \log_2(\text{last} - \text{first}) + \Theta(1) \) comparisons and projections.

### 27.8.5 Partitions

[alg.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);

template<input_iterator I, sentinel_for<I> S, class Proj = identity,  
indirect_unary_predicate<projected<I, Proj>> Pred>
constexpr bool ranges::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 ranges::is_partitioned(R&& r, Pred pred, Proj proj = {});

Let \( \text{proj} \) be \( \text{identity}{} \) for the overloaded with no parameter named \( \text{proj} \).

Returns: true if and only if the elements \( e \) of \([\text{first}, \text{last})\) are partitioned with respect to the expression 
\( \text{bool}(\text{invoke}(\text{pred, invoke}(\text{proj}, e))) \).

Complexity: Linear. At most \( \text{last} - \text{first} \) applications of \( \text{pred} \) and \( \text{proj} \).
ranges::partition(R&& r, Pred pred, Proj proj = {});

Let \texttt{proj} be \texttt{identity()} for the overloads with no parameter named \texttt{proj} and let \(E(x)\) be \texttt{bool(invoke(pred, invoke(proj, x)))}.

**Preconditions:** For the overloads in namespace \texttt{std}, \texttt{ForwardIterator} meets the \texttt{Cpp17ValueSwappable} requirements (16.4.4.3).

**Effects:** Places all the elements \(e\) in \([\texttt{first}, \texttt{last})\) that satisfy \(E(e)\) before all the elements that do not.

**Returns:** Let \(i\) be an iterator such that \(E(*j)\) is \texttt{true} for every iterator \(j\) in \([\texttt{first}, i)\) and \texttt{false} for every iterator \(j\) in \([i, \texttt{last})\). Returns:

- \(i\) for the overloads in namespace \texttt{std}.
- \{\texttt{i, last}\} for the overloads in namespace \texttt{ranges}.

**Complexity:** Let \(N = \texttt{last} - \texttt{first}:

- For the overload with no \texttt{ExecutionPolicy}, exactly \(N\) applications of the predicate and projection. At most \(N/2\) swaps if the type of \texttt{first} meets the \texttt{Cpp17BidirectionalIterator} requirements for the overloads in namespace \texttt{std} or models \texttt{bidirectional_iterator} for the overloads in namespace \texttt{ranges}, and at most \(N\) swaps otherwise.

- For the overload with an \texttt{ExecutionPolicy}, \(\mathcal{O}(N \log N)\) swaps and \(\mathcal{O}(N)\) applications of the predicate.

\[
\begin{align*}
\text{template<bidirectional_iterator I, sentinel_for<I> S, class Proj = identity,} \\
\text{indirect_unary_predicate<projected<I>, Proj>} & \text{ Pred>}
\text{ requires permuturable<I>} \\
\text{ subrange<I>} & \text{ ranges::stable_partition(I first, S last, Pred pred, Proj proj = {});} \\
\text{template<bidirectional_range R, class Proj = identity,} \\
\text{indirect_unary_predicate<projected<iterator_t<R>>, Proj>} & \text{ Pred>}
\text{ requires permutatable<iterator_t<R>>} \\
\text{borrowed_subrange_t<R>} & \text{ ranges::stable_partition(R&& r, Pred pred, Proj proj = {});} \\
\end{align*}
\]

Let \texttt{proj} be \texttt{identity()} for the overloads with no parameter named \texttt{proj} and let \(E(x)\) be \texttt{bool(invoke(pred, invoke(proj, x)))}.

**Preconditions:** For the overloads in namespace \texttt{std}, \texttt{BidirectionalIterator} meets the \texttt{Cpp17ValueSwappable} requirements (16.4.4.3) and the type of \texttt{*first} meets the \texttt{Cpp17MoveConstructible} (Table 30) and \texttt{Cpp17MoveAssignable} (Table 32) requirements.

**Effects:** Places all the elements \(e\) in \([\texttt{first}, \texttt{last})\) 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 \([\texttt{first}, i)\), \(E(*j)\) is \texttt{true}, and for every iterator \(j\) in the range \([i, \texttt{last})\), \(E(*j)\) is \texttt{false}. Returns:

- \(i\) for the overloads in namespace \texttt{std}.
- \{\texttt{i, last}\} for the overloads in namespace \texttt{ranges}.

**Complexity:** Let \(N = \texttt{last} - \texttt{first}:

- For the overloads with no \texttt{ExecutionPolicy}, at most \(N \log N\) swaps, but only \(\mathcal{O}(N)\) swaps if there is enough extra memory. Exactly \(N\) applications of the predicate and projection.

- For the overload with an \texttt{ExecutionPolicy}, \(\mathcal{O}(N \log N)\) swaps and \(\mathcal{O}(N)\) applications of the predicate.
template<typename OutputIterator1, typename OutputIterator2, typename Predicate>
OutputIterator1 out_true, OutputIterator2 out_false, Predicate pred();

template<typename ExecutionPolicy, typename ForwardIterator1, typename ForwardIterator2, typename Predicate>
pair<ForwardIterator1, ForwardIterator2>
partition_copy(ExecutionPolicy&& exec,
ForwadIterator first, ForwardIterator last,
ForwardIterator1 out_true, ForwardIterator2 out_false, Predicate pred);

template<typename InputIterator, typename Sentinel, typename ForwardIterator1, typename ForwardIterator2, typename Predicate = identity, typename Proj = identity, typename Pred = indirect_unary_predicate<projected<InputIterator, Proj>>>
requires indirectly_copyable<InputIterator, ForwardIterator1> && indirectly_copyable<InputIterator, ForwardIterator2>
constexpr ranges::partition_copy_result<InputIterator, ForwardIterator1, ForwardIterator2>
ranges::partition_copy(InputIterator first, Sentinel last, ForwardIterator1 out_true, ForwardIterator2 out_false, Predicate pred, Proj proj = {});

template<typename Range, typename ForwardIterator1, typename ForwardIterator2, typename Predicate = identity, typename Proj = identity, typename Pred = indirect_unary_predicate<projected<iterator_t<Range>, Proj>>>
requires indirectly_copyable<iterator_t<Range>, ForwardIterator1> && indirectly_copyable<iterator_t<Range>, ForwardIterator2>
constexpr borrowed_iterator_t<Range>
ranges::partition_copy(Range&& r, ForwardIterator1 out_true, ForwardIterator2 out_false, Predicate pred, Proj proj = {});

Let proj be identity() for the overloads with no parameter named proj and let \( E(x) \) be \( \text{bool}(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, x))) \).

Mandates: For the overloads in namespace std, the expression \(*\text{first}\) 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 \texttt{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.

\( - \{\text{last}, o1, o2\} \) for the overloads in namespace ranges.

Complexity: Exactly \( \text{last} - \text{first} \) applications of \texttt{pred} and \texttt{proj}.

27.8.6  
Merge [alg.merge]

\( \text{§ 27.8.6} \)
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<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 \( N \) be \((last1 - first1) + (last2 - first2)\). Let \( \text{comp} \) be \( \text{less}() \), \( \text{proj1} \) be \( \text{identity}() \), and \( \text{proj2} \) be \( \text{identity}() \), for the overloads with no parameters by those names.

Preconditions: The ranges \([first1, last1)\) and \([first2, last2)\) 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 all the elements of the two ranges \([first1, last1)\) and \([first2, last2)\) 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 \( e1 \) is an element of \([first1, last1)\) and \( e2 \) of \([first2, last2)\), \( e2 \) is copied into the output range before \( e1 \) if and only if \( \text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj2}, e2), \text{invoke}(\text{proj1}, e1))) \) is true.

Returns:

(4.1) \( \text{result}\_\text{last} \) for the overloads in namespace \( \text{std} \).
(4.2) \{last1, last2, result\_last\} for the overloads in namespace \( \text{ranges} \).

Complexity:

(5.1) For the overloads with no \( \text{ExecutionPolicy} \), at most \( N - 1 \) comparisons and applications of each projection.
(5.2) For the overloads with an \( \text{ExecutionPolicy} \), \( \mathcal{O}(N) \) comparisons.

Remarks: Stable (16.4.6.8).
template<class BidirectionalIterator>
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);

template<class BidirectionalIterator, class Compare>
void inplace_merge(BidirectionalIterator first, 
    BidirectionalIterator middle, 
    BidirectionalIterator last, Compare comp);

template<class ExecutionPolicy, class BidirectionalIterator, class Compare>
void inplace_merge(ExecutionPolicy&& exec, 
    BidirectionalIterator first, 
    BidirectionalIterator middle, 
    BidirectionalIterator last, Compare comp);

template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less, 
    class Proj = identity>
requires sortable<I, Comp, Proj>
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: [first,middle) and [middle,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 30) and Cpp17MoveAssignable (Table 32) requirements.

Effects: Merges two sorted consecutive ranges [first,middle) and [middle,last), putting the result of the merge into the range [first,last). The resulting range is sorted with respect to comp and proj.

Returns: last for the overload in namespace ranges.

Complexity: Let \( N = \text{last} - \text{first} \):

- For the overloads with no ExecutionPolicy, and if enough additional memory is available, exactly \( N - 1 \) comparisons.
- Otherwise, \( \Theta(N \log N) \) comparisons.

In either case, twice as many projections as comparisons.

Remarks: Stable (16.4.6.8).

template<bidirectional_range R, class Comp = ranges::less, class Proj = identity>
requires sortable<iterator_t<R>, Comp, Proj>
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

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<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 = {});

1 Let comp be less{}, proj1 be identity{}, and proj2 be identity{}, for the overloads with no
   parameters by those names.
2 Preconditions: The ranges [first1, last1) and [first2, last2) are sorted with respect to comp and
   proj1 or proj2, respectively.
3 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]
4 Complexity: At most 2 * ((last1 - first1) + (last2 - first2)) - 1 comparisons and applications
   of each projection.

27.8.7.3 set_union

template<class InputIterator1, class InputIterator2, class OutputIterator>
constexpr OutputIterator
set_union(InputIterator1 first1, InputIterator1 last1,
  InputIterator2 first2, InputIterator2 last2,
  OutputIterator result);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
  class ForwardIterator3>
ForwardIterator
set_union(ExecutionPolicy&& exec,
  ForwardIterator1 first1, ForwardIterator1 last1,
  ForwardIterator2 first2, ForwardIterator2 last2,
  ForwardIterator3 result);

template<class InputIterator1, class InputIterator2, class OutputIterator, class Compare>
constexpr OutputIterator
set_union(InputIterator1 first1, InputIterator1 last1,
  InputIterator2 first2, InputIterator2 last2,
  OutputIterator result, Compare comp);

template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
  class ForwardIterator3, class Compare>
ForwardIterator
set_union(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_union_result<I1, I2, O>
ranges::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<iterator_t<R1>, iterator_t<R2>, O, Comp, Proj1, Proj2>
constexpr ranges::set_union_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
ranges::set_union(R1&& r1, R2&& r2, O result, Comp comp = {},
Proj1 proj1 = {}, Proj2 proj2 = {});

Let \( \text{comp} \) be less\{\}, and \( \text{proj1} \) and \( \text{proj2} \) be identity\{\} for the overloads with no parameters by those names.

2. **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.

3. **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.

4. **Returns:** Let \( \text{result.last} \) be the end of the constructed range. Returns

\[
\text{(4.1)} \quad \text{result.last} \\
\text{(4.2)} \quad \{\text{last1}, \text{last2}, \text{result.last}\}
\]

5. **Complexity:** At most \( 2 \ast ((\text{last1} - \text{first1}) + (\text{last2} - \text{first2})) - 1 \) comparisons and applications of each projection.

6. **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 set_intersection

**set.intersection**

```cpp
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, class Compare>
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,
```
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 = {});

27.8.7.5 set_difference

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: 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.

Returns: Let result_last be the end of the constructed range. Returns
— result_last for the overloads in namespace std.
— {last1, last2, result_last} for the overloads in namespace ranges.

Complexity: At most \(2 \times ((last1 - first1) + (last2 - first2)) - 1\) 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, the first \(\min(m, n)\) elements are 
copied from the first range to the output range, in order.
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 \texttt{comp} be \texttt{less{}}, and \texttt{proj1} and \texttt{proj2} be \texttt{identity{}} for the overloads with no parameters by those names.

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.

Effects: Copies the elements of the range \([\texttt{first1}, \texttt{last1})\) which are not present in the range \([\texttt{first2}, \texttt{last2})\) to the range beginning at \texttt{result}. The elements in the constructed range are sorted.

Returns: Let \texttt{result\_last} be the end of the constructed range. Returns

\begin{align*}
1 & \text{— } \texttt{result\_last} \text{ for the overloads in namespace \texttt{std}.} \\
2 & \text{— } \{\texttt{last1}, \texttt{result\_last}\} \text{ for the overloads in namespace \texttt{ranges}.}
\end{align*}

Complexity: At most \(2 * ((\texttt{last1} - \texttt{first1}) + (\texttt{last2} - \texttt{first2})) - 1\) comparisons and applications of each projection.

Remarks: 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 last \(\max(m - n, 0)\) elements from \([\texttt{first1}, \texttt{last1})\) is copied to the output range, in order.

27.8.7.6 \texttt{set\_symmetric\_difference} [set.symmetric.difference]

\begin{verbatim}
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);
\end{verbatim}
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, 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_symmetric_difference_result<borrowed_iterator_t<R1>,
borrowed_iterator_t<R2>, O>
ranges::set_symmetric_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 \([\text{first1}, \text{last1})\) that are not present in the range \([\text{first2}, \text{last2})\), and the elements of the range \([\text{first2}, \text{last2})\) that are not present in the range \([\text{first1}, \text{last1})\) to the range beginning at \( \text{result} \). The elements in the constructed range are sorted.

Returns: Let \( \text{result_last} \) be the end of the constructed range. Returns

\[ \text{result_last} \]

— \( \text{result_last} \) for the overloads in namespace \( \text{std} \).

— \( \{\text{last1}, \text{last2}, \text{result_last}\} \) for the overloads in namespace \( \text{ranges} \).

Complexity: At most \( 2 * ((\text{last1} - \text{first1}) + (\text{last2} - \text{first2})) - 1 \) comparisons and applications of each projection.

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 \( |m - n| \) of those elements shall be copied to the output range: the last \( m - n \) of these elements from \([\text{first1}, \text{last1})\) 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 [alg.heap.operations]

27.8.8.1 General [alg.heap.operations.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:

\[ \text{(1.1)} \]
— With \( N = b - a \), for all \( i, 0 < i < N \), \( \text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, a[\lfloor i/2 \rfloor])), \text{invoke}(\text{proj}, a[i]))) \) is false.

\[ \text{(1.2)} \]
— \( *a \) may be removed by \( \text{pop_heap} \), or a new element added by \( \text{push_heap} \), in \( \mathcal{O}(\log N) \) time.

These properties make heaps useful as priority queues.

\text{make_heap} \text{ converts a range into a heap and \text{sort_heap} \text{ turns a heap into a sorted sequence.}

27.8.8.2 push_heap [push.heap]

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);

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 = {});

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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 = {});

Let \( \text{comp} \) be \text{less\{\}} and \( \text{proj} \) be \text{identity\{\}} for the overloads with no parameters by those names.

**Preconditions:** The range \([\text{first}, \text{last} - 1)\) is a valid heap with respect to \( \text{comp} \) and \( \text{proj} \). For the overloads in namespace std, the type of \*\text{first} meets the \text{Cpp17MoveConstructible} requirements (Table 30) and the \text{Cpp17MoveAssignible} requirements (Table 32).

**Effects:** Places the value in the location \( \text{last} - 1 \) into the resulting heap \([\text{first}, \text{last})\).

**Returns:** last for the overloads in namespace ranges.

**Complexity:** At most \( \log(\text{last} - \text{first}) \) comparisons and twice as many projections.

### 27.8.8.3 pop_heap

```
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);
```

```
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 = {});
```

```
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 = {});
```

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 non-empty heap with respect to \( \text{comp} \) and \( \text{proj} \). For the overloads in namespace std, \text{RandomAccessIterator} meets the \text{Cpp17ValueSwappable} requirements (16.4.4.3) and the type of \*\text{first} meets the \text{Cpp17MoveConstructible} (Table 30) and \text{Cpp17MoveAssignible} (Table 32) 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:** last for the overloads in namespace ranges.

**Complexity:** At most \( 2 \log(\text{last} - \text{first}) \) comparisons and twice as many projections.

### 27.8.8.4 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.
2 Preconditions: For the overloads in namespace std, the type of *first meets the Cpp17MoveConstructible (Table 30) and Cpp17MoveAssignable (Table 32) requirements.

3 Effects: Constructs a heap with respect to comp and proj out of the range [first, last).

4 Returns: last for the overloads in namespace ranges.

5 Complexity: At most 3(last - first) comparisons and twice as many projections.

27.8.8.5 sort_heap

```cpp
template<class RandomAccessIterator>
constexpr void sort_heap(RandomAccessIterator first, RandomAccessIterator last);
```

```cpp
template<class RandomAccessIterator, class Compare>
constexpr void sort_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::sort_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::sort_heap(R&& r, Comp comp = {}, Proj proj = {});
```

1 Let comp be less{} and proj be identity{} for the overloads with no parameters by those names.

2 Preconditions: The range [first, last) is a valid heap with respect to comp and proj. For the overloads in namespace std, RandomAccessIterator meets the Cpp17ValueSwappable requirements (16.4.4.3) and the type of *first meets the Cpp17MoveConstructible (Table 30) and Cpp17MoveAssignable (Table 32) requirements.

3 Effects: Sorts elements in the heap [first, last) with respect to comp and proj.

4 Returns: last for the overloads in namespace ranges.

5 Complexity: At most 2N log N comparisons, where N = last - first, and twice as many projections.

27.8.8.6 is_heap

```cpp
template<class RandomAccessIterator>
constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last);
```

```cpp
template<class ExecutionPolicy, class RandomAccessIterator>
bool is_heap(ExecutionPolicy&& exec, 
             RandomAccessIterator first, RandomAccessIterator last);
```

```cpp
template<class RandomAccessIterator, class Compare>
constexpr bool is_heap(RandomAccessIterator first, RandomAccessIterator last, 
                      Compare comp);
```

```cpp
template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
bool is_heap(ExecutionPolicy&& exec, 
             RandomAccessIterator first, RandomAccessIterator last, 
             Compare comp);
```

1 Effects: Equivalent to: return is_heap_until(first, last) == last;

2 Effects: Equivalent to: return is_heap_until(std::forward<ExecutionPolicy>(exec), first, last) == last;

3 Effects: Equivalent to: return is_heap_until(first, last, comp) == last;

4 Effects: Equivalent to: return is_heap_until(std::forward<ExecutionPolicy>(exec), first, last, comp) == last;
template<random_access_iterator I, sentinel_for<I> S, class Proj = identity,
    indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr bool ranges::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 ranges::is_heap(R&& r, Comp comp = {}, Proj proj = {});

Effects: Equivalent to: return ranges::is_heap_until(first, last, comp, proj) == last;

template<class RandomAccessIterator>
constexpr RandomAccessIterator
is_heap_until(RandomAccessIterator first, RandomAccessIterator last);

template<class ExecutionPolicy, class RandomAccessIterator>
RandomAccessIterator
is_heap_until(ExecutionPolicy&& exec,
    RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
constexpr RandomAccessIterator
is_heap_until(RandomAccessIterator first, RandomAccessIterator last,
    Compare comp);

template<class ExecutionPolicy, class RandomAccessIterator, class Compare>
RandomAccessIterator
is_heap_until(ExecutionPolicy&& exec,
    RandomAccessIterator first, RandomAccessIterator last,
    Compare comp);

template<random_access_iterator I, sentinel_for<I> S, class Proj = identity,
    indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr I ranges::is_heap_until(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 borrowed_iterator_t<R>
ranges::is_heap_until(R&& r, Comp comp = {}, Proj proj = {});

Effects: Equivalent to: return ranges::is_heap_until(first, last, comp, proj) == last;

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

template<class T>
constexpr const T& min(const T& a, const T& b);

template<class T, class Compare>
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 28).

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.

template<class T>
constexpr T min(initializer_list<T> r);

template<class T, class Compare>
constexpr T min(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::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>
ranges::min(R&& r, Comp comp = {}, Proj proj = {});

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 28).

Returns: The smallest value in the input range. Returns a copy of the leftmost element when several
elements are equivalent to the smallest.

Complexity: Exactly ranges::distance(r) - 1 comparisons 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.

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);  

template<class T, class Proj = identity,
    indirect_strict_weak_order<
        projected<const T*, Proj>
    > Comp = ranges::less>
constexpr const T& ranges::max(const T& a, const T& b, Comp comp = {}, Proj proj = {});

Preconditions: For the first form, T meets the Cpp17LessThanComparable requirements (Table 28).

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 = {});

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 28).

Returns: The largest value in the input range. Returns a copy of the leftmost element when several
elements are equivalent to the largest.

Complexity: Exactly ranges::distance(r) - 1 comparisons 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.

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 = {});

Preconditions: For the first form, T meets the Cpp17LessThanComparable requirements (Table 28).

Returns: \{b, a\} if b is smaller than a, and \{a, b\} otherwise.

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 pair<const T&, const T&> minmax(initializer_list<T> t);

template<class T, class Compare>
constexpr pair<const T&, const 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 = {});

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 ranges::minmax_result<range_value_t<R>>
ranges::minmax(R&& r, Comp comp = {}, Proj proj = {});

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 28).

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.

template<class ForwardIterator>
constexpr ForwardIterator min_element(ForwardIterator first, ForwardIterator last);

template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator min_element(ExecutionPolicy&& exec,
    ForwardIterator first, ForwardIterator last);

template<class ForwardIterator, class Compare>
constexpr ForwardIterator min_element(ForwardIterator first, ForwardIterator last,
    Compare comp);

template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator min_element(ExecutionPolicy&& exec,
    ForwardIterator first, ForwardIterator last, Compare comp);

template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
          indirect_strict_weak_order<projected<iterator_t<I>, Proj>> Comp = ranges::less>
constexpr I ranges::min_element(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 borrowed_iterator_t<R>
ranges::min_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 \([\text{first}, \text{last})\) such that for every iterator \(j\) in the range \([\text{first}, \text{last})\),

\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \ast j), \text{invoke}(\text{proj}, \ast i)))
\]

is false. Returns \(\text{last}\) if \(\text{first} == \text{last}\).

Complexity: Exactly \(\max(\text{last} - \text{first} - 1, 0)\) comparisons and twice as many projections.

```
template<class ForwardIterator>
constexpr ForwardIterator max_element(ForwardIterator first, ForwardIterator last);
```

```
template<class ExecutionPolicy, class ForwardIterator>
ForwardIterator max_element(ExecutionPolicy&& exec,
ForwardIterator first, ForwardIterator last);
```

```
template<class ForwardIterator, class Compare>
constexpr ForwardIterator max_element(ForwardIterator first, ForwardIterator last,
Compare comp);
```

```
template<class ExecutionPolicy, class ForwardIterator, class Compare>
ForwardIterator max_element(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::max_element(I first, S last, 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.

Returns: The first iterator \(i\) in the range \([\text{first}, \text{last})\) such that for every iterator \(j\) in the range \([\text{first}, \text{last})\),

\[
\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \ast i), \text{invoke}(\text{proj}, \ast j)))
\]

is false. Returns \(\text{last}\) if \(\text{first} == \text{last}\).

Complexity: Exactly \(\max(\text{last} - \text{first} - 1, 0)\) comparisons and twice as many projections.

```
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);
```

```
template<forward_iterator I, sentinel_for<I> S, class Proj = identity,
indirect_strict_weak_order<projected<I, Proj>> Comp = ranges::less>
constexpr ranges::minmax_result<I>
ranges::minmax_element(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 ranges::minmax_result<borrowed_iterator_t<R>>
ranges::minmax_element(R&& r, Comp comp = {}, Proj proj = {});
```

Returns: \{first, first\} if \([\text{first}, \text{last})\) is empty, otherwise \{m, M\}, where \(m\) is the first iterator in
\([\text{first}, \text{last})\) such that no iterator in the range refers to a smaller element, and where \(M\) is the last
iterator in \([\texttt{first}, \texttt{last})\) such that no iterator in the range refers to a larger element.

**Complexity:** Let \(N\) be \(\texttt{last} - \texttt{first}\). At most \(\max\left(\frac{3}{2}(N-1), 0\right)\) comparisons and twice as many applications of the projection, if any.

### 27.8.10 Bounded value

\[\texttt{template<class T> constexpr const T& clamp(const T& v, const T& lo, const T& hi);}\]

\[\texttt{template<class T, class Compare> constexpr const T& clamp(const T& v, const T& lo, const T& hi, Compare comp);}\]

\[\texttt{template<class T, class Proj = \text{identity},\
\hspace{1em} indirect_strict_weak_order<\text{projected<const T*, Proj>> Comp = \text{ranges::less}>\
\hspace{1em} constexpr const T&\
\hspace{1em} ranges::clamp(const T& v, const T& lo, const T& hi, Comp comp = {}, Proj proj = {});}\]

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. **Preconditions:** \(\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \text{hi}), \text{invoke}(\text{proj}, \text{lo}))\) is \(\text{false}\). For the first form, type \(T\) meets the \text{Cpp17LessThanComparable} requirements (Table 28).

3. **Returns:** \(\text{lo}\) if \(\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, v), \text{invoke}(\text{proj}, \text{lo})))\) is \(\text{true}\), \(\text{hi}\) if \(\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \text{hi}), \text{invoke}(\text{proj}, v)))\) is \(\text{true}\), otherwise \(v\).

4. **Note 1:** If NaN is avoided, \(T\) 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

\[\texttt{template<class InputIterator1, class InputIterator2>\
\hspace{1em} constexpr bool lexicographical_compare(InputIterator1 first1, InputIterator1 last1,\
\hspace{1em} InputIterator2 first2, InputIterator2 last2);}\]

\[\texttt{template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>\
\hspace{1em} bool lexicographical_compare(ExecutionPolicy&& exec,\
\hspace{1em} ForwardIterator1 first1, ForwardIterator1 last1,\
\hspace{1em} ForwardIterator2 first2, ForwardIterator2 last2);}\]

\[\texttt{template<class InputIterator1, class InputIterator2, class Compare>\
\hspace{1em} constexpr bool lexicographical_compare(InputIterator1 first1, InputIterator1 last1,\
\hspace{1em} InputIterator2 first2, InputIterator2 last2, Compare comp);}\]

\[\texttt{template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,\
\hspace{1em} class Compare>\
\hspace{1em} bool lexicographical_compare(ExecutionPolicy&& exec,\
\hspace{1em} ForwardIterator1 first1, ForwardIterator1 last1,\
\hspace{1em} ForwardIterator2 first2, ForwardIterator2 last2, Compare comp);}\]

\[\texttt{template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,\
\hspace{1em} class Proj1 = \text{identity}, class Proj2 = \text{identity},\
\hspace{1em} indirect_strict_weak_order<\text{projected<I1, Proj1>,\
\hspace{1em} projected<I2, Proj2>> Comp = \text{ranges::less}>\
\hspace{1em} constexpr bool\
\hspace{1em} ranges::lexicographical_compare(I1 first1, S1 last1, I2 first2, S2 last2,\
\hspace{1em} Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});}\]

224) This behavior intentionally differs from \texttt{max_element}.
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>

cconstexpr bool ranges::lexicographical_compare(R1&& r1, R2&& r2, Comp comp = {}, Proj1 proj1 = {}, Proj2 proj2 = {});

1 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).

2 Complexity: At most \(2 \min(\text{last1} - \text{first1}, \text{last2} - \text{first2})\) applications of the corresponding comparison and each projection, if any.

3 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]

4 [Note 1: An empty sequence is lexicographically less than any non-empty sequence, but not less than any empty sequence. — end note]

27.8.12 Three-way comparison algorithms [alg.three.way]

template<class InputIterator1, class InputIterator2, class Cmp>

cconstexpr auto

lexicographical_compare_three_way(InputIterator1 b1, InputIterator1 e1, InputIterator2 b2, InputIterator2 e2, Cmp comp)

-> decltype(comp(*b1, *b2));

1 Let \(N\) be \(\min(e1 - b1, e2 - b2)\). Let \(E(n)\) be \(\text{comp}(* (b1 + n), *(b2 + n))\).

2 Mandates: \(\text{decltype}(\text{comp}(*b1, *b2))\) is a comparison category type.

3 Returns: \(E(i)\), where \(i\) is the smallest integer in \([0, N)\) such that \(E(i) \neq 0\), or \((e1 - b1) <= (e2 - b2)\) if no such integer exists.

4 Complexity: At most \(N\) applications of \(\text{comp}\).

template<class InputIterator1, class InputIterator2>

cconstexpr auto

lexicographical_compare_three_way(InputIterator1 b1, InputIterator1 e1, InputIterator2 b2, InputIterator2 e2);

5 Effects: Equivalent to:

```cpp
return lexicographical_compare_three_way(b1, e1, b2, e2, compare_three_way());
```

27.8.13 Permutation generators [alg.permutation.generators]

template<class BidirectionalIterator>

cconstexpr bool next_permutation(BidirectionalIterator first, BidirectionalIterator last);

template<class BidirectionalIterator, class Compare>

cconstexpr bool next_permutation(BidirectionalIterator first, BidirectionalIterator last, Compare comp);
template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less,
        class Proj = identity>
constexpr ranges::next_permutation_result<I>
ranges::next_permutation(I first, S last, Comp comp = {}, Proj proj = {});

template<bidirectional_iterator I, sentinel_for<I> S, class Comp = ranges::less,
        class Proj = identity>
constexpr ranges::next_permutation_result<borrowed_iterator_t<I>>
ranges::next_permutation(I&& r, Comp comp = {}, Proj proj = {});

1 Let comp be less{} and proj be identity{} for overloads with no parameters by those names.

2 Preconditions: For the overloads in namespace std, BidirectionalIterator meets the Cpp17Value-
Swappable requirements (16.4.4.3).

3 Effects: Takes a sequence defined by the range [first, last) and transforms it into the next permutation.
The next 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 first permutation; that is, the ascendingly-sorted one.

4 Returns: Let B be true if a next permutation was found and otherwise false. Returns:

(4.1) — B for the overloads in namespace std.
(4.2) — { last, B } for the overloads in namespace ranges.

5 Complexity: At most (last - first) / 2 swaps.

template<class BidirectionalIterator>
constexpr bool prev_permutation(BidirectionalIterator first,
        BidirectionalIterator last);

template<class BidirectionalIterator, class Compare>
constexpr bool prev_permutation(BidirectionalIterator first,
        BidirectionalIterator last, Compare comp);

6 Let comp be less{} and proj be identity{} for overloads with no parameters by those names.

7 Preconditions: For the overloads in namespace std, BidirectionalIterator meets the Cpp17Value-
Swappable requirements (16.4.4.3).

8 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.

9 Returns: Let B be true if a previous permutation was found and otherwise false. Returns:

(9.1) — B for the overloads in namespace std.
(9.2) — { last, B } for the overloads in namespace ranges.

10 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);
constexpr T accumulate(InputIterator first, InputIterator last, T init,
                         BinaryOperation binary_op);

// 27.10.4, reduce
template<class InputIterator>
constexpr typename iterator_traits<InputIterator>::value_type
reduce(InputIterator first, InputIterator last);
template<class InputIterator, class T>
constexpr T reduce(InputIterator first, InputIterator last, T init);
template<class InputIterator, class T, class BinaryOperation>
constexpr T reduce(InputIterator first, InputIterator last, T init,
                  BinaryOperation binary_op);

// 27.10.5, inner product
template<class InputIterator1, class InputIterator2, class T>
constexpr T inner_product(InputIterator1 first1, InputIterator1 last1,
                           InputIterator2 first2, T init);
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);

// 27.10.6, transform reduce
template<class InputIterator1, class InputIterator2, class T>
constexpr T transform_reduce(InputIterator1 first1, InputIterator1 last1,
                            InputIterator2 first2, T init);
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);

// 27.9 1248

§ 27.9
// 27.10.7, partial sum
template<class InputIterator, class OutputIterator>
constexpr OutputIterator
partial_sum(InputIterator first, InputIterator last,
            OutputIterator result, BinaryOperation binary_op);

// 27.10.8, exclusive scan
template<class InputIterator, class OutputIterator, class T>
constexpr OutputIterator
exclusive_scan(InputIterator first, InputIterator last,
                OutputIterator result, T init, BinaryOperation binary_op);

// 27.10.9, inclusive scan
template<class InputIterator, class OutputIterator, class BinaryOperation, class T>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
                OutputIterator result, BinaryOperation binary_op, T init);
// 27.10.10, transform exclusive scan

```cpp
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);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2, class T,
    class BinaryOperation, class UnaryOperation>
ForwardIterator2
transform_exclusive_scan(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, T init,
    BinaryOperation binary_op, UnaryOperation unary_op);
```

// 27.10.11, transform inclusive scan

```cpp
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);
```

```cpp
template<class InputIterator, class OutputIterator,
    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);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class BinaryOperation, class UnaryOperation>
ForwardIterator2
transform_inclusive_scan(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, BinaryOperation binary_op,
    UnaryOperation unary_op);
```

```cpp
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

```cpp
template<class InputIterator, class OutputIterator>
constexpr OutputIterator
adjacent_difference(InputIterator first, InputIterator last,
    OutputIterator result);
```

```cpp
template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
adjacent_difference(InputIterator first, InputIterator last,
    OutputIterator result, BinaryOperation binary_op);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
adjacent_difference(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
    class BinaryOperation>
ForwardIterator2
adjacent_difference(ExecutionPolicy&& exec, // see 27.3.5
    ForwardIterator1 first, ForwardIterator1 last,
    ForwardIterator2 result, BinaryOperation binary_op);
```
// 27.10.13, iota
template<class ForwardIterator, class T>
constexpr void iota(ForwardIterator first, ForwardIterator last, T value);

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;
template<class T>
constexpr T* midpoint(T* a, T* b);

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 \texttt{GENERALIZED\_NONCOMMUTATIVE\_SUM}(\texttt{op}, a_1, \ldots, a_N) as follows:

(1.1) \quad \text{a}_1 \text{ when } N \text{ is 1, otherwise}

(1.2) \quad \text{op}(\texttt{GENERALIZED\_NONCOMMUTATIVE\_SUM}(\texttt{op}, a_1, \ldots, a_K),
\texttt{GENERALIZED\_NONCOMMUTATIVE\_SUM}(\texttt{op}, a_M, \ldots, a_N)) \text{ for any } K \text{ where } 1 < K + 1 = M \leq N.

2 Define \texttt{GENERALIZED\_SUM}(\texttt{op}, a_1, \ldots, a_N) as \texttt{GENERALIZED\_NONCOMMUTATIVE\_SUM}(\texttt{op}, b_1, \ldots, b_N), where \texttt{b}_1, \ldots, b_N may be any permutation of \texttt{a}_1, \ldots, a_N.

27.10.3 Accumulate [accumulate]

template<class InputIterator, class T>
constexpr T accumulate(InputIterator first, InputIterator last, T init);

[Preconditions: \texttt{T} meets the \texttt{Cpp17CopyConstructible} (Table 31) and \texttt{Cpp17CopyAssignable} (Table 33) requirements. In the range \texttt{[first,last]}, \texttt{binary_op} neither modifies elements nor invalidates iterators or subranges.]

2 Effect: Computes its result by initializing the accumulator \texttt{acc} with the initial value \texttt{init} and then modifies it with \texttt{acc = std::move(acc) + *i} or \texttt{acc = binary_op(std::move(acc), *i)} for every iterator \texttt{i} in the range \texttt{[first,last]} in order.

225) The use of fully closed ranges is intentional.

226) \texttt{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.
27.10.4 Reduce

\[\text{reduce}\]

\[
template<\text{class InputIterator}>
\text{constexpr typename iterator_traits<InputIterator>::value_type}
\text{reduce(InputIterator first, InputIterator last);}\]

1. **Effects:** Equivalent to:
   \[
   \text{return reduce(first, last,}
   \text{typename iterator_traits<InputIterator>::value_type());}\]

\[
template<\text{class ExecutionPolicy, class ForwardIterator}>
\text{typename iterator_traits<ForwardIterator>::value_type}
\text{reduce(ExecutionPolicy\&\& exec,}
\text{ForwardIterator first, ForwardIterator last);}\]

2. **Effects:** Equivalent to:
   \[
   \text{return reduce(std::forward<ExecutionPolicy>(exec), first, last,}
   \text{typename iterator_traits<ForwardIterator>::value_type());}\]

\[
template<\text{class InputIterator, class T}>
\text{constexpr T reduce(InputIterator first, InputIterator last, T init);}\]

3. **Effects:** Equivalent to:
   \[
   \text{return reduce(first, last, init, plus<>());}\]

\[
template<\text{class ExecutionPolicy, class ForwardIterator, class T}>
\text{T reduce(ExecutionPolicy\&\& exec,}
\text{ForwardIterator first, ForwardIterator last, T init);}\]

4. **Effects:** Equivalent to:
   \[
   \text{return reduce(std::forward<ExecutionPolicy>(exec), first, last, init, plus<>());}\]

\[
template<\text{class InputIterator, class T, class BinaryOperation}>
\text{constexpr T reduce(InputIterator first, InputIterator last, T init,}
\text{BinaryOperation binary_op);}\]

5. **Mandates:** All of
   - binary_op(init, *first),
   - binary_op(*first, init),
   - binary_op(init, init), and
   - binary_op(*first, *first)
     are convertible to T.

6. **Preconditions:**
   - T meets the Ccpp17MoveConstructible (Table 30) requirements.
   - binary_op neither invalidates iterators or subranges, nor modifies elements in the range [first, last].

7. **Returns:** GENERALIZED_SUM(binary_op, init, *i, ...) for every i in [first, last).

8. **Complexity:** \(\Theta(|\text{last} - \text{first}|)\) applications of binary_op.

9. [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

\[\text{inner.product}\]

\[
template<\text{class InputIterator1, class InputIterator2, class T}>
\text{constexpr T inner_product(InputIterator1 first1, InputIterator1 last1,}
\text{InputIterator2 first2, T init);}\]
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);

Preconditions: T meets the Cpp17CopyConstructible (Table 31) and Cpp17CopyAssignable (Table 33) requirements. In the ranges \([first1, \text{last1}]\) and \([first2, first2 + (last1 - first1)]\), binary_op1 and \(\text{binary\_op\_2}\) neither modifies elements nor invalidates iterators or subranges.\(^{227}\)

Effects: Computes its result by initializing the accumulator \(\text{acc}\) with the initial value \(\text{init}\) and then modifying it with \(\text{acc} = \text{std::move} (\text{acc}) + (\text{*}\text{i1}) \times (\text{*}\text{i2})\) or \(\text{acc} = \text{binary\_op\_1} (\text{std::move} (\text{acc}), \text{binary\_op\_2}(\text*i1, \text{i2}))\) for every iterator \(\text{i1}\) in the range \([first1, \text{last1}]\) and iterator \(\text{i2}\) in the range \([first2, first2 + (last1 - first1)]\) in order.

### 27.10.6 Transform reduce

#### [transform.reduce]

template<class InputIterator1, class InputIterator2, class T>
constexpr T transform_reduce(InputIterator1 first1, InputIterator1 last1,
    InputIterator2 first2,
    T init);

Effects: Equivalent to:

\[
\text{return transform\_reduce (first1, last1, first2, init, plus()\rangle, multiplies()\rangle)};
\]

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:

\[
\text{return transform\_reduce (std::forward<ExecutionPolicy>(exec),
    first1, last1, first2, init, plus()\rangle, multiplies()\rangle)};
\]

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);

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))

\(^{227}\) The use of fully closed ranges is intentional.
are convertible to T.

**Preconditions:**

1. T meets the Cpp17MoveConstructible (Table 30) requirements.
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);
```

**Mandates:** All of

1. binary_op(init, init),
2. binary_op(init, unary_op(*first)),
3. binary_op(unary_op(*first), init), and
4. binary_op(unary_op(*first), unary_op(*first))

are convertible to T.

**Preconditions:**

1. T meets the Cpp17MoveConstructible (Table 30) requirements.
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:** $O(\text{last} - \text{first})$ 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

```cpp
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’s value type. acc is writable (25.3.1) to result.

**Preconditions:** In the ranges [first, last] and [result, result + (last - first)] binary_op neither modifies elements nor invalidates iterators or subranges.²²₈

²²₈ The use of fully closed ranges is intentional.
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

```cpp
template<class InputIterator, class OutputIterator, class T> constexpr OutputIterator exclusive_scan(InputIterator first, InputIterator last, OutputIterator result, T init);
```

**Effects:** Equivalent to:

```cpp
return exclusive_scan(first, last, result, init, plus<>());
```

```cpp
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:

```cpp
return exclusive_scan(std::forward<ExecutionPolicy>(exec), first, last, result, init, plus<>());
```

```cpp
template<class InputIterator, class OutputIterator, class T, class BinaryOperation> constexpr OutputIterator exclusive_scan(InputIterator first, InputIterator last, OutputIterator result, T init, BinaryOperation binary_op);
```

```cpp
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

1. `binary_op(init, init)`,
2. `binary_op(init, *first)`, and
3. `binary_op(*first, *first)`

are convertible to `T`.

Preconditions:

1. `T` meets the *Cpp17MoveConstructible* (Table 30) requirements.
2. `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
```

```cpp
binary_op, init, *(first + 0), *(first + 1), ..., *(first + K - 1))
```

Returns: The end of the resulting range beginning at `result`.

Complexity: `O(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

```cpp
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<>());
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
              ForwardIterator1 first, ForwardIterator1 last,
              ForwardIterator2 result);
```

**Effects:** Equivalent to:
```
return inclusive_scan(std::forward<ExecutionPolicy>(exec), first, last, result, plus<>());
```

```cpp
template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result, BinaryOperation binary_op);
```

```cpp
template<class ExecutionPolicy, class ForwardIterator1, class ForwardIterator2,
         class BinaryOperation>
ForwardIterator2
inclusive_scan(ExecutionPolicy&& exec,
              ForwardIterator1 first, ForwardIterator1 last,
              ForwardIterator2 result, BinaryOperation binary_op);
```

```cpp
template<class InputIterator, class OutputIterator, class BinaryOperation, class T>
constexpr OutputIterator
inclusive_scan(InputIterator first, InputIterator last,
               OutputIterator result, BinaryOperation binary_op, T init);
```

```cpp
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 \( \text{decltype}(\text{first}) \).

**Mandates:** If \( \text{init} \) is provided, all of

1. \( \text{binary_op}(\text{init}, \text{init}) \)
2. \( \text{binary_op}(\text{init}, \text{*first}) \)
3. \( \text{binary_op}(*\text{first}, *\text{first}) \)

are convertible to \( T \); otherwise, \( \text{binary_op}(\text{*first}, \text{*first}) \) is convertible to \( U \).

**Preconditions:**

1. If \( \text{init} \) is provided, \( T \) meets the \( \text{Cpp17MoveConstructible} \) requirements; otherwise, \( U \) meets the \( \text{Cpp17MoveConstructible} \) requirements.
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 \( \text{result} + K \) the value of

1. \( \text{GENERALIZED_NONCOMMUTATIVE_SUM}(\text{binary_op}, \text{init}, \text{*(first + 0)}, \text{*(first + 1)}, \ldots, \text{*(first + K)}) \)
   if \( \text{init} \) is provided, or
2. \( \text{GENERALIZED_NONCOMMUTATIVE_SUM}(\text{binary_op}, \text{*(first + 0)}, \text{*(first + 1)}, \ldots, \text{*(first + K)}) \)
   otherwise.
Returns: The end of the resulting range beginning at result.

Complexity: $\Theta(\text{last} - \text{first})$ applications of 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 $i^{th}$ input element in the $i^{th}$ sum. If binary_op is not mathematically associative, the behavior of inclusive_scan can be nondeterministic. — end note]

### 27.10.10 Transform exclusive scan

Template:

```cpp
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);
```

```cpp
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);
```

Mandates: All of

1. binary_op(init, init),
2. binary_op(init, unary_op(*first)), and
3. binary_op(unary_op(*first), unary_op(*first))

are convertible to T.

Preconditions:

1. T meets the Cpp17MoveConstructible (Table 30) requirements.
2. Neither unary_op nor binary_op invalidates iterators or subranges, nor modifies elements in the ranges [first, last] or [result, result + (last - first)].

Effects: For each integer $K$ in $[0, \text{last} - \text{first})$ 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))
```

Returns: The end of the resulting range beginning at result.

Complexity: $\Theta(\text{last} - \text{first})$ 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_exclusive_scan excludes the $i^{th}$ input element from the $i^{th}$ sum. If binary_op is not mathematically associative, the behavior of transform_exclusive_scan can be nondeterministic. transform_exclusive_scan does not apply unary_op to init. — end note]

### 27.10.11 Transform inclusive scan

Template:

```cpp
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);
```

```cpp
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);
```

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transform_inclusive_scan(ExecutionPolicy&& exec,  
  ForwardIterator1 first, ForwardIterator1 last,  
  ForwardIterator2 result,  
  BinaryOperation binary_op, UnaryOperation unary_op);

template<class InputIterator, class OutputIterator,  
  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);

transform_inclusive_scan(ExecutionPolicy&& exec,  
  ForwardIterator1 first, ForwardIterator1 last,  
  ForwardIterator2 result,  
  BinaryOperation binary_op, UnaryOperation unary_op,  
  T init);

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 Ccpp17MoveConstructible (Table 30) requirements; otherwise, U meets the Ccpp17MoveConstructible requirements.
(3.2) — Neither unary_op nor binary_op 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

(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 result.

Complexity: \(\Theta(last - first)\) 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]
adjacent_difference(ExecutionPolicy&& exec, ForwardIterator1 first, ForwardIterator1 last, ForwardIterator2 result);

```cpp
template<class InputIterator, class OutputIterator, class BinaryOperation>
constexpr OutputIterator
adjacent_difference(InputIterator first, InputIterator last, OutputIterator result, BinaryOperation binary_op);
```

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 32) requirements.
- For all overloads, in the ranges `[first, last]` and `[result, result + (last - first)]`, `binary_op` neither modifies elements nor invalidate iterators or subranges.229

**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, last - 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

```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.

---

229) The use of fully closed ranges is intentional.
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);

template<weakly_incrementable T, output_range<const T&> R>
constexpr ranges::iota_result<borrowed_iterator_t<R>, T> ranges::iota(R&& r, T value);

Effects: Equivalent to:
while (first != last) {
  *first = as_const(value);
  ++first;
  ++value;
} return {std::move(first), std::move(value)};

27.10.14 Greatest common divisor [numeric.ops.gcd]

template<class M, class N>
constexpr common_type_t<M, N> gcd(M m, N n);

M 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. —end note]

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]

template<class M, class N>
constexpr common_type_t<M, N> lcm(M m, N n);

M 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]

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.

template<class T>
constexpr T* midpoint(T* a, T* b);

Constraints: T is an object type.

M 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 6.8.3, 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 + \frac{j-i}{2} of x, where the result of the division is truncated towards zero.

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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.

[Note 1: When invoked on ranges of potentially-overlapping subobjects (6.7.2), the algorithms specified in 27.11 result in undefined behavior. — end note]

Some algorithms specified in 27.11 make use of the exposition-only function `voidify`:

```cpp
template<class T>
constexpr void* voidify(T& obj) noexcept {
    return const_cast<void*>(static_cast<const volatile void*>(addressof(obj)));
}
```

27.11.2 Special memory concepts

Some algorithms in this subclause are constrained with the following exposition-only concepts:

```cpp
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]

```cpp
template<class S, class I>
concept nothrow-sentinel-for = sentinel_for<S, I>; // exposition only
```

Types `S` and `I` model `nothrow-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]

```cpp
template<class R>
concept nothrow-input-range = // exposition only
    range<R> &&
    nothrow-input-iterator<iterator_t<R>> &&
    nothrow-sentinel-for<sentinel_t<R>, iterator_t<R>>;
```

A type `R` models `nothrow-input-range` only if no exceptions are thrown from calls to `ranges::begin` and `ranges::end` on an object of type `R`.

```cpp
template<class I>
concept nothrow-forward-iterator = // exposition only
    nothrow-input-iterator<I> &&
    forward_iterator<I> &&
    nothrow-sentinel-for<I, I>;
```

[Note 3: This concept allows some `forward_iterator` (25.3.4.11) operations to throw exceptions. — end note]

```cpp
template<class R>
concept nothrow-forward-range = // exposition only
    nothrow-input-range<R> &&
    nothrow-forward-iterator<iterator_t<R>>;
```

27.11.3 uninitialized_default_construct

```cpp
template<class NoThrowForwardIterator>
void uninitialized_default_construct(NoThrowForwardIterator first, NoThrowForwardIterator last);
```

[uninitialized.construct.default]

1 Effects: Equivalent to:
namespace ranges {
  for (; first != last; ++first)
    ::new (voidify(*first))
    typename iterator_traits<NoThrowForwardIterator>::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<NoThrowForwardIterator>::value_type;
return first;

namespace ranges {
  template<typename I>
  requires default_initializable<iter_value_t<I>>
  I uninitialized_default_construct_n(I first, iter_difference_t<I> n);
}

Effects: Equivalent to:
return uninitialized_default_construct_n(counted_iterator(first, n),
  default_sentinel).base();

27.11.4 uninitialized_value_construct [uninitialized.construct.value]

template<class NoThrowForwardIterator>
void uninitialized_value_construct(NoThrowForwardIterator first, NoThrowForwardIterator last);

Effects: Equivalent to:
for (; first != last; ++first)
  ::new (voidify(*first))
  typename iterator_traits<NoThrowForwardIterator>::value_type();

namespace ranges {
  template<typename I, nothrow-sentinel-for<I> S>
  requires default_initializable<iter_value_t<I>>
  I uninitialized_value_construct(I first, S last);
  template<typename R>
  requires default_initializable<range_value_t<R>>
  borrowed_iterator_t<R> uninitialized_value_construct(R&& r);
}

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_value_construct_n(NoThrowForwardIterator first, Size n);

Effects: Equivalent to:
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:
    return uninitialized_value_construct(counted_iterator(first, n),
                                           default_sentinel).base();

27.11.5 uninitialized_copy

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:
    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: [ofirst, olast) does not overlap with [ifirst, ilast).

Effects: Equivalent to:
    for (; ifirst != ilast && ofirst != olast; ++ofirst, (void)++ifirst)
        ::new (voidify(*ofirst)) remove_reference_t<iter_reference_t<O>>(*ifirst);
    return {std::move(ifirst), ofirst};

template<class InputIterator, class Size, class NoThrowForwardIterator>
NoThrowForwardIterator uninitialized_copy_n(InputIterator first, Size n,
                                          NoThrowForwardIterator result);

Preconditions: result + [0, n) does not overlap with first + [0, n).

Effects: Equivalent to:
    for ( ; n > 0; ++result, (void) ++first, --n)
        ::new (voidify(*result))
            typename iterator_traits<NoThrowForwardIterator>::value_type(*first);

Returns: result.

namespace ranges {  
    template<input_iterator I, nothrow-forward_iterator O, nothrow-sentinel_for<O> S>
    requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
    uninitialized_copy_n_result<I, O>
    uninitialized_copy_n(I ifirst, iter_difference_t<I> n, O ofirst, S olast);
}

§ 27.11.5
Preconditions: \([\text{ofirst}, \text{olast})\) does not overlap with \(\text{ifirst} + [0, n)\).

Effects: Equivalent to:

\[
\begin{align*}
\text{auto } t &= \text{uninitialized_copy(} \text{counted_iterator(} \text{ifirst}, n), \\
& \quad \text{default_sentinel, ofirst, olast}); \\
\text{return } \{\text{std::move(} t.\text{in}.\text{base}), t.\text{out}\};
\end{align*}
\]

27.11.6 uninitialized_move

\[
\text{template}<\text{class InputIterator, class NoThrowForwardIterator} > \\
\text{NoThrowForwardIterator \text{uninitialized}\_move(InputIterator \text{first}, InputIterator \text{last},} \\
\text{NoThrowForwardIterator \text{result})};
\]

Preconditions: \(\text{result} + [0, (\text{last} - \text{first}))\) does not overlap with \([\text{first}, \text{last})\).

Effects: Equivalent to:

\[
\begin{align*}
&\text{for (; \text{first} != \text{last}; (void)++\text{result}, ++\text{first})} \\
&\quad \text{::new (} \text{voidify(} *\text{result}) \\
&\quad \text{typename iterator_traits<NoThrowForwardIterator>::value_type(} \text{std::move(} *\text{first}); \\
&\text{return } \text{result};
\end{align*}
\]

namespace ranges {

\[
\begin{align*}
&\text{template<\text{input_iterator I, sentinel_for<I> S1,} \\
&\quad \text{nothrow-forward-iterator O, nothrow-sentinel-for<O> S2}> \\
&\quad \text{requires constructible_from<iter_value_t<O>, iter_rvalue_reference_t<I>}> \\
&\quad \text{uninitialized_move_result<I, O>}; \\
&\text{uninitialized_move(I \text{ifirst}, S1 \text{ilast}, O \text{ofirst}, S2 \text{olast});}
\end{align*}
\]

\[
\begin{align*}
&\text{template<\text{input_range IR, nothrow-forward-range OR}> \\
&\quad \text{requires constructible_from<range_value_t<OR>, range_rvalue_reference_t<IR>}> \\
&\quad \text{uninitialized_move_result<borrowed_iterator_t<IR>, borrowed_iterator_t<OR>}> \\
&\quad \text{uninitialized_move(IR&& \text{in_range}, OR&& \text{out_range});}
\end{align*}
\]

Preconditions: \([\text{ofirst}, \text{olast})\) does not overlap with \([\text{ifirst}, \text{ilast})\).

Effects: Equivalent to:

\[
\begin{align*}
&\text{for (; \text{ifirst} != \text{ilast} \&\& \text{ofirst} != \text{olast}; ++\text{ofirst}, (void)++\text{ifirst})} \\
&\quad \text{::new (} \text{voidify(} *\text{ofirst}) \\
&\quad \text{remove_reference_t<iter_reference_t<O>>(} \text{ranges::iter_move(} \text{ifirst}); \\
&\text{return} \{\text{std::move(} \text{ifirst), \text{ofirst}\};
\end{align*}
\]

[Note 1: If an exception is thrown, some objects in the range \([\text{first}, \text{last})\) are left in a valid, but unspecified state. — end note]

\[
\begin{align*}
&\text{template<\text{class InputIterator, class Size, class NoThrowForwardIterator} >} \\
&\quad \text{pair<InputIterator, NoThrowForwardIterator>} \\
&\quad \text{uninitialized_move_n(InputIterator \text{first}, Size n, NoThrowForwardIterator \text{result})};
\end{align*}
\]

Preconditions: \(\text{result} + [0, n)\) does not overlap with \(\text{first} + [0, n)\).

Effects: Equivalent to:

\[
\begin{align*}
&\text{for (; } n > 0; ++\text{result}, (void)++\text{first}, \text{--}n) \\
&\quad \text{::new (} \text{voidify(} *\text{result}) \\
&\quad \text{typename iterator_traits<NoThrowForwardIterator>::value_type(} \text{std::move(} *\text{first}); \\
&\text{return } \{\text{first, result}\};
\end{align*}
\]

namespace ranges {

\[
\begin{align*}
&\text{template<\text{input_iterator I, nothrow-forward-iterator O, nothrow-sentinel-for<O> S}> \\
&\quad \text{requires constructible_from<iter_value_t<O>, iter_rvalue_reference_t<I>}> \\
&\quad \text{uninitialized_move_n_result<I, O>}; \\
&\text{uninitialized_move_n(I \text{ifirst}, \text{iter_difference_t<I> n, O \text{ofirst}, S \text{olast});}
\end{align*}
\]

Preconditions: \([\text{ofirst}, \text{olast})\) does not overlap with \([\text{ifirst}, [0, n])\).

Effects: Equivalent to:
auto t = uninitialized_move(counted_iterator(ifirst, n),
    default_sentinel, ofirst, olast);
return {std::move(t.in).base(), t.out};

[Note 2: If an exception is thrown, some objects in the range first + [0, n) are left in a valid but unspecified state. — end note]

### 27.11.7 uninitialized_fill

```
template<class NoThrowForwardIterator, class T>
void uninitialized_fill(NoThrowForwardIterator first, NoThrowForwardIterator last, const T& x);
```

**Effects:** Equivalent to:
```
for (; first != last; ++first)
    ::new (voidify(*first))
        typename iterator_traits<NoThrowForwardIterator>::value_type(x);
```

**namespace ranges**
```
template<nothrow-forward-iterator I, nothrow-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);
```

**Effects:** Equivalent to:
```
for (; first != last; ++first)
    ::new (voidify(*first)) remove_reference_t<iter_reference_t<I>>(x);
return first;
```

```
template<class NoThrowForwardIterator, class Size, class T>
    NoThrowForwardIterator uninitialized_fill_n(NoThrowForwardIterator first, Size n, const T& x);
```

**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);
```

**Effects:** Equivalent to:
```
return uninitialized_fill(counted_iterator(first, n), default_sentinel, x).base();
```

### 27.11.8 construct_at

```
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);
```

**Constraints:** The expression ::new (declval<void*>(void)) T(declval<Args>(...)) is well-formed when treated as an unevaluated operand (7.2.3).

**Effects:** Equivalent to:
```
return ::new (voidify(*location)) T(std::forward<Args>(args)...);
```
27.11.9  destroy

```
template<class T>
constexpr void destroy_at(T* location);
```

```
namespace ranges {
    template<destructible T>
    constexpr void destroy_at(T* location) noexcept;
}
```

1  **Effects:**

1.1  If T is an array type, equivalent to `destroy(begin(*location), end(*location))`.

1.2  Otherwise, equivalent to `location->~T()`.

```
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);
```

4  **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;
}
```

5  **Effects:** Equivalent to:

```
return destroy(counted_iterator(first, n), default_sentinel).base();
```

27.12  C library algorithms

1  **[Note 1:]** The header `<cstdlib>` (17.2.2) declares the functions described in this subclause.  — end note**

```
void* bsearch(const void* key, const void* base, size_t nmemb, size_t size,
               c-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,
           c-compare-pred* compar);
```

```
void qsort(void* base, size_t nmemb, size_t size, compare-pred* compar);
```

2  **Preconditions:** For `qsort`, the objects in the array pointed to by `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 `compar` (16.4.6.13).
See also: ISO C 7.22.5
28 Numerics library [numerics]

28.1 General [numerics.general]

1 This Clause describes components that C++ programs may use to perform seminumerical operations.

2 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 90.

Table 90: Numerics library summary [tab:numerics.summary]

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28.2 Numeric type requirements [numeric.requirements]

1 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).\(^\text{230}\)

2 If any operation on T throws an exception the effects are undefined.

3 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.

4 [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 [cfenv]

28.3.1 Header <cfenv> synopsis [cfenv.syn]

    #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

    namespace std {
      // types
      using fenv_t = object type;
      using fexcept_t = integer type;
    }

\(^{230}\) In other words, value types. These include arithmetic types, pointers, the library class complex, and instantiations of valarray for value types.
// functions
int feclearexcept(int except);
int fegetexceptflag(fexcept_t* pflag, int except);
int feraiseexcept(int except);
int fesetexceptflag(const fexcept_t* pflag, 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 C 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]

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 other than float, double, or long double is unspecified. The specializations complex<float>, complex<double>, and complex<long double> are 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;

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// 28.4.4, specializations
    template<> class complex<float>;
    template<> class complex<double>;
    template<> class complex<long double>;

// 28.4.7, 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> constexpr bool operator==(const complex<T>&, const complex<T>&);
    template<class T> constexpr bool operator==(const complex<T>&, const 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>&);

// 28.4.8, values
    template<class T> constexpr T real(const complex<T>&);
    template<class T> constexpr T imag(const complex<T>&);
    template<class T> T abs(const complex<T>&);
    template<class T> T arg(const complex<T>&);
    template<class T> constexpr T norm(const complex<T>&);
    template<class T> complex<T> conj(const complex<T>&);
    template<class T> complex<T> proj(const complex<T>&);
    template<class T> complex<T> polar(const T&, const T&);

// 28.4.9, transcendentals
    template<class T> complex<T> acos(const complex<T>&);
    template<class T> complex<T> asin(const complex<T>&);
    template<class T> complex<T> atan(const complex<T>&);
    template<class T> complex<T> acosh(const complex<T>&);
    template<class T> complex<T> asinh(const complex<T>&);
    template<class T> complex<T> atanh(const complex<T>&);
    template<class T> complex<T> cos(const complex<T>&);
    template<class T> complex<T> cosh(const complex<T>&);
    template<class T> complex<T> exp(const complex<T>&);
    template<class T> complex<T> log(const complex<T>&);
    template<class T> complex<T> log10(const complex<T>&);
    template<class T> complex<T> pow(const complex<T>&, const T&);
    template<class T> complex<T> pow(const complex<T>&, const complex<T>&);
    template<class T> complex<T> pow(const T&, const complex<T>&);
template<class T> complex<T> sin (const complex<T>&);
template<class T> complex<T> sinh (const complex<T>&);
template<class T> complex<T> sqrt (const complex<T>&);
template<class T> complex<T> tan (const complex<T>&);
template<class T> complex<T> tanh (const complex<T>&);

// 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"i(long double);
        constexpr complex<double> operator"i(unsigned long long);
        constexpr complex<float> operator"if(long double);
        constexpr complex<float> operator"if(unsigned long long);
    }
}

28.4.3 Class template complex

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&);
            template<class X> constexpr 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>&);
    };
}

1 The class complex describes an object that can store the Cartesian components, real() and imag(), of a complex number.

28.4.4 Specializations

namespace std {
    template<> class complex<float> {
        public:
            using value_type = float;
            constexpr complex(float re = 0.0f, float im = 0.0f);
            constexpr complex(const complex<float>&) = default;
            constexpr explicit complex(const complex<double>&);
            constexpr explicit complex(const complex<long double>&);
    };
}
constexpr float real() const;
constexpr void real(float);
constexpr float imag() const;
constexpr void imag(float);

constexpr complex& operator= (float);
constexpr complex& operator+=(float);
constexpr complex& operator-=(float);
constexpr complex& operator*=(float);
constexpr complex& operator/=(float);

constexpr complex& operator=(const complex&);
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>&);

};

template<> class complex<double> {
public:
    using value_type = double;

customexpr complex(double re = 0.0, double im = 0.0);
constexpr complex(const complex<float>&);
constexpr complex(const complex<double>&) = default;
constexpr explicit complex(const complex<long double>&);

constexpr double real() const;
constexpr void real(double);
constexpr double imag() const;
constexpr void imag(double);

constexpr complex& operator= (double);
constexpr complex& operator+=(double);
constexpr complex& operator-=(double);
constexpr complex& operator*=(double);
constexpr complex& operator/=(double);

constexpr complex& operator=(const complex&);
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>&);
};

template<> class complex<long double> {
public:
    using value_type = long double;

customexpr complex(long double re = 0.0L, long double im = 0.0L);
constexpr complex(const complex<float>&);
constexpr complex(const complex<double>&);
constexpr complex(const complex<long double>&) = default;

constexpr long double real() const;
constexpr void real(long double);
constexpr long double imag() const;
constexpr void imag(long double);

constexpr complex& operator= (long double);
constexpr complex& operator+=(long double);
constexpr complex& operator-=(long double);

};
constexpr complex& operator*=(long double);
constexpr complex& operator/=(long double);

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>&);

28.4.5 Member functions

template<class T> constexpr complex(const T& re = T(), const T& im = T());
1

Postconditions: real() == re && imag() == im is true.

constexpr T real() const;
2
Returns: The value of the real component.

constexpr void real(T val);
3
Effects: Assigns val to the real component.

constexpr T imag() const;
4
Returns: The value of the imaginary component.

constexpr void imag(T val);
5
Effects: Assigns val to the imaginary component.

28.4.6 Member operators

constexpr complex& operator+=(const T& rhs);
1
Effects: Adds the scalar value rhs to the real part of the complex value *this and stores the result in the real part of *this, leaving the imaginary part unchanged.

Returns: *this.

constexpr complex& operator-=(const T& rhs);
3
Effects: Subtracts the scalar value rhs from the real part of the complex value *this and stores the result in the real part of *this, leaving the imaginary part unchanged.

Returns: *this.

constexpr complex& operator*=(const T& rhs);
5
Effects: Multiplies the scalar value rhs by the complex value *this and stores the result in *this.

Returns: *this.

constexpr complex& operator/=(const T& rhs);
7
Effects: Divides the scalar value rhs into the complex value *this and stores the result in *this.

Returns: *this.

template<class X> constexpr complex& operator+=(const complex<X>& rhs);
9
Effects: Adds the complex value rhs to the complex value *this and stores the sum in *this.

Returns: *this.

template<class X> constexpr complex& operator-=(const complex<X>& rhs);
11
Effects: Subtracts the complex value rhs from the complex value *this and stores the difference in *this.

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.

Effects: Divides the complex value rhs into the complex value *this and stores the quotient in *this.

Returns: *this.

28.4.7 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);

Returns: complex<T>(-lhs.real(),-lhs.imag()).

template<class T> constexpr complex<T> operator-(const complex<T>& lhs, const complex<T>& rhs);

Returns: complex<T>(lhs) -= rhs.

Returns: complex<T>(lhs) /= rhs.

template<class T> constexpr complex<T> operator*(const complex<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);

Returns: complex<T>(lhs) /= rhs.

Returns: complex<T>(lhs) /= rhs.

Returns: complex<T>(lhs) /= rhs.

template<class T> constexpr bool operator==(const complex<T>& lhs, const complex<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 (31.7.4.3).

If bad input is encountered, calls is.setstate(ios_base::failbit) (which may throw ios_base::failure (31.5.4.4)).

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.

Returns: is.

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_ostream<CharT, traits> s;
"s.flags(o.flags());

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s.imbue(o.getloc());
s.precision(o.precision());
s << '(' << x.real() << "," << x.imag() << ')';
return o << s.str();
15

[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]

28.4.8

Value operations

[complex.value.ops]

template<class T> constexpr T real(const complex<T>& x);
1

Returns: x.real().
template<class T> constexpr T imag(const complex<T>& x);

2

Returns: x.imag().
template<class T> T abs(const complex<T>& x);

3

Returns: The magnitude of x.
template<class T> T arg(const complex<T>& x);

4

Returns: The phase angle of x, or atan2(imag(x), real(x)).
template<class T> constexpr T norm(const complex<T>& x);

5

Returns: The squared magnitude of x.
template<class T> constexpr complex<T> conj(const complex<T>& x);

6

Returns: The complex conjugate of x.
template<class T> complex<T> proj(const complex<T>& x);

7

Returns: The projection of x onto the Riemann sphere.

8

Remarks: Behaves the same as the C function cproj. See also: ISO C 7.3.9.5
template<class T> complex<T> polar(const T& rho, const T& theta = T());

9
10

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.

28.4.9

Transcendentals

[complex.transcendentals]

template<class T> complex<T> acos(const complex<T>& x);
1

Returns: The complex arc cosine of x.

2

Remarks: Behaves the same as the C function cacos. See also: ISO C 7.3.5.1
template<class T> complex<T> asin(const complex<T>& x);

3

Returns: The complex arc sine of x.

4

Remarks: Behaves the same as the C function casin. See also: ISO C 7.3.5.2
template<class T> complex<T> atan(const complex<T>& x);

5

Returns: The complex arc tangent of x.

6

Remarks: Behaves the same as the C function catan. See also: ISO C 7.3.5.3
template<class T> complex<T> acosh(const complex<T>& x);

7

Returns: The complex arc hyperbolic cosine of x.

8

Remarks: Behaves the same as the C function cacosh. See also: ISO C 7.3.6.1

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template<class T> complex<T> asinh(const complex<T>& x);

   Returns: The complex arc hyperbolic sine of x.

   Remarks: Behaves the same as the C function casinh. See also: ISO C 7.3.6.2

template<class T> complex<T> atanh(const complex<T>& x);

   Returns: The complex arc hyperbolic tangent of x.

   Remarks: Behaves the same as the C function catanh. See also: ISO C 7.3.6.3

template<class T> complex<T> cos(const complex<T>& x);

   Returns: The complex cosine of x.

template<class T> complex<T> cosh(const complex<T>& x);

   Returns: The complex hyperbolic cosine of x.

template<class T> complex<T> exp(const complex<T>& x);

   Returns: The complex base-e exponential of x.

template<class T> complex<T> log(const complex<T>& x);

   Returns: The complex natural (base-e) logarithm of x. For all x, \(\text{imag(log}(x))\) 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 clog in C. — end note]

   Remarks: The branch cuts are along the negative real axis.

template<class T> 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> complex<T> pow(const complex<T>& x, const complex<T>& y);

   Returns: The complex power of base \(x\) raised to the \(y\)th power, defined as \(\exp(y \times \text{log}(x))\). The value returned for \(\text{pow}(0, 0)\) is implementation-defined.

   Remarks: The branch cuts are along the negative real axis.

template<class T> complex<T> sin(const complex<T>& x);

   Returns: The complex sine of x.

template<class T> complex<T> sinh(const complex<T>& x);

   Returns: The complex hyperbolic sine of x.

template<class T> 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 csqrt in C. — end note]

   Remarks: The branch cuts are along the negative real axis.

template<class T> complex<T> tan(const complex<T>& x);

   Returns: The complex tangent of x.

template<class T> complex<T> tanh(const complex<T>& x);

   Returns: The complex hyperbolic tangent of x.

28.4.10 Additional overloads

1 The following function templates shall have additional overloads:
2 The additional overloads shall be sufficient to ensure:

(2.1) — If the argument has type `long double`, then it is effectively cast to `complex<long double>`.
(2.2) — Otherwise, if the argument has type `double` or an integer type, then it is effectively cast to `complex<double>`.
(2.3) — Otherwise, if the argument has type `float`, then it is effectively cast to `complex<float>`.

3 Function template `pow` shall have additional overloads sufficient to ensure, for a call with at least one argument of type `complex<T>`:

(3.1) — If either argument has type `complex<long double>` or type `long double`, then both arguments are effectively cast to `complex<long double>`.
(3.2) — Otherwise, if either argument has type `complex<double>`, `double`, or an integer type, then both arguments are effectively cast to `complex<double>`.
(3.3) — Otherwise, if either argument has type `complex<float>` or `float`, then both arguments are effectively cast to `complex<float>`.

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 `complex<double>`, `complex<long double>`, and `complex<float>` respectively, with their imaginary part denoted by the given literal number and the real part being zero.

```cpp
constexpr complex<long double> operator"il(long double d);
constexpr complex<long double> operator"il(unsigned long long d);
Returns: complex<long double>{0.0L, static_cast<long double>(d)}.
```

```cpp
constexpr complex<double> operator"i(long double d);
constexpr complex<double> operator"i(unsigned long long d);
Returns: complex<double>{0.0, static_cast<double>(d)}.
```

```cpp
constexpr complex<float> operator"if(long double d);
constexpr complex<float> operator"if(unsigned long long d);
Returns: complex<float>{0.0f, static_cast<float>(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 `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>::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>::is_signed`.

Unless otherwise specified, all descriptions of calculations in 28.5 use mathematical real numbers.
Throughout 28.5, the operators \texttt{bitand}, \texttt{bitor}, and \texttt{xor} denote the respective conventional bitwise operations. Further:

(5.1) — the operator \texttt{rshift} denotes a bitwise right shift with zero-valued bits appearing in the high bits of the result, and

(5.2) — the operator \texttt{lshift} 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

```
#include <initializer_list>

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;
    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;

```

§ 28.5.2
// 28.5.8.2, function template generate_canonical
template<class RealType, size_t bits, class URBG>
RealType generate_canonical(URBG& g);

// 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;

// 28.5.9.6.1, 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;

28.5.3 Requirements
28.5.3.1 General requirements

(1.1) that has a template type parameter named Sseq 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).
(1.3) 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).
(1.4) 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.
(1.5) 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.
(1.6) 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.

2 Throughout this subclause 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”.

3 Throughout this subclause 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 $i$, $0 \leq i < 2^{32}$, 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]

(2.1) that T is the type named by S’s associated result_type;
(2.2) that q is a value of S and r is a possibly const value of S;
(2.3) that 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 initializer_list<T>.

Table 91: Seed sequence requirements  [tab:rand.req.seedseq]

<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>
<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 generate’s previous invocations.</td>
<td>$O(re - rb)$</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 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>$O(r.size())$</td>
</tr>
</tbody>
</table>

28.5.3.3 Uniform random bit generator requirements  [rand.req.urng]

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]

```cpp
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. $G::min() <= g()$,
2. $g() <= G::max()$, and
A class \( G \) meets the uniform random bit generator requirements if \( G \) models \texttt{uniform\_random\_bit\_generator} \((6.8.2)\), and \( G \) provides a nested \texttt{typedef-name result\_type} that denotes the same type as \texttt{invoke\_result\_t\langle\&G\rangle}.

### 28.5.3.4 Random number engine requirements

1. 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.

2. 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\(\gg\).

3. \( E \)'s specification shall define:
   
   \begin{enumerate}
   \item the size of \( E \)'s state in multiples of the size of \texttt{result\_type}, given as an integral constant expression;
   \item the transition algorithm \( TA \) by which \( e \)'s state \( e_i \) is advanced to its successor state \( e_{i+1} \); and
   \item the generation algorithm \( GA \) by which an engine’s state is mapped to a value of type \texttt{result\_type}.
   \end{enumerate}

4. 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 92 are valid and have the indicated semantics, and if \( E \) also meets all other requirements of this subclause 28.5.3.4. In that Table and throughout this subclause:
   
   \begin{enumerate}
   \item \( T \) is the type named by \( E \)'s associated \texttt{result\_type};
   \item \( e \) is a value of \( E \), \( v \) is an lvalue of \( E \), \( x \) and \( y \) are (possibly \texttt{const}) values of \( E \);
   \item \( s \) is a value of \( T \);
   \item \( q \) is an lvalue meeting the requirements of a seed sequence (28.5.3.2);
   \item \( z \) is a value of type \texttt{unsigned long long};
   \item \( os \) is an lvalue of the type of some class template specialization \texttt{basic\_ostream\langle charT, traits\rangle}; and
   \item \( is \) is an lvalue of the type of some class template specialization \texttt{basic\_istream\langle charT, traits\rangle};
   \end{enumerate}

where \texttt{charT} and \texttt{traits} are constrained according to Clause 23 and Clause 31.

#### Table 92: 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></td>
<td>Creates an engine with the same initial state as all other default-constructed engines of type ( E ).</td>
<td>( \Theta(\text{size of state}) )</td>
</tr>
<tr>
<td>( E(x) )</td>
<td></td>
<td>Creates an engine that compares equal to ( x ).</td>
<td>( \Theta(\text{size of state}) )</td>
</tr>
<tr>
<td>( E(s) )</td>
<td></td>
<td>Creates an engine with initial state determined by ( s ).</td>
<td>( \Theta(\text{size of state}) )</td>
</tr>
<tr>
<td>( E(q)^{231} )</td>
<td></td>
<td>Creates an engine with an initial state that depends on a sequence produced by one call to ( q_.\text{generate} ).</td>
<td>same as complexity of ( q_.\text{generate} ) called on a sequence whose length is size of state</td>
</tr>
<tr>
<td>( e_.\text{seed}() )</td>
<td>\texttt{void}</td>
<td>\texttt{Postconditions: e == E()}.</td>
<td>same as ( E() )</td>
</tr>
<tr>
<td>( e_.\text{seed}(s) )</td>
<td>\texttt{void}</td>
<td>\texttt{Postconditions: e == E(s)}.</td>
<td>same as ( E(s) )</td>
</tr>
<tr>
<td>( e_.\text{seed}(q) )</td>
<td>\texttt{void}</td>
<td>\texttt{Postconditions: e == E(q)}.</td>
<td>same as ( E(q) )</td>
</tr>
<tr>
<td>( e() )</td>
<td>( T )</td>
<td>Advances ( e )'s state ( e_i ) to ( e_{i+1} ) ( = TA(e_i) ) and returns ( GA(e_i) ).</td>
<td>per 28.5.3.3</td>
</tr>
</tbody>
</table>

231) This constructor (as well as the subsequent corresponding \texttt{seed()} function) can be particularly useful to applications requiring a large number of independent random sequences.
<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>e.discard(z)</code></td>
<td>void</td>
<td>Advances e’s state e, to e_{i+z} by any means equivalent to z consecutive calls e().</td>
<td>no worse than the complexity of z consecutive calls e().</td>
</tr>
<tr>
<td><code>x == y</code></td>
<td>bool</td>
<td>This operator is an equivalence relation. With S_x and S_y as the infinite sequences of values that would be generated by repeated future calls to x() and y(), respectively, returns true if S_x = S_y; else returns false.</td>
<td>(O(\text{size of state}))</td>
</tr>
<tr>
<td><code>x != y</code></td>
<td>bool</td>
<td>!(x == y).</td>
<td>(O(\text{size of state}))</td>
</tr>
<tr>
<td><code>os &lt;&lt; x</code></td>
<td>reference to the type of os</td>
<td>With os.fmtflags set to ios_base::dec</td>
<td>ios_base::left and the fill character set to the space character, writes to os the textual representation of x’s current state. In the output, adjacent numbers are separated by one or more space characters. <strong>Postconditions:</strong> The os.fmtflags and fill character are unchanged.</td>
</tr>
<tr>
<td><code>is &gt;&gt; v</code></td>
<td>reference to the type of is</td>
<td>With is.fmtflags set to ios_base::dec, sets v’s state as determined by reading its textual representation from is. If bad input is encountered, ensures that v’s state is unchanged by the operation and calls is.setstate(ios_base::failbit) (which may throw ios_base::failure (31.5.4.4)). If a textual representation written via os &lt;&lt; x was subsequently read via is &gt;&gt; v, then x == v provided that there have been no intervening invocations of x or of v. <strong>Preconditions:</strong> is provides a textual representation that was previously written using an output stream whose imbued locale was the same as that of is, and whose type’s template specialization arguments charT and traits were respectively the same as those of is. <strong>Postconditions:</strong> The is.fmtflags are unchanged.</td>
<td>(O(\text{size of state}))</td>
</tr>
</tbody>
</table>

5 E shall meet the Cpp17CopyConstructible (Table 31) and Cpp17CopyAssignable (Table 33) requirements. These operations shall each be of complexity no worse than \(O(\text{size of state})\).

232) 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().
28.5.3.5 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 \(a\text{.base()}\) 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.

\[A::A();\]

3 Effects: The base engine is initialized as if by its default constructor.

\[\text{bool operator==}(\text{const } A & a1, \text{const } A & a2);\]

4 Returns: true if \(a1\)'s base engine is equal to \(a2\)'s base engine. Otherwise returns false.

\[A::A(\text{result_type } s);\]

5 Effects: The base engine is initialized with \(s\).

\[\text{template<class Sseq> } A::A(Sseq & q);\]

6 Effects: The base engine is initialized with \(q\).

\[\text{void seed();}\]

7 Effects: With \(b\) as the base engine, invokes \(b\text{.seed()}.\)

\[\text{void seed(\text{result_type } s);}\]

8 Effects: With \(b\) as the base engine, invokes \(b\text{.seed(s)}.\)

\[\text{template<class Sseq> void seed(Sseq & q);}\]

9 Effects: With \(b\) as the base engine, invokes \(b\text{.seed(q)}.\)

10 \(A\) 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]

1 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 \(P(z_i)\). A distribution's specification identifies its associated probability function \(p(z)\) or \(P(z_i)\).

2 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, \(p(z \mid a, b)\) or \(P(z_i \mid a, b)\), to name specific parameters, or by writing, for example, \(p(z \mid \{p\})\) or \(P(z_i \mid \{p\})\), to denote a distribution's parameters \(p\) taken as a whole.

3 A class \(D\) meets the requirements of a random number distribution if the expressions shown in Table 93 are valid and have the indicated semantics, and if \(D\) and its associated types also meet all other requirements of this subclause 28.5.3.6. In that Table 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 \(D\);
— \( glb \) 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 \texttt{operator()}, as determined by the current values of \( d \)’s parameters;

— \( p \) is a (possibly \texttt{const}) value of \( P \);

— \( g, g_1, \) and \( g_2 \) are lvalues of a type meeting the requirements of a uniform random bit generator (28.5.3.3);

— \( os \) is an lvalue of the type of some class template specialization \texttt{basic_ostream<charT, traits>}; and

— \( is \) is an lvalue of the type of some class template specialization \texttt{basic_istream<charT, traits>};

where \texttt{charT} and \texttt{traits} are constrained according to Clause 23 and Clause 31.

### Table 93: Random number distribution requirements

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Pre/post-condition</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D::\text{result_type} )</td>
<td>( T )</td>
<td>( T ) is an arithmetic type (6.8.2).</td>
<td>compile-time</td>
</tr>
<tr>
<td>( D::\text{param_type} )</td>
<td>( P )</td>
<td></td>
<td>compile-time</td>
</tr>
<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>\texttt{void}</td>
<td>Subsequent uses of ( d ) do not depend on values produced by any engine prior to invoking \texttt{reset}.</td>
<td>constant</td>
</tr>
<tr>
<td>( x.param() )</td>
<td>( P )</td>
<td>Returns a value ( p ) such that ( D(p).\text{param()} == p ).</td>
<td>no worse than the complexity of ( D(p) )</td>
</tr>
<tr>
<td>( d.param(p) )</td>
<td>\texttt{void}</td>
<td>\textit{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>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>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 g1 == g2. Otherwise returns false.</td>
<td>constant</td>
</tr>
<tr>
<td>x != y</td>
<td>bool</td>
<td>!(x == y). same as x == y.</td>
<td></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></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)). 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.</td>
<td></td>
</tr>
</tbody>
</table>

4 D shall meet the Cpp17CopyConstructible (Table 31) and Cpp17CopyAssignable (Table 33) 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 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 this subclause 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 31), Cpp17CopyAssignable (Table 33), and Cpp17EqualityComparable (Table 27) 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

```cpp
using distribution_type = D;
```
28.5.4 Random number engine class templates

28.5.4.1 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.

6 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.

7 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

1 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 \( TA(x_i) = (a \cdot x_i + c) \mod m \); the generation algorithm is \( GA(x_i) = x_{i+1} \).

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);
    }
Let

With

Concatenate the upper

The generation algorithm determines the unsigned integer values

Effects

If the template parameter

The transition algorithm employs a twisted generalized feedback shift register defined by shift values

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

The state transition is performed as follows:

\begin{align}
(2.1) & \quad \text{Concatenate the upper } w - r \text{ bits of } X_{i-n} \text{ with the lower } r \text{ bits of } X_{i+1-n} \text{ to obtain an unsigned integer value } Y. \\
(2.2) & \quad \text{With } \alpha = a \cdot (Y \text{ bitand } 1), \text{ set } X_1 \text{ to } X_{i+m-n} \text{ xor } (Y \text{ rshift } 1) \text{ xor } \alpha. \\
\end{align}

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:

\begin{align}
(3.1) & \quad \text{Let } z_1 = X_1 \text{ xor } ((X_1 \text{ rshift } u) \text{ bitand } d). \\
(3.2) & \quad \text{Let } z_2 = z_1 \text{ xor } ((z_1 \text{ lshift } s) \text{ bitand } b). \\
(3.3) & \quad \text{Let } z_3 = z_2 \text{ xor } ((z_2 \text{ lshift } t) \text{ bitand } c). \\
\end{align}

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.
Let $z_4 = z_3 \text{xor} (z_3 \text{rshift} \ell)$.

```cpp
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 = n;
    static constexpr size_t shift_size = m;
    static constexpr size_t mask_bits = r;
    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 UIntType tempering_c = c;
    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 2^w - 1; }
    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);
};
```

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4 The following relations shall hold: $0 < m, m <= n, 2u < w, r <= w, u <= w, s <= w, l <= w, w <= \text{numeric\_limits<UIntType>\_digits}, a <= (1u<<w) - 1u, b <= (1u<<w) - 1u, c <= (1u<<w) - 1u, d <= (1u<<w) - 1u, \text{and} f <= (1u<<w) - 1u.$

5 The textual representation of $x_i$ consists of the values of $X_{i-n}, \ldots, X_{i-1}$, in that order.

```cpp
explicit mersenne_twister_engine(result_type value);
```

Effects: Sets $X_{i-n}$ to value mod $2^w$. Then, iteratively for $i = 1 - n, \ldots, -1$, sets $X_i$ to

$\lfloor f \cdot (X_{i-1} \text{xor} (X_{i-1} \text{rshift} (w - 2))) + i \mod n \rfloor \mod 2^w.$
7 Complexity: \( \Theta(n) \).

```
template<class Sseq> explicit mersenne_twister_engine(Sseq& q);
```

8 Effects: With \( k = \lceil w/32 \rceil \) and \( a \) an array (or equivalent) of length \( n \cdot k \), invokes \( q \).generate\((a + 0, a + n \cdot k) \) and then, iteratively for \( i = \neg n, \ldots, -1 \), 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

```
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 \( \Theta(r) \), 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:

\[
\begin{align*}
(3.1) & \quad \text{Let } Y = X_{i-s} - X_{i-r} - c. \\
(3.2) & \quad \text{Set } X_i \text{ to } y = Y \mod m. \text{ Set } c \text{ to 1 if } Y < 0, \text{ otherwise set } c \text{ to 0.}
\end{align*}
\]

[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]

4 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 result_type default_seed = 19780503u;

        // constructors and seeding functions
        subtract_with_carry_engine() : subtract_with_carry_engine(default_seed) {}
        explicit subtract_with_carry_engine(result_type value);
        template<class Sseq> explicit subtract_with_carry_engine(Sseq& q);
        void seed(result_type value = default_seed);
        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 \( w \leq \text{numeric_limits}<\text{UIntType}>::\text{digits} \).

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 \( X_{i-r}, \ldots, X_{i-1} \), in that order, as specified below. If \( X_{i-1} \) 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<result_type, 
40014u,0u,2147483563u> e(value == 0u ? default_seed : value);
```

Then, to set each \( X_k \), obtain new values \( z_0, \ldots, z_{n-1} \) from \( n = \lfloor w/32 \rfloor \) successive invocations of \( e \). Set \( X_k \) to \( \sum_{j=0}^{n-1} z_j \cdot 2^{32j} \mod m \).

**Complexity:** Exactly \( n \cdot r \) invocations of \( e \).

```cpp
template<class Sseq> explicit subtract_with_carry_engine(Sseq& q);
```

**Effects:** With \( k = \lfloor w/32 \rfloor \) and \( a \) 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 \( X_{i-1} \) 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 In general

Each type instantiated from a class template specified in this subclause 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 this subclause 28.5.5 is constant.

Except where specified otherwise, no function described in this subclause 28.5.5 throws an exception.

Every function described in this subclause 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 this subclause 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 this subclause 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(); }
static constexpr result_type max() { return Engine::max(); }

// constructors and seeding functions
discard_block_engine();
explicit discard_block_engine(const Engine& e);
explicit discard_block_engine(Engine&& e);
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);

// generating functions
result_type operator()();
void discard(unsigned long long z);

// property functions
const Engine& base() const noexcept { return e; }

// exposition only
private:
    Engine e;
    // exposition only
    size_t n;  // exposition only
};

The following relations shall hold: 0 < r and r <= p.
The textual representation consists of the textual representation of e followed by the value of n.
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

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.

The transition and generation algorithms are described in terms of the following integral constants:

(2.1) Let \( R = e.\max() - e.\min() + 1 \) and \( m = \lceil \log_2 R \rceil \).

(2.2) With n as determined below, let \( w_0 = \lceil w/n \rceil \), \( n_0 = n - w \mod n \), \( y_0 = 2^{w_0} \lfloor R/2^{w_0} \rfloor \), and \( y_1 = 2^{w_0+1} \lfloor R/2^{w_0+1} \rfloor \).

(2.3) Let \( n = \lceil w/m \rceil \) if and only if the relation \( R - y_0 \leq \lfloor y_0/n \rfloor \) holds as a result. Otherwise let \( n = 1 + \lceil w/m \rceil \).

[Note 1: The relation \( w = n_0 w_0 + (n - n_0)(w_0 + 1) \) 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 \( y_0 + e.\min() \) and \( n - n_0 \) values less than \( y_1 + e.\min() \).
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:

\[
S = 0;
\]

\[
\text{for } (k = 0; k \neq n_0; k += 1) \{ \\
\quad \text{do } u = e() - e.\text{min}(); \text{ while } (u \geq y_0); \\
\quad S = 2^{n_0} \cdot S + u \text{ mod } 2^{n_0}; \\
\}
\]

\[
\text{for } (k = n_0; k \neq n_1; k += 1) \{ \\
\quad \text{do } u = e() - e.\text{min}(); \text{ while } (u \geq y_1); \\
\quad S = 2^{n_0+1} \cdot S + u \text{ mod } 2^{n_0+1}; \\
\}
\]

```cpp
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);
    template<class charT, class traits>
    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 \( w \leq \text{numeric_limits<result_type>::digits} \).

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 \( e_i \) 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 \( k + 1 \).
2 The transition algorithm permutes the values produced by \( e \). The state transition is performed as follows:

\[
\text{(2.1)} \quad \text{Calculate an integer } j = \left\lfloor \frac{k \cdot (Y - e_{\min})}{e_{\max} - e_{\min} + 1} \right\rfloor.
\]

\[
\text{(2.2)} \quad \text{Set } Y \text{ to } V_j \text{ and then set } V_j \text{ to } e() \text{.}
\]

3 The generation algorithm yields the last value of \( Y \) produced while advancing \( e \)'s state as described above.

```cpp
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 \( V[0], \ldots, V[k-1] \) and \( Y \), in that order, with values returned by successive invocations of \( e() \).

28.5.6 Engines and engine adaptors with predefined parameters [rand.predef] using minstd_rand0 =
linear_congruential_engine<uint_fast32_t, 16'807, 0, 2'147'483'647>;

1 Required behavior: The 10000\textsuperscript{th} 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>;

2 Required behavior: The 10000\textsuperscript{th} 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, 0xfffe'ffff, 7, 0x9d2c'5680, 15, 0xefc6'0000, 18, 1'812'433'253>;

3 Required behavior: The 10000\textsuperscript{th} 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,
0x71d6'7ff'edaf'0000, 37, 0xfffe'ee00'0000'0000, 43, 6'364'136'223'846'793'005>;

4 Required behavior: The 10000\textsuperscript{th} 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 10000\textsuperscript{th} 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 10000\textsuperscript{th} consecutive invocation of a default-constructed object of type ranlux48_base produces the value 6183912858275.

using ranlux24 = discard_block_engine<ranlux24_base, 223, 23>;

7 Required behavior: The 10000\textsuperscript{th} 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 10000\textsuperscript{th} 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 10000\textsuperscript{th} consecutive invocation of a default-constructed object of type knuth_b produces the value 1112339016.

using default_random_engine = implementation-defined;

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:

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// 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;

// no copy functions
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.

double entropy() const noexcept;

Returns: If the implementation employs a random number engine, returns 0.0. Otherwise, returns an entropy estimate 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.

28.5.8 Utilities [rand.util]

28.5.8.1 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);

234) The parameter is intended to allow an implementation to differentiate between different sources of randomness.
235) If a device has \( n \) states whose respective probabilities are \( P_0, \ldots, P_{n-1} \), the device entropy \( S \) is defined as
\[
S = - \sum_{i=0}^{n-1} P_i \cdot \log P_i.
\]
// 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
};

seed_seq() noexcept;

1 Postconditions: v.empty() is true.

template<class T>
seed_seq(initializer_list<T> il);

2 Constraints: T is an integer type.

3 Effects: Same as seed_seq(il.begin(), il.end()).

template<class InputIterator>
seed_seq(InputIterator begin, InputIterator end);

4 Mandates: iterator_traits<InputIterator>::value_type is an integer type.

5 Preconditions: InputIterator meets the Cpp17InputIterator requirements (25.3.5.3).

6 Effects: Initializes v by the following algorithm:
  for (InputIterator s = begin; s != end; ++s)
      v.push_back((*s) mod 32);

7 Mandates: iterator_traits<RandomAccessIterator>::value_type is an unsigned integer type capable of accommodating 32-bit quantities.

8 Preconditions: RandomAccessIterator meets the Cpp17RandomAccessIterator requirements (25.3.5.7) and the requirements of a mutable iterator.

9 Effects: Does nothing if begin == end. Otherwise, with s = v.size() and n = end - begin, fills the supplied range [begin, end) according to the following algorithm in which each operation is to be carried out modulo $2^{32}$, each indexing operator applied to begin is to be taken modulo n, and $T(x)$ is defined as $x \xor (x \text{shift } 27)$:

9.1 By way of initialization, set each element of the range to the value 0x8b8b8b8b. Additionally, for use in subsequent steps, let $p = (n - t)/2$ and let $q = p + t$, where

$$t = (n \geq 623) \ ? 11 : (n \geq 68) \ ? 7 : (n \geq 39) \ ? 5 : (n \geq 7) \ ? 3 : (n - 1)/2;$$

9.2 With $m$ as the larger of $s + 1$ and $n$, transform the elements of the range: iteratively for $k = 0, \ldots, m - 1$, calculate values

$$r_1 = 1664525 \cdot T(begin[k] \xor begin[k + p] \xor begin[k - 1])$$

$$r_2 = r_1 + \begin{cases} 
  s, & k = 0 \\
  k \mod n + v[k - 1], & 0 < k \leq s \\
  k \mod n, & s < k 
\end{cases}$$

and, in order, increment begin[k + p] by $r_1$, increment begin[k + q] by $r_2$, and set begin[k] to $r_2$. 

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Transform the elements of the range again, beginning where the previous step ended: iteratively for \( k = m, \ldots, m + n - 1 \), calculate values

\[
\begin{align*}
  r_3 &= 1566083941 \cdot T(b_{\text{begin}[k]} + b_{\text{begin}[k+p]} + b_{\text{begin}[k-1]}) \\
  r_4 &= r_3 - (k \mod n)
\end{align*}
\]

and, in order, update \( b_{\text{begin}[k+p]} \) by xoring it with \( r_3 \), update \( b_{\text{begin}[k+q]} \) by xoring it with \( r_4 \), and set \( b_{\text{begin}[k]} \) to \( r_4 \).

Throws: What and when RandomAccessIterator operations of \( \text{begin} \) and \( \text{end} \) throw.

\[
\text{size_t size() const noexcept;}
\]

Returns: The number of 32-bit units that would be returned by a call to \( \text{param}() \).

Complexity: Constant time.

\[
\text{template<class OutputIterator>}
\begin{align*}
  \text{void param(OutputIterator dest) const;}
\end{align*}
\]

Mandates: Values of type result_type are writable (25.3.1) to \( \text{dest} \).

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:

\[
\text{copy(v.begin(), v.end(), dest)};
\]

Throws: What and when OutputIterator operations of \( \text{dest} \) throw.

28.5.8.2 Function template \text{generate\_canonical} \ [rand.util.canonical]

\[
\text{template<class RealType, size_t bits, class URBG>}
\begin{align*}
  \text{RealType generate\_canonical(URBG& g);} \\
  \text{Effects: Invokes } g() \text{ } k \text{ times to obtain values } g_0, \ldots, g_{k-1}, \text{ respectively. Calculates a quantity}
\end{align*}
\]

\[
S = \sum_{i=0}^{k-1} (g_i - g.\text{min}) \cdot R^i
\]

using arithmetic of type RealType.

Returns: \( S/R^k \).

[Note 1: \( 0 \leq S/R^k < 1 \) — end note]

Throws: What and when \( g \) throws.

Complexity: Exactly \( k = \max(1, \lceil b/\log_2 R \rceil) \) invocations of \( g \), where \( b \)\(^{236}\) is the lesser of \( \text{numeric\_limits<RealType>::digits} \) and \( \text{bits} \), and \( R \) is the value of \( g.\text{max}() - g.\text{min}() + 1 \).

[Note 2: 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]

28.5.9 Random number distribution class templates \ [rand.dist]

28.5.9.1 In general \ [rand.dist.general]

Each type instantiated from a class template specified in this subclause 28.5.9 meets the requirements of a random number distribution (28.5.3.6) type.

Descriptions are provided in this subclause 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.

\(^{236}\) \( b \) is introduced to avoid any attempt to produce more bits of randomness than can be held in RealType.
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 \( i, a \leq i \leq b \), distributed according to the constant discrete probability function

\[
P(i \mid a, b) = \frac{1}{b - a + 1}.
\]

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);
    };
}

explicit uniform_int_distribution(IntType a, IntType b = numeric_limits<IntType>::max());

Preconditions: \( a \leq b \).

Remarks: \( a \) and \( b \) correspond to the respective parameters of the distribution.

1. result_type a() const;
   Returns: The value of the \( a \) parameter with which the object was constructed.

2. result_type b() const;
   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

\[
p(x \mid a, b) = \frac{1}{b - a}.
\]
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);
    }
}

explicit uniform_real_distribution(RealType a, RealType b = 1.0);

Preconditions: $a \leq b$ and $b - a \leq \text{numeric_limits}<\text{RealType}>::\text{max}().$

Remarks: $a$ and $b$ correspond to the respective parameters of the distribution.

result_type a() const;

Returns: The value of the $a$ parameter with which the object was constructed.

result_type b() const;

Returns: The value of the $b$ parameter with which the object was constructed.

28.5.9.3 Bernoulli distributions

28.5.9.3.1 Class bernoulli_distribution

A bernoulli_distribution random number distribution produces bool values $b$ distributed according to the discrete probability function

$$P(b | p) = \begin{cases} p & \text{if } b = \text{true}, \\
1 - p & \text{if } b = \text{false}. \end{cases}$$
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);
    };
}

explicit bernoulli_distribution(double p);

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

$$P(i \mid t, p) = \binom{t}{i} \cdot p^i \cdot (1 - p)^{t-i}.$$

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;
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 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 \leq p \leq 1 and 0 \leq 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
\[
P(i \mid p) = p \cdot (1 - p)^i.
\]

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

\[
P(i \mid k, p) = \binom{k + i - 1}{i} \cdot p^k \cdot (1 - p)^i.
\]

[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(); 

    // equality operators
    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);

explicit negative_binomial_distribution(IntType k, double p = 0.5);

2
Preconditions:
0 < p ≤ 1 and 0 < k.

3
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

\[ P(i | \mu) = \frac{e^{-\mu} \mu^i}{i!} \].

The distribution parameter \( \mu \) is also known as this distribution’s mean.

template<class IntType = int>
class poisson_distribution
{
  public:
    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 URBG>
    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

An exponential_distribution random number distribution produces random numbers \( x > 0 \) distributed according to the probability density function

\[
p(x | \lambda) = \lambda e^{-\lambda x}.
\]

namespace std {
  template<class RealType = double>
class exponential_distribution {
  public:
    // types
    using result_type = RealType;
    using param_type = unspecified;

    // constructors and reset functions
    exponential_distribution() : exponential_distribution(1.0) {}  
exponential_distribution(RealType lambda);  
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 URBG>
    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);
template<class charT, class traits>
friend basic_istream<charT, traits>&
    operator>>(basic_istream<charT, traits>& is, 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  [rand.dist.pois.gamma]

A gamma_distribution random number distribution produces random numbers \( x > 0 \) distributed according to the probability density function

\[
p(x | \alpha, \beta) = \frac{e^{-x/\beta}}{\beta^\alpha \Gamma(\alpha)} \cdot x^{\alpha-1}.
\]

namespace std {

    template<class RealType = double>
    class gamma_distribution {
    public:
        // types
        using result_type = RealType;
        using param_type = unspecified;

        // constructors and reset functions
        gamma_distribution() : gamma_distribution(1.0) {} 
        explicit gamma_distribution(RealType alpha, RealType beta = 1.0);
        explicit gamma_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const gamma_distribution& x, const gamma_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 alpha() const;
        RealType beta() 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 gamma_distribution& x);
        template<class charT, class traits>
        friend basic_istream<charT, traits>&
            operator>>(basic_istream<charT, traits>& is, gamma_distribution& x);
    };

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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.

RealType alpha() const;

Returns: The value of the $\alpha$ parameter with which the object was constructed.

RealType beta() const;

Returns: The value of the $\beta$ parameter with which the object was constructed.

28.5.9.4.4 Class template weibull_distribution

A weibull_distribution random number distribution produces random numbers $x \geq 0$ distributed according to the probability density function

$$p(x | a, b) = \frac{a}{b} \left( \frac{x}{b} \right)^{a-1} \exp \left( - \left( \frac{x}{b} \right)^a \right).$$

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>;
            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

\[
p(x \mid a, b) = \frac{1}{b} \exp \left( \frac{a - x}{b} - \exp \left( \frac{a - x}{b} \right) \right).
\]

namespace std {
    template<class RealType = double>
    class extreme_value_distribution {
    public:
        // types
        using result_type = RealType;
        using param_type = unspecified;

        // constructor and reset functions
        extreme_value_distribution() : extreme_value_distribution(0.0) {};
        explicit extreme_value_distribution(RealType a, RealType b = 1.0);
        explicit extreme_value_distribution(const param_type& parm);
        void reset();

        // equality operators
        friend bool operator==(const extreme_value_distribution& x,
                               const extreme_value_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 extreme_value_distribution& x);
        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.

237) 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.
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

#### 28.5.9.5.1 Class template normal_distribution

A normal_distribution random number distribution produces random numbers \( x \) distributed according to the probability density function

\[
p(x | \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right).
\]

The distribution parameters \( \mu \) and \( \sigma \) are also known as this distribution’s mean and standard deviation.

```cpp
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) {} // The default constructor.
        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);
        template<class charT, class traits>
        friend basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& is, normal_distribution& x);
    }
}
```

### Preconditions

\( 0 < \text{stddev} \).

### Remarks

\( \text{mean} \) and \( \text{stddev} \) correspond to the respective parameters of the distribution.

RealType mean() const;

Returns: The value of the \( \text{mean} \) 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

\[
p(x | m, s) = \frac{1}{sx\sqrt{2\pi}} \exp\left(-\frac{(\ln x - m)^2}{2s^2}\right).
\]

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

\[
p(x \mid n) = \frac{x^{(n/2)-1} \cdot e^{-x/2}}{\Gamma(n/2) \cdot 2^{n/2}}.
\]

```cpp
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);
}
```

2

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.

28.5.9.5.4 Class template cauchy_distribution

A cauchy_distribution random number distribution produces random numbers \( x \) distributed according to the probability density function

\[
p(x \mid a, b) = \left(\pi b \left(1 + \left(\frac{x-a}{b}\right)^2\right)\right)^{-1}.
\]
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);
2 Preconditions: 0 < b.
3 Remarks: a and b correspond to the respective parameters of the distribution.

RealType a() const;
4 Returns: The value of the a parameter with which the object was constructed.

RealType b() const;
5 Returns: The value of the b parameter with which the object was constructed.

28.5.9.5.5 Class template fisher_f_distribution [rand.dist.norm.f]
1 A fisher_f_distribution random number distribution produces random numbers \( x \geq 0 \) distributed according to the probability density function

\[
p(x | m, n) = \frac{\Gamma((m + n)/2)}{\Gamma(m/2) \Gamma(n/2)} \cdot \left(\frac{m}{n}\right)^{m/2} \cdot x^{(m/2) - 1} \cdot \left(1 + \frac{m x}{n}\right)^{-(m+n)/2}.
\]
namespace std {
    template<class RealType = double>
    class fisher_f_distribution {
        public:
            // types
            using result_type = RealType;
            using param_type = unspecified;

            // constructor and reset functions
            fisher_f_distribution() : fisher_f_distribution(1.0) {}
            explicit fisher_f_distribution(RealType m, RealType n = 1.0);
            explicit fisher_f_distribution(const param_type& parm);
            void reset();

            // equality operators
            friend bool operator==(const fisher_f_distribution& x, const fisher_f_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 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 fisher_f_distribution& x);
            template<class charT, class traits>
            friend basic_istream<charT, traits>&
                operator>>(basic_istream<charT, traits>& is, fisher_f_distribution& x);
    }
}

explicit fisher_f_distribution(RealType m, RealType n = 1);

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 [rand.dist.norm.t]

A student_t_distribution random number distribution produces random numbers x distributed according to the probability density function

\[ p(x \mid n) = \frac{1}{\sqrt{n \pi}} \cdot \frac{\Gamma\left((n + 1)/2\right)}{\Gamma(n/2)} \cdot \left(1 + \frac{x^2}{n}\right)^{-(n+1)/2}. \]
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.

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

\[
P(i \mid p_0, \ldots, p_{n-1}) = p_i .
\]

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 weights, shall be non-negative, non-NaN, and non-infinity. Moreover, the following relation shall hold: \( 0 < S = w_0 + \cdots + w_{n-1} \).

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> wl);
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);
}

discrete_distribution();
3

Effects: Constructs a discrete_distribution object with $n = 1$ and $p_0 = 1$.

[Note 1: Such an object will always deliver the value 0. — end note]

template<class InputIterator>
discrete_distribution(InputIterator firstW, InputIterator lastW);
4

Mandates: is_convertible_v<iterator_traits<InputIterator>::value_type, double> is true.

Preconditions: InputIterator meets the Cpp17InputIterator requirements (25.3.5.3). If \begin{array}{l}
\text{firstW} \not= \text{lastW}, \text{let } n = 1 \text{ and } w_0 = 1. \\
\text{Otherwise, } [\text{firstW}, \text{lastW}) \text{ forms a sequence } w \text{ of length } n > 0.
\end{array}

Effects: Constructs a discrete_distribution object with probabilities given by the formula above.

discrete_distribution(initializer_list<double> wl);
5

Effects: Same as discrete_distribution(wl.begin(), wl.end()).

template<class UnaryOperation>
discrete_distribution(size_t nw, double xmin, double xmax, UnaryOperation fw);
6

Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.

Preconditions: If $nw = 0$, let $n = 1$, otherwise let $n = nw$. The relation $0 < \delta = (\text{xmax} - \text{xmin})/n$ holds.
Effects: Constructs a `discrete_distribution` object with probabilities given by the formula above, using the following values: If \( n_w = 0 \), let \( w_0 = 1 \). Otherwise, let \( w_k = f_w(x_{\text{min}} + k \cdot \delta + \delta/2) \) for \( k = 0, \ldots, n - 1 \).

Complexity: The number of invocations of \( f_w \) does not exceed \( n \).

```cpp
def probabilities() const;
```

Returns: A `vector<double>` whose `size` member returns \( n \) and whose `operator[]` member returns \( p_k \) when invoked with argument \( k \) for \( k = 0, \ldots, n - 1 \).

### 28.5.9.6.2 Class template `piecewise_constant_distribution` [rand.dist.samp.pconst]

A `piecewise_constant_distribution` random number distribution produces random numbers \( x, b_0 \leq x < b_n \), uniformly distributed over each subinterval \( [b_i, b_{i+1}) \) according to the probability density function

\[
p(x \mid b_0, \ldots, b_n, \rho_0, \ldots, \rho_{n-1}) = \rho_i, \text{ for } b_i \leq x < b_{i+1}.
\]

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 \( n \) distribution parameters are calculated as:

\[
\rho_k = \frac{w_k}{S \cdot (b_{k+1} - b_k)} \text{ for } k = 0, \ldots, n - 1,
\]

in which the values \( w_k \), commonly known as the 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 RealType = double>
    class piecewise_constant_distribution {
        public:
            // types
            using result_type = RealType;
            using param_type = unspecified;

            // constructor and reset functions
            piecewise_constant_distribution();
            template<class InputIteratorB, class InputIteratorW>
                piecewise_constant_distribution(InputIteratorB firstB, InputIteratorB lastB,
                                                InputIteratorW firstW);
            template<class UnaryOperation>
                piecewise_constant_distribution(initializer_list<RealType> bl, UnaryOperation fw);
            template<class UnaryOperation>
                piecewise_constant_distribution(size_t nw, RealType xmin, RealType xmax,
                                                UnaryOperation fw);
            explicit piecewise_constant_distribution(const param_type& parm);
            void reset();

            // equality operators
            friend bool operator==(const piecewise_constant_distribution& x,
                                   const piecewise_constant_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;
    };
}
```
template<class charT, class traits>
friend basic_ostream<charT, traits>&
operator<<(basic_istream<charT, traits>& is, const piecewise_constant_distribution& x);
}

piecewise_constant_distribution();

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);

Mandates: Both of

\[
\begin{align*}
&\text{— } \text{is_convertible_v<iterator_traits<InputIteratorB>::value_type, double>} \\
&\text{— } \text{is_convertible_v<iterator_traits<InputIteratorW>::value_type, double>}
\end{align*}
\]

to true.

Preconditions: InputIteratorB and InputIteratorW each meet the C++17InputIterator requirements (25.3.5.3). If \( \text{firstB} == \text{lastB} \) or \( ++\text{firstB} == \text{lastB} \), let \( n = 1, \rho_0 = 1, b_0 = 0, \) 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 \( \text{firstW} \) is at least \( n \), and any \( w_k \) for \( k \geq n \) are ignored by the distribution.

Effects: Constructs a piecewise_constant_distribution object with parameters as specified above.

template<class UnaryOperation>
piecewise_constant_distribution(initializer_list<RealType> bl, UnaryOperation fw);

Mandates: \text{is_invocable_r_v<double, UnaryOperation&, double>} is true.

Effects: Constructs a piecewise_constant_distribution object with parameters taken or calculated from the following values: If \( \text{bl.size()} < 2 \), let \( n = 1, \rho_0 = 1, b_0 = 0, \) and \( b_1 = 1. \) Otherwise, let \( [\text{bl.begin()}, \text{bl.end()}] \) form a sequence \( b_0, \ldots, b_n \), and let \( w_k = f w((b_{k+1} + b_k)/2) \) for \( k = 0, \ldots, n - 1 \).

Complexity: The number of invocations of \( fw \) does not exceed \( n \).

template<class UnaryOperation>

piecewise_constant_distribution(size_t nw, RealType xmin, RealType xmax, UnaryOperation fw);

Mandates: \text{is_invocable_r_v<double, UnaryOperation&, double>} is true.

Preconditions: If \( nw = 0 \), let \( n = 1 \), otherwise let \( n = nw \). The relation \( 0 < \delta = (xmax - xmin)/n \) holds.

Effects: Constructs a piecewise_constant_distribution object with parameters taken or calculated from the following values: Let \( b_k = xmin + k \cdot \delta \) for \( k = 0, \ldots, n \), and \( w_k = fw(b_k + \delta/2) \) for \( k = 0, \ldots, n - 1 \).

Complexity: The number of invocations of \( fw \) does not exceed \( n \).

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 \( p_k \) 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

\[
p(x \mid b_0, \ldots, b_n, p_0, \ldots, p_n) = p_i \cdot \frac{b_{i+1} - x}{b_{i+1} - b_i} + p_{i+1} \cdot \frac{x - b_i}{b_{i+1} - b_i}, \text{ for } b_i \leq x < b_{i+1}.
\]
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:

$$0 < S = \frac{1}{2} \sum_{k=0}^{n-1} (w_k + w_{k+1}) \cdot (b_{k+1} - b_k).$$

namespace std {
    template<class RealType = double>
    class piecewise_linear_distribution {
        public:
            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);
            template<class charT, class traits>
                friend basic_istream<charT, traits>&
                    operator>>(basic_istream<charT, traits>& is, piecewise_linear_distribution& x);
    }

Effects: Constructs a piecewise_linear_distribution object with $n = 1$, $\rho_0 = \rho_1 = 1$, $b_0 = 0$, and $b_1 = 1$. 

§ 28.5.9.6.3
template<class InputIteratorB, class InputIteratorW>
  piecewise_linear_distribution(InputIteratorB firstB, InputIteratorB lastB,
                                 InputIteratorW firstW);

  // Mandates: is_invocable_r_v<double, UnaryOperation&, double> is true.
  // Preconditions: InputIteratorB and InputIteratorW each meet the Cpp17InputIterator requirements
  // (25.3.5.3). If firstB == lastB or ++firstB == lastB, let n = 1, ρ0 = ρ1 = 1, b0 = 0, and b1 = 1.
  // Otherwise, [firstB, lastB] forms a sequence b of length n + 1, the length of the sequence w starting
  // from firstW is at least n + 1, and any wk for k ≥ 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 bl.size() < 2, let n = 1, ρ0 = ρ1 = 1, b0 = 0, and b1 = 1. Otherwise, let
  // [bl.begin(), bl.end()) form a sequence b0, ..., bn, and let wk = fw(bk) for k = 0, ..., n.

  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 nw = 0, let n = 1, otherwise let n = nw. The relation 0 < δ = (xmax − xmin)/n holds.
  // Effects: Constructs a piecewise_linear_distribution object with parameters taken or calculated
  // from the following values: Let bk = xmin + k · δ for k = 0, ..., n, and wk = fw(bk) for k = 0, ..., n.
  // Complexity: The number of invocations of 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 bk when invoked with argument k for k = 0, ..., n.

  vector<result_type> densities() const;

  // Returns: A vector<result_type> whose size member returns n and whose operator[] member
  // returns pk when invoked with argument k for k = 0, ..., 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 C 7.22.2

28.6 Numeric arrays  [numarray]

28.6.1 Header <valarray> synopsis  [valarray.syn]

  #include <initializer_list>

  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 generalized slice out of an array
template<class T> class gslice_array; // a generalized slice out of an array
template<class T> class mask_array; // a masked array
template<class T> class indirect_array; // an indireced 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>&);

\section{28.6.1 1320}
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 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 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 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 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>&);

template<class T> valarray<T> asin (const valarray<T>&);

template<class T> valarray<T> atan (const valarray<T>&);

template<class T> valarray<T> atan2(const valarray<T>&, const valarray<T>&);

template<class T> valarray<T> atan2(const valarray<T>&, const typename valarray<T>::value_type&);

template<class T> valarray<T> atan2(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<T> cos (const valarray<T>&);

template<class T> valarray<T> cosh (const valarray<T>&);

template<class T> valarray<T> exp (const valarray<T>&);

template<class T> valarray<T> log (const valarray<T>&);

template<class T> valarray<T> log10 (const valarray<T>&);
template<class T> valarray<T> pow(const valarray<T>&, const valarray<T>&);

template<class T> valarray<T> pow(const valarray<T>&, const typename valarray<T>::value_type&);

template<class T> valarray<T> pow(const typename valarray<T>::value_type&, const valarray<T>&);

template<class T> valarray<T> sin (const valarray<T>&);

template<class T> valarray<T> sinh (const valarray<T>&);

template<class T> valarray<T> sqrt (const valarray<T>&);

template<class T> valarray<T> tan (const valarray<T>&);

template<class T> valarray<T> tanh (const valarray<T>&);

template<class T> unspecified1 begin(valarray<T>& v);

template<class T> unspecified1 end(valarray<T>& v);

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.

The valarray array classes are defined to be free of certain forms of aliasing, thus allowing operations on these classes to be optimized.

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.

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, 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

namespace std {
  template<class T> class valarray {
  public:
    using value_type = T;
    // 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();
  }
}

Annex B recommends a minimum number of recursively nested template instantiations. This requirement thus indirectly suggests a minimum allowable complexity for valarray expressions.
// 28.6.2.3, 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&);
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&);
valarray& operator&= (const valarray&);
valarray& operator<<=(const valarray&);
valarray& operator>>=(const valarray&);

// 28.6.2.8, member functions
void swap(valarray&) noexcept;

size_t size() const;
T sum() const;
T min() const;
T max() const;

valarray shift (int) const;
valarray cshift(int) const;
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.\footnote{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.}

### 28.6.2.2 Constructors

- **valarray();**
  - **Effects:** Constructs a `valarray` that has zero length.\footnote{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.}

- **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.\footnote{This constructor is the preferred method for converting a C array to a `valarray` object.}

- **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`.\footnote{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(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`.

- **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 \hfill \text{[valarray.assign]}

\text{valarray}\& \text{operator=} (\text{const valarray}\& \text{v});

\hspace{1em} \text{Effects}: Each element of the \text{*this} array is assigned the value of the corresponding element of \text{v}. If the length of \text{v} is not equal to the length of \text{*this}, resizes \text{*this} to make the two arrays the same length, as if by calling \text{resize(v.size())}, before performing the assignment.

\hspace{1em} \text{Postconditions}: \text{size()} == \text{v.size()}. \hfill \text{1}

\hspace{1em} \text{Returns}: \text{*this}. \hfill \text{2}

\text{valarray}\& \text{operator=} (\text{valarray&& \text{v}) noexcept;}

\hspace{1em} \text{Effects}: \text{*this} obtains the value of \text{v}. The value of \text{v} after the assignment is not specified.

\hspace{1em} \text{Returns}: \text{*this}. \hfill \text{3}

\hspace{1em} \text{Complexity}: Linear. \hfill \text{4}

\text{valarray}\& \text{operator=} (\text{initializer_list<T> il});

\hspace{1em} \text{Effects}: Equivalent to: return \text{*this} = \text{valarray(il)}; \hfill \text{5}

\text{valarray}\& \text{operator=} (\text{const T& \text{v});}

\hspace{1em} \text{Effects}: Assigns \text{v} to each element of \text{*this}. \hfill \text{6}

\hspace{1em} \text{Returns}: \text{*this}. \hfill \text{7}

\text{valarray}\& \text{operator=} (\text{const slice_array<T>&});
\text{valarray}\& \text{operator=} (\text{const gslice_array<T>&});
\text{valarray}\& \text{operator=} (\text{const mask_array<T>&});
\text{valarray}\& \text{operator=} (\text{const indirect_array<T>&});

\hspace{1em} \text{Preconditions}: The length of the array to which the argument refers equals \text{size()}. The value of an element in the left-hand side of a \text{valarray} assignment operator does not depend on the value of another element in that left-hand side.

\hspace{1em} These operators allow the results of a generalized subscripting operation to be assigned directly to a \text{valarray}. \hfill \text{8}

28.6.2.4 Element access \hfill \text{[valarray.access]}

\text{const T& \text{operator[]} (\text{size_t n}) const;}
\text{T& \text{operator[]} (\text{size_t n);}}

\hspace{1em} \text{Preconditions}: \text{n} < \text{size()} is true. \hfill \text{1}

\hspace{1em} \text{Returns}: A reference to the corresponding element of the array.

\hspace{1em} \text{[Note 1: The expression \text{a[i]} = \text{q}, \text{a[i]} == \text{q} evaluates to true for any non-constant \text{valarray<T> a}, any \text{T q}, and for any \text{size_t i} such that the value of \text{i} is less than the length of \text{a}. — end note]}

\hspace{1em} \text{Remarks}: The expression \text{offsetof(a[i+j]) == offsetof(a[i]) + j} evaluates to true for all \text{size_t i} and \text{size_t j} such that \text{i+j < a.size()}. \hfill \text{2}

\hspace{1em} The expression \text{offsetof(a[i]) != offsetof(b[j])} evaluates to true for any two arrays \text{a} and \text{b} and for any \text{size_t i} and \text{size_t j} such that \text{i < a.size()} and \text{j < b.size()}. \hfill \text{3}

\hspace{1em} \text{[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 \text{new}, and other techniques to generate efficient \text{valarrays}. — end note]}

\hspace{1em} The reference returned by the subscript operator for an array shall be valid until the member function \text{resize(size_t, T) (28.6.2.8)} is called for that array or until the lifetime of that array ends, whichever happens first. \hfill \text{4}

28.6.2.5 Subset operations \hfill \text{[valarray.sub]}

\hspace{1em} The member \text{operator[]} is overloaded to provide several ways to select sequences of elements from among those controlled by \text{*this}. Each of these operations returns a subset of the array. The const-qualified versions return this subset as a new \text{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 \text{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;

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);

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;

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>("dfhkmo", 6)
  —end example]

gslice_array<T> operator[](const gslice& gslicearr);

Returns: An object that holds references to elements of the controlled sequence selected by gslicearr.

[Example 4:
  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)] = v1;
  // v0 == valarray<char>("abcAeBgCijDlEnFp", 16)
  —end example]

valarray operator[](const valarray<bool>& boolarr) const;

Returns: A valarray containing those elements of the controlled sequence designated by boolarr.

[Example 5:
  const valarray<char> v0("abcdefghijklmnop", 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> operator[](const valarray<bool>& boolarr);

Returns: An object that holds references to elements of the controlled sequence selected by boolarr.

[Example 6:
  valarray<char> v0("abcdefghijklmnop", 16);

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valarray<char> v1("ABC", 3);
const bool vb[] = { false, false, true, true, false, true }
v0[valarray<bool>(vb, 6)] = v1;
// 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("abcdefghijkmnop", 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> operator[] (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("abcdefghijkmnop", 16);
valarray<char> v1("ABCDE", 5);
const size_t vi[] = { 7, 5, 2, 3, 8 }
// v0[valarray<size_t>(vi, 5)] = v1;
// 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);

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.
5 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);

6 Mandates: The indicated operator can be applied to two operands of type T.

7 Effects: Each of these operators applies the indicated operation to each element of *this and v.

8 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;

1 Effects: *this obtains the value of v. v obtains the value of *this.

2 Complexity: Constant.

size_t size() const;

3 Returns: The number of elements in the array.

4 Complexity: Constant time.

T sum() const;

5 Mandates: operator+= can be applied to operands of type T.

6 Preconditions: size() > 0 is true.

7 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;

8 Preconditions: size() > 0 is true.

9 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;

10 Preconditions: size() > 0 is true.

11 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;

12 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 the argument; 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 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.

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 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 [valarray.comparison]

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>&);

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.

28.6.3.4 Specialized algorithms

Effects: Equivalent to x.swap(y).

28.6.4 Class slice

28.6.4.1 Overview
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.

### 28.6.4.2 Constructors

- `slice();`
- `slice(size_t start, size_t length, size_t stride);`
- `slice(const slice&);`

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.*

### 28.6.4.3 Access functions

- `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.

### 28.6.4.4 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();
```

### 28.6.5 Class template `slice_array`

#### 28.6.5.1 Overview

```cpp
namespace std {
  template<class T> class slice_array {
    using value_type = T;

    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&);  // as implied by declaring copy constructor above
    ~slice_array();
    const slice_array& operator=(const slice_array&);  
    void operator=(const T&);  
    slice_array() = delete;  
  };
}
```

This template is a helper template used by the `slice` subscript operator

```cpp
slice_array<T> valarray<T>::operator[](slice);
```

---

243) 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.
It has reference semantics to a subset of an array specified by a \texttt{slice} object.

\textit{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 $1, 4, \ldots, 13$. \textit{— end example}

\subsection*{28.6.5.2 Assignment}

\begin{verbatim}
void operator=(const valarray<T>&) const;
const slice_array& operator=(const slice_array&) const;
\end{verbatim}

These assignment operators have reference semantics, assigning the values of the argument array elements to selected elements of the \texttt{valarray<T>} object to which the \texttt{slice_array} object refers.

\subsection*{28.6.5.3 Compound assignment}

\begin{verbatim}
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;
\end{verbatim}

These compound assignments have reference semantics, applying the indicated operation to the elements of the argument array and selected elements of the \texttt{valarray<T>} object to which the \texttt{slice_array} object refers.

\subsection*{28.6.5.4 Fill function}

\begin{verbatim}
void operator=(const T&) const;
\end{verbatim}

This function has reference semantics, assigning the value of its argument to the elements of the \texttt{valarray<T>} object to which the \texttt{slice_array} object refers.

\section*{28.6.6 The \texttt{gslice} class}

\subsection*{28.6.6.1 Overview}

\begin{verbatim}
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;
    }
}
\end{verbatim}

This class represents a generalized slice out of an array. A \texttt{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.

A \texttt{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 \texttt{valarray} template, which is one-dimensional. The set of one-dimensional index values specified by a \texttt{gslice} are

$$k = s + \sum_j i_j d_j$$

where the multidimensional indices $i_j$ range in value from 0 to $l_j - 1$.

\textit{Example 1:} The \texttt{gslice} specification

\begin{verbatim}
    start = 3
    length = {2, 4, 3}
    stride = {19, 4, 1}
\end{verbatim}
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:

\[
\begin{align*}
(i_0, & \quad i_1, \quad i_2, \quad k) = \\
(0, & \quad 0, \quad 0, \quad 3), \\
(0, & \quad 0, \quad 1, \quad 4), \\
(0, & \quad 0, \quad 2, \quad 5), \\
(0, & \quad 1, \quad 0, \quad 7), \\
(0, & \quad 1, \quad 1, \quad 8), \\
(0, & \quad 1, \quad 2, \quad 9), \\
(0, & \quad 2, \quad 0, \quad 11), \\
(0, & \quad 2, \quad 1, \quad 12), \\
(0, & \quad 2, \quad 2, \quad 13), \\
(0, & \quad 3, \quad 0, \quad 15), \\
(0, & \quad 3, \quad 1, \quad 16), \\
(0, & \quad 3, \quad 2, \quad 17), \\
(1, & \quad 0, \quad 0, \quad 22), \\
(1, & \quad 0, \quad 1, \quad 23), \\
\ldots \\
(1, & \quad 3, \quad 2, \quad 36)
\end{align*}
\]

That is, the highest-ordered index turns fastest. — end example]
28.6.7 Class template gslice_array

28.6.7.1 Overview

```cpp
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:
   ```cpp
   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
   ```cpp
   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

```cpp
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

```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;
```

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

```cpp
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

namespace std {
    template<class T> class mask_array {
        using value_type = T;

        public:

            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;

            mask_array() = delete; // as implied by declaring copy constructor above
    };
}

1 This template is a helper template used by the mask subscript operator:

    mask_array<T> valarray<T>::operator[](const valarray<bool>&).

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).

28.6.8.2 Assignment

void operator=(const valarray<T>&) const;
const mask_array& operator=(const mask_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 mask_array object refers.

28.6.8.3 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 mask_array object refers.

28.6.8.4 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 mask_array object refers.
28.6.9 Class template \texttt{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

\texttt{indirect\_array} T \texttt{valarray\langle} T \rangle \texttt{::operator[] (const valarray<\texttt{size\_t}>&)}.

2 It has reference semantics to a subset of an array specified by an \texttt{indirect\_array}. Thus, the expression \texttt{a[indirect] = b;} has the effect of assigning the elements of \texttt{b} to the elements in \texttt{a} whose indices appear in \texttt{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 \texttt{valarray<T>} object to which it refers.

2 If the \texttt{indirect\_array} specifies an element in the \texttt{valarray<T>} object to which it refers more than once, the behavior is undefined.

3 [\textit{Example 1}:]

int addr[] = \{2, 3, 1, 4, 4\};
valarray<\texttt{size\_t}> indirect(addr, 5);
valarray<\texttt{double}> a(0., 10), b(1., 5);
\texttt{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;

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 indirect_array object 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.

28.6.9.4 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 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&.

2 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);

3 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);

4 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_ILOGB0 see below
#define FP_ILOGBNAN see below
#define MATH_ERRNO see below
#define MATH_ERREXCEPT see below
#define math_errhandling see below
namespace std {
    float acos(float x); // see 16.2
    double acos(double x);
    long double acos(long double x); // see 16.2
    float acosf(float x);
    long double acosl(long double x);

    float asin(float x); // see 16.2
    double asin(double x);
    long double asin(long double x); // see 16.2
    float asinf(float x);
    long double asinl(long double x);

    float atan(float x); // see 16.2
    double atan(double x);
    long double atan(long double x); // see 16.2
    float atanf(float x);
    long double atanl(long double x);

    float atan2(float y, float x); // see 16.2
    double atan2(double y, double x);
    long double atan2(long double y, long double x); // see 16.2
    float atan2f(float y, float x);
    long double atan2l(long double y, long double x);

    float cos(float x); // see 16.2
    double cos(double x);
    long double cos(long double x); // see 16.2
    float cosf(float x);
    long double cosl(long double x);

    float sin(float x); // see 16.2
    double sin(double x);
    long double sin(long double x); // see 16.2
    float sinf(float x);
    long double sinl(long double x);

    float tan(float x); // see 16.2
    double tan(double x);
    long double tan(long double x); // see 16.2
    float tanf(float x);
    long double tanl(long double x);

    float acosh(float x); // see 16.2
    double acosh(double x);
    long double acosh(long double x); // see 16.2
    float acoshf(float x);
    long double acoshl(long double x);

    float asinh(float x); // see 16.2
    double asinh(double x);
    long double asinh(long double x); // see 16.2
    float asinhf(float x);
    long double asinhl(long double x);

    float atanh(float x); // see 16.2
    double atanh(double x);
    long double atanh(long double x); // see 16.2
    float atanhf(float x);
    long double atanhl(long double x);

    float cosh(float x); // see 16.2
    double cosh(double x);
    long double cosh(long double x); // see 16.2
    float coshf(float x);
    long double coshl(long double x);
float coshf(float x);
long double coshl(long double x);

float sinh(float x); // see 16.2
double sinh(double x);
long double sinh(long double x); // see 16.2
float sinhf(float x);
long double sinhl(long double x);

float tanhf(float x); // see 16.2
double tanh(double x);
long double tanh(long double x); // see 16.2
float tanhf(float x);
long double tanhl(long double x);

float exp(float x); // see 16.2
double exp(double x);
long double exp(long double x); // see 16.2
float expf(float x);
long double expl(long double x);

float exp2(float x); // see 16.2
double exp2(double x);
long double exp2(long double x); // see 16.2
float exp2f(float x);
long double exp2l(long double x);

float expm1(float x); // see 16.2
double expm1(double x);
long double expm1(long double x); // see 16.2
float expm1f(float x);
long double expm1l(long double x);

constexpr float frexp(float value, int* exp); // see 16.2
cconstexpr double frexp(double value, int* exp);
cconstexpr long double frexp(long double value, int* exp); // see 16.2
constexpr float frexpf(float value, int* exp);
cconstexpr long double frexpl(long double value, int* exp);

constexpr int ilogb(float x); // see 16.2
cconstexpr int ilogb(double x);
cconstexpr int ilogb(long double x); // see 16.2
constexpr int ilogbf(float x);
cconstexpr int ilogbl(long double x);

cconstexpr float ldexp(float x, int exp); // see 16.2
cconstexpr double ldexp(double x, int exp);
cconstexpr long double ldexp(long double x, int exp); // see 16.2
constexpr float ldexpf(float x, int exp);
cconstexpr long double ldexpl(long double x, int exp);

float log(float x); // see 16.2
double log(double x);
long double log(long double x); // see 16.2
float logf(float x);
long double logl(long double x);

float log10(float x); // see 16.2
double log10(double x);
long double log10(long double x); // see 16.2
float log10f(float x);
long double log10l(long double x);
float log1p(float x); // see 16.2
double log1p(double x);
long double log1p(long double x); // see 16.2
float log1pf(float x);
long double log1pl(long double x);

float log2(float x); // see 16.2
double log2(double x);
long double log2(long double x); // see 16.2
float log2f(float x);
long double log2l(long double x);

constexpr float logb(float x); // see 16.2
custom double logb(double x);
custom long double logb(long double x); // see 16.2
constexpr float logbf(float x);
custom long double logbl(long double x);

constexpr float modf(float value, float* iptr); // see 16.2
custom double modf(double value, double* iptr);
custom long double modf(long double value, long double* iptr); // see 16.2
constexpr float modff(float value, float* iptr);
custom long double modfl(long double value, long double* iptr);

constexpr float scalbn(float x, int n); // see 16.2
custom double scalbn(double x, int n);
custom long double scalbn(long double x, int n); // see 16.2
constexpr float scalbnf(float x, int n);
custom long double scalbln(long double x, int n);

float cbrt(float x); // see 16.2
double cbrt(double x);
long double cbrt(long double x); // see 16.2
float cbrtf(float x);
long double cbrtl(long double x);

float hypot(float x, float y); // see 16.2
double hypot(double x, double y);
long double hypot(long double x, long double y); // see 16.2
float hypotf(float x, float y);
long double hypotl(long double x, long double y);

// 28.7.2, absolute values
constexpr int abs(int j);
custom long int abs(long int j);
custom long long int abs(long long int j);
custom float abs(float j);
custom double abs(double j);
custom long double abs(long double j);

constexpr float fabs(float x); // see 16.2
custom double fabs(double x);
custom long double fabs(long double x); // see 16.2
constexpr float fabsf(float x);
custom long double fabsl(long double x);

float hypot(float x, float y, float z); // 28.7.3, three-dimensional hypotenuse
float hypot(float x, float y, float z);
double hypot(double x, double y, double z);
long double hypot(long double x, long double y, long double z);

float pow(float x, float y);  // see § 16.2
double pow(double x, double y);
long double pow(long double x, long double y);  // see § 16.2
float powf(float x, float y);
long double powl(long double x, long double y);

float sqrt(float x);  // see § 16.2
double sqrt(double x);
long double sqrt(long double x);  // see § 16.2
float sqrtf(float x);
long double sqrtl(long double x);

float erf(float x);  // see § 16.2
double erf(double x);
long double erf(long double x);  // see § 16.2
float erff(float x);
long double erfl(long double x);

float erfc(float x);  // see § 16.2
double erfc(double x);
long double erfc(long double x);  // see § 16.2
float erfcf(float x);
long double erfcl(long double x);

float lgamma(float x);  // see § 16.2
double lgamma(double x);
long double lgamma(long double x);  // see § 16.2
float lgammaf(float x);
long double lgammal(long double x);

float tgamma(float x);  // see § 16.2
double tgamma(double x);
long double tgamma(long double x);  // see § 16.2
float tgammaf(float x);
long double tgammal(long double x);

constexpr float ceil(float x);  // see § 16.2
cconstexpr double ceil(double x);
cconstexpr long double ceil(long double x);  // see § 16.2
cconstexpr float ceilf(float x);
cconstexpr long double ceill(long double x);

constexpr float floor(float x);  // see § 16.2
cconstexpr double floor(double x);
cconstexpr long double floor(long double x);  // see § 16.2
cconstexpr float floorf(float x);
cconstexpr long double floorl(long double x);

float nearbyint(float x);  // see § 16.2
double nearbyint(double x);
long double nearbyint(long double x);  // see § 16.2
float nearbyintf(float x);
long double nearbyintl(long double x);

float rint(float x);  // see § 16.2
double rint(double x);
long double rint(long double x);  // see § 16.2
float rintf(float x);
long double rintl(long double x);
long int lrint(float x); // see 16.2
long int lrint(double x);
long int lrint(long double x); // see 16.2
long int lrintf(float x);
long int llrint(long double x);
long long int llrint(float x);
long long int llrint(double x);
long long int llrint(long double x);
long long int llrintf(float x);
long long int llrintl(long double x);

constexpr float round(float x); // see 16.2
constexpr double round(double x);
constexpr long double round(long double x); // see 16.2
constexpr float roundf(float x);
constexpr long double roundl(long double x);

constexpr long int lround(float x); // see 16.2
constexpr long int lround(double x);
constexpr long int lround(long double x);
constexpr long int lroundf(float x);
constexpr long int lroundl(long double x);

constexpr long long int llround(float x); // see 16.2
constexpr long long int llround(double x);
constexpr long long int llround(long double x);
constexpr long long int llroundf(float x);
constexpr long long int llroundl(long double x);

constexpr float trunc(float x); // see 16.2
constexpr double trunc(double x);
constexpr long double trunc(long double x); // see 16.2
constexpr float truncf(float x);
constexpr long double truncl(long double x);

constexpr float fmod(float x, float y); // see 16.2
constexpr double fmod(double x, double y);
constexpr long double fmod(long double x, long double y); // see 16.2
constexpr float fmodf(float x, float y);
constexpr long double fmodl(long double x, long double y);

constexpr float remainder(float x, float y); // see 16.2
constexpr double remainder(double x, double y);
constexpr long double remainder(long double x, long double y); // see 16.2
constexpr float remainderf(float x, float y);
constexpr long double remainderl(long double x, long double y);

constexpr float remquo(float x, float y, int* quo); // see 16.2
constexpr double remquo(double x, double y, int* quo);
constexpr long double remquo(long double x, long double y, int* quo); // see 16.2
constexpr float remquof(float x, float y, int* quo);
constexpr long double remquol(long double x, long double y, int* quo);

constexpr float copysign(float x, float y); // see 16.2
constexpr double copysign(double x, double y);
constexpr long double copysign(long double x, long double y); // see 16.2
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 float nextafter(float x, float y); // see 16.2
constexpr double nextafter(double x, double y);
constexpr long double nextafter(long double x, long double y); // see 16.2
constexpr float nextafterf(float x, float y);
constexpr long double nextafterl(long double x, long double y);
constexpr float nexttoward(float x, long double y); // see 16.2
constexpr double nexttoward(double x, long double y);
constexpr long double nexttowardl(long double x, long double y);
constexpr float nexttowardf(float x, long double y);
constexpr long double nexttowardl(long double x, long double y);

constexpr float fdim(float x, float y); // see 16.2
constexpr double fdim(double x, double y);
constexpr long double fdim(long double x, long double y); // see 16.2
constexpr float fdimf(float x, float y);
constexpr long double fdiml(long double x, long double y);

constexpr float fmax(float x, float y); // see 16.2
constexpr double fmax(double x, double y);
constexpr long double fmax(long double x, long double y); // see 16.2
constexpr float fmaxf(float x, float y);
constexpr long double fmaxl(long double x, long double y);

constexpr float fmin(float x, float y); // see 16.2
constexpr double fmin(double x, double y);
constexpr long double fmin(long double x, long double y); // see 16.2
constexpr float fminf(float x, float y);
constexpr long double fminl(long double x, long double y);

constexpr float fma(float x, float y, float z); // see 16.2
constexpr double fma(double x, double y, double z);
constexpr long double fma(long double x, long double y, long double z); // see 16.2
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 float lerp(float a, float b, float t) noexcept;
constexpr double lerp(double a, double b, double t) noexcept;
constexpr long double lerp(long double a, long double b, long double t) noexcept;

// 28.7.5, classification / comparison functions
constexpr int fpclassify(float x);
constexpr int fpclassify(double x);
constexpr int fpclassify(long double x);

constexpr bool infinite(float x);
constexpr bool infinite(double x);
constexpr bool infinite(long double x);

constexpr bool isninf(float x);
constexpr bool isninf(double x);
constexpr bool isninf(long double x);

constexpr bool innan(float x);
constexpr bool innan(double x);
constexpr bool innan(long double x);

constexpr bool isnormal(float x);
constexpr bool isnormal(double x);
constexpr bool isnormal(long double x);

constexpr bool signbit(float x);
constexpr bool signbit(double x);
constexpr bool signbit(long double x);
constexpr bool isgreater(float x, float y);
constexpr bool isgreater(double x, double y);
constexpr bool isgreater(long double x, long double y);
constexpr bool isgreater_equal(float x, float y);
constexpr bool isgreater_equal(double x, double y);
constexpr bool isgreater_equal(long double x, long double y);
constexpr bool isless(float x, float y);
constexpr bool isless(double x, double y);
constexpr bool isless(long double x, long double y);
constexpr bool isless_equal(float x, float y);
constexpr bool isless_equal(double x, double y);
constexpr bool isless_equal(long double x, long double y);
constexpr bool isless_greater(float x, float y);
constexpr bool isless_greater(double x, double y);
constexpr bool isless_greater(long double x, long double y);
constexpr bool isunordered(float x, float y);
constexpr bool isunordered(double x, double y);
constexpr bool isunordered(long double x, long double y);

// 28.7.6, mathematical special functions

// 28.7.6.2, associated Laguerre polynomials
double assoc_laguerre(unsigned n, unsigned m, double 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
double assoc_legendre(unsigned l, unsigned m, double 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
double beta(double x, double 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
double comp_ellint_1(double 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
double comp_ellint_2(double 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
double comp_ellint_3(double k, double 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
double cyl_bessel_i(double nu, double 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
double cyl_bessel_j(double nu, double 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
double cyl_bessel_k(double nu, double 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
double cyl_neumann(double nu, double 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
double ellint_1(double k, double 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
double ellint_2(double k, double 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
double ellint_3(double k, double nu, double 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
double expint(double x);
float expintf(float x);
long double expintl(long double x);

// 28.7.6.16, Hermite polynomials
double hermite(unsigned n, double x);
float hermitef(unsigned n, float x);
long double hermitel(unsigned n, long double x);

// 28.7.6.17, Laguerre polynomials
double laguerre(unsigned n, double x);
float laguerref(unsigned n, float x);
long double laguerrel(unsigned n, long double x);

// 28.7.6.18, Legendre polynomials
double legendre(unsigned l, double x);
float legendref(unsigned l, float x);
long double legendrel(unsigned l, long double x);

// 28.7.6.19, Riemann zeta function
double riemann_zeta(double x);
float riemann_zetaf(float x);
long double riemann_zetal(long double x);

// 28.7.6.20, spherical Bessel functions of the first kind
double sph_bessel(unsigned n, double 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
double sph_legendre(unsigned l, unsigned m, double 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
double sph_neumann(unsigned n, double 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 set of overloaded functions within `<cmath>`, with the exception of `abs`, there shall be additional overloads sufficient to ensure:

(2.1) — If any argument of arithmetic type corresponding to a `double` parameter has type `long double`, then all arguments of arithmetic type (6.8.2) corresponding to `double` parameters are effectively cast to `long double`.

(2.2) — Otherwise, if any argument of arithmetic type corresponding to a `double` parameter has type `double` or an integer type, then all arguments of arithmetic type corresponding to `double` parameters are effectively cast to `double`.

(2.3) — [Note 2: Otherwise, all arguments of arithmetic type corresponding to `double` parameters have type `float`. — end note]

[Note 3: `abs` is exempted from these rules in order to stay compatible with C. — end note]

See also: ISO C 7.12

28.7.2 Absolute values

1 [c.math.abs]

constexpr int abs(int j);
constexpr long int abs(long int j);
constexpr long long int abs(long long int j);
constexpr float abs(float j);
constexpr double abs(double j);
constexpr long double abs(long double j);

2 Effects: The `abs` functions have the semantics specified in the C standard library for the functions `abs`, `labs`, `llabs`, `fabsf`, `fabs`, and `fabsl`.

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: Arguments that can be promoted to `int` are permitted for compatibility with C. — end note]

See also: ISO C 7.12.7.2, 7.22.6.1

28.7.3 Three-dimensional hypotenuse

[c.math.hypot3]

float hypot(float x, float y, float z);
double hypot(double x, double y, double z);
long double hypot(long double x, long double y, long double z);

1 Returns: $\sqrt{x^2 + y^2 + z^2}$.

28.7.4 Linear interpolation

[c.math.lerp]

constexpr float lerp(float a, float b, float t) noexcept;
castexpr double lerp(double a, double b, double t) noexcept;
costexpr long double lerp(long double a, long double b, long double t) noexcept;

1 Returns: $a + t(b - a)$.
Remarks: Let \( r \) be the value returned. If isfinite(a) \&\& isfinite(b), then:

\[ \begin{align*}
(2.1) & \quad \text{If } t == 0, \text{ then } r == a. \\
(2.2) & \quad \text{If } t == 1, \text{ then } r == b. \\
(2.3) & \quad \text{If } t >= 0 \&\& t <= 1, \text{ then isfinite(r).} \\
(2.4) & \quad \text{If isfinite(t) \&\& a == b, then } r == a. \\
(2.5) & \quad \text{If isfinite(t) || !isnan(t) \&\& b-a != 0, then !isnan(r).}
\end{align*} \]

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 \( CMP(lerp(a, b, t_2), lerp(a, b, t_1)) \), \( CMP(t_2, t_1) \), and \( CMP(b, a) \) is non-negative.

### 28.7.5 Classification / comparison functions

The classification / comparison functions behave the same as the C macros with the corresponding names defined in the C standard library. Each function is overloaded for the three floating-point types.

See also: ISO C 7.12.3, 7.12.4

### 28.7.6 Mathematical special functions

#### 28.7.6.1 General

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:

\[ \begin{align*}
(1.1) & \quad \text{the function description’s Returns: element explicitly specifies a domain and those argument values fall outside the specified domain, or} \\
(1.2) & \quad \text{the corresponding mathematical function value has a nonzero imaginary component, or} \\
(1.3) & \quad \text{the corresponding mathematical function is not mathematically defined.} \quad \text{(244)}
\end{align*} \]

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

\[
\begin{align*}
\text{double} & \quad \text{assoc_laguerre(unsigned n, unsigned m, double x);} \\
\text{float} & \quad \text{assoc_laguerref(unsigned n, unsigned m, float x);} \\
\text{long double} & \quad \text{assoc_laguerrel(unsigned n, unsigned m, long double x);} \\
\end{align*}
\]

**Effects:** These functions compute the associated Laguerre polynomials of their respective arguments \( n \), \( m \), and \( x \).

**Returns:**

\[
L_n^m(x) = (-1)^m \frac{d^m}{dx^m} L_{n+m}(x), \quad \text{for } x \geq 0,
\]

where \( n \) is \( n \), \( m \) is \( m \), and \( x \) is \( x \).

**Remarks:** The effect of calling each of these functions is implementation-defined if \( n >= 128 \) or if \( m >= 128 \).

#### 28.7.6.3 Associated Legendre functions

\[
\begin{align*}
\text{double} & \quad \text{assoc_legendre(unsigned l, unsigned m, double x);} \\
\text{float} & \quad \text{assoc_legendref(unsigned l, unsigned m, float x);} \\
\text{long double} & \quad \text{assoc_legendrel(unsigned l, unsigned m, long double x);} \\
\end{align*}
\]

**Effects:** These functions compute the associated Legendre functions of their respective arguments \( l \), \( m \), and \( x \).

**Returns:**

\[
P_l^m(x) = (1 - x^2)^{m/2} \frac{d^m}{dx^m} P_l(x), \quad \text{for } |x| \leq 1,
\]

where \( l \) is \( l \), \( m \) is \( m \), and \( x \) is \( x \).

**Remarks:** The effect of calling each of these functions is implementation-defined if \( l >= 128 \).

---

244) 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.
28.7.6.4 Beta function

\texttt{double beta(double x, double y);}  
\texttt{float betaf(float x, float y);}  
\texttt{long double betal(long double x, long double y);}  

\textbf{Effects:} These functions compute the beta function of their respective arguments \(x\) and \(y\).

\textbf{Returns:}

\[ B(x, y) = \frac{\Gamma(x) \Gamma(y)}{\Gamma(x + y)} , \quad \text{for } x > 0, \ y > 0, \]

where \(x\) is \(x\) and \(y\) is \(y\).

28.7.6.5 Complete elliptic integral of the first kind

\texttt{double comp_ellint_1(double k);}  
\texttt{float comp_ellint_1f(float k);}  
\texttt{long double comp_ellint_1l(long double k);}  

\textbf{Effects:} These functions compute the complete elliptic integral of the first kind of their respective arguments \(k\).

\textbf{Returns:}

\[ K(k) = F(k, \pi/2) , \quad \text{for } |k| \leq 1, \]

where \(k\) is \(k\).

See also 28.7.6.12.

28.7.6.6 Complete elliptic integral of the second kind

\texttt{double comp_ellint_2(double k);}  
\texttt{float comp_ellint_2f(float k);}  
\texttt{long double comp_ellint_2l(long double k);}  

\textbf{Effects:} These functions compute the complete elliptic integral of the second kind of their respective arguments \(k\).

\textbf{Returns:}

\[ E(k) = E(k, \pi/2) , \quad \text{for } |k| \leq 1, \]

where \(k\) is \(k\).

See also 28.7.6.13.

28.7.6.7 Complete elliptic integral of the third kind

\texttt{double comp_ellint_3(double k, double nu);}  
\texttt{float comp_ellint_3f(float k, float nu);}  
\texttt{long double comp_ellint_3l(long double k, long double nu);}  

\textbf{Effects:} These functions compute the complete elliptic integral of the third kind of their respective arguments \(k\) and \(\nu\).

\textbf{Returns:}

\[ \Pi(\nu, k) = \Pi(\nu, k, \pi/2) , \quad \text{for } |k| \leq 1, \]

where \(k\) is \(k\) and \(\nu\) is \(\nu\).

See also 28.7.6.14.

28.7.6.8 Regular modified cylindrical Bessel functions

\texttt{double cyl_bessel_i(double nu, double x);}  
\texttt{float cyl_bessel_if(float nu, float x);}  
\texttt{long double cyl_bessel_il(long double nu, long double x);}  

\textbf{Effects:} These functions compute the regular modified cylindrical Bessel functions of their respective arguments \(\nu\) and \(x\).

\textbf{Returns:}

\[ I_{\nu}(x) = i^{-\nu} J_{\nu}(ix) = \sum_{k=0}^{\infty} \frac{(x/2)^{\nu+2k}}{k! \Gamma(\nu + k + 1)} , \quad \text{for } x \geq 0, \]
where \( \nu \) is \( nu \) and \( x \) is \( x \).

**Remarks**: The effect of calling each of these functions is implementation-defined if \( nu \geq 128 \).

See also 28.7.6.9.

### 28.7.6.9 Cylindrical Bessel functions of the first kind

[\texttt{sf.cmath.cyl.bessel.j}]

double cyl_bessel_j(double nu, double x);
float cyl_bessel_jf(float nu, float x);
long double cyl_bessel_jl(long double nu, long double x);

**Effects**: These functions compute the cylindrical Bessel functions of the first kind of their respective arguments \( nu \) and \( x \).

**Returns**:

\[
J_\nu(x) = \sum_{k=0}^{\infty} \frac{(-1)^k (x/2)^{\nu+2k}}{k! \Gamma(\nu + k + 1)}, \quad \text{for} \ x \geq 0,
\]

where \( \nu \) is \( nu \) and \( x \) is \( x \).

**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

[\texttt{sf.cmath.cyl.bessel.k}]

double cyl_bessel_k(double nu, double x);
float cyl_bessel_kf(float nu, float 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**:

\[
K_\nu(x) = (\pi/2)^{\nu+1} (J_\nu(ix) + iN_\nu(ix)) = \begin{cases} 
\frac{\pi I_{-\nu}(x) - I_\nu(x)}{\sin \nu \pi}, & \text{for} \ x \geq 0 \text{ and non-integral} \ \nu \\
\frac{\pi}{2} \lim_{\mu \to \nu} \frac{I_{-\mu}(x) - I_\mu(x)}{\sin \mu \pi}, & \text{for} \ x \geq 0 \text{ and integral} \ \nu
\end{cases}
\]

where \( \nu \) is \( nu \) and \( x \) is \( x \).

**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

[\texttt{sf.cmath.cyl.neumann}]

double cyl_neumann(double nu, double x);
float cyl_neumannf(float nu, float 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**:

\[
N_\nu(x) = \begin{cases} 
\frac{J_\nu(x) \cos \nu \pi - J_{-\nu}(x)}{\sin \nu \pi}, & \text{for} \ x \geq 0 \text{ and non-integral} \ \nu \\
\lim_{\mu \to \nu} \frac{J_\mu(x) \cos \mu \pi - J_{-\mu}(x)}{\sin \mu \pi}, & \text{for} \ x \geq 0 \text{ and integral} \ \nu
\end{cases}
\]

where \( \nu \) is \( nu \) and \( x \) is \( x \).

**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

```c
double ellint_1(double k, double phi);
float ellint_1f(float k, float 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**: 

$$F(k, \phi) = \int_{0}^{\phi} \frac{d\theta}{\sqrt{1 - k^2 \sin^2 \theta}}, \text{ for } |k| \leq 1,$$

where $k$ is $k$ and $\phi$ is $\phi$.

28.7.6.13 Incomplete elliptic integral of the second kind

```c
double ellint_2(double k, double phi);
float ellint_2f(float k, float 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**: 

$$E(k, \phi) = \int_{0}^{\phi} \sqrt{1 - k^2 \sin^2 \theta} d\theta, \text{ for } |k| \leq 1,$$

where $k$ is $k$ and $\phi$ is $\phi$.

28.7.6.14 Incomplete elliptic integral of the third kind

```c
double ellint_3(double k, double nu, double phi);
float ellint_3f(float k, float nu, float phi);
long double ellint_3l(long double k, long double nu, long double phi);
```

**Effects**: These functions compute the incomplete elliptic integral of the third kind of their respective arguments $k$, $nu$, and $\phi$ ($\phi$ measured in radians).

**Returns**: 

$$\Pi(\nu, k, \phi) = \int_{0}^{\phi} \frac{d\theta}{(1 - \nu \sin^2 \theta)\sqrt{1 - k^2 \sin^2 \theta}}, \text{ for } |k| \leq 1,$$

where $\nu$ is $nu$, $k$ is $k$, and $\phi$ is $\phi$.

28.7.6.15 Exponential integral

```c
double expint(double x);
float expintf(float x);
long double expintl(long double x);
```

**Effects**: These functions compute the exponential integral of their respective arguments $x$.

**Returns**: 

$$\text{Ei}(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt$$

where $x$ is $x$.

28.7.6.16 Hermite polynomials

```c
double hermite(unsigned n, double x);
float hermitef(unsigned n, float x);
long double hermitel(unsigned n, long double x);
```

**Effects**: These functions compute the Hermite polynomials of their respective arguments $n$ and $x$.

**Returns**: 

$$H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2}$$

where $n$ is $n$ and $x$ is $x$.

**Remarks**: The effect of calling each of these functions is implementation-defined if $n \geq 128$. 

§ 28.7.6.16
28.7.6.17  Laguerre polynomials

double     laguerre(unsigned n, double x);
float      laguerref(unsigned n, float x);
long double laguerrel(unsigned n, long double x);

Effects: These functions compute the Laguerre polynomials of their respective arguments \( n \) and \( x \).

Returns:

\[ L_n(x) = e^x \frac{d^n}{dx^n} (x^n e^{-x}) \text{, for } x \geq 0, \]

where \( n \) is \( n \) and \( x \) is \( x \).

Remarks: The effect of calling each of these functions is implementation-defined if \( n \geq 128 \).

28.7.6.18  Legendre polynomials

double     legendre(unsigned l, double x);
float      legendref(unsigned l, float x);
long double legendrel(unsigned l, long double x);

Effects: These functions compute the Legendre polynomials of their respective arguments \( l \) and \( x \).

Returns:

\[ P_l(x) = \frac{1}{2^l l!} \frac{d^l}{dx^l} (x^2 - 1)^l \text{, for } |x| \leq 1, \]

where \( l \) is \( l \) and \( x \) is \( x \).

Remarks: The effect of calling each of these functions is implementation-defined if \( l \geq 128 \).

28.7.6.19  Riemann zeta function

double     riemann_zeta(double x);
float      riemann_zetaf(float x);
long double riemann_zetal(long double x);

Effects: These functions compute the Riemann zeta function of their respective arguments \( x \).

Returns:

\[ \zeta(x) = \begin{cases} 
\sum_{k=1}^{\infty} k^{-x}, & \text{for } x > 1 \\
\frac{1}{1 - 2^{1-x}} \sum_{k=1}^{\infty} (-1)^{k-1} k^{-x}, & \text{for } 0 \leq x \leq 1 \\
2^x \pi^{x-1} \sin(\frac{\pi x}{2}) \Gamma(1 - x) \zeta(1 - x), & \text{for } x < 0 
\end{cases} \]

where \( x \) is \( x \).

28.7.6.20  Spherical Bessel functions of the first kind

double     sph_bessel(unsigned n, double x);
float      sph_besself(unsigned n, float x);
long double sph_bessell(unsigned n, long double x);

Effects: These functions compute the spherical Bessel functions of the first kind of their respective arguments \( n \) and \( x \).

Returns:

\[ j_n(x) = (\pi/2x)^{1/2} J_{n+1/2}(x) \text{, for } x \geq 0, \]

where \( n \) is \( n \) and \( x \) is \( x \).

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

```c
double sph_legendre(unsigned l, unsigned m, double theta);
float sph_legendref(unsigned l, unsigned m, float theta);
long double sph_legendrel(unsigned l, unsigned m, long double theta);
```

**Effects:** These functions compute the spherical associated Legendre functions of their respective arguments \( l \), \( m \), and \( \theta \) (\( \theta \) measured in radians).

**Returns:**

\[
Y^m_\ell(\theta, 0) = (-1)^m \left[ \frac{(2\ell + 1)}{4\pi} \frac{\ell - m)!}{(\ell + m)!} \right]^{1/2} P^m_\ell(\cos \theta)e^{im\phi}, \quad \text{for } |m| \leq \ell,
\]

where \( l \) is \( l \), \( m \) is \( m \), and \( \theta \) is \( \theta \).

**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

```c
double sph_neumann(unsigned n, double x);
float sph_neumannf(unsigned n, float x);
long double sph_neumannl(unsigned n, long double x);
```

**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 \( x \).

**Returns:**

\[
n_n(x) = (\pi/2x)^{1/2}N_{n+1/2}(x), \quad \text{for } x \geq 0,
\]

where \( n \) is \( n \) and \( x \) is \( x \).

**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

```c
namespace std::numbers {
    template<class T> inline constexpr T e_v = unspecified;
    template<class T> inline constexpr T log2e_v = unspecified;
    template<class T> inline constexpr T log10e_v = unspecified;
    template<class T> inline constexpr T pi_v = unspecified;
    template<class T> inline constexpr T inv_pi_v = unspecified;
    template<class T> inline constexpr T inv_sqrtpi_v = unspecified;
    template<class T> inline constexpr T ln2_v = unspecified;
    template<class T> inline constexpr T ln10_v = unspecified;
    template<class T> inline constexpr T sqrt2_v = unspecified;
    template<class T> inline constexpr T sqrt3_v = unspecified;
    template<class T> inline constexpr T inv_sqrt3_v = unspecified;
    template<class T> inline constexpr T egamma_v = unspecified;
    template<class T> inline constexpr T phi_v = unspecified;
    template<floating_point T> inline constexpr T e_v<T> = see below;
    template<floating_point T> inline constexpr T log2e_v<T> = see below;
    template<floating_point T> inline constexpr T log10e_v<T> = see below;
    template<floating_point T> inline constexpr T pi_v<T> = see below;
    template<floating_point T> inline constexpr T inv_pi_v<T> = see below;
    template<floating_point T> inline constexpr T inv_sqrtpi_v<T> = see below;
    template<floating_point T> inline constexpr T ln2_v<T> = see below;
    template<floating_point T> inline constexpr T ln10_v<T> = see below;
    template<floating_point T> inline constexpr T sqrt2_v<T> = see below;
    template<floating_point T> inline constexpr T sqrt3_v<T> = see below;
    template<floating_point T> inline constexpr T inv_sqrt3_v<T> = see below;
    template<floating_point T> inline constexpr T egamma_v<T> = see below;
    template<floating_point T> inline constexpr T phi_v<T> = see below;
}
```
template<floating_point T> inline 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
[math.constants]

1 The library-defined partial specializations of mathematical constant variable templates are initialized with the nearest representable values of $e$, $\log_2 e$, $\log_{10} e$, $\pi$, $\frac{1}{\pi}$, $\ln 2$, $\ln 10$, $\sqrt{2}$, $\sqrt{3}$, $\frac{1}{\sqrt{3}}$, 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.
29  Time library

29.1 General

This Clause describes the chrono library (29.2) and various C functions (29.14) that provide generally useful time utilities, as summarized in Table 94.

Table 94: Time library summary

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2. Let `STATICALLY-WIDEN<

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>
    inline 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> inline constexpr bool is_clock_v = is_clock<T>::value;
```
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 Period, class Rep2>
constexpr duration<common_type_t<Rep1, Rep2>, Period>
operator*(const duration<Rep1, Period>& d, const Rep2& s);

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);

// 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);
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);

// 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 35 bits>;
using minutes     = 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);

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);

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);

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);

// 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);

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator<( const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator<=(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator>( const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& rhs);

template<class Clock, class Duration1, class Duration2>
    constexpr bool operator>=(const time_point<Clock, Duration1>& lhs, const time_point<Clock, Duration2>& 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);

// 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);

§ 29.2
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;

template<class Duration>
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;

template<class Duration>
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;

template<class Duration>
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);

§ 29.2
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);

// 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;

cconstexpr bool operator==(const day& x, const day& y) noexcept;
cconstexpr strong_ordering operator<=>(const day& x, const day& y) noexcept;

cconstexpr day operator+(const day& x, const days& y) noexcept;
cconstexpr day operator+(const days& x, const day& y) noexcept;
cconstexpr day operator-(const day& x, const days& y) noexcept;
cconstexpr days 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;

cconstexpr bool operator==(const month& x, const month& y) noexcept;
cconstexpr strong_ordering operator<=>(const month& x, const month& y) noexcept;

cconstexpr month operator+(const month& x, const months& y) noexcept;
cconstexpr month operator+(const months& x, const month& y) noexcept;
cconstexpr month operator-(const month& x, const months& y) noexcept;
cconstexpr 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;

cconstexpr bool operator==(const year& x, const year& y) noexcept;
cconstexpr strong_ordering operator<=>(const year& x, const year& y) noexcept;

cconstexpr year operator+(const year& x, const years& y) noexcept;
cconstexpr year operator+(const years& x, const year& y) noexcept;
cconstexpr year operator-(const year& x, const years& y) noexcept;
cconstexpr 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);

// 29.8.10, class month_day_last
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);

// 29.8.11, class month_weekday
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);

// 29.8.12, class month_weekday_last
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);

// 29.8.13, class year_month
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);

// 29.8.14, class year_month_day
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 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;
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;

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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, const weekday_indexed& wdi) noexcept;
constexpr month_day_last
    operator/(int m, const weekday_indexed& wdi) noexcept;
constexpr month_day_last
    operator/(const weekday_indexed& wdi, const month& m) noexcept;
constexpr month_day_last
    operator/(const weekday_indexed& wdi, 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;

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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_day_last
    operator/(const year_month_day_last& mld, int y) noexcept;
constexpr year_month_day_last
    operator/(const year_month_day_last& mld, 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);
    template<class Duration>
        constexpr bool operator< (const leap_second& x, const sys_time<Duration>& y);
    template<class Duration>
        constexpr bool operator< (const sys_time<Duration>& x, const leap_second& y);
    template<class Duration>
        constexpr bool operator> (const leap_second& x, const sys_time<Duration>& y);
    template<class Duration>
        constexpr bool operator> (const sys_time<Duration>& x, const leap_second& y);
    template<class Duration>
        constexpr bool operator<=(const leap_second& x, const sys_time<Duration>& y);
    template<class Duration>
        constexpr bool operator<=(const sys_time<Duration>& x, const leap_second& y);
    template<class Duration>
        constexpr bool operator>=(const leap_second& x, const sys_time<Duration>& y);
    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);
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);

namespace std {
    template<class Rep, class Period, class charT>
    struct formatter<chrono::duration<Rep, Period>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::sys_time<Duration>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::utc_time<Duration>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::tai_time<Duration>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::gps_time<Duration>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::file_time<Duration>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::local_time<Duration>, charT>;
    template<class Duration, class charT>
    struct formatter<chrono::local_time_format<Duration>, charT>;
    template<class charT> struct formatter<chrono::day, charT>;
    template<class charT> struct formatter<chrono::month, charT>;
    template<class charT> struct formatter<chrono::year, charT>;
    template<class charT> struct formatter<chrono::weekday, charT>;
    template<class charT> struct formatter<chrono::weekday_indexed, charT>;
    template<class charT> struct formatter<chrono::weekday_last, charT>;
    template<class charT> struct formatter<chrono::month_day, charT>;
    template<class charT> struct formatter<chrono::month_day_last, charT>;
    template<class charT> struct formatter<chrono::month_weekday, charT>;
    template<class charT> struct formatter<chrono::month_weekday_last, charT>;
    template<class charT> struct formatter<chrono::year_month, charT>;
    template<class charT> struct formatter<chrono::year_month_day, charT>;
    template<class charT> struct formatter<chrono::year_month_day_last, charT>;
    template<class charT> struct formatter<chrono::year_month_weekday, charT>;
    template<class charT> struct formatter<chrono::year_month_weekday_last, charT>;
    template<class Rep, class Period, class charT>
    struct formatter<chrono::hh_mm_ss<duration<Rep, Period>>, charT>;
    template<class charT> struct formatter<chrono::sys_info, charT>;
    template<class charT> struct formatter<chrono::local_info, charT>;
    template<class Duration, class TimeZonePtr, class charT>
    struct formatter<chrono::zoned_time<Duration, TimeZonePtr>, charT>;
}

namespace std::chrono {
    template<class charT, class Parsable>
    unspecified
    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);

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template<class charT, class traits, class Alloc, class Parsable>
unspecified
parse(const charT* fmt, Parsable& tp,
basic_string<charT, traits, Alloc>& abbrev);

// 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::hours operator"h(long double);

constexpr chrono::minutes operator"min(unsigned long long);
constexpr chrono::minutes operator"min(long double);

constexpr chrono::seconds operator"s(unsigned long long);
constexpr chrono::seconds operator"s(long double);

constexpr chrono::milliseconds operator"ms(unsigned long long);
constexpr chrono::milliseconds operator"ms(long double);
```cpp
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);
```

```cpp
// 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;
```

```cpp
namespace std::chrono {
    using namespace literals::chrono_literals;
}
```

### 29.3 \textit{Cpp17Clock} requirements \[time.clock.req\]

1. A clock is a bundle consisting of a \textit{duration}, a \textit{time_point}, and a function \texttt{now()} to get the current \textit{time_point}. The origin of the clock’s \textit{time_point} is referred to as the clock’s \textit{epoch}. A clock shall meet the requirements in Table 95.

2. In Table 95 \texttt{C1} and \texttt{C2} denote clock types. \texttt{t1} and \texttt{t2} are values returned by \texttt{C1::now()} where the call returning \texttt{t1} happens before (6.9.2) the call returning \texttt{t2} and both of these calls occur before \texttt{C1::time_point::max()}.

   \begin{itemize}
   \item [Note 1: This means \texttt{C1} did not wrap around between \texttt{t1} and \texttt{t2}. -- end note]
   \end{itemize}

<table>
<thead>
<tr>
<th>Expression</th>
<th>Return type</th>
<th>Operational semantics</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{C1::rep}</td>
<td>An arithmetic type or a class emulating an arithmetic type</td>
<td>The representation type of \texttt{C1::duration}</td>
</tr>
<tr>
<td>\texttt{C1::period}</td>
<td>a specialization of \texttt{ratio}</td>
<td>The tick period of the clock in seconds.</td>
</tr>
<tr>
<td>\texttt{C1::duration}</td>
<td>\texttt{chrono::duration\langle C1::rep, C1::period\rangle}</td>
<td>The \textit{duration} type of the clock.</td>
</tr>
<tr>
<td>\texttt{C1::time_point}</td>
<td>\texttt{chrono::time_point\langle C1\rangle} or \texttt{chrono::time_point\langle C2, C1::duration\rangle}</td>
<td>The \textit{time_point} type of the clock. \texttt{C1} and \texttt{C2} shall refer to the same epoch.</td>
</tr>
<tr>
<td>\texttt{C1::is_steady}</td>
<td>\texttt{const bool}</td>
<td>\texttt{true} if \texttt{t1} \textless{}= \texttt{t2} is always \texttt{true} and the time between clock ticks is constant, otherwise \texttt{false}.</td>
</tr>
<tr>
<td>\texttt{C1::now()}</td>
<td>\texttt{C1::time_point}</td>
<td>Returns a \textit{time_point} object representing the current point in time.</td>
</tr>
</tbody>
</table>

3. \begin{itemize} \item [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] \end{itemize}

4. A type \texttt{TC} meets the \textit{Cpp17TrivialClock} requirements if:

   \begin{itemize}
   \item [(4.1)] \texttt{TC} meets the \textit{Cpp17Clock} requirements,
   \item [(4.2)] the types \texttt{TC::rep}, \texttt{TC::duration}, and \texttt{TC::time_point} meet the \textit{Cpp17EqualityComparable} (Table 27) and \textit{Cpp17LessThanComparable} (Table 28) requirements and the requirements of numeric types (28.2).
   \item [Note 3: This means, in particular, that operations on these types will not throw exceptions. -- end note]
   \item [(4.3)] \texttt{lvalues} of the types \texttt{TC::rep}, \texttt{TC::duration}, and \texttt{TC::time_point} are swappable (16.4.4.3),
   \item [(4.4)] the function \texttt{TC::now()} does not throw exceptions, and
   \item [(4.5)] the type \texttt{TC::time_point::clock} meets the \textit{Cpp17TrivialClock} requirements, recursively.
   \end{itemize}
29.4 Time-related traits

29.4.1 treat_as_floating_point

```cpp
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 `duration`s. Otherwise, the implicit convertibility depends on the tick periods of the `duration`s.

[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

```cpp
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.

```cpp
static constexpr Rep zero() noexcept;
```

2. 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]

3. Remarks: The value returned shall be the additive identity.

```cpp
static constexpr Rep min() noexcept;
```


5. Remarks: The value returned shall compare less than or equal to `zero()`.

```cpp
static constexpr Rep max() noexcept;
```


7. Remarks: The value returned shall compare greater than `zero()`.

29.4.3 Specializations of common_type

```cpp
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>;
};
```

1. 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]

2. [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 `duration`s can have round-off errors. — end note]

```cpp
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>>;
};
```

§ 29.4.3 1370
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`

```cpp
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. The qualified-ids `T::rep, T::period, T::duration, and T::time_point` are valid and each denotes a type (13.10.3),
2. The expression `T::is_steady` is well-formed when treated as an unevaluated operand (7.2.3),
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_point`s). 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`.

```cpp
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&);

            // 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+=(const duration& d);
            constexpr duration& operator--();
            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;
};

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.

If Period is not a specialization of ratio, the program is ill-formed. If Period::num is not positive, the program is ill-formed.

Members of duration do not throw exceptions other than those thrown by the indicated operations on their representations.

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 satisfy the requirements for a constexpr function.

[Example 1:
  duration<long, ratio<60>> d0; // holds a count of minutes using a long
duration<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 1/30 of a second
  // (30 Hz) using a double
—end example]

29.5.2 Constructors

template<class Rep2>
constexpr explicit duration(const Rep2& r);

1 Constraints: is_convertible_v<const Rep2&, rep> is true and
(1.1) — treat_as_floating_point_v<rep> is true or
(1.2) — treat_as_floating_point_v<Rep2> is false.

[Example 1:
  duration<int, milli> d(3); // OK
duration<int, milli> d(3.5); // error
—end example]

2 Effects: Initializes rep_ with r.

template<class Rep2, class Period2>
constexpr duration(const duration<Rep2, Period2>& d);

3 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:
  duration<int, milli> ms(3);
duration<int, micro> us = ms; // OK
duration<int, milli> ms2 = us; // error
—end example]

4 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;  
    Returns: common_type_t<duration>(*this).
```

```cpp
constexpr common_type_t<duration> operator-() 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--);
```

```cpp
constexpr duration& operator+=(const duration& d);  
    Effects: Equivalent to: rep_ += d.count().  
    Returns: *this.
```

```cpp
constexpr duration& operator-=(const duration& d);  
    Effects: Equivalent to: rep_ -= d.count().  
    Returns: *this.
```

```cpp
constexpr duration& operator*=(const rep& rhs);  
    Effects: Equivalent to: rep_ *= rhs.  
    Returns: *this.
```

```cpp
constexpr duration& operator/=(const rep& rhs);  
    Effects: Equivalent to: rep_ /= rhs.  
    Returns: *this.
```

```cpp
constexpr duration& operator%=(const duration& rhs);  
    Effects: Equivalent to: rep_ %= rhs.count().  
    Returns: *this.
```

29.5.5 Special values

```cpp
static constexpr duration zero() noexcept;  
    Returns: duration(duration_values<rep>::zero()).
```

§ 29.5.5
static constexpr duration min() noexcept;  
   Returns: duration(duration_values<rep>::min()).

static constexpr duration max() noexcept;  
   Returns: duration(duration_values<rep>::max()).

29.5.6 Non-member arithmetic

In the function descriptions that follow, unless stated otherwise, let CD represent the return type of the function.

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);
   Returns: CD(CD(lhs).count() + CD(rhs).count()).

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);
   Returns: CD(CD(lhs).count() - CD(rhs).count()).

template<class Rep1, class Rep2, class Period>
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.
   Returns: CD(CD(d).count() * s).

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 Rep2, class Period>
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 Rep2, 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);
   Let CD be common_type_t<duration<Rep1, Period1>, duration<Rep2, Period2>>.
   Returns: CD(lhs).count() / CD(rhs).count().

§ 29.5.6
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.

\[\text{template<class Rep1, class Period1, class Rep2, class Period2>}
\text{constexpr bool operator==}(\text{const duration<Rep1, Period1>&} \text{lhs},
\text{const duration<Rep2, Period2>&} \text{rhs});\]

\[\text{Returns: CT(lhs).count() == CT(rhs).count().}\]

\[\text{template<class Rep1, class Period1, class Rep2, class Period2>}
\text{constexpr bool operator<}(\text{const duration<Rep1, Period1>&} \text{lhs},
\text{const duration<Rep2, Period2>&} \text{rhs});\]

\[\text{Returns: CT(lhs).count() < CT(rhs).count().}\]

\[\text{template<class Rep1, class Period1, class Rep2, class Period2>}
\text{constexpr bool operator>(\text{const duration<Rep1, Period1>&} \text{lhs},
\text{const duration<Rep2, Period2>&} \text{rhs});\]

\[\text{Returns: rhs < lhs.}\]

\[\text{template<class Rep1, class Period1, class Rep2, class Period2>}
\text{constexpr bool operator<=}(\text{const duration<Rep1, Period1>&} \text{lhs},
\text{const duration<Rep2, Period2>&} \text{rhs});\]

\[\text{Returns: !(rhs < lhs).}\]

\[\text{template<class Rep1, class Period1, class Rep2, class Period2>}
\text{constexpr bool operator>=}(\text{const duration<Rep1, Period1>&} \text{lhs},
\text{const duration<Rep2, Period2>&} \text{rhs});\]

\[\text{Returns: !(lhs < rhs).}\]

\[\text{template<class Rep1, class Period1, class Rep2, class Period2>}
\text{requires three_way_comparable<\text{typename CT::rep}>}
\text{constexpr auto operator<=>}(\text{const duration<Rep1, Period1>&} \text{lhs},
\text{const duration<Rep2, Period2>&} \text{rhs});\]

\[\text{Returns: CT(lhs).count() <=> CT(rhs).count().}\]

29.5.8 Conversions

\[\text{template<class ToDuration, class Rep, class Period>}
\text{constexpr ToDuration duration_cast(const duration<Rep, Period>& d);}\]

\[\text{Constraints: ToDuration is a specialization of duration.}\]

\[\text{Returns: Let CF be ratio_divide<Period, \text{typename ToDuration::period>, and CR be common_type<\text{typename ToDuration::rep, Rep, intmax_t::type.}}\]

\[\text{(2.1) If CF::num == 1 and CF::den == 1, returns}
\text{ToDuration(static_cast<\text{typename ToDuration::rep}>(d.count()))}\]

\[\text{(2.2) Otherwise, if CF::num != 1 and CF::den == 1, returns}
\text{ToDuration(static_cast<\text{typename ToDuration::rep}>(}
\text{static_cast<CR>(d.count()) * static_cast<CR>(CF::num)))}\]

\[\text{(2.3) Otherwise, if CF::num == 1 and CF::den != 1, returns}
\text{ToDuration(static_cast<\text{typename ToDuration::rep}>(}
\text{static_cast<CR>(d.count()) / static_cast<CR>(CF::den)))}\]

\[\text{(2.4) Otherwise, returns}
\text{ToDuration(static_cast<\text{typename ToDuration::rep}>(}
\text{static_cast<CR>(d.count()) * static_cast<CR>(CF::num) / static_cast<CR>(CF::den)))}\]

\[\text{[Note 1: This function does not use any implicit conversions; all conversions are done with static_cast.}
\text{It avoids multiplications and divisions when it is known at compile time that one or more arguments is 1.}
\text{Intermediate computations are carried out in the widest representation and only converted to the destination}
\text{representation at the final step. — end note]}\]
template<class ToDuration, class Rep, class Period>
constexpr ToDuration floor(const duration<Rep, Period>& d);

Constraints: ToDuration is a specialization of duration.
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);

Constraints: ToDuration is a specialization of duration.
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);

Constraints: ToDuration is a specialization of duration and treat_as_floating_point_v<typename ToDuration::rep> is false.
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

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-literal.

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.

If any of these suffixes are applied to an integer-literal and the resulting chrono::duration value cannot be represented in the result type because of overflow, the program is ill-formed.

[Example 1: The following code shows some duration literals.
using namespace std::chrono_literals;
auto constexpr aday=24h;
auto constexpr lesson=45min;
auto constexpr halfanhour=0.5h;
—end example]

constexpr chrono::hours operator"h(unsigned long long hours);
constexpr chrono::duration<unspecified, ratio<3600, 1>> operator"h(long double hours);

Returns: A duration literal representing hours hours.

constexpr chrono::minutes operator"min(unsigned long long minutes);
constexpr chrono::duration<unspecified, ratio<60, 1>> operator"min(long double minutes);

Returns: A duration literal representing minutes minutes.

constexpr chrono::seconds operator"s(unsigned long long sec);
constexpr chrono::duration<unspecified> operator"s(long double sec);

Returns: A duration literal representing sec seconds.

[Note 1: The same suffix s is used for basic_string but there is no conflict, since duration suffixes apply to numbers and string literal suffixes apply to character array literals. —end note]

constexpr chrono::milliseconds operator"ms(unsigned long long msec);
constexpr chrono::duration<unspecified, milli> operator"ms(long double msec);

Returns: A duration literal representing msec milliseconds.

constexpr chrono::microseconds operator"us(unsigned long long usec);
constexpr chrono::duration<unspecified, micro> operator"us(long double usec);

Returns: A duration literal representing usec microseconds.

constexpr chrono::nanoseconds operator"ns(unsigned long long nsec);
constexpr chrono::duration<unspecified, nano> operator""ns(long double nsec);

Returns: A duration literal representing nsec nanoseconds.

29.5.10 Algorithms

```cpp
template<class Rep, class Period>
constexpr duration<Rep, Period> abs(duration<Rep, Period> d);
```

1 Constraints: numeric_limits<Rep>::is_signed is true.

2 Returns: If d >= d.zero(), return d, otherwise return -d.

29.5.11 I/O

```cpp
template<class charT, class traits, class Rep, class Period>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const duration<Rep, Period>& d);
```

1 Effects: Inserts the duration d onto the stream os as if it were implemented as follows:

```
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();
```

where units-suffix depends on the type Period::type as follows:

1. If Period::type is atto, units-suffix is "as".
2. Otherwise, if Period::type is femto, units-suffix is "fs".
3. Otherwise, if Period::type is pico, units-suffix is "ps".
4. Otherwise, if Period::type is nano, units-suffix is "ns".
5. Otherwise, if Period::type is micro, it is implementation-defined whether units-suffix is "µs" ("\u00b5\u0073") or "us".
6. Otherwise, if Period::type is milli, units-suffix is "ms".
7. Otherwise, if Period::type is centi, units-suffix is "cs".
8. Otherwise, if Period::type is deci, units-suffix is "ds".
9. Otherwise, if Period::type is ratio<1>, units-suffix is "s".
10. Otherwise, if Period::type is deca, units-suffix is "das".
11. Otherwise, if Period::type is hecto, units-suffix is "hs".
12. Otherwise, if Period::type is kilo, units-suffix is "ks".
13. Otherwise, if Period::type is mega, units-suffix is "Ms".
14. Otherwise, if Period::type is giga, units-suffix is "Gs".
15. Otherwise, if Period::type is tera, units-suffix is "Ts".
16. Otherwise, if Period::type is peta, units-suffix is "Ps".
17. Otherwise, if Period::type is exa, units-suffix is "Es".
18. Otherwise, if Period::type is ratio<60>, units-suffix is "min".
19. Otherwise, if Period::type is ratio<3600>, units-suffix is "h".
20. Otherwise, if Period::type is ratio<86400>, units-suffix is "d".
21. Otherwise, if Period::type::den == 1, units-suffix is 
   
   
2 Returns: os.

In the list above, the use of num and den refer to the static data members of Period::type, which are converted to arrays of charT using a decimal conversion with no leading zeroes.
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 {
        using clock = Clock;
        using duration = Duration;
        using rep = typename duration::rep;
        using period = typename duration::period;

        private:
            duration d_; // exposition only

        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.
  Effects: Initializes d_ with t.time_since_epoch().

29.6.3 Observer

constexpr duration time_since_epoch() const;

  Returns: d_.

29.6.4 Arithmetic

constexpr time_point& operator++();

  Effects: Equivalent to: ++d_.
  Returns: *this.

constexpr time_point operator++(int);

  Effects: Equivalent to: return time_point{d_++};

constexpr time_point& operator--();

  Effects: Equivalent to: --d_.
  Returns: *this.

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.

constexpr 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, common_type_t<Duration1, duration<Rep2, Period2>>>& 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>, duration<Rep2, Period2>>
        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<duration<Rep1, Period1>, 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: 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: !(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, class 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

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
29.7.1 General

The types defined in 29.7 meet the Cpp17TrivialClock requirements (29.3) unless otherwise specified.

29.7.2 Class system_clock
29.7.2.1 Overview

namespace std::chrono {
    class system_clock {
        using rep = unspecified;
        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;
        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:
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

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]

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.

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

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:
return os << format(os.getloc(), STATICA LLY-WIDEN("{:L%F %T}"), tp);

Example 1:
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

Effects:
eturn os << year_month_day{dp}.

Returns: os.

Effects: Attempts to parse the input stream is into the sys_time tp using the format flags given in
the NCTS 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 {

  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

time_point now();

static sys_time<common_type_t<Duration, seconds>>
to_sys(const utc_time<Duration>& u);

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);

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

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)
cout << 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

§ 29.7.3.3
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.

29.7.4 Class tai_clock

29.7.4.1 Overview

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).

§ 29.7.4.1 1384
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

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>static time_point now();</td>
<td>Returns: from_utc(utc_clock::now()), or a more accurate value of tai_time.</td>
</tr>
</tbody>
</table>

#### static utc_time<common_type_t<Duration, seconds>> to_utc(const tai_time<Duration>& t) noexcept;

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]

#### static tai_time<common_type_t<Duration, seconds>> from_utc(const utc_time<Duration>& t) noexcept;

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

#### template<class charT, class traits, class Duration>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic_ostream&lt;charT, traits&gt;&amp; operator&lt;&lt;(basic_ostream&lt;charT, traits&gt;&amp; os, const tai_time&lt;Duration&gt;&amp; t);</td>
<td>Effects: Equivalent to: return os &lt;&lt; format(os.getloc(), STATICALLY-WIDEN&lt;charT&gt;(&quot;{:L%F %T}&quot;), t);</td>
</tr>
</tbody>
</table>

[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]

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic_istream&lt;charT, traits&gt;&amp; from_stream(basic_istream&lt;charT, traits&gt;&amp;&amp; is, const charT* fmt, tai_time&lt;Duration&gt;&amp; tp, basic_string&lt;charT, traits, Alloc&gt;* abbrev = nullptr, minutes* offset = nullptr);</td>
<td>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.</td>
</tr>
</tbody>
</table>

§ 29.7.4.3
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 19s due to the 10s offset between 1958 and 1970 and the additional 9 leap seconds inserted between 1970 and 1980.

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

**[time.clock.file]**

#### 29.7.6.1 Overview

**[time.clock.file.overview]**

```
namespace std::chrono {
    using file_clock = see below;
}
```

**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

**[time.clock.file.members]**

The type denoted by `file_clock` provides precisely one of the following two sets of static member functions:

```template<class Duration>

static sys_time<see below>

to_sys(const file_time<Duration>&);
```

```template<class Duration>

to_utc(const file_time<Duration>&);
```

or:

```template<class Duration>

static utc_time<see below>

to_utc(const file_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`. 

§ 29.7.6.2
29.7.6.3 Non-member functions

\[\text{template<class charT, class traits, class Duration>}
\text{basic_ostream<charT, traits>&}
\text{operator<<(basic_ostream<charT, traits>& os, const file_time<Duration>& t);}\]
\[\text{Effects: Equivalent to:}
\text{return os \text{\textless\textgreater format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%F %T"}, t);}\]
\[\text{template<class charT, class traits, class Duration, class Alloc = allocator<charT>>}
\text{basic_istream<charT, traits>&}
\text{from_stream(basic_istream<charT, traits>& is, const charT* fmt,}
\text{file_time<Duration>& tp, basic_string<charT, traits, Alloc>* abbrev = nullptr,}
\text{minutes* offset = nullptr);}\]
\[\text{Effects: Attempts to parse the input stream is into the file_time tp using the format flags given}
\text{in the NTCTS fmt as specified in 29.13. If the parse fails to decode a valid date, is.setstate(ios_base::failbit) is called and tp is not modified. If %Z is used and successfully parsed, that value will be assigned to *abbrev if abbrev is non-null. If %z (or a modified variant) is used and successfully parsed, that value will be assigned to *offset if offset is non-null. Additionally, the parsed offset will be subtracted from the successfully parsed timestamp prior to assigning that difference to tp.}
\text{Returns: is.}\]

29.7.7 Class steady_clock

\[\text{namespace std::chrono {}
\text{class steady_clock {}
\text{public:}
\text{using rep = unspecified;}
\text{using period = ratio<unspecified, unspecified>;}\]
\[\text{using duration = chrono::duration<rep, period>;}\]
\[\text{using time_point = chrono::time_point<unspecified, duration>;}\]
\[\text{static constexpr bool is_steady = true;}\]
\[\text{static time_point now() noexcept;}
\text{}}\]
\[\text{}}\]
\[\text{1 Objects of class steady_clock represent clocks for which values of time_point never decrease as physical}
\text{time advances and for which values of time_point advance at a steady rate relative to real time. That is,}
\text{the clock may not be adjusted.}\]

29.7.8 Class high_resolution_clock

\[\text{namespace std::chrono {}
\text{class high_resolution_clock {}
\text{public:}
\text{using rep = unspecified;}
\text{using period = ratio<unspecified, unspecified>;}\]
\[\text{using duration = chrono::duration<rep, period>;}\]
\[\text{using time_point = chrono::time_point<unspecified, duration>;}\]
\[\text{static constexpr bool is_steady = unspecified;}\]
\[\text{static time_point now() noexcept;}
\text{}}\]
\[\text{}}\]
\[\text{1 Objects of class high_resolution_clock represent clocks with the shortest tick period. high_resolution_}
\text{clock may be a synonym for system_clock or steady_clock.}\]

29.7.9 Local time

\[\text{The family of time points denoted by local_time<Duration> are based on the pseudo clock local_t.}
\text{local_t has no member now() and thus does not meet the clock requirements. Nevertheless local_time<}
\text{Duration> serves the vital role of representing local time with respect to a not-yet-specified time zone.}
\text{Aside from being able to get the current time, the complete time_point algebra is available for}
\text{local_time<Duration> (just as for sys_time<Duration>).}\]

\[\text{§ 29.7.9}\]
template<class charT, class traits, class Duration>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const local_time<Duration>& lt);

    Effects:
    os << sys_time<Duration>{lt.time_since_epoch()};

    Returns: os.

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);

    Effects: Attempts to parse the input stream is into the local_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.

    Returns: is.

29.7.10 time_point conversions

29.7.10.1 Class template clock_time_conversion

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;

        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;

>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;

>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;

>Returns: utc_clock::from_sys(t).

template<>
struct clock_time_conversion<system_clock, utc_clock> {
    template<class Duration>
        sys_time<Duration>
            operator()(const utc_time<Duration>& t) const;
    
};

template<class Duration>
    sys_time<Duration>
        operator()(const utc_time<Duration>& t) const;

(Returns: utc_clock::to_sys(t).

29.7.10.4 Conversions between system_clock and other clocks

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));
    
};

template<class Duration>
    auto operator()(const time_point<SourceClock, Duration>& t) const
        -> decltype(SourceClock::to_sys(t));

1 Constraints: SourceClock::to_sys(t) is well-formed.

2 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));

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};

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

[time.clock.cast.utc]
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));
};

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

[time.clock.cast.fn]
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}}}

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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 In 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`

```cpp
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

```cpp
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;
  };
}
```

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 27) and `Cpp17LessThanComparable` (Table 28) requirements, and participates in basic arithmetic with `days` objects, which represent a difference between two `day` objects.

`day` is a trivially copyable and standard-layout class type.

#### 29.8.3.2 Member functions

```cpp
constexpr explicit day(unsigned d) noexcept;
```

**Effects:** Initializes `d_` with `d`. The value held is unspecified if `d` is not in the range `[0, 255]`.

```cpp
constexpr day& operator++() noexcept;
```

**Effects:** `++d_`.

**Returns:** `*this`. 
constexpr day operator++(int) noexcept;

Effects: ++(*this).

Returns: A copy of *this as it existed on entry to this member function.

constexpr day& operator--() noexcept;

Effects: Equivalent to: --d_.

Returns: *this.

constexpr day operator--(int) noexcept;

Effects: --(*this).

Returns: A copy of *this as it existed on entry to this member function.

constexpr day& operator+=(const days& d) noexcept;

Effects: *this = *this + d.

Returns: *this.

constexpr day& operator-=(const days& d) noexcept;

Effects: *this = *this - d.

Returns: *this.

constexpr explicit operator unsigned() const noexcept;

Returns: d_.

constexpr bool ok() const noexcept;

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("{:%d}", d) :
    format("{:%d} is not a valid day");

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.

cconstexpr 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 months& m) noexcept;
    constexpr explicit operator unsigned() const noexcept;
    constexpr bool ok() const noexcept;
  };
}

1 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 27) and Cpp17LessThanComparable (Table 28) requirements, and participates in basic arithmetic with months objects, which represent a difference between two month objects.

2 month is a trivially copyable and standard-layout class type.

29.8.4.2 Member functions

cconstexpr explicit month(unsigned m) noexcept;

Effects: Initializes m_ with m. The value held is unspecified if m is not in the range [0, 255].

1

cconstexpr month& operator++() noexcept;

Effects: *this += months{1}.

Returns: *this.

2

cconstexpr month operator++(int) noexcept;

Effects: ++(*this).

Returns: A copy of *this as it existed on entry to this member function.

3

cconstexpr month& operator--() noexcept;

Effects: *this -= months{1}.

Returns: *this.

4

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constexpr month operator--(int) noexcept;
8    Effects: --(*this).
9    Returns: A copy of *this as it existed on entry to this member function.

constexpr month& operator+=(const months& m) noexcept;
10   Effects: *this = *this + m.
11   Returns: *this.

constexpr month& operator-=(const months& m) noexcept;
12   Effects: *this = *this - m.
13   Returns: *this.

constexpr explicit operator unsigned() const noexcept;
14   Returns: m_.

constexpr bool ok() const noexcept;
15   Returns: 1 <= m_ && m_ <= 12.

29.8.4.3 Non-member functions  [time.cal.month.nonmembers]

constexpr bool operator===(const month& x, const month& y) noexcept;
1   Returns: unsigned{x} == unsigned{y}.

constexpr strong_ordering operator<=>(const month& x, const month& y) noexcept;
2   Returns: unsigned{x} <=> unsigned{y}.

constexpr month operator+(const month& x, const months& y) noexcept;
3   Returns: month{modulo(static_cast<long long>(unsigned{x}) + (y.count() - 1), 12) + 1}
where 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 of [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]

constexpr month operator+(const months& x, const month& y) noexcept;
4   Returns: y + x.

constexpr month operator-(const month& x, const months& y) noexcept;
5   Returns: x + -y.

constexpr months operator-(const month& x, const month& y) noexcept;
6   Returns: If x.ok() == true and y.ok() == true, returns a value m in the range [months{0}, months{11}] satisfying y + m == x. Otherwise the value returned is unspecified.
[Example 2: January - February == months{11}. — end example]

template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const month& m);
7   Effects: Equivalent to:
   return os << (m.ok() ?
      format(os.getloc(), STATICALLY-WIDEN<charT>("{:L%b}"), m) :
      format(os.getloc(), STATICALLY-WIDEN<charT>("{} is not a valid month"),
      static_cast<unsigned>(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);

Effects: Attempts to parse the input stream is into the month m using the format flags given in the
NTCTS 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.

Returns: is.

29.8.5 Class year

29.8.5.1 Overview

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-=(const years& y) noexcept;
    constexpr year operator+() const noexcept;
    constexpr year operator-() const noexcept;
    constexpr bool is_leap() const noexcept;
    constexpr explicit operator int() const noexcept;
    constexpr bool ok() const noexcept;
    static constexpr year min() noexcept;
    static constexpr year max() noexcept;
  };
}

1 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 27) and Cpp17LessThanComparable (Table 28)
requirements, and participates in basic arithmetic with years objects, which represent a difference between
two year objects.

2 year is a trivially copyable and standard-layout class type.

29.8.5.2 Member functions

constexpr explicit year(int y) noexcept;

1 Effects: Initializes y_ with y. The value held is unspecified if y is not in the range [-32767, 32767].

constexpr year& operator++() noexcept;

2 Effects: ++y_.

3 Returns: *this.

constexpr year operator++(int) noexcept;

4 Effects: ++(*this).
Returns: A copy of *this as it existed on entry to this member function.

constexpr year& operator--() noexcept;
   Effects: --y_.
   Returns: *this.

constexpr year operator--(int) noexcept;
   Effects: --(*this).
   Returns: A copy of *this as it existed on entry to this member function.

constexpr year& operator+=(const years& y) noexcept;
   Effects: *this = *this + y.
   Returns: *this.

constexpr year& operator-=(const years& y) noexcept;
   Effects: *this = *this - y.
   Returns: *this.

constexpr year operator+(const years& x, const year& y) noexcept;
   Returns: *this.

constexpr year operator+(const year& x, const years& y) noexcept;
   Returns: *this.

constexpr year year::operator-() const noexcept;
   Returns: year{-y_}.

static constexpr year min() noexcept;
   Returns: year{-32767}.

static constexpr year max() noexcept;
   Returns: year{32767}.

29.8.5.3 Non-member functions

constexpr bool operator==(const year& x, const year& y) noexcept;
   Returns: int{x} == int{y}.

constexpr strong_ordering operator<=>(const year& x, const year& y) noexcept;
   Returns: int{x} <=> int{y}.

constexpr year operator+(const year& x, const years& y) noexcept;
   Returns: year{int{x} + static_cast<int>(y.count())}.

constexpr year operator+(const years& x, const year& y) noexcept;
   Returns: y + x.

constexpr year operator-(const year& x, const years& y) noexcept;
   Returns: x + -y.

constexpr years operator-(const year& x, const year& y) noexcept;
   Returns: years{int{x} - int{y}}.
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const year& y);

Effects: Equivalent to:

    return os << (y.ok() ?
        format(STATICALLY-WIDEN<charT>("{:%Y}"), y) :
        format(STATICALLY-WIDEN<charT>("{:%Y} is not a valid 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);

Effects: Attempts to parse the input stream is into the year 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.

Returns: is.

constexpr chrono::year operator"y(unsigned long long y) noexcept;

Returns: year{static_cast<int>(y)}.

29.8.6 Class weekday

29.8.6.1 Overview

namespace std::chrono {

    class weekday { // exposition only

    public:
        weekday() = default;
        constexpr explicit weekday(unsigned wd) noexcept;
        constexpr weekday(const sys_days& dp) noexcept;
        constexpr explicit weekday(const local_days& dp) noexcept;

        constexpr weekday& operator++() noexcept;
        constexpr weekday operator++(int) noexcept;
        constexpr weekday& operator--() noexcept;
        constexpr weekday operator--(int) noexcept;
        constexpr weekday& operator+=(const days& d) noexcept;
        constexpr weekday& operator-=(const days& d) noexcept;
        constexpr unsigned c_encoding() const noexcept;
        constexpr unsigned iso_encoding() const noexcept;
        constexpr bool ok() const noexcept;
        constexpr weekday_indexed operator[](unsigned index) const noexcept;
        constexpr weekday_last operator[](last_spec) const noexcept;
    }

}\n
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 27) 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;
1   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;
2   Effects: Computes what day of the week corresponds to the sys_days dp, and initializes that day of the week in wd_.
3   [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;
4   Effects: Computes what day of the week corresponds to the local_days dp, and initializes that day of the week in wd_.
5   Postconditions: The value is identical to that constructed from sys_days(dp.time_since_epoch()).

constexpr weekday& operator++() noexcept;
6   Effects: *this += days{1}.
7   Returns: *this.

constexpr weekday operator++(int) noexcept;
8   Effects: ++(*this).
9   Returns: A copy of *this as it existed on entry to this member function.

constexpr weekday& operator--() noexcept;
10  Effects: *this -= days{1}.
11  Returns: *this.

constexpr weekday operator--(int) noexcept;
12  Effects: --(*this).
13  Returns: A copy of *this as it existed on entry to this member function.

constexpr weekday& operator=(const days& d) noexcept;
14  Effects: *this = *this + d.
15  Returns: *this.

constexpr weekday& operator=(const days& d) noexcept;
16  Effects: *this = *this - d.
17  Returns: *this.

constexpr unsigned c_encoding() const noexcept;
18  Returns: wd_.

constexpr unsigned iso_encoding() const noexcept;
19  Returns: wd_ == 0u ? 7u : wd_.

constexpr bool ok() const noexcept;
20  Returns: wd_ <= 6.

constexpr weekday_indexed operator[](unsigned index) const noexcept;
21  Returns: {*this, index}.

constexpr weekday_last operator[](last_spec) const noexcept;
22  Returns: weekday_last{*this}.
29.8.6.3 Non-member functions

\texttt{constexpr bool operator\(==\)(const \texttt{weekday} \& x, const \texttt{weekday} \& y) noexcept;}

\textit{Returns:} \(x.wd_ == y.wd_\).

\texttt{constexpr \texttt{weekday} operator\(+\)(const \texttt{weekday} \& x, const \texttt{days} \& y) noexcept;}

\textit{Returns:}

\texttt{\texttt{weekday}(\texttt{modulo}(\texttt{static\_cast<long long>}(x.wd_), y.count(), 7))}

where \texttt{modulo}(n, 7) computes the remainder of \(n\) divided by 7 using Euclidean division.

\textit{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 \texttt{weekday} holding a value in the range \([0, 6]\) even if \(!x.ok()\). — end note

\textit{Example 1:} \texttt{Monday + days\{6\} == Sunday}. — end example

\texttt{constexpr \texttt{weekday} operator\(-\)(const \texttt{weekday} \& x, const \texttt{days} \& y) noexcept;}

\textit{Returns:} \(x + -y\).

\texttt{constexpr \texttt{days} operator\(-\)(const \texttt{weekday} \& x, const \texttt{weekday} \& y) noexcept;}

\textit{Returns:} If \(x.ok() == true\) and \(y.ok() == true\), returns a value \(d\) in the range \([\texttt{days}\{0\}, \texttt{days}\{6\}]\) satisfying \(y + d == x\). Otherwise the value returned is unspecified.

\textit{Example 2:} \texttt{Sunday - Monday == days\{6\}}. — end example

\texttt{template<class charT, class traits> basic_ostream<\texttt{charT}, \texttt{traits}>\& operator<<\(\)(basic_ostream<\texttt{charT}, \texttt{traits}>\& os, const \texttt{weekday} \& \texttt{wd});}

\textit{Effects:} Equivalent to:

\begin{verbatim}
return os << (wd.ok() ?
    format(os.getloc(), STATICALLY-WIDEN<\texttt{charT}>("{:L%a}\"), wd) :
    format(os.getloc(), STATICALLY-WIDEN<\texttt{charT}>("{} is not a valid weekday"),
        static\_cast<\texttt{unsigned}>((\texttt{wd}.wd_)));
\end{verbatim}

\texttt{template<class charT, class traits, class Alloc = \texttt{allocator<\texttt{charT}>}}>

\texttt{basic\_istream<\texttt{charT}, \texttt{traits}>\& from\_stream\(\)(basic\_istream<\texttt{charT}, \texttt{traits}>\& is, const \texttt{charT}\* fmt, \texttt{weekday} \& \texttt{wd}, basic\_string<\texttt{charT}, \texttt{traits}, \texttt{Alloc}>\* \texttt{abbrev} = \texttt{nullptr}, \texttt{minutes}\* \texttt{offset} = \texttt{nullptr});}

\textit{Effects:} Attempts to parse the input stream \texttt{is} into the \texttt{weekday} \texttt{wd} using the format flags given in the NTCTS \texttt{fmt} as specified in 29.13. If the parse fails to decode a valid weekday, \texttt{is.setstate(ios\_-base::failbit)} is called and \texttt{wd} is not modified. If \%Z is used and successfully parsed, that value will be assigned to \*\texttt{abbrev} if \texttt{abbrev} is non-null. If \%Z (or a modified variant) is used and successfully parsed, that value will be assigned to \*\texttt{offset} if \texttt{offset} is non-null.

\textit{Returns:} \texttt{is}.

29.8.7 Class \texttt{weekday\_indexed}

29.8.7.1 Overview

\texttt{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;
\}}
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

```cpp
cconstexpr weekday_indexed(const chrono::weekday& wd, unsigned index) noexcept;
1 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].
```

```cpp
cconstexpr chrono::weekday weekday() const noexcept;
2 Returns: wd_.
```

```cpp
cconstexpr unsigned index() const noexcept;
3 Returns: index_.
```

```cpp
cconstexpr bool ok() const noexcept;
4 Returns: wd_.ok() && 1 <= index_ && index_ <= 5.
```

### 29.8.7.3 Non-member functions

```cpp
cconstexpr bool operator==(const weekday_indexed& x, const weekday_indexed& y) noexcept;
1 Returns: x.weekday() == y.weekday() && x.index() == y.index().
```

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& os, const weekday_indexed& wdi);
2 Effects: Equivalent to:
auto i = wdi.index();
return os << (i >= 1 && i <= 5 ?
  format(os.getloc(), "{:L}[{}]", wdi.weekday(), i) :
  format(os.getloc(), "{:L}[{} is not a valid index]", wdi.weekday(), i));
```

### 29.8.8 Class weekday_last

#### 29.8.8.1 Overview

```cpp
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;
  
  }
```

§ 29.8.8.1
\texttt{weekday\_last} represents the last weekday of a month.

[Note 1: A \texttt{weekday\_last} object can be constructed by indexing a \texttt{weekday} with \texttt{last}. — end note]

\begin{verbatim}
constexpr auto wdl = Sunday[\texttt{last}];  // \texttt{wdl} is the last Sunday of an as yet unspecified month
static_assert(wdl.weekday() == Sunday);
\end{verbatim}

— end example

\texttt{weekday\_last} is a trivially copyable and standard-layout class type.

29.8.8.2 Member functions

\texttt{constexpr explicit weekday\_last\(\texttt{const chrono::weekday\& wd}\) noexcept;}

\begin{enumerate}
\item \textbf{Effects}: Initializes \texttt{wd\_} with \texttt{wd}.
\item \textbf{Returns}: \texttt{wd\_}.
\item \texttt{constexpr bool ok\() const noexcept;}
\item \textbf{Returns}: \texttt{wd\_.ok\()\).}
\end{enumerate}

29.8.8.3 Non-member functions

\texttt{constexpr bool operator==(\texttt{const weekday\_last& x, const weekday\_last& y}) noexcept;}

\begin{enumerate}
\item \textbf{Returns}: \texttt{x.weekday\() == y.weekday\()\).
\end{enumerate}

29.8.9 Class \texttt{month\_day}

29.8.9.1 Overview

\begin{verbatim}
namespace std::chrono {
    class month\_day {
        \texttt{chrono::month m\_;}  // exposition only
        \texttt{chrono::day d\_;}  // exposition only

        public:
        \texttt{month\_day()} = default;
        \texttt{constexpr month\_day\(\texttt{const chrono::month\& m, const chrono::day\& d}\) noexcept;}

        \texttt{constexpr chrono::month month\() const noexcept;}
        \texttt{constexpr chrono::day day\() const noexcept;}
        \texttt{constexpr bool ok\() const noexcept;}
    };
}
\end{verbatim}

\texttt{month\_day} represents a specific day of a specific month, but with an unspecified year. \texttt{month\_day} meets the \textit{Cpp17EqualityComparable} (Table 27) and \textit{Cpp17LessThanComparable} (Table 28) requirements.

\texttt{month\_day} is a trivially copyable and standard-layout class type.

29.8.9.2 Member functions

\texttt{constexpr month\_day\(\texttt{const chrono::month\& m, const chrono::day\& d}\) noexcept;}

\begin{enumerate}
\item \textbf{Effects}: Initializes \texttt{m\_} with \texttt{m}, and \texttt{d\_} with \texttt{d}.
\item \textbf{Returns}: \texttt{m\_}.
\end{enumerate}
constexpr chrono::day day() const noexcept;

Returns: d_.

constexpr bool ok() const noexcept;

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;

Returns: x.month() == y.month() && x.day() == y.day().

constexpr strong_ordering operator<=>(const month_day& x, const month_day& y) noexcept;

Effects: Equivalent to:

if (auto c = x.month() <=> y.month(); c != 0) return c;
return x.day() <=> y.day();

Effects: Equivalent to:

return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}/{}"),
md.month(), md.day());

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.

Returns: is.

29.8.10 Class month_day_last

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;

};

month_day_last represents the last day of a month.

[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]

[Example 1:]

cconstexpr auto mdl = February/last; // mdl is the last day of February of an as yet unspecified year
static_assert(mdl.month() == February);

— end example]

month_day_last is a trivially copyable and standard-layout class type.

§ 29.8.10
constexpr explicit month_day_last(const chrono::month& m) noexcept;

Effects: Initializes m_ with m.

constexpr month month() const noexcept;

Returns: m_.

constexpr bool ok() const noexcept;

Returns: m_.ok().

constexpr bool operator==(const month_day_last& x, const month_day_last& y) noexcept;

Returns: x.month() == y.month().

constexpr strong_ordering operator<=>(const month_day_last& x, const month_day_last& y) noexcept;

Returns: x.month() <=> y.month().

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 [time.cal.mwd]

29.8.11.1 Overview [time.cal.mwd.overview]

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 month month() const noexcept;

    constexpr chrono::weekday_indexed weekday_indexed() const noexcept;

    constexpr bool ok() const noexcept;

};
}

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.

[Example 1:

```c++
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 [time.cal.mwd.members]

constexpr month_weekday(const chrono::month& m, const chrono::weekday_indexed& wdi) noexcept;

Effects: Initializes m_ with m, and wdi_ with wdi.

constexpr chrono::month month() const noexcept;

Returns: m_.

constexpr chrono::weekday_indexed weekday_indexed() const noexcept;

Returns: wdi_.

constexpr bool ok() const noexcept;

Returns: m_.ok() && wdi_.ok().

§ 29.8.11.2
29.8.11.3 Non-member functions

```cpp
constexpr bool operator==(const month_weekday& x, const month_weekday& y) noexcept;
```

Returns:
\[ x.m() == y.m() \&\& x.w() == y.w(). \]

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const month_weekday& mwd);
```

Effects:
\[ \text{return } os \ll \text{format(os.getloc(), } \text{STATICALLY-WIDEN}\ll<\text{charT}>\ll("\{L\}/\{L\}"), mwd.m(), mwd.w()); } \]

29.8.12 Class month_weekday_last

29.8.12.1 Overview

```cpp
namespace std::chrono {
    class month_weekday_last {
    // exposition only
    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 m() const noexcept;
    constexpr chrono::weekday_last wdl() 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`.

```cpp
constexpr auto mwd
    = February/Tuesday[last]; // mwd is the last Tuesday of February of an as yet unspecified year
static_assert(mwd.m() == February);
static_assert(mwd.wdl() == Tuesday[last]);
```

Example 1:

```cpp
constexpr chrono::month m();
constexpr chrono::weekday_last wdl();
```

29.8.12.2 Member functions

```cpp
constexpr month_weekday_last(const chrono::month& m,
                        const chrono::weekday_last& wdl) noexcept;
```

Effects:
\[ \text{Initializes } m_ \text{ with } m, \text{ and } wdl_ \text{ with } wdl. \]

Returns:
\[ m_. \]

```cpp
constexpr chrono::weekday_last wdl() const noexcept;
```

Returns:
\[ wdl_. \]

```cpp
constexpr bool ok() const noexcept;
```

Returns:
\[ m_.ok() \&\& wdl_.ok(). \]

29.8.12.3 Non-member functions

```cpp
constexpr bool operator==(const month_weekday_last& x, const month_weekday_last& y) noexcept;
```

Returns:
\[ x.m() == y.m() \&\& x.w() == y.w(). \]
template<class charT, class traits>
    basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const month_weekday_last& mwdl);

Effects: Equivalent to:

    return os << format(os.getloc(), STATICALLY-WIDEN<charT>("{:L}/{:L}"),
                        mwdl.month(), mwdl.weekday_last());

29.8.13 Class year_month

29.8.13.1 Overview

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 27) and Cpp17LessThanComparable (Table 28) requirements.

2 year_month is a trivially copyable and standard-layout class type.

29.8.13.2 Member functions

constexpr 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.

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.
constexpr year_month& operator+=(const years& dy) noexcept;
   Effects: *this = *this + dy.
   Returns: *this.
constexpr 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 [time.cal.ym.nonmembers]

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 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() + months{static_cast<int>(unsigned{x.month()}) -
   static_cast<int>(unsigned{y.month()})}

constexpr year_month operator+(const year_month& ym, const years& dy) noexcept;
   Returns: (ym.year() + dy) / ym.month().

constexpr year_month operator+(const years& dy, const year_month& ym) noexcept;
   Returns: ym + dy.

constexpr 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:

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return os << format(os.getloc(), STATICALLY-WIDEN<charT>("/{}/: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 [time.cal.ymd]
29.8.14.1 Overview [time.cal.ymd.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 explicit operator local_days() const noexcept;

        constexpr bool ok() const noexcept;
    };
}

1 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 27) and Cpp17LessThanComparable (Table 28) requirements.

2 year_month_day is a trivially copyable and standard-layout class type.

29.8.14.2 Member functions [time.cal.ymd.members]

constexpr year_month_day(const chrono::year& y, const chrono::month& m,
                         const chrono::day& d) noexcept;

1 Effects: Initializes y_ with y, m_ with m, and d_ with d.
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]

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.

constexpr explicit year_month_day(const local_days& dp) noexcept;

Effects: Equivalent to constructing with sys_days{dp.time_since_epoch()}.  

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.

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.

constexpr year_month_day& year_month_day::operator+=(const years& y) noexcept;

Effects: *this = *this + y.

Returns: *this.

constexpr year_month_day& year_month_day::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::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

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 (or a modified variant) 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 {
    chrono::year y_; // exposition only
    chrono::month_day_last mdl_; // exposition only
  public:
    constexpr year_month_day_last(const chrono::year& y, const chrono::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 chrono::year year() const noexcept;
    constexpr chrono::month month() const noexcept;
    constexpr chrono::month_day_last month_day_last() const noexcept;
    constexpr chrono::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 27) and Cpp17LessThanComparable (Table 28) requirements.

year_month_day_last is a trivially copyable and standard-layout class type.

29.8.15.2 Member functions

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;

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.

constexpr year_month_day_last& 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).
```cpp
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 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

```cpp
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).

cconstexpr year_month_day_last
operator+(const year_month_day_last& ymdl, const years& dy) noexcept;

Returns: {ymdl.year()+dy, ymdl.month_day_last()}.  
cconstexpr year_month_day_last
operator+(const years& dy, const year_month_day_last& ymdl) noexcept;

Returns: ymdl + dy.

cconstexpr 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>("{}/{}"),
ymdl.year(), ymdl.month_day_last());

§ 29.8.16 Class year_month_weekday  [time.cal.ymwd]

namespace std::chrono {
class year_month_weekday {
  chrono::year y_; // exposition only
  chrono::month m_; // exposition only
  chrono::weekday_indexed wdi_; // exposition only

c  public:
  year_month_weekday() = default;
  constexpr year_month_weekday(const chrono::year& y, const chrono::month& m,
                              const chrono::weekday_indexed& wdi) noexcept;
  constexpr year_month_weekday(const sys_days& dp) noexcept;
  constexpr explicit year_month_weekday(const local_days& dp) noexcept;
  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;
}
year_month_weekday meets the Cpp17EqualityComparable (Table 27) requirements.
year_month_weekday is a trivially copyable and standard-layout class type.

29.8.16.2 Member functions

```cpp
constexpr year_month_weekday(const chrono::year& y, const chrono::month& m,
    const chrono::weekday_indexed& wdi) noexcept;
Effects: Initializes y_ with y, m_ with m, and wdi_ with wdi.
```

```cpp
constexpr year_month_weekday(const sys_days& dp) noexcept;
Effects: Constructs an object of type year_month_weekday which corresponds to the date represented by dp.
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.
```

```cpp
constexpr explicit year_month_weekday(const local_days& dp) noexcept;
Effects: Equivalent to constructing with sys_days{dp.time_since_epoch()}.
```

```cpp
constexpr year_month_weekday& 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_weekday& 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_weekday& operator+=(const years& y) noexcept;
Effects: *this = *this + y.
Returns: *this.
```

```cpp
constexpr year_month_weekday& 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_.
```

```cpp
constexpr chrono::weekday weekday() const noexcept;
Returns: wdi_.weekday().
```

```cpp
constexpr unsigned index() const noexcept;
Returns: wdi_.index().
```

```cpp
constexpr chrono::weekday_indexed weekday_indexed() const noexcept;
Returns: wdi_.
```

```cpp
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.

```cpp
constexpr explicit operator local_days() const noexcept;
```

*Returns:* `local_days(sys_days{*this}.time_since_epoch())`.

```cpp
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

```cpp
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()`.

```cpp
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()`.

```cpp
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`.

```cpp
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)`.

```cpp
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.year()+dy, ymwd.month(), ymwd.weekday_indexed()}`.

```cpp
constexpr year_month_weekday operator+(const years& dy, const year_month_weekday& ymwd) noexcept;
```

*Returns:* `ymwd + dy`.

```cpp
constexpr year_month_weekday operator-(const year_month_weekday& ymwd, const years& dy) noexcept;
```

*Returns:* `ymwd + (-dy)`.

```cpp
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

```cpp
namespace std::chrono {
    class year_month_weekday_last {
    
    public:
        constexpr year_month_weekday_last(const chrono::year y, const chrono::month m, 
                                          const chrono::weekday_last wdl) noexcept;
    
    chrono::year y_;  // exposition only
    chrono::month m_;  // exposition only
    chrono::weekday_last wdl_;  // exposition only

    
};
```
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;

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 27) requirements.

year_month_weekday_last is a trivially copyable and standard-layout class type.
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(*this).time_since_epoch() / years().

constexpr bool ok() const noexcept;
  Returns: y_.ok() && m_.ok() && wdl_.ok() / years().

29.8.17.3  Non-member functions

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() / years().

constexpr year_month_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 / years(). + dm / years(). / years().

constexpr year_month_weekday_last operator+(const years& dy, const year_month_weekday_last& ymwdl) noexcept;
  Returns: ymwdl + dy / years().

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 required, 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]

constexpr year_month operator/(const year& y, const month& m) noexcept;
Returns: {y, m}.

constexpr year_month operator/(const year& y, int m) noexcept;
Returns: y / month(m).

constexpr 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: y / md.

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/(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.

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 is_negative() indicates the structure is representing a negative duration.

2 If Duration is not a specialization of duration, the program is ill-formed.

29.9.2 Members
[time.hms.members]

static constexpr unsigned fractional_width = see below;

1 fractional_width is the number of fractional decimal digits represented by precision. fractional_width has the value of the smallest possible integer in the range [0, 18] such that precision will exactly represent all values of Duration. If no such value of fractional_width exists, then fractional_width is 6.

[Example 1: See Table 96 for some durations, the resulting fractional_width, and the formatted fractional second output of Duration(1).]

<table>
<thead>
<tr>
<th>Duration</th>
<th>fractional_width</th>
<th>Formatted fractional second output</th>
</tr>
</thead>
<tbody>
<tr>
<td>hours, minutes, and seconds</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>milliseconds</td>
<td>3</td>
<td>0.000001</td>
</tr>
<tr>
<td>microseconds</td>
<td>6</td>
<td>0.000001</td>
</tr>
</tbody>
</table>
Table 96: Examples for \texttt{fractional\_width} (continued)

<table>
<thead>
<tr>
<th>Duration</th>
<th>\texttt{fractional_width}</th>
<th>Formatted fractional second output</th>
</tr>
</thead>
<tbody>
<tr>
<td>nanoseconds</td>
<td>9</td>
<td>0.000000001</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 2&gt;&gt;}</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 3&gt;&gt;}</td>
<td>6</td>
<td>0.333333</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 4&gt;&gt;}</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 5&gt;&gt;}</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 6&gt;&gt;}</td>
<td>6</td>
<td>0.166666</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 7&gt;&gt;}</td>
<td>6</td>
<td>0.142857</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 8&gt;&gt;}</td>
<td>3</td>
<td>0.125</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;1, 9&gt;&gt;}</td>
<td>6</td>
<td>0.111111</td>
</tr>
<tr>
<td>\texttt{duration&lt;int, ratio&lt;756, 625&gt;&gt;}</td>
<td>4</td>
<td>0.2096</td>
</tr>
</tbody>
</table>

--- end example ---

using precision = see below;

2 precision is

\begin{verbatim}
duration<common_type_t<Duration::rep, seconds::rep>, ratio<1, 10>>
\end{verbatim}

constexpr explicit \texttt{hh\_mm\_ss}(Duration \texttt{d});

3 Effects: Constructs an object of type \texttt{hh\_mm\_ss} which represents the \texttt{Duration} \texttt{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() - minutes() - 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 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)}.

constexpr bool \texttt{is\_negative()} const noexcept;

Returns: \texttt{is\_neg}.

constexpr chrono::hours hours() const noexcept;

Returns: \texttt{h}.

constexpr chrono::minutes minutes() const noexcept;

Returns: \texttt{m}.

constexpr chrono::seconds seconds() const noexcept;

Returns: \texttt{s}.

constexpr precision subseconds() const noexcept;

Returns: \texttt{ss}.

constexpr precision to\_duration() const noexcept;

Returns: If \texttt{is\_neg}, returns \texttt{-(h + m + s + ss)}, otherwise returns \texttt{h + m + s + ss}.

constexpr explicit operator precision() const noexcept;

Returns: \texttt{to\_duration}().

§ 29.9.2
### 29.9.3 Non-members  
**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:

```cpp
return os << format(os.getloc(), STATICALLY_WIDEN<charT>("{:L%T}"), hms);
```

**Example 1:**

```cpp
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.

```cpp
constexpr bool is_am(const hours& h) noexcept;
```

*Returns:* $0h \leq h \&\& h \leq 11h$.

```cpp
constexpr bool is_pm(const hours& h) noexcept;
```

*Returns:* $12h \leq h \&\& h \leq 23h$.

```cpp
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.

```cpp
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 $[1h, 12h]$, the value returned is unspecified.

### 29.11 Time zones  
**[time.zone]**

#### 29.11.1 In general  
**[time.zone.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  
**[time.zone.db]**

##### 29.11.2.1 Class tzdb  
**[time.zone.db.tzdb]**

```cpp
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;
    };
}
```
Each vector in a tzdb object is sorted to enable fast lookup.

    const time_zone* locate_zone(string_view tz_name) const;

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]

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;

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 {
    public:
        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;
        };
    };
}

The tzdb_list database is a singleton; the unique object of type tzdb_list can be accessed via the get_tzdb_list() function.

[Note 1: This access is only needed for those applications that need to have long uptimes and have a need to update the time zone database while running. Other applications can implicitly access the front() of this list via the read-only namespace scope functions get_tzdb(), locate_zone(), and current_zone(). — end note]

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]

8 Returns: An iterator pointing to the element following the one that was erased, or end() if no such element exists.

9 Throws: Nothing.

const_iterator begin() const noexcept;

10 Returns: An iterator referring to the first tzdb in the container.

const_iterator end() const noexcept;

11 Returns: An iterator referring to the position one past the last tzdb in the container.

const_iterator cbegin() const noexcept;

12 Returns: begin().

const_iterator cend() const noexcept;

13 Returns: end().

29.11.2.3 Time zone database access [time.zone.db.access]

tzdb_list& get_tzdb_list();

1 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.

2 Synchronization: It is safe to call this function from multiple threads at one time.

3 Returns: A reference to the database.

4 Throws: runtime_error if for any reason a reference cannot be returned to a valid tzdb_list containing one or more valid tzdb.

const tzdb& get_tzdb();

5 Returns: get_tzdb_list().front().

const time_zone* locate_zone(string_view tz_name);

6 Returns: get_tzdb().locate_zone(tz_name).

7 [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();

8 Returns: get_tzdb().current_zone().

29.11.2.4 Remote time zone database support [time.zone.db.remote]

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.

const tzdb& reload_tzdb();

1 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().

2 Synchronization: This function is thread-safe with respect to get_tzdb_list().front() and get_tzdb_list().erase_after().

3 Postconditions: No pointers, references, or iterators are invalidated.

4 Returns: get_tzdb_list().front().

5 Throws: runtime_error if for any reason a reference cannot be returned to a valid tzdb.
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

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);
    }
  }
}

1 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.

template<class Duration>
nonexistent_local_time(const local_time<Duration>& tp, const local_info& i);

2 Preconditions: i.result == local_info::nonexistent is true.

3 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 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";

4 [Example 1]:

   #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() << '\n';
     }
   }

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

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);
    }
  }
}
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.

```cpp
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:

```cpp
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:**

```cpp
#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() << "\n";
    }
}
```

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

29.11.4.1 Class sys_info

```cpp
namespace std::chrono {
    struct sys_info {
        sys_seconds begin;
        sys_seconds end;
        seconds offset;
        minutes save;
        string abbrev;
    };
}
```

1. **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.**

2. **[Note 1: This type provides a low-level interface to time zone information. Typical conversions from sys_time to local_time will use this class implicitly, not explicitly. — end note]**

3. 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.

4. 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:
   
   offset = local_time - sys_time

5. **The save data member is extra information not normally needed for conversion between local_time and sys_time. If save != 0min, 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 == 0min`. 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 != 0min` 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);
```

7 Effects: Streams out the `sys_info` object `r` in an unspecified format.

8 Returns: `os`.

### 29.11.4.2 Class `local_info`

```cpp
namespace std::chrono {
  struct local_info {
    static constexpr int unique = 0;
    static constexpr int nonexistent = 1;
    static constexpr int ambiguous = 2;

    int result;
    sys_info first;
    sys_info second;
  };
}
```

1 [Note 1: This type provides a low-level interface to time zone information. Typical conversions from `local_time` to `sys_time` will use this class implicitly, not explicitly. — end note]

2 Describes the result of converting a `local_time` to a `sys_time` as follows:

- (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) 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`.

- (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`.

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>&
operator<<(basic_ostream<charT, traits>& os, const local_info& r);
```

3 Effects: Streams out the `local_info` object `r` in an unspecified format.

4 Returns: `os`.

### 29.11.5 Class `time_zone`

#### 29.11.5.1 Overview

```cpp
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;

1 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;

1 Returns: The name of the time_zone.

2 [Example 1: "America/New_York". — end example]

template<class Duration>
    sys_info get_info(const sys_time<Duration>& st) const;

3 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;

4 Returns: A local_info for tp.

template<class Duration>
    sys_time<common_type_t<Duration, seconds>>
    to_sys(const local_time<Duration>& tp) const;

5 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.

6 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;

7 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;

8 Returns: The local_time associated with tp and this time_zone.
29.11.5.3 Non-member functions

bool operator==(const timeZone& x, const timeZone& y) noexcept;

Returns: x.name() == y.name().

strong_ordering operator<=>(const timeZone& x, const timeZone& 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 {
        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>& zt);
            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);

zoned_time represents a logical pairing of a time_zone and a time_point with precision Duration. zoned_time 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.

If Duration is not a specialization of chrono::duration, the program is ill-formed.

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::locate_zone(name) and default constructs tp_.

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 [time.zone.zonedtime.members]

    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.

    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("{: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 <= 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
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: \(+1\)s to indicate a positive leap second or \(-1\)s to indicate a negative leap second.

[Note 1: All leap seconds inserted up through 2019 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 leap_second& x, const sys_time<Duration>& y) noexcept;
```

Returns: \(!y < x\).

```cpp
template<class Duration>
constexpr bool operator>(const leap_second& x, const sys_time<Duration>& y) noexcept;
```

Returns: \(y < x\).

```cpp
template<class Duration>
constexpr bool operator>=(const leap_second& x, const sys_time<Duration>& y) noexcept;
```

Returns: \(!x < y\).

§ 29.11.8.3
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

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 0
The productions fill-and-align, width, and precision are described in [22.14.2]. Giving a precision specification in the \texttt{chrono-format-spec} is valid only for \texttt{std::chrono::duration} types where the representation type Rep is a floating-point type. For all other Rep types, an exception of type \texttt{format_error} is thrown if the \texttt{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 \texttt{locale} used by a formatting function, defined as

\begin{itemize}
\item [(2.1)] the "C" locale if the \texttt{L} option is not present in \texttt{chrono-format-spec}, otherwise
\item [(2.2)] the locale passed to the formatting function if any, otherwise
\item [(2.3)] the global locale.
\end{itemize}

Each conversion specifier conversion-spec is replaced by appropriate characters as described in Table 97; the formats specified in ISO 8601:2004 shall be used where so described. Some of the conversion specifiers depend on the formatting locale. If the formatted object does not contain the information the conversion specifier refers to, an exception of type \texttt{format_error} is thrown.

The result of formatting a \texttt{std::chrono::duration} instance holding a negative value, or an \texttt{hh_mm_ss} object \texttt{h} for which \texttt{h.is_negative()} is true, is equivalent to the output of the corresponding positive value, with a \texttt{STATICALLY-WIDEN<charT>("-")} character sequence placed before the replacement of the initial conversion specifier.

```
Example 1:

```
Table 97: Meaning of conversion specifiers (continued)

<table>
<thead>
<tr>
<th>Specifier</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>%d</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 %Od produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%D</td>
<td>Equivalent to %m/%d/%y.</td>
</tr>
<tr>
<td>%e</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 %Oe produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%F</td>
<td>Equivalent to %Y-%m-%d.</td>
</tr>
<tr>
<td>%g</td>
<td>The last two decimal digits of the ISO week-based year. If the result is a single digit it is prefixed by 0.</td>
</tr>
<tr>
<td>%G</td>
<td>The ISO week-based year as a decimal number. If the result is less than four digits it is left-padded with 0 to four digits.</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. If the result is a single digit, it is prefixed with 0. The modified command %OH produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%I</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 %OI produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%j</td>
<td>If the type being formatted is a specialization of duration, the decimal number of days without padding. Otherwise, the day of the year as a decimal number. Jan 1 is 001. If the result is less than three digits, it is left-padded with 0 to three digits.</td>
</tr>
<tr>
<td>%m</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 %Om produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%M</td>
<td>The minute as a decimal number. If the result is a single digit, it is prefixed with 0. The modified command %OM produces the locale’s alternative representation.</td>
</tr>
<tr>
<td>%n</td>
<td>A new-line character.</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>%q</td>
<td>The duration’s unit suffix as specified in 29.5.11.</td>
</tr>
<tr>
<td>%Q</td>
<td>The duration’s numeric value (as if extracted via .count()).</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:%S.</td>
</tr>
<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 ISO weekday as a decimal number (1-7), 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 ISO week-based week number as a decimal number. 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>
</tbody>
</table>
### Table 97: Meaning of conversion specifiers (continued)

<table>
<thead>
<tr>
<th>Specifier</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<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 <code>%OW</code> produces the locale's alternative representation.</td>
</tr>
<tr>
<td>%x</td>
<td>The locale's date representation. The modified command <code>%Ex</code> produces the locale's alternate date representation.</td>
</tr>
<tr>
<td>%X</td>
<td>The locale's time representation. The modified command <code>%EX</code> 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 <code>%Oy</code> produces the locale's alternative representation. The modified command <code>%Ey</code> produces the locale's alternative representation of offset from <code>%EC</code> (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 <code>%EY</code> produces the locale's alternative full year representation.</td>
</tr>
<tr>
<td>%z</td>
<td>The offset from UTC in the ISO 8601:2004 format. For example -0430 refers to 4 hours 30 minutes behind UTC. If the offset is zero, +0000 is used. The modified commands <code>%Ez</code> and <code>%Oz</code> insert a : between the hours and minutes: -04:30. If the offset information is not available, an exception of type <code>format_error</code> 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 <code>format_error</code> is thrown.</td>
</tr>
</tbody>
</table>

7 If the `chrono-specs` is omitted, the chrono object is formatted as if by streaming it to `std::stringstream 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:

```c++
string s = format("{:=>8}", 42ms); // value of s is "====42ms"

-- end example]
```

8 **template<class Duration, class charT>**

```c++
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.

9 **template<class Duration, class charT>**

```c++
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")`.

10 **template<class Duration, class charT>**

```c++
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 `sys_time<Duration>(tp.time_since_epoch()) - (sys_days{1970y/January/1} - sys_days{1958y/January/1})`

11 **template<class Duration, class charT>**

```c++
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

§ 29.12 1439
sys_time<Duration>{tp.time_since_epoch()} +
(sys_days{1980y/January/Sunday[1]} - 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 \texttt{STATICALLY-WIDEN\langle charT\rangle\text{"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 \texttt{sys_time} initialized with \texttt{clock_cast\langle system_clock\rangle\langle t\rangle}, or by a \texttt{utc_time} initialized with \texttt{clock_cast\langle utc_clock\rangle\langle t\rangle}, where \texttt{t} is the first argument to \texttt{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 \texttt{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\}.

template<class Duration, 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);
};

template<class FormatContext>
typename FormatContext::iterator
format(const chrono::zoned_time<Duration, TimeZonePtr>& tp, FormatContext& ctx);

Effects: Equivalent to:

\begin{verbatim}
sys_info info = tp.get_info();
return formatter<chrono::local-time-format-t<Duration>, charT>::
  format((tp.get_local_time(), &info.abbrev, &info.offset), ctx);
\end{verbatim}

29.13 Parsing [time.parse]

1 Each \texttt{parse} overload specified in this subclause calls \texttt{from_stream} unqualified, so as to enable argument dependent lookup (6.5.4). In the following paragraphs, let \texttt{is} denote an object of type \texttt{basic_istream\langle charT, traits\rangle} and let \texttt{I} be \texttt{basic_istream\langle charT, traits\rangle\&}, where \texttt{charT} and \texttt{traits} are template parameters in that context.

2 \textit{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 \texttt{parse} immovable and preventing stream extraction into an lvalue of such a manipulator type.
template<class charT, class Parsable>
  unspecified
  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);

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

$$\text{from\_stream(declval<basic\_istream<charT, traits>>&()), } F, \ tp$$

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 $\text{from\_stream(is, } F, \ tp)$.

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);

Let $F$ be $fmt$ for the first overload and $fmt\.c\_str()$ for the second overload.

Constraints: The expression

$$\text{from\_stream(declval<basic\_istream<charT, traits>>&()), } F, \ tp, \ \text{addressof(abbrev)}$$

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 $\text{from\_stream(is, } F, \ tp, \ \text{addressof(abbrev)})$.

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 $\text{allocator}<charT>$ for the first overload.

Constraints: The expression

$$\text{from\_stream(declval<basic\_istream<charT, traits>>&()), } F, \ tp,$$

$$\text{declval<basic\_string<charT, traits, Alloc>>&(), }&\text{static\_cast<basic\_string<charT, traits, Alloc>&>(nullptr), }&\text{offset})$$

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:

$$\text{from\_stream(is, } F, \ tp,$$

$$\text{static\_cast<basic\_string<charT, traits, Alloc>&>(nullptr), }&\text{offset})$$

template<class charT, class traits, class Alloc, class Parsable>
  unspecified
  parse(const charT* fmt, Parsable& tp, basic_string<charT, traits, Alloc>& abbrev, minutes& offset);
Let $F$ be $\text{fmt}$ for the first overload and $\text{fmt}.\text{c_str}()$ for the second overload.

Constraints: The expression

$$\text{from_stream(declval<basic_istream<charT, traits>&>(), F, tp, addressof(abbrev), &offset)}$$

is well-formed when treated as an unevaluated operand (7.2.3).

Returns: A manipulator such that the expression $\text{is} >> \text{parse}(\text{fmt}, \text{tp}, \text{abbrev}, \text{offset})$ has type $I$, has value $\text{is}$, and calls $\text{from_stream(is, F, tp, addressof(abbrev), koffset)}$.

All $\text{from_stream}$ overloads behave as unformatted input functions, except that they have an unspecified effect on the value returned by subsequent calls to $\text{basic_istream<>::gcount()}$. 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 98. 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 98, 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, $\text{is.setstate(ios_-_base::failbit)}$ 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.

If the $\text{from_stream}$ 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, $\text{setstate(ios_-_base::failbit)}$ is called on the $\text{basic_istream}$.

<table>
<thead>
<tr>
<th>Flag</th>
<th>Parsed value</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>%a</code></td>
<td>The locale’s full or abbreviated case-insensitive weekday name.</td>
</tr>
<tr>
<td><code>%A</code></td>
<td>Equivalent to <code>%a</code>.</td>
</tr>
<tr>
<td><code>%b</code></td>
<td>The locale’s full or abbreviated case-insensitive month name.</td>
</tr>
<tr>
<td><code>%B</code></td>
<td>Equivalent to <code>%b</code>.</td>
</tr>
<tr>
<td><code>%c</code></td>
<td>The locale’s date and time representation. The modified command <code>%Ec</code> interprets the locale’s alternate date and time representation.</td>
</tr>
<tr>
<td><code>%C</code></td>
<td>The century as a decimal number. The modified command <code>%NC</code> 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 <code>%EC</code> interprets the locale’s alternative representation of the century.</td>
</tr>
<tr>
<td><code>%d</code></td>
<td>The day of the month as a decimal number. The modified command <code>%Nd</code> 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 <code>%Od</code> interprets the locale’s alternative representation of the day of the month.</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>Equivalent to <code>%d</code> and can be modified like <code>%d</code>.</td>
</tr>
<tr>
<td><code>%F</code></td>
<td>Equivalent to <code>%Y-%m-%d</code>. If modified with a width $N$, the width is applied to only <code>%Y</code>.</td>
</tr>
<tr>
<td><code>%g</code></td>
<td>The last two decimal digits of the ISO week-based year. The modified command <code>%Ng</code> 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><code>%G</code></td>
<td>The ISO week-based year as a decimal number. The modified command <code>%NG</code> 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>
</tbody>
</table>
Table 98: Meaning of parse flags (continued)

<table>
<thead>
<tr>
<th>Flag</th>
<th>Parsed value</th>
</tr>
</thead>
<tbody>
<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 duration, a decimal number of days. Otherwise, the day of the year as a decimal number. Jan 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. The modified command %OJ interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%m</td>
<td>The month as a decimal number. Jan 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>
<tr>
<td>%M</td>
<td>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.</td>
</tr>
<tr>
<td>%n</td>
<td>Matches one whitespace character.</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>The seconds as a decimal number. The modified command %NS specifies the maximum number of characters to read. If N is not specified, the default is 2 if the input time has a precision convertible to seconds. Otherwise the default width is determined by the decimal precision of the input and the field is interpreted as a long double in a fixed format. If encountered, the locale determines the decimal point character. Leading zeroes are permitted but not required. The modified command %OS interprets the locale’s alternative representation.</td>
</tr>
<tr>
<td>%t</td>
<td>Matches zero or one whitespace characters.</td>
</tr>
<tr>
<td>%T</td>
<td>Equivalent to %H:%M.</td>
</tr>
<tr>
<td>%u</td>
<td>The ISO weekday as a decimal number (1-7), 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 ISO week-based week number as a decimal number. 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 %NW 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>
</tbody>
</table>

§ 29.13 1443
### Table 98: Meaning of parse flags (continued)

<table>
<thead>
<tr>
<th>Flag</th>
<th>Parsed value</th>
</tr>
</thead>
<tbody>
<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 %0W 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 %NY 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>
<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 Header `<ctime>` synopsis

```cpp
#include <ctime>

#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(const 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);
    tm* gmtime(const time_t* timer);
    tm* localtime(const time_t* timer);
    size_t strftime(char* s, size_t maxsize, const char* format, const tm* timeptr);
}
```

1 The contents of the header `<ctime>` are the same as the C standard library header `<time.h>`.\(^{245}\)

---

\(^{245}\) `strftime` supports the C conversion specifiers C, D, E, F, G, h, r, R, t, T, u, V, and z, and the modifiers E and O.
The functions `asctime`, `ctime`, `gmtime`, and `localtime` are not required to avoid data races (16.4.6.10).

See also: ISO C 7.27
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 ISO C library, as summarized in Table 99.

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.3</td>
<td>&lt;locale&gt;</td>
</tr>
<tr>
<td>30.4</td>
<td>Standard locale categories</td>
</tr>
<tr>
<td>30.5</td>
<td>C library locales &lt;locale&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 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);
  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;
  template<> class ctype<char>;
  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 InputIterator = istreambuf_iterator<charT>>
  class num_get;
  template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
  class num_put;
  template<class charT>
  class numpunct;
```

§ 30.2
template<class charT>
    class numpunct_byname;

    // 30.4.5, collation
    template<class charT> class collate;
    template<class charT> class collate_byname;

    // 30.4.6, date and time
    class time_base;
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
        class time_get;
    template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
        class time_put;
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
        class time_get_byname;
    template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
        class time_put_byname;

    // 30.4.7, money
    class money_base;
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
        class money_get;
    template<class charT, class OutputIterator = ostreambuf_iterator<charT>>
        class money_put;

    template<class charT, bool Intl = false>
        class moneypunct;
    template<class charT, bool Intl = false>
        class moneypunct_byname;

    // 30.4.8, message retrieval
    class messages_base;
    template<class charT> class messages;
    template<class charT> class messages_byname;
}

1 The header `<locale>` defines classes and declares functions that encapsulate and manipulate the information peculiar to a locale.\[246\]

30.3 Locales

30.3.1 Class locale

30.3.1.1 General

namespace std {
    class locale {
        public:
            // types
            class facet;
            class id;
            using category = int;
            static const category // values assigned here are for exposition only
                none = 0,
                collate = 0x010, ctype = 0x020,
                monetary = 0x040, numeric = 0x080,
                time = 0x100, messages = 0x200,
                all = collate | ctype | monetary | numeric | time | messages;

            // 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);

\[246\] In this subclause, the type name `tm` is an incomplete type that is defined in `<ctime>` (29.14).
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;
template<class Facet> locale combine(const locale& other) const;

// locale operations
string name() 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;

// global locale objects
static locale global(const locale&);
static const locale& classic();

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.

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:

```cpp
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 example]

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.

[Note 1: All locale semantics are accessed via `use_facet<>` and `has_facet<>`, except that:

(5.1) A member operator template

```cpp
operator()(const basic_string<C, T, A>&, const basic_string<C, T, A>&)
```

is provided so that a locale can be used as a predicate argument to the standard collections, to collate strings.

(5.2) 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 (31.7.4.3).)

—end note]

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.

247) Note that in the call to `put`, the stream is implicitly converted to an `ostreambuf_iterator<charT, traits>`. 

§ 30.3.1.1
In successive calls to a locale facet member function on a facet object installed in the same locale, the returned result shall be identical.

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 "*".

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

#### 30.3.1.2.1 Type `locale::category`

```cpp
using category = int;
```

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.

`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 100.

<table>
<thead>
<tr>
<th>Category</th>
<th>Includes facets</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>collate</code></td>
<td><code>collate&lt;char&gt;</code>, <code>collate&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td><code>ctype</code></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;char16_t, char8_t, mbstate_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt&lt;char32_t, char8_t, mbstate_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt&lt;wchar_t, char, mbstate_t&gt;</code></td>
</tr>
<tr>
<td><code>monetary</code></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><code>numeric</code></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><code>time</code></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><code>messages</code></td>
<td><code>messages&lt;char&gt;</code>, <code>messages&lt;wchar_t&gt;</code></td>
</tr>
</tbody>
</table>

For any locale `loc` either constructed, or returned by `locale::classic()`, and any facet `Facet` shown in Table 100, `has_facet<Facet>(loc)` is `true`. Each `locale` member function which takes a `locale::category` argument operates on the corresponding set of facets.

An implementation is required to provide those specializations for facet templates identified as members of a category, and for those shown in Table 101.

The provided implementation of members of facets `num_get<charT>` and `num_put<charT>` calls `use_facet<F>(1)` 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.

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

§ 30.3.1.2.1
Table 101: Required specializations  

<table>
<thead>
<tr>
<th>Category</th>
<th>Includes facets</th>
</tr>
</thead>
<tbody>
<tr>
<td>collate</td>
<td><code>collate_byname&lt;char&gt;</code>, <code>collate_byname&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td>ctype</td>
<td><code>ctype_byname&lt;char&gt;</code>, <code>ctype_byname&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt_byname&lt;char, char, mbstate_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt_byname&lt;char16_t, char8_t, mbstate_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt_byname&lt;char32_t, char8_t, mbstate_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>codecvt_byname&lt;wchar_t, char, mbstate_t&gt;</code></td>
</tr>
<tr>
<td>monetary</td>
<td><code>moneypunct_byname&lt;char, International&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>moneypunct_byname&lt;wchar_t, International&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>money_get&lt;C, InputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>money_put&lt;C, OutputIterator&gt;</code></td>
</tr>
<tr>
<td>numeric</td>
<td><code>numpunct_byname&lt;char&gt;</code>, <code>numpunct_byname&lt;wchar_t&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>num_get&lt;C, InputIterator&gt;</code>, <code>num_put&lt;C, OutputIterator&gt;</code></td>
</tr>
<tr>
<td>time</td>
<td><code>time_get&lt;char, InputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_get_byname&lt;char, InputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_get&lt;wchar_t, InputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_get_byname&lt;wchar_t, InputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_put&lt;char, OutputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_put_byname&lt;char, OutputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_put&lt;wchar_t, OutputIterator&gt;</code></td>
</tr>
<tr>
<td></td>
<td><code>time_put_byname&lt;wchar_t, OutputIterator&gt;</code></td>
</tr>
<tr>
<td>messages</td>
<td><code>messages_byname&lt;char&gt;</code>, <code>messages_byname&lt;wchar_t&gt;</code></td>
</tr>
</tbody>
</table>

*Cp17OutputIterator* 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 types 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`

```cpp
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:248

   ```cpp
   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.

3. 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.

4. 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.

---

248 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.
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;
    };
}
```

1. The class `locale::id` provides identification of a locale facet interface, used as an index for lookup and to encapsulate initialization.

2. [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]

### 30.3.1.3 Constructors and destructor

```cpp
locale() noexcept;
```

1. **Effects:** Constructs a copy of the argument last passed to `locale::global(locale&)`, if it has been called; else, the resulting facets have virtual function semantics identical to those of `locale::classic()`.

   [Note 1: This constructor yields a copy of the current global locale. It is commonly used as a default argument for function parameters of type `const locale&`. — end note]

```cpp
explicit locale(const char* std_name);
```

2. **Effects:** Constructs a locale using standard C locale names, e.g., "POSIX". The resulting locale implements semantics defined to be associated with that name.

3. **Throws:** `runtime_error` if the argument is not valid, or is null.

4. **Remarks:** The set of valid string argument values is "C", ",", and any implementation-defined values.

```cpp
explicit locale(const string& std_name);
```

5. **Effects:** The same as `locale(std_name.c_str())`.

```cpp
locale(const locale& other, const char* std_name, category);
```

6. **Effects:** Constructs a locale as a copy of `other` except for the facets identified by the `category` argument, which instead implement the same semantics as `locale(std_name)`.

7. **Throws:** `runtime_error` if the argument is not valid, or is null.

8. **Remarks:** The locale has a name if and only if `other` has a name.

```cpp
locale(const locale& other, const string& std_name, category cat);
```

9. **Effects:** The same as `locale(other, std_name.c_str(), cat)`.

```cpp
template<class Facet> locale(const locale& other, Facet* f);
```

10. **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`.

11. **Remarks:** The resulting locale has no name.
locale(const locale& other, const locale& one, category cats);

**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**: The resulting locale has a name if and only if the first two arguments have names.

const locale& operator=(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 "*".

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, 24.3.11):

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);

Each of these functions isF returns the result of the expression:

use_facet<ctype<charT>>(loc).is(ctype_base::F, c)

where F is the ctype_base::mask value corresponding to that function (30.4.2).

30.3.3.2 Character conversions

template<class charT> charT toupper (charT c, const locale& loc);
template<class charT> charT tolower (charT c, const locale& loc);

Returns: use_facet<ctype<charT>>(loc).toupper(c).

Returns: use_facet<ctype<charT>>(loc).tolower(c).

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.

249) 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.
Within subclause 30.4 it is unspecified whether one virtual function calls another virtual function.

### 30.4.2 The ctype category

#### 30.4.2.1 General

```cpp
namespace std {
    class ctype_base {
    public:
        using mask = see below;

        // numeric values are for exposition only.
        static const mask space = 1 << 0;
        static const mask print = 1 << 1;
        static const mask cntrl = 1 << 2;
        static const mask upper = 1 << 3;
        static const mask lower = 1 << 4;
        static const mask alpha = 1 << 5;
        static const mask digit = 1 << 6;
        static const mask punct = 1 << 7;
        static const mask xdigit = 1 << 8;
        static const mask blank = 1 << 9;
        static const mask alnum = alpha | digit;
        static const mask graph = alnum | punct;
    }
}
```

1 The type `mask` is a bitmask type (16.3.3.3.4).

#### 30.4.2.2 Class template ctype

```cpp
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, mask* 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, charT* to) const;
        char narrow(charT c, char dfault) const;
        const charT* narrow(const charT* low, const charT* high, char dfault, char* to) const;

        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 charT do_tolower(charT) const;
        virtual const charT* do_tolower(charT* low, const charT* high) const;
    }
```
Class `ctype` encapsulates the C library `<cctype>` features. `istream` members are required to use `ctype<>` for character classing during input parsing.

The specializations required in Table 100 (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

```cpp
bool is(mask m, charT c) const;
const charT* is(const charT* low, const charT* high, mask* vec) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.

```cpp
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;
```

Returns: The smallest pointer `p` in the range `[low, high)` such that `is(m, *p)` would return `true`; otherwise, returns `high`.

```cpp
charT toupper(charT c) const;
const charT* toupper(charT* low, const charT* high) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.

```cpp
charT widen(char c) const;
const char* widen(const char* low, const char* high, charT* to) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.

```cpp
char narrow(charT c, char dfault) const;
const charT* narrow(const charT* low, const charT* high, char dfault, char* to) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.

### 30.4.2.2.3 ctype virtual functions

```cpp
bool do_is(mask m, charT c) const;
const charT* do_is(const charT* low, const charT* high, mask* vec) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.

```cpp
const charT* do_scan_is(mask m, const charT* low, const charT* high) const;
const charT* do_scan_not(mask m, const charT* low, const charT* high) const;
```

Returns: The smallest pointer `p` in the range `[low, high)` such that `is(m, *p)` would return `true`; otherwise, returns `high`.

```cpp
charT do_toupper(charT c) const;
const charT* do_toupper(charT* low, const charT* high) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.

```cpp
char do_narrow(charT c, char dfault) const;
const charT* do_narrow(const charT* low, const charT* high, char dfault, char* to) const;
```

Returns: The first form returns the result of the expression `(M & m) != 0`; i.e., `true` if the character has the characteristics specified. The second form returns `high`.
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 [low, 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 high.

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 [low, 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 high.

charT do_widen(char c) const;
const char* do_widen(const char* low, const char* high, charT* dest) const;

Effects: Applies the simplest reasonable transformation from a char value or sequence of char values to the corresponding charT value or values.\(^{250}\) The only characters for which unique transformations are required are those in the basic character set (5.3).

For any named ctype category with a ctype<charT> facet ctc and valid ctype_base::mask value M, (ctc.is(M, c) || !is(M, do_widen(c))) is true.\(^{251}\) The second form transforms each character *p in the range [low, high), placing the result in dest[p - low].

Returns: The first form returns the transformed value. The second form returns high.

char do_narrow(charT c, char dfault) const;
const charT* do_narrow(const charT* low, const charT* high, char dfault, char* dest) const;

Effects: Applies the simplest reasonable transformation from a charT value or sequence of charT values to the corresponding char value or values. For any character c in the basic character set (5.3) the transformation is such that do_widen(do_narrow(c, 0)) == c

For any named ctype category with a ctype<char> facet ctc however, and ctype_base::mask value M,

(is(M, c) || !ctc.is(M, do_narrow(c, dfault)))

is true (unless do_narrow returns dfault). In addition, for any digit character c, the expression (do_narrow(c, dfault) - '0') evaluates to the digit value of the character. The second form transforms each character *p in the range [low, high), placing the result (or dfault if no simple transformation is readily available) in dest[p - low].

Returns: The first form returns the transformed value; or dfault if no mapping is readily available. The second form returns high.

30.4.2.3 Class template ctype_byname

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();

    private:

250) The parameter c of do_widen is intended to accept values derived from character-literals for conversion to the locale’s encoding.
251) In other words, the transformed character is not a member of any character classification that c is not also a member of.
30.4.2.4 `ctype<char>` specialization

30.4.2.4.1 General

```cpp
namespace std {
    template<>
    class ctype<char> : public locale::facet, public ctype_base {
        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;

        static locale::id id;
        static const size_t table_size = implementation-defined;
        const mask* table() const noexcept;
        static const mask* classic_table() noexcept;
    };
}
```

1 A specialization `ctype<char>` is provided so that the member functions on type `char` can be implemented inline.\(^{252}\) The implementation-defined value of member `table_size` is at least 256.

30.4.2.4.2 Destructor

```cpp
~ctype();
```

1 *Effects*: If the constructor’s first argument was nonzero, and its second argument was `true`, does delete `[]` table().

---

\(^{252}\) Only the `char` (not `unsigned char` and `signed char`) form is provided. The specialization is specified in the standard, and not left as an implementation detail, because it affects the derivation interface for `ctype<char>`.
30.4.2.4.3 Members

In the following member descriptions, for unsigned char values v where v >= table_size, table()[v] is assumed to have an implementation-specific value (possibly different for each such value v) without performing the array lookup.

```cpp
explicit ctype(const mask* tbl = nullptr, bool del = false, size_t refs = 0);
```

**Preconditions:** Either tbl == nullptr is true or [tbl, tbl+table_size) is a valid range.

**Effects:** Passes its refs argument to its base class constructor.

```cpp
bool is(mask m, char c) const;
const char* is(const char* low, const char* high, mask* vec) const;
```

**Effects:** The second form, for all *p in the range [low, high), assigns into vec[p - low] the value table()[(unsigned char)*p].

**Returns:** The first form returns table()[(unsigned char)c] & m; the second form returns high.

```cpp
const char* scan_is(mask m, const char* low, const char* high) const;
```

**Returns:** The smallest p in the range [low, high) such that table()[(unsigned char) *p] & m is true.

```cpp
const char* scan_not(mask m, const char* low, const char* high) const;
```

**Returns:** The smallest p in the range [low, high) such that table()[(unsigned char) *p] & m is false.

```cpp
char toupper(char c) const;
const char* toupper(char* low, const char* high) const;
```

**Returns:** do_toupper(c) or do_toupper(low, high), respectively.

```cpp
char tolower(char c) const;
const char* tolower(char* low, const char* high) const;
```

**Returns:** do_tolower(c) or do_tolower(low, high), respectively.

```cpp
char widen(char c) const;
const char* widen(const char* low, const char* high, char* to) const;
```

**Returns:** do_widen(c) or do_widen(low, high, to), respectively.

```cpp
char narrow(char c, char dfault) const;
const char* narrow(const char* low, const char* high, char* to) const;
```

**Returns:** do_narrow(c, dfault) or do_narrow(low, high, dfault, to), respectively.

```cpp
const mask* table() const noexcept;
```

**Returns:** The first constructor argument, if it was nonzero, otherwise classic_table().

30.4.2.4.4 Static members

```cpp
static const mask* classic_table() noexcept;
```

**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

```cpp
char do_toupper(char) const;
const char* do_toupper(char* low, const char* high) const;
char do_tolower(char) const;
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;

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

30.4.2.5.1 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& state, const externT* from, const externT* end, size_t max) const;

    static locale::id id;

  };

  protected:

  ~codecvt();

  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& state, const externT* from, const externT* end, size_t max) const;

  };
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.

The `stateT` argument selects the pair of character encodings being mapped between.

The specializations required in Table 100 (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. The specialization `codecvt<char16_t, char8_t, mbstate_t>` converts between the UTF-16 and UTF-8 encoding forms, and the specialization `codecvt<char32_t, char8_t, mbstate_t>` converts between the UTF-32 and UTF-8 encoding forms. `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

#### result out

```cpp
result out(
    stateT& state,
    const internT* from, const internT* from_end, const internT*& from_next,
    externT* to, externT* to_end, externT*& to_next) const;
```

Returns: `do_out(state, from, from_end, from_next, to, to_end, to_next)` const;

### result unshift

```cpp
result unshift(stateT& state, externT* to, externT* to_end, externT*& to_next) const;
```

Returns: `do_unshift(state, to, to_end, to_next)` const;

### result in

```cpp
result in(
    stateT& state,
    const externT* from, const externT* from_end, const externT*& from_next,
    internT* to, internT* to_end, internT*& to_next) const;
```

Returns: `do_in(state, from, from_end, from_next, to, to_end, to_next)` const;

### int encoding

```cpp
int encoding() const noexcept;
```

Returns: `do_encoding()`.

### bool always_noconv

```cpp
bool always_noconv() const noexcept;
```

Returns: `do_always_noconv()`.

### int length

```cpp
int length(stateT& state, const externT* from, const externT* from_end, size_t max) const;
```

Returns: `do_length(state, from, from_end, max)`.

### int max_length

```cpp
int max_length() const noexcept;
```

Returns: `do_max_length()`.

### 30.4.2.5.3 Virtual functions

#### result do_out

```cpp
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

```cpp
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;
```

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.
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
   do_out(state, from, from_end, from_next, to, to_end, to_next)
would return ok, where from != from_end, then
   do_out(state, from, from + 1, from_next, to, to_end, to_next)
shall also return ok, and that if
   do_in(state, from, from_end, from_next, to, to_end, to_next)
would return ok, where to != to_end, then
   do_in(state, from, from_end, from_next, to, +1, to_next)
shall also return ok.253

[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]

Returns: An enumeration value, as summarized in Table 102.

Table 102: do_in/do_out result values  [tab:locale.codecvt.inout]

<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]

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.254 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 103.

253) 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.

254) Typically these will be characters to return the state to stateT().

§ 30.4.2.5.3 1461
Table 103: \texttt{do\_unshift} result values
tab:locale.codecvt.unshift

<table>
<thead>
<tr>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{ok}</td>
<td>completed the sequence</td>
</tr>
<tr>
<td>\texttt{partial}</td>
<td>space for more than \texttt{to_end} - \texttt{to} destination elements was needed to terminate a sequence given the value of \texttt{state}</td>
</tr>
<tr>
<td>\texttt{error}</td>
<td>an unspecified error has occurred</td>
</tr>
<tr>
<td>\texttt{noconv}</td>
<td>no termination is needed for this \texttt{state_type}</td>
</tr>
</tbody>
</table>

\begin{verbatim}
int do_encoding() const noexcept;

Returns: \(-1\) if the encoding of the \texttt{externT} sequence is state-dependent; else the constant number of \texttt{externT} characters needed to produce an internal character; or \(0\) if this number is not a constant.\(^{255}\)

bool do_always_noconv() const noexcept;

Returns: \texttt{true} if \texttt{do\_in()} and \texttt{do\_out()} return \texttt{noconv} for all valid argument values. \texttt{codecvt<char, char, mbstate\_t>} returns \texttt{true}.

int do_length(stateT& state, const externT* from, const externT* from\_end, size\_t max) const;

Preconditions: \((from \leq from\_end)\) is well-defined and \texttt{true}; \texttt{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 \texttt{state} argument is as if it called \texttt{do\_in(state, from, from\_end, from, to, to+max, to)} for to pointing to a buffer of at least \texttt{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 \texttt{max} or fewer valid complete characters of type \texttt{internT}. The specialization \texttt{codecvt<char, char, mbstate\_t>\_do\_max\_length()} returns the lesser of \texttt{max} and \((from\_end-from)\).

int do_max_length() const noexcept;

Returns: The maximum value that \texttt{do\_length(state, from, from\_end, 1)} can return for any valid range \([from, from\_end)\) and \texttt{state\_t} value \texttt{state}. The specialization \texttt{codecvt<char, char, mbstate\_t>\_do\_max\_length()} returns \(1\).
\end{verbatim}

30.4.2.6 Class template \texttt{codecvt\_byname} [locale.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();
        }
    }

30.4.3 The numeric category [category.numeric]
30.4.3.1 General [category.numeric.general]

1 The classes \texttt{num\_get<>} and \texttt{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.\(^{256}\)

\begin{verbatim}
255\) If \texttt{encoding()} yields \(-1\), then more than \texttt{max\_length()} \texttt{externT} elements can be consumed when producing a single \texttt{internT} character, and additional \texttt{externT} elements can appear at the end of a sequence after those that yield the final \texttt{internT} character.\(^{256}\) Parsing \("-1"\) correctly into, e.g., an \texttt{unsigned short} requires that the corresponding member \texttt{get()} at least extract the sign before delegating.

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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 100 and 101 (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<`b`** 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 (31.7.4.3.1, 31.7.5.3.1).

### 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 in, iter_type end, ios_base&,
                                       ios_base::iostate& err, bool& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, long& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, long long& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, unsigned short& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, unsigned int& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, unsigned long& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, unsigned long long& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, float& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, double& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, long double& v) const;
            virtual iter_type do_get(iter_type in, iter_type end, ios_base&,
                                       ios_base::iostate& err, void*& v) const;

        protected:
            ~num_get();
    }
}
```

§ 30.4.3.2.1 1463
The facet `num_get` is used to parse numeric values from an input sequence such as an istream.

### 30.4.3.2.2 Members

```cpp
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;
};
```

1 The facet `num_get` is used to parse numeric values from an input sequence such as an istream.

### 30.4.3.2.3 Virtual functions

```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;
```

1 Returns: `do_get(in, end, str, err, val)`.

### 30.4.3.2.3 Virtual functions

```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;
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;
```

1 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()`.

2 The details of this operation occur in three stages.
Stage 1: Determine a conversion specifier

Stage 2: Extract characters from in and determine a corresponding char value for the format expected by the conversion specification determined in stage 1.

Stage 3: Store results

The details of the stages are presented below.

**Stage 1:** The function initializes local variables via

```c
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 104. The table is ordered. That is, the first line whose condition is true applies.

<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>%d</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, with a length modifier added as indicated in Table 105.

<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>
<tr>
<td>long 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

```c
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 =
  ct == 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:

```c
static const char src[] = "0123456789abcdefpfxABCDEFPX+-";
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 \( \text{in} \) is advanced by \( \text{++in} \) and processing returns to the beginning of stage 2.

[Example 1: Given an input sequence of "0x1a.bp+07p",]

(3.1) if the conversion specifier returned by Stage 1 is \( %d, "0\) is accumulated;
(3.2) if the conversion specifier returned by Stage 1 is \( %i, "0x1a\) are accumulated;
(3.3) if the conversion specifier returned by Stage 1 is \( %g, "0x1a.bp+07\) 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 \(<\text{cstdlib}\>:

(3.4) For a signed integer value, the function \text{strtol}.
(3.5) For an unsigned integer value, the function \text{strtoul}.
(3.6) For a float value, the function \text{strtof}.
(3.7) For a double value, the function \text{strtod}.
(3.8) For a long double value, the function \text{strtold}.

The numeric value to be stored can be one of:

(3.9) zero, if the conversion function does not convert the entire field.
(3.10) 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 \( \text{val} \).
(3.11) the most positive representable value, if the field to be converted to an unsigned integer type represents a value that cannot be represented in \( \text{val} \).
(3.12) the converted value, otherwise.

The resultant numeric value is stored in \( \text{val} \). If the conversion function does not convert the entire field, or if the field represents a value outside the range of representable values, \text{ios_base}\::\text{failbit} is assigned to \( \text{err} \).

Digit grouping is checked. That is, the positions of discarded separators are examined for consistency with \text{use_facet<\text{numpunct<charT>>>(loc)}.\text{grouping()}}. If they are not consistent then \text{ios_base}\::\text{failbit} is assigned to \( \text{err} \).

In any case, if stage 2 processing was terminated by the test for \( \text{in == end} \) then \( \text{err |=} \text{ios_base}\::\text{eofbit} \) is performed.

\[
\text{iter_type do_get(iter_type in, iter_type end, ios_base& str,}
\text{ ios_base::iostate& err, bool& val) const;}
\]

**Effects:** If \( (\text{str.flags()&ios_base::boolalpha}) == 0 \) then input proceeds as it would for a long except that if a value is being stored into \( \text{val} \), the value is determined according to the following: If the value to be stored is 0 then \text{false} is stored. If the value is 1 then \text{true} is stored. Otherwise \text{true} is stored and \text{ios_base}\::\text{failbit} is assigned to \( \text{err} \).

Otherwise target sequences are determined “as if” by calling the members \text{falseName()} and \text{trueName()} of the facet obtained by \text{use_facet<\text{numpunct<charT>>>(str.getloc())}. Successive characters in the range \([\text{in,end})\) (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 \( \text{in} \) is compared to \( \text{end} \) only when necessary to obtain a character. If a target sequence is uniquely matched, \( \text{val} \) is set to the corresponding value. Otherwise \text{false} is stored and \text{ios_base}\::\text{failbit} is assigned to \( \text{err} \).

The \( \text{in} \) iterator is always left pointing one position beyond the last character successfully matched. If \( \text{val} \) is set, then \( \text{err} \) is set to \text{str.goodbit}; or to \text{str.eofbit} if, when seeking another character to match, it is found that \( (\text{in == end}) \). If \( \text{val} \) is not set, then \( \text{err} \) is set to \text{str.failbit}; or to \( (\text{str.failbit}|\text{str.eofbit}) \) if the reason for the failure was that \( (\text{in == end}) \).

[Example 2: For targets \text{true: } "a" and \text{false: } "abb\), the input sequence "a\) yields \( \text{val} == \text{true} \) and \( \text{err} == \text{str.eofbit}\); the input sequence "abc\) yields \( \text{err} == \text{str.failbit}\), with \text{in} ending at the 'c' element. For targets \text{true: } "1" and \text{false: } "0\), the input sequence "1\) yields \( \text{val} == \text{true} \) and \( \text{err} == \text{str.goodbit}. \) For empty targets ("\), any input sequence yields \( \text{err} == \text{str.failbit}. — end example]

Returns: \text{in}.
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;

        protected:
            ~num_put();
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, bool v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, long v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, long long v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, unsigned long v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, unsigned long long v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, double v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, long double v) const;
            virtual iter_type do_put(iter_type, ios_base&, char_type fill, const void* v) const;
        }

    };

1 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;
iter_type put(iter_type out, ios_base& str, char_type fill, const void* val) const;

1 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;
iter_type do_put(iter_type out, ios_base& str, char_type fill, const void* val) const;

1 Effects: Writes characters to the sequence out, formatting val as desired. In the following description, loc names a local variable initialized as

    locale loc = str.getloc();

2 The details of this operation occur in several stages:
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 106.

**Table 106: Integer conversions**  
<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;&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 107.

**Table 107: Floating-point conversions**  
<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;&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;&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 108.

The conversion specifier has the following optional additional qualifiers prepended as indicated in Table 109.

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.
Table 108: Length modifier [tab:facet.num.put.length]

<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>

Table 109: Numeric conversions [tab:facet.num.put.conv]

<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 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 a is the conversion specifier determined above.

**Stage 2:** Any character c other than a decimal point(.) is converted to a charT via

use_facet<ctype<charT>>(loc).widen(c)

A local variable punct is initialized via

const numnumpunct<charT>& punct = use_facet<numnumpunct<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

fmtflags adjustfield = (flags & (ios_base::adjustfield));

The location of any padding\(^{257}\) is determined according to Table 110.

Table 110: Fill padding [tab:facet.num.put.fill]

<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.

**Stage 4:** The sequence of charT’s at the end of stage 3 are output via

*out++ = c

\(^{257}\) The conversion specification #o generates a leading 0 which is not a padding character.
iter_type do_put(iter_type out, ios_base& str, char_type fill, bool val) const;

5 Returns: If (str.flags() & ios_base::boolalpha) == 0 returns do_put(out, str, fill, (int)val), otherwise obtains a string \( s \) as if by

\[
\text{string\_type } s =
\begin{align*}
\text{val } & \Rightarrow \text{use\_facet<numpunct<charT>>(loc).truename()} \\
\text{false } & \Rightarrow \text{use\_facet<numpunct<charT>>(loc).falsename()}
\end{align*}
\]

and then inserts each character \( c \) of \( s \) into \( out \) via \( *out++ = c \) and returns \( out \).

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 100 (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 fmtflags argument value, and thousands-sep and decimal-point are the results of corresponding numpunct<charT> members. Integer values have the format:

\[
\text{intval}: \quad \text{sign}_{\text{opt}} \text{ units} \\
\text{sign}: \quad + \quad - \\
\text{units}: \quad \text{digits} \\
\text{digits thousands-sep units} \\
\text{digits}: \quad \text{digit digits}_{\text{opt}}
\]

and floating-point values have:

\[
\text{floatval}: \quad \text{sign}_{\text{opt}} \text{ units fractional}_{\text{opt}} \text{ exponent}_{\text{opt}} \quad \text{sign}_{\text{opt}} \text{ decimal-point digits exponent}_{\text{opt}}
\]
fractional:
    decimal-point digits_{opt}
exponent:
    e sign_{opt} digits
e:
    e
E

where the number of digits between thousands-seps 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

char_type decimal_point() const;
  Returns: do_decimal_point().

char_type thousands_sep() const;
  Returns: do_thousands_sep().

string grouping() const;
  Returns: do_grouping().

string_type truename() const;
string_type falsename() const;
  Returns: do_truename() or do_falsename(), respectively.

30.4.4.1.3 Virtual functions

char_type do_decimal_point() const;
  Returns: A character for use as the decimal radix separator. The required specializations return '.' or L'.'.

char_type do_thousands_sep() const;
  Returns: A character for use as the digit group separator. The required specializations return ',' or L','.

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 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.

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

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;
      using string_type = basic_string<charT>;

258) 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".
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

30.4.5.1.1 General

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 100 (30.3.1.2.1), namely collate<char> and collate<wchar_t>, apply lexicographic 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;

1 Returns: 1 if the first string is greater than the second, -1 if less, zero otherwise. The specializations required in Table 100 (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.  

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 \((1.0/\text{numeric_limits<unsigned long>::max()})\).

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 100 and 101 (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);

            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;

            259) This function is useful when one string is being compared to many other strings.
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& f, 
ios_base::iostate& err, tm* t) const;
virtual iter_type do_get_date(iter_type s, iter_type end, ios_base& f, 
ios_base::iostate& err, tm* t) const;
virtual iter_type do_get_weekday(iter_type s, iter_type end, ios_base& f, 
ios_base::iostate& err, tm* t) const;
virtual iter_type do_get_monthname(iter_type s, iter_type end, ios_base& f, 
ios_base::iostate& err, tm* t) const;
virtual iter_type do_get_year(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.260

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 [locale.time.get.members]
dateorder date_order() const;

1 Returns: do_date_order().

iter_type get_time(iter_type s, iter_type end, ios_base& str, 
ios_base::iostate& err, tm* t) const;

2 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;

3 Returns: do_get_date(s, end, str, err, t).

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;

4 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;

5 Returns: do_get_year(s, end, str, err, t).

260 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(iter_type s, iter_type end, ios_base& f, ios_base::iostate& err, tm* t, char format, char modifier = 0) const;

6  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;

7  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 strftime. 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

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

[locale.time.get.virtuals]

dateorder do_date_order() const;

1  Returns: An enumeration value indicating the preferred order of components for those date formats that are composed of day, month, and year. Returns no_order if the date format specified by 'x' contains other variable components (e.g., Julian day, week number, week day).

iter_type do_get_time(iter_type s, iter_type end, ios_base& str, ios_base::iostate& err, tm* t) const;

2  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;

3  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 111.

261) This function is intended as a convenience only, for common formats, and can return no_order in valid locales.

§ 30.4.6.2.3 1475
Table 111: do\_get\_date effects

<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.

\begin{verbatim}
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;
\end{verbatim}

Effects: Reads characters starting at \texttt{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 \texttt{tm} member accordingly.

Returns: An iterator pointing immediately beyond the last character recognized as part of a valid name.

\begin{verbatim}
iter_type do_get_year(iter_type s, iter_type end, ios_base& str,
    ios_base::iostate& err, tm* t) const;
\end{verbatim}

Effects: Reads characters starting at \texttt{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 \texttt{t->tm\_year} member accordingly.

Returns: An iterator pointing immediately beyond the last character recognized as part of a valid year identifier.

\begin{verbatim}
iter_type do_get(iter_type s, iter_type end, ios_base& f,
    ios_base::iostate& err, tm* t, char format, char modifier) const;
\end{verbatim}

Preconditions: \texttt{t} points to an object.

Effects: The function starts by evaluating \texttt{err = ios\_base::goodbit}. It then reads characters starting at \texttt{s} until it encounters an error, or until it has extracted and assigned those \texttt{tm} members, and any remaining format characters, corresponding to a conversion specification appropriate for the POSIX function \texttt{strptime}, formed by concatenating \texttt{"%"}, the \texttt{modifier} character, when non-NUL, and the \texttt{format} character. When the concatenation fails to yield a complete valid directive the function leaves the object pointed to by \texttt{t} unchanged and evaluates \texttt{err |= ios\_base::failbit}. When \texttt{s == end} evaluates to \texttt{true} after reading a character the function evaluates \texttt{err |= ios\_base::eofbit}.

For complex conversion specifications such as \texttt{%c}, \texttt{%x}, or \texttt{%X}, or conversion specifications that involve the optional modifiers \texttt{E} or \texttt{O}, when the function is unable to unambiguously determine some or all \texttt{tm} members from the input sequence \texttt{[s, end)}, it evaluates \texttt{err |= ios\_base::eofbit}. In such cases the values of those \texttt{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 \texttt{format} and \texttt{modifier}.

Remarks: It is unspecified whether multiple calls to \texttt{do\_get() with the address of the same \texttt{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

\begin{verbatim}
namespace std {
    template<class charT, class InputIterator = istreambuf_iterator<charT>>
        class time_get_byname : public time_get<charT, InputIterator> {
\end{verbatim}
public:
    using dateorder = time_base::dateorder;
    using iter_type = InputIterator;

    explicit time_getbyname(const char*, size_t refs = 0);
    explicit time_getbyname(const string&, size_t refs = 0);

protected:
    ~time_getbyname();
};

30.4.6.4 Class template time_put

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);

            // the following is implemented in terms of other member functions.
            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;
        }
    }

30.4.6.4.1 Members

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;

1 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 mod 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).

2 The second form calls do_put(s, str, fill, t, format, modifier).

3 [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]

4 Returns: An iterator pointing immediately after the last character produced.

262) Although the C programming language defines no modifiers, most vendors do.
30.4.6.4.2 Virtual functions

```cpp
iter_type do_put(iter_type s, ios_base&, char_type fill, const tm* t,
                 char format, char modifier) const;
```

1. **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]

2. **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]

3. **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

```cpp
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);
        ~time_put_byname();
    }
}
```

30.4.7 The monetary category

30.4.7.1 General

1. These templates handle monetary formats. A template parameter indicates whether local or international monetary formats are to be used.

2. All specifications of member functions for `money_put` and `money_get` in the subclauses of 30.4.7 only apply to the specializations required in Tables 100 and 101 (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.

30.4.7.2 Class template money_get

```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;
};

30.4.7.2.1 Members [locale.money.get.members]

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).

30.4.7.2.2 Virtual functions [locale.money.get.virtuals]

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

\[
\text{for } (\text{int } i = 0; i < n; ++i) \\
\quad \text{buf2}[i] = \text{src}[\text{find}(\text{atoms}, \text{atoms} + \text{sizeof}(\text{src}), \text{buf1}[i]) - \text{atoms}]; \\
\text{buf2}[n] = 0; \\
\text{sscanf}(\text{buf2}, "\%Lf", &\text{units});
\]

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

\[
\text{static const char src[]} = "0123456789-"; \\
\text{charT atoms}[\text{sizeof}(\text{src})]; \\
\text{ct.widen(src, src + \text{sizeof}(\text{src}) - 1, atoms)};
\]

`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

```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, 
                          char_type fill, const string_type& digits) const;

        private:
            ~money_put();
            virtual iter_type do_put(iter_type, bool, ios_base&, char_type fill, 
                                      long double units) const;
            virtual iter_type do_put(iter_type, bool, ios_base&, char_type fill, 
                                      const string_type& digits) const;
    };
}
```

#### 30.4.7.3.1 Members

```cpp
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).

#### 30.4.7.3.2 Virtual functions

```cpp
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

\[
\text{ct.widen(buf1, buf1 + sprintf(buf1, "\%Lf", units), buf2)}
\]

The semantics here are different from ct.narrow.
for character buffers `buf1` and `buf2`. If the first character in `digits` or `buf2` is equal to \texttt{ct.widen(’-’)}, then the pattern used for formatting is the result of \texttt{mp.neg_format()}; otherwise the pattern is the result of \texttt{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 \texttt{str.width(0)}.

Returns: An iterator pointing immediately after the last character produced.

Remarks: The currency symbol is generated if and only if (\texttt{str.flags() & str.showbase}) is nonzero. If the number of characters generated for the specified format is less than the value returned by \texttt{str.width()} on entry to the function, then copies of \texttt{fill} are inserted as necessary to pad to the specified width. For the value \texttt{af} equal to (\texttt{str.flags() & str.adjustfield}), if (\texttt{af == str.internal}) is true, the fill characters are placed where none or space appears in the formatting pattern; otherwise if (\texttt{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 \texttt{num_get<>::get}. — end note]

### 30.4.7.4 Class template moneypunct

#### 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;
            pattern pos_format() const;
            pattern neg_format() const;

            static locale::id id;
            static const bool intl = International;

        protected:
            ~moneypunct();
            virtual charT do_decimal_point() const;
            virtual charT do_thousands_sep() const;
            virtual string do_grouping() const;
            virtual string_type do_curr_symbol() const;
            virtual string_type do_positive_sign() const;
            virtual string_type do_negative_sign() const;
            virtual int do_frac_digits() const;
            virtual pattern do_pos_format() const;
            virtual pattern do_neg_format() 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.\(^{264}\) 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 `moneypunct<>::do_grouping()`.

### 30.4.7.4.2 Members

```
locale.moneypunct.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 `do_F()`.

### 30.4.7.4.3 Virtual functions

```locale.moneypunct.virtuals

charT do_decimal_point() const;
```

Returns: The radix separator to use in case `do_frac_digits()` is greater than zero.\(^{265}\)

\(^{264}\) An array of `char`, rather than an array of `part`, is specified for `pattern::field` purely for efficiency.

\(^{265}\) In common U.S. locales this is ‘.‘.
charT do_thousands_sep() const;

Returns: The digit group separator to use in case do_grouping() specifies a digit grouping pattern.\textsuperscript{266}

string do_grouping() const;

Returns: A pattern defined identically as, but not necessarily equal to, the result of numpunct<charT>::do_grouping().\textsuperscript{267}

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 \texttt{true}, this is typically four characters long: a three-letter code as specified by ISO 4217 followed by a space. — end note]

string_type do_positive_sign() const;
string_type do_negative_sign() const;

Returns: do_positive_sign() returns the string to use to indicate a positive monetary value;\textsuperscript{268} 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.\textsuperscript{269}

pattern do_pos_format() const;
pattern do_neg_format() const;

Returns: The specializations required in Table 101 (30.3.1.2.1), namely
\begin{align*}
&\text{— moneypunct<char>}, \\
&\text{— moneypunct<wchar_t>}, \\
&\text{— moneypunct<char, true>, and} \\
&\text{— moneypunct<wchar_t, true>},
\end{align*}
return an object of type pattern initialized to \{ symbol, sign, none, value \}.\textsuperscript{270}

30.4.7.5 Class template moneypunct_byname\textsuperscript{[locale.moneypunct.basename]}

namespace std {
    template<class charT, bool Intl = false>
    class moneypunct_byname : public moneypunct<charT, Intl> {
    public:
        using pattern = money_base::pattern;
        using string_type = basic_string<charT>;

        explicit moneypunct_byname(const char*, size_t refs = 0);
        explicit moneypunct_byname(const string&, size_t refs = 0);

        protected:
            ~moneypunct_byname();
    };
}

30.4.8 The message retrieval category\textsuperscript{[category.messages]}

30.4.8.1 General\textsuperscript{[category.messages.general]}

Class messages<charT> implements retrieval of strings from message catalogs.

\textsuperscript{266} In common U.S. locales this is ‘,’.
\textsuperscript{267} To specify grouping by 3s, the value is “\003” not “3”.
\textsuperscript{268} This is usually the empty string.
\textsuperscript{269} In common U.S. locales, this is 2.
\textsuperscript{270} Note that the international symbol returned by do_curr_symbol() usually contains a space, itself; for example, ”USD “.
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& loc) 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;

2 Returns: do_get(cat, set, msgid, dfault).

void close(catalog cat) const;

3 Effects: Calls do_close(cat).

30.4.8.2.3 Virtual functions

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.

string_type do_get(catalog cat, int set, int msgid, 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.
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 messagesbyname

```cpp
namespace std {
    template<class charT>
    class messagesbyname : public messages<charT> {
    public:
        using catalog = messages_base::catalog;
        using string_type = basic_string<charT>;

        explicit messagesbyname(const char*, size_t refs = 0);
        explicit messagesbyname(const string&, size_t refs = 0);

    protected:
        ~messagesbyname();
    };
}
```

### 30.5 C library locales

#### 30.5.1 Header <locale>

```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 112.

**See also:** ISO C 7.11

<table>
<thead>
<tr>
<th><code>fprintf</code></th>
<th><code>isprint</code></th>
<th><code>iswdigit</code></th>
<th><code>localeconv</code></th>
<th><code>tolower</code></th>
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</thead>
<tbody>
<tr>
<td><code>fscanf</code></td>
<td><code>ispunct</code></td>
<td><code>iswgraph</code></td>
<td><code>mblen</code></td>
<td><code>toupper</code></td>
</tr>
<tr>
<td><code>isalnum</code></td>
<td><code>isspace</code></td>
<td><code>islower</code></td>
<td><code>mbstowcs</code></td>
<td><code>tolower</code></td>
</tr>
<tr>
<td><code>isalpha</code></td>
<td><code>isupper</code></td>
<td><code>iswprint</code></td>
<td><code>mbtowc</code></td>
<td><code>toupper</code></td>
</tr>
<tr>
<td><code>isblank</code></td>
<td><code>iswalpha</code></td>
<td><code>iswspace</code></td>
<td><code>strcoll</code></td>
<td><code>wcstod</code></td>
</tr>
<tr>
<td><code>iscntrl</code></td>
<td><code>iswblank</code></td>
<td><code>iswupper</code></td>
<td><code>strerror</code></td>
<td><code>wsctombs</code></td>
</tr>
<tr>
<td><code>isdigit</code></td>
<td><code>iswctype</code></td>
<td><code>isxdigit</code></td>
<td><code>strxfrm</code></td>
<td><code>wcstombs</code></td>
</tr>
<tr>
<td><code>isgraph</code></td>
<td><code>iswctrl</code></td>
<td><code>iswxdigit</code></td>
<td><code>strtod</code></td>
<td><code>wcsxfrm</code></td>
</tr>
<tr>
<td><code>islower</code></td>
<td><code>iswctype</code></td>
<td><code>isxdigit</code></td>
<td><code>strxfrm</code></td>
<td><code>wctomb</code></td>
</tr>
</tbody>
</table>
# 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 113.

### Table 113: Input/output library summary

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<tr>
<td>31.13</td>
<td>C library files &lt;cstdio&gt;,&lt;cinttypes&gt;</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

```cpp
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.\(^{271}\)

```cpp
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.\(^{272}\)

### 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.

\[Note 1: \text{For each of the specializations of } \text{char_traits defined in 23.2.4, state_type denotes mbstate_t, pos_type denotes fpos<mbstate_t>, and off_type denotes streamoff.} \text{— end note}\]

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 types that meet the requirements for a character on which any of the iostream components can be instantiated.

\(^{271}\) Typically `long long`.

\(^{272}\) Most places where `streamsize` is used would use `size_t` in ISO 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_iostream;
    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;
}
```

§ 31.3.1
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 = basic_istreamstream<char>;
using ostringstream = basic_ostringstream<char>;
using stringstream = basic_stringstream<char>;

using spanbuf = basic_spanbuf<char>;
using ispanstream = basic_ispanstream<char>;
using ospanstream = basic_ospanstream<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 syncbuf = basic_syncbuf<char>;
using osyncstream = basic_osyncstream<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 wstringstream = basic_stringstream<wchar_t>;

using wspanbuf = basic_spanbuf<wchar_t>;
using wispanstream = basic_ispanstream<wchar_t>;
using wospanstream = basic_ospanstream<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>;

using wsyncbuf = basic_syncbuf<wchar_t>;
using wosyncstream = basic_osyncstream<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 1488
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>;
}

1 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.274

31.3.2 Overview

The class template specialization basic_ios<
T, traits> serves as a virtual base class for the class templates basic_istream, basic_ostream, and class templates derived from them. basic_ios is a class template derived from both basic_istream<
T, traits> and basic_ostream<
T, traits>.

2 The class template specialization basic_streambuf<
T, traits> serves as a base class for class templates basic_stringbuf, basic_filebuf, and basic_syncbuf.

3 The class template specialization basic_istream<
T, traits> serves as a base class for class templates basic_istringstream and basic_ifstream.

4 The class template specialization basic_ostream<
T, traits> serves as a base class for class templates basic_ostringstream, basic_ofstream, and basic_osyncstream.

5 The class template specialization basic_iostream<
T, 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 char
T (23.2). — end note]

7 Other typedef-names define instances of class templates specialized for char or wchar_t types.

8 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]

9 [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

#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 <stdio> (31.13.1).

The header <iostream> declares objects that associate objects with the standard C streams provided for by the functions declared in <stdio>, and includes all the headers necessary to use these objects.

274 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` (6.9.3.1) begins execution. The objects are not destroyed during program execution.\(^\text{274}\)

**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.

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 (31.7.4.2) and output (31.7.5.2) functions or a standard C stream by multiple threads does not result in a data race (6.9.2).

\[\text{Note 1: Unsyncrhonized concurrent use of these objects and streams by multiple threads can result in interleaved characters. — end note} \]

See also: ISO C 7.21.2

### 31.4.3 Narrow stream objects

`istream cin;`

The object `cin` controls input from a stream buffer associated with the object `stdin`, declared in `<cstdio>` (31.13.1).

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).

`ostream cout;`

The object `cout` controls output to a stream buffer associated with the object `stdout`, declared in `<cstdio>` (31.13.1).

`ostream cerr;`

The object `cerr` controls output to a stream buffer associated with the object `stderr`, declared in `<cstdio>` (31.13.1).

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).

`ostream clog;`

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

`wistream wcin;`

The object `wcin` controls input from a stream buffer associated with the object `stdin`, declared in `<cstdio>` (31.13.1).

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).

`wostream wcout;`

The object `wcout` controls output to a stream buffer associated with the object `stdout`, declared in `<cstdio>` (31.13.1).

`wostream wcerr;`

The object `wcerr` controls output to a stream buffer associated with the object `stderr`, declared in `<cstdio>` (31.13.1).

\(^{274}\) 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`. 
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).

```cpp
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

#### [iostreams.base] 31.5.1 Header `<ios>` synopsis

```cpp
#include <iosfwd> // see 31.3.1
```

namespace std {

```cpp
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;
```

// 31.5.5, manipulators
```cpp
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& shoupos (ios_base& str);
ios_base& noshoupos (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);
```

// 31.5.5.2, adjustfield
```cpp
ios_base& internal (ios_base& str);
ios_base& left (ios_base& str);
ios_base& right (ios_base& str);
```

// 31.5.5.3, basefield
```cpp
ios_base& dec (ios_base& str);
ios_base& hex (ios_base& str);
ios_base& oct (ios_base& str);
```

// 31.5.5.4, floatfield
```cpp
ios_base& fixed (ios_base& str);
ios_base& scientific (ios_base& str);
ios_base& hexfloat (ios_base& str);
ios_base& defaultfloat(ios_base& str);
```

// 31.5.6, error reporting
```cpp
enum class io_errc {
    stream = 1
};
```
template<> struct is_error_code_enum<io_errc> : public true_type { }
error_code make_error_code(io_errc e) noexcept;
error_condition make_error_condition(io_errc e) noexcept;
const error_category& iostream_category() noexcept;

31.5.2 Class ios_base

31.5.2.1 General

namespace std {
  class ios_base {
  public:
    class failure; // see below

    // 31.5.2.2, 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 = see below;
    static constexpr fmtflags basefield = see below;
    static constexpr fmtflags floatfield = see below;

    // 31.5.2.3, iostate
    using iostate = T2;
    static constexpr iostate badbit = unspecified;
    static constexpr iostate eofbit = unspecified;
    static constexpr iostate failbit = unspecified;
    static constexpr iostate goodbit = see below;

    // 31.5.2.4, 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 out = unspecified;
    static constexpr openmode trunc = unspecified;

    // 31.5.2.5, seekdir
    using seekdir = T4;
    static constexpr seekdir beg = unspecified;
    static constexpr seekdir cur = unspecified;
    static constexpr seekdir end = unspecified;

    class Init;

    // 31.5.2.6, 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:

(3.1) — 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;

(3.2) — long* iarray, points to the first element of an arbitrary-length long array maintained for the private use of the program;

(3.3) — 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);
    }
}

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 is required 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.

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);

Effects: Constructs the base class with msg and ec.

explicit failure(const char* msg, const error_code& ec = io_errc::stream);

Effects: Constructs the base class with msg and ec.

31.5.2.2.2 Type ios_base::fmtflags

using fmtflags = T1;

The type fmtflags is a bitmask type (16.3.3.3.4). Setting its elements has the effects indicated in Table 114.

<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 right (final 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 left (initial 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>showpoint</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>

Type fmtflags also defines the constants indicated in Table 115.
Table 115: fmtflags constants [tab:ios.fmtflags.const]

<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>

31.5.2.2.3 Type ios_base::iostate [ios.iostate]

using iostate = T2;

1 The type iostate is a bitmask type (16.3.3.4) that contains the elements indicated in Table 116.

Table 116: iostate effects [tab:ios.iostate]

<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>

2 Type iostate also defines the constant:

(2.1) goodbit, the value zero.

31.5.2.2.4 Type ios_base::openmode [ios.openmode]

using openmode = T3;

1 The type openmode is a bitmask type (16.3.3.4). It contains the elements indicated in Table 117.

Table 117: openmode effects [tab:ios.openmode]

<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>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 [ios.seekdir]

using seekdir = T4;

1 The type seekdir is an enumerated type (16.3.3.3) that contains the elements indicated in Table 118.

Table 118: seekdir effects [tab:ios.seekdir]

<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>
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:

(2.1) — static int init_cnt, counts the number of constructor and destructor calls for class Init, initialized to zero.

Init();

3 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();

4 Effects: If there are no other instances of the class still in existence, calls cout.flush(), cerr.flush(), clog.flush(), wcout.flush(), wcerr.flush(), wclog.flush().

31.5.2.3 State functions

fmtflags flags() const;

1 Returns: The format control information for both input and output.

fmtflags flags(fmtflags fmtfl);

2 Postconditions: fmtfl == flags().

3 Returns: The previous value of flags().

fmtflags setf(fmtflags fmtfl);

4 Effects: Sets fmtfl in flags().

5 Returns: The previous value of flags().

fmtflags setf(fmtflags fmtfl, fmtflags mask);

6 Effects: Clears mask in flags(), sets fmtfl & mask in flags().

7 Returns: The previous value of flags().

void unsetf(fmtflags mask);

8 Effects: Clears mask in flags().

streamsize precision() const;

9 Returns: The precision to generate on certain output conversions.

streamsize precision(streamsize prec);

10 Postconditions: prec == precision().

11 Returns: The previous value of precision().

streamsize width() const;

12 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

```cpp
locale imbue(const locale& loc);
```

1. **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.

2. **Postconditions:** loc == getloc().

3. **Returns:** The previous value of getloc().

```cpp
locale getloc() const;
```

4. **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

```cpp
static bool sync_with_stdio(bool sync = true);
```

1. **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.

2. **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`.

3. **Remarks:** When a standard iostream object `str` is synchronized with a standard stdio stream `f`, the effect of inserting a character `c` by

   ```cpp
   fputc(f, c);
   ```

   is the same as the effect of

   ```cpp
   str.rdbuf()->sputc(c);
   ```

   for any sequences of characters; the effect of extracting a character `c` by

   ```cpp
   c = fgetc(f);
   ```

   is the same as the effect of

   ```cpp
   c = str.rdbuf()->sbumpc();
   ```

   for any sequences of characters; and the effect of pushing back a character `c` by

   ```cpp
   ungetc(c, f);
   ```

   is the same as the effect of

   ```cpp
   str.rdbuf()->sputbackc(c);
   ```

   for any sequence of characters.

### 31.5.2.6 Storage functions

```cpp
static int xalloc();
```

1. **Returns:** `index ++`.

2. **Remarks:** Concurrent access to this function by multiple threads does not result in a data race (6.9.2).

```cpp
long& iword(int idx);
```

3. **Preconditions:** idx 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 operations on the object. However, the value of the storage referred to is retained, so that until the next call to copyfmt, calling iword with the same index yields another reference to the same value. If the function fails 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: idx 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 operations 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 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

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

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.

~ios_base();

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

namespace std {
    template<class stateT> class fpos {
    public:
        // 31.5.3.1, members
        stateT state() const;
        void state(stateT);
    private:
        stateT st;
        // exposition only
    }
}

276) 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.
277) For example, because it cannot allocate space.
278) For example, because it cannot allocate space.
31.5.3.1 Members

void state(stateT s);

Effects: Assigns s to st.

stateT state() const;

Returns: Current value of st.

31.5.3.2 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 29), Cpp17CopyConstructible (Table 31), Cpp17CopyAssignable (Table 33), and Cpp17Destructible (Table 34) requirements. If is_trivially_copy_constructible_v<stateT> is true, then fpos<stateT> has a trivial copy constructor. If is_trivially_copy_assignable<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 27) requirements. In addition, the expressions shown in Table 119 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 refers to a value of type streamoff or const streamoff.

Table 119: Position type 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>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>P</td>
<td></td>
<td>Postconditions: p == P(o)</td>
</tr>
<tr>
<td>P()</td>
<td>P</td>
<td>P(0)</td>
<td></td>
</tr>
<tr>
<td>P p;</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(p)</td>
<td>streamoff</td>
<td>converts to offset</td>
<td>P(0(p)) == p</td>
</tr>
<tr>
<td>p != q</td>
<td>convertible to bool</td>
<td>!(p == q)</td>
<td></td>
</tr>
<tr>
<td>p + o</td>
<td>P</td>
<td>+ offset</td>
<td>Remarks: With ql = p + o; then: ql - 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 == ql</td>
</tr>
<tr>
<td>p - o</td>
<td>P</td>
<td>- offset</td>
<td>Remarks: With ql = p - o; then: ql + 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 == ql</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>

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);

        basic_streambuf<charT, traits>* rdbuf() const;
        basic_streambuf<charT, traits>* rdbuf(basic_streambuf<charT, traits>* sb);

        basic_ios& copyfmt(const basic_ios& rhs);
        char_type fill() const;
        char_type fill(char_type ch);
        locale imbue(const locale& loc);

        char    narrow(char_type c, char dfault) const;
        char_type widen(char c) const;

        basic_ios(const basic_ios&) = delete;
        basic_ios& operator=(const basic_ios&) = delete;

        protected:
            basic_ios();
            void init(basic_streambuf<charT, traits>* sb);
            void move(basic_ios& rhs);
            void move(basic_ios&& rhs);
            void swap(basic_ios& rhs) noexcept;
            void set_rdbuf(basic_streambuf<charT, traits>* sb);
    }
}
```
31.5.4.2 Constructors

```cpp
explicit basic_ios(basic_streambuf<charT, traits>* sb);
```

**Effects**: Assigns initial values to its member objects by calling `init(sb)`.

```cpp
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()`.

```cpp
void init(basic_streambuf<charT, traits>* sb);
```

**Postconditions**: The postconditions of this function are indicated in Table 120.

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rdbuf()</td>
<td><code>sb</code> if <code>sb</code> is not a null pointer, otherwise <code>badbit</code></td>
</tr>
<tr>
<td>tie()</td>
<td>0</td>
</tr>
<tr>
<td>rdstate()</td>
<td><code>goodbit</code> if <code>sb</code> is not a null pointer, otherwise <code>badbit</code></td>
</tr>
<tr>
<td>exceptions()</td>
<td><code>goodbit</code></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><code>widen(' ')</code></td>
</tr>
<tr>
<td>getloc()</td>
<td>a copy of the value returned by <code>locale()</code></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

```cpp
basic_ostream<charT, traits>* tie() const;
```

**Returns**: An output sequence that is tied to (synchronized with) the sequence controlled by the stream buffer.

```cpp
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()`.

```cpp
basic_streambuf<charT, traits>* rdbuf() const;
```

**Effects**: Calls `clear()`.

**Postconditions**: `sb == rdbuf()`.

**Returns**: The previous value of `rdbuf()`.

```cpp
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;279 and
(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()).

[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 121.

Table 121: 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.

279) This suggests an infinite amount of copying, but the implementation can keep track of the maximum element of the arrays that is nonzero.
void swap(basic_ios& rhs) noexcept;
   \textbf{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);
   \textbf{Preconditions}: sb != nullptr is true.
   \textbf{Effects}: Associates the basic_streambuf object pointed to by sb with this stream without calling clear().
   \textbf{Postconditions}: rdbuf() == sb is true.
   \textbf{Throws}: Nothing.

31.5.4.4 Flags functions \hfill [iostate.flags]

   \begin{verbatim}
   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);
   \textbf{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.
   \textbf{Postconditions}: If rdbuf() != 0 then state == rdstate(); otherwise rdstate() == (state | ios_base::badbit).

   void setstate(iostate state);
   \textbf{Effects}: Calls clear(rdstate() | state) (which may throw ios_base::failure (31.5.2.2.1)).

   bool good() const;
   Returns: rdstate() == 0

   bool eof() const;
   Returns: true if eofbit is set in rdstate().

   bool fail() const;
   Returns: true if failbit or badbit is set in rdstate().\footnote{Checking badbit also for fail() is historical practice.}

   bool bad() const;
   Returns: true if badbit is set in rdstate().

   iostate exceptions() const;
   Returns: A mask that determines what elements set in rdstate() cause exceptions to be thrown.

   void exceptions(iostate except);
   \textbf{Effects}: Calls clear(rdstate()).
   \textbf{Postconditions}: except == exceptions().
\end{verbatim}

31.5.5 ios_base manipulators \hfill [std.ios.manip]

31.5.5.1 fmtflags manipulators \hfill [fmtflags.manip]

\footnote{Each function specified in this subclause is a designated addressable function (16.4.5.2.1).}
ios_base& boolalpha(ios_base& str);
   Effects: Calls str.setf(ios_base::boolalpha).
   Returns: str.

ios_base& noboolalpha(ios_base& str);
   Effects: Calls str.unsetf(ios_base::boolalpha).
   Returns: str.

ios_base& showbase(ios_base& str);
   Effects: Calls str.setf(ios_base::showbase).
   Returns: str.

ios_base& noshowbase(ios_base& str);
   Effects: Calls str.unsetf(ios_base::showbase).
   Returns: str.

ios_base& showpoint(ios_base& str);
   Effects: Calls str.setf(ios_base::showpoint).
   Returns: str.

ios_base& noshowpoint(ios_base& str);
   Effects: Calls str.unsetf(ios_base::showpoint).
   Returns: str.

ios_base& showpos(ios_base& str);
   Effects: Calls str.setf(ios_base::showpos).
   Returns: str.

ios_base& noshowpos(ios_base& str);
   Effects: Calls str.unsetf(ios_base::showpos).
   Returns: str.

ios_base& skipws(ios_base& str);
   Effects: Calls str.setf(ios_base::skipws).
   Returns: str.

ios_base& noskipws(ios_base& str);
   Effects: Calls str.unsetf(ios_base::skipws).
   Returns: str.

ios_base& uppercase(ios_base& str);
   Effects: Calls str.setf(ios_base::uppercase).
   Returns: str.

ios_base& nouppercase(ios_base& str);
   Effects: Calls str.unsetf(ios_base::uppercase).
   Returns: str.

ios_base& unitbuf(ios_base& str);
   Effects: Calls str.setf(ios_base::unitbuf).
   Returns: str.

ios_base& nounitbuf(ios_base& str);
   Effects: Calls str.unsetf(ios_base::unitbuf).
Returns: str.

31.5.5.2 adjustfield manipulators  

Each function specified in this subclause is a designated addressable function (16.4.5.2.1).

ios_base& internal(ios_base& str);
  
  Effects: Calls str.setf(ios_base::internal, ios_base::adjustfield).

Returns: str.

ios_base& left(ios_base& str);
  
  Effects: Calls str.setf(ios_base::left, ios_base::adjustfield).

Returns: str.

ios_base& right(ios_base& str);
  
  Effects: Calls str.setf(ios_base::right, ios_base::adjustfield).

Returns: str.

31.5.5.3 basefield manipulators

Each function specified in this subclause is a designated addressable function (16.4.5.2.1).

ios_base& dec(ios_base& str);
  
  Effects: Calls str.setf(ios_base::dec, ios_base::basefield).

Returns: str.

ios_base& hex(ios_base& str);
  
  Effects: Calls str.setf(ios_base::hex, ios_base::basefield).

Returns: str.

ios_base& oct(ios_base& str);
  
  Effects: Calls str.setf(ios_base::oct, ios_base::basefield).

Returns: str.

31.5.5.4 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 115). —end note]

ios_base& defaultfloat(ios_base& str);
  
  Effects: Calls str.unsetf(ios_base::floatfield).

Returns: str.

281) 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.
31.5.6 Error reporting

```c++
error_code make_error_code(io_errc e) noexcept;
Returns: error_code(static_cast<int>(e), iostream_category());
```

```c++
error_condition make_error_condition(io_errc e) noexcept;
Returns: error_condition(static_cast<int>(e), iostream_category());
```

```c++
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

```c++
namespace std {
    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. **The controlled input sequence can be not readable.**
2. **The controlled output sequence can be not writable.**
3. **The controlled sequences can be associated with the contents of other representations for character sequences, such as external files.**
4. **The controlled sequences can support operations directly to or from associated sequences.**
5. **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:

1. **the beginning pointer,** or lowest element address in the array (called xbeg here);
2. **the next pointer,** or next element address that is a current candidate for reading or writing (called xnext here);
3. **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:

1. 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.
2. 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).
3. 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 \texttt{xnext} is not a null pointer and \texttt{xnext < xend} for an input sequence, then a \textit{read position} is available. In this case, \texttt{*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 \texttt{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();

    // 31.6.3.3.1, locales
    locale imbue(const locale& loc);
    locale getloc() const;

    // 31.6.3.3.2, buffer and positioning
    basic_streambuf* setbuf(char_type* s, streamsize n);
    pos_type seekoff(off_type off, ios_base::seekdir way,
                     ios_base::openmode which = ios_base::in | ios_base::out);
    pos_type seekpos(pos_type sp, ios_base::openmode which = ios_base::in | ios_base::out);
    int sync();

    // get and put areas
    // 31.6.3.3.3, get area
    streamsize in_avail();
    int_type snextc();
    int_type sbumpc();
    int_type sgetc();
    streamsize sgetn(char_type* s, streamsize n);

    // 31.6.3.3.4, putback
    int_type sputbackc(char_type c);
    int_type sungetc();

    // 31.6.3.3.5, 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);

```cpp
void swap(basic\_streambuf& rhs);```

#### 31.6.3.4.2, get area access

```cpp
char_type* eback() const;
char_type* gptr() const;
char_type* gbump(int n);
void setg(char_type* gbeg, char_type* gnext, char_type* gend);
```
The class template `basic_streambuf` serves as an abstract 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

```
basic_streambuf();
```

**Effects:** Initializes:

(1.1) — all pointer member objects to null pointers,
(1.2) — the `getloc()` member to a copy 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.

```
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()`

---

282) The default constructor is protected for class `basic_streambuf` to assure that only objects for classes derived from this class can be constructed.
Returns: If \texttt{pubimbue()} has ever been called, then the last value of \texttt{loc} supplied, otherwise the current global locale, \texttt{locale()}, in effect at the time of construction. If called after \texttt{pubimbue()} has been called but before \texttt{pubimbue} has returned (i.e., from within the call of \texttt{imbue()}) then it returns the previous value.

31.6.3.3.2 Buffer management and positioning

\begin{verbatim}
locale pubimbue(const locale& loc);

Effects: Calls \texttt{imbue(loc)}.

Postconditions: loc == getloc().

Returns: Previous value of \texttt{getloc()}.

locale getloc() const;

Returns: If \texttt{pubimbue()} has ever been called, then the last value of \texttt{loc} supplied, otherwise the current global locale, \texttt{locale()}, in effect at the time of construction. If called after \texttt{pubimbue()} has been called but before \texttt{pubimbue} has returned (i.e., from within the call of \texttt{imbue()}) then it returns the previous value.

basic_streambuf* pubsetbuf(char_type* s, streamsize n);

Returns: \texttt{setbuf(s, n)}.

pos_type pubseekoff(off_type off, ios_base::seekdir way,
  ios_base::openmode which
  = ios_base::in | ios_base::out);

Returns: \texttt{seekoff(off, way, which)}.

pos_type pubseekpos(pos_type sp,
  ios_base::openmode which
  = ios_base::in | ios_base::out);

Returns: \texttt{seekpos(sp, which)}.

int pubsync();

Returns: \texttt{sync()}.
\end{verbatim}

31.6.3.3.3 Get area

\begin{verbatim}
streamsize in_avail();

Returns: If a read position is available, returns \texttt{egptr()} - \texttt{gptr()}. Otherwise returns \texttt{showmanyc()} (31.6.3.5.3).

int_type snextc();

Effects: Calls \texttt{sbumpc()}.

Returns: If that function returns \texttt{traits::eof()}, returns \texttt{traits::eof()}. Otherwise, returns \texttt{sgetc()}.

int_type sbumpc();

Effects: If the input sequence read position is not available, returns \texttt{uflow()}. Otherwise, returns \texttt{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 \texttt{underflow()}. Otherwise, returns \texttt{traits::to_int_type(*gptr())}.
\end{verbatim}
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()
(1.4) pbase() == rhs.pbase()
(1.5) pptr() == rhs.pptr()
(1.6) eptr() == rhs.eptr()
(1.7) getloc() == rhs.getloc()

Returns: *this.

void swap(basic_streambuf& rhs);

Effects: Swaps the data members of rhs and *this.

31.6.3.4.2 Get area access

char_type* eback() const;

Returns: The beginning pointer for the input sequence.

char_type* gptr() const;

Returns: The next pointer for the input sequence.

char_type* egptr() const;

Returns: The end pointer for the input sequence.

void gbump(int n);

Effects: Adds n to the next pointer for the input sequence.

void setg(char_type* gbeg, char_type* gnext, char_type* gend);

Postconditions: gbeg == eback(), gnext == gptr(), and gend == egptr() are all true.
31.6.3.4.3 Put area access

char_type* pbase() const;

Returns: The beginning pointer for the output sequence.

char_type* pptr() const;

Returns: The next pointer for the output sequence.

char_type* epptr() const;

Returns: The end pointer for the output sequence.

void pbump(int n);

Effects: Adds n to the next pointer for the output sequence.

void setp(char_type* pbeg, char_type* pend);

Postconditions: pbeg == pbase(), pbeg == pptr(), and pend == epptr() are all true.

31.6.3.5 Virtual functions

31.6.3.5.1 Locales

void imbue(const locale&);

Effects: Change any translations based on locale.

Remarks: Allows the derived class to be informed of changes in locale at the time they occur. Between invocations of this function a class derived from streambuf can safely cache results of calls to locale functions and to members of facets so obtained.

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, 31.10.2.5).

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, 31.10.2.5).

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, 31.10.2).

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 (31.10.2.5).

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 gp\texttt{tr}() is null, otherwise the characters in [gp\texttt{tr}(), eg\texttt{ptr}()) followed by

(7.2) — some (possibly empty) sequence of characters read from the input sequence.

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 e\texttt{back}() is null, otherwise the characters in [e\texttt{back}(), gp\texttt{tr}()).

Effects: The function sets up the gp\texttt{tr}() and eg\texttt{ptr}() such that if the pending sequence is non-empty, then eg\texttt{ptr}() is non-null and the characters in [gp\texttt{tr}(), eg\texttt{ptr}()) are the characters in the pending sequence, otherwise either gp\texttt{tr}() is null or gp\texttt{tr}() == eg\texttt{ptr}().

If e\texttt{back}() and gp\texttt{tr}() are non-null then the function is not constrained as to their contents, but the “usual backup condition” is that either

(11.1) — the backup sequence contains at least gp\texttt{tr}() - e\texttt{back}() characters, in which case the characters in [e\texttt{back}(), gp\texttt{tr}()) agree with the last gp\texttt{tr}() - e\texttt{back}() characters of the backup sequence, or

(11.2) — the characters in [gp\texttt{tr}() - n, gp\texttt{tr}()) 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 gp\texttt{tr}() is null or gp\texttt{tr}() >= eg\texttt{ptr}().

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.

---

283) The morphemes of showmanyc are “es-how-many-see”, not “show-manic”.

284) 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”.

285) Classes derived from basic_streambuf can provide more efficient ways to implement xsgetn() and xsputn() by overriding these definitions from the base class.
Default behavior: Calls underflow(). If underflow() returns traits::eof(), returns traits::eof(). Otherwise, returns the value of traits::to_int_type(*gptr()) and increment 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());

The pending sequence is defined as for underflow(), with the modifications that
(1.1) — 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.
(1.2) — 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 sputc(c) would return traits::eof(). It is unspecified whether the function calls overflow() when pptr() == epptr() becomes true or whether it achieves the same effects by other means.

Returns: The number of characters written.

int_type overflow(int_type c = traits::eof());

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 pbase() is null, otherwise the pptr() - pbase() characters beginning at pbase(), followed by
(3.2) — the empty sequence if traits::eq_int_type(c, traits::eof()) returns true, otherwise the sequence consisting of c.

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.\(^ {286} \)
(4.2) — Let r be the number of characters in the pending sequence not consumed. If r is nonzero then pbase() and pptr() are set so that: pptr() - pbase() == r and the r characters starting at pbase() are the associated output stream. In case r is zero (all characters of the pending sequence have been consumed) then either pbase() is set to nullptr, or pbase() and 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 pbase() and pptr() according to the above rules.

\(^ {286} \) That is, for each class derived from a specialization of basic_streambuf in this Clause (31.8.2, 31.10.2), a specification of how consuming a character effects the associated output sequence is given. There is no requirement on a program-defined class.
Returns: traits::eof() or throws an exception if the function fails.
Otherwise, returns some value other than traits::eof() to indicate success.\footnote{Typically, overflow returns c to indicate success, except when traits::eq_int_type(c, traits::eof()) returns true, in which case it returns traits::not_eof(c).}

Default behavior: Returns traits::eof().

Remarks: The member functions sputc() and 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 \[iostream.format\]

31.7.1 Header \(<\text{istream}>\) synopsis \[istream.syn\]

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_istream;

    using istream = basic_istream<char>;
    using wistream = basic_istream<wchar_t>;

    template<class charT, class traits = char_traits<charT>>
    class basic_iostream;

    using iostream = basic_iostream<char>;
    using wiostream = basic_iostream<wchar_t>;

    template<class charT, class traits = char_traits<charT>>
    basic_istream<charT, traits>& ws(basic_istream<charT, traits>& is);

    template<class Istream, class T>
    Istream&& operator>>(Istream&& is, T&& x);
}
```

31.7.2 Header \(<\text{ostream}>\) synopsis \[ostream.syn\]

```cpp
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ostream;

    using ostream = basic_ostream<char>;
    using wostream = basic_ostream<wchar_t>;

    template<class charT, class traits = char_traits<charT>>
    basic_ostream<charT, traits>& endl(basic_ostream<charT, traits>& os);

    template<class charT, class traits = char_traits<charT>>
    basic_ostream<charT, traits>& ends(basic_ostream<charT, traits>& os);

    template<class charT, class traits = char_traits<charT>>
    basic_ostream<charT, traits>& flush(basic_ostream<charT, traits>& os);

    template<class charT, class traits = char_traits<charT>>
    basic_ostream<charT, traits>& emit_on_flush(basic_ostream<charT, traits>& os);

    template<class charT, class traits = char_traits<charT>>
    basic_ostream<charT, traits>& noemit_on_flush(basic_ostream<charT, traits>& os);

    template<class charT, class traits = char_traits<charT>>
    basic_ostream<charT, traits>& flush_emit(basic_ostream<charT, traits>& os);

    template<class Ostream, class T>
    Ostream&& operator<<(Ostream&& os, const T& x);
}
```

31.7.3 Header \(<\text{iomanip}>\) synopsis \[iomanip.syn\]

```cpp
namespace std {
    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);

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);


31.7.4 Input streams

31.7.4.1 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.

31.7.4.2 Class template basic_istream

31.7.4.2.1 General

namespace std {
  template<class charT, class traits, class Allocator>
  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_view<charT, traits> s,
                     charT delim = charT('"'), charT escape = charT('"'));
}
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 \texttt{rdbuf()\texttt{\rightarrow sbumpc}} or \texttt{rdbuf()\texttt{\rightarrow sgetc}}. They may use other public members of \texttt{istream}.

If \texttt{rdbuf()\texttt{\rightarrow sbumpc}} or \texttt{rdbuf()\texttt{\rightarrow sgetc}} returns \texttt{traits::eof()}, then the input function, except as explicitly noted otherwise, completes its actions and does \texttt{setstate(eofbit)}, which may throw \texttt{ios\_base::failure} (31.5.4.4), before returning.

If one of these called functions throws an exception, then unless explicitly noted otherwise, the input function sets \texttt{badbit} in the error state. If \texttt{badbit} is set in \texttt{exceptions()}, the input 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.

### 31.7.4.2.2 Constructors

```cpp
explicit basic_istream(basic_streambuf<charT, traits>* sb);
```

*Effects:* Initializes the base class subobject with \texttt{basic_ios::init(sb)} (31.5.4.2).

*Postconditions:* \texttt{gcount() == 0}.

```cpp
basic_istream(basic_istream&& rhs);
```

*Effects:* Default constructs the base class, copies the \texttt{gcount()} from \texttt{rhs}, calls \texttt{basic_ios<charT, traits>::move(rhs)} to initialize the base class, and sets the \texttt{gcount()} for \texttt{rhs} to 0.

```cpp
virtual ~basic_istream();
```

*Remarks:* Does not perform any operations of \texttt{rdbuf()}.

### 31.7.4.2.3 Assignment and swap

```cpp
basic_istream& operator=(basic_istream&& rhs);
```

*Effects:* Equivalent to: \texttt{swap(rhs)}.

*Returns:* \texttt{*this}.

```cpp
void swap(basic_istream& rhs);
```

*Effects:* Calls \texttt{basic_ios<charT, traits>::swap(rhs)}. Exchanges the values returned by \texttt{gcount()} and \texttt{rhs.gcount()}.  

### 31.7.4.2.4 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 \texttt{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 \texttt{is.good()} is \texttt{false}, calls \texttt{is.setstate(failbit)}. Otherwise, prepares for formatted or unformatted input. First, if \texttt{is.tie()} is not a null pointer, the function calls \texttt{is.tie()\texttt{\rightarrow 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()\texttt{\rightarrow underflow}} occurs. If no such call occurs before

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the `sentry` object is destroyed, the call to `flush` may be eliminated entirely. If `noskipws` is zero and `is.flags() & ios_base::skipws` is nonzero, the function extracts and discards each character as long as the next available input character `c` is a whitespace character. If `is.rdbuf()->sbumpc()` or `is.rdbuf()->sgetc()` returns `traits::eof()`, the function calls `setstate(failbit | eofbit)` (which may throw `ios_base::failure`).

Remarks: The constructor

```cpp
class sentry
{
public:
    explicit sentry(basic_istream& is, bool noskipws = false)
    uses the currently imbued locale in `is`, to determine whether the next input character is whitespace or not.

To decide if the character `c` is a whitespace character, the constructor performs as if it executes the following code fragment:

```cpp
const ctype<charT>& ctype = use_facet<ctype<charT>>(is.getloc());
if (ctype.is(ctype.space, c) != 0)
    // `c` is a whitespace character.
```cpp
```

If, after any preparation is completed, `is.good()` is true, `ok_` != false otherwise, `ok_ == false`. During preparation, the constructor may call `setstate(failbit)` (which may throw `ios_base::failure`).

```cpp
~sentry();
```cpp
```

Effects: None.

```cpp
explicit operator bool() const;
```cpp
```
Returns: `ok_`.

31.7.4.3 Formatted input functions [istream.formatted]
31.7.4.3.1 Common requirements [istream.formatted.reqmts]

Each formatted input function begins execution by constructing an object of class `sentry` with the `noskipws` (second) argument false. If the `sentry` object returns true, when converted to a value of type `bool`, the function endeavors to obtain the requested input. If an exception is thrown during input then `ios_base::badbit` is turned on in `*this`’s error state. If `(exceptions()&badbit) != 0` then the exception is rethrown. In any case, the formatted input function destroys the `sentry` object. If no exception has been thrown, it returns `*this`.

31.7.4.3.2 Arithmetic extractors [istream.formatted.arithmetic]

```cpp
basic_istream& operator>>(unsigned short& val);
basic_istream& operator>>(unsigned int& val);
basic_istream& operator>>(long& val);
basic_istream& operator>>(unsigned long& val);
basic_istream& operator>>(long long& val);
basic_istream& operator>>(unsigned long long& val);
basic_istream& operator>>(float& val);
basic_istream& operator>>(double& val);
basic_istream& operator>>(long double& val);
basic_istream& operator>>(bool& val);
basic_istream& operator>>(void*& val);
```cpp
```

As in the case of the inserters, 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 31.7.4.3.1). After a `sentry` object is constructed, the conversion occurs as if performed by the following code fragment:

```cpp
using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
iosstate err = iostate::goodbit;
use_facet<numget>(loc).get(*this, 0, *this, err, val);
setstate(err);
```cpp
```

288) 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.

289) The `sentry` constructor and destructor can also perform additional implementation-dependent operations.

290) This is done without causing an `ios_base::failure` to be thrown.
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`.

```cpp
basic_istream& operator>>(short& val);
```

The conversion occurs as if performed by the following code fragment (using the same notation as for the preceding code fragment):

```cpp
using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
iosstate err = ios_base::goodbit;
long lval;
use_facet<numget>(loc).get(*this, 0, *this, err, lval);
if (lval < numeric_limits<short>::min()) {
    err |= ios_base::failbit;
    val = numeric_limits<short>::min();
} else if (numeric_limits<short>::max() < lval) {
    err |= ios_base::failbit;
    val = numeric_limits<short>::max();
} else
    val = static_cast<short>(lval);
setstate(err);
```

```cpp
basic_istream& operator>>(int& val);
```

The conversion occurs as if performed by the following code fragment (using the same notation as for the preceding code fragment):

```cpp
using numget = num_get<charT, istreambuf_iterator<charT, traits>>;
iosstate err = ios_base::goodbit;
long lval;
use_facet<numget>(loc).get(*this, 0, *this, err, lval);
if (lval < numeric_limits<int>::min()) {
    err |= ios_base::failbit;
    val = numeric_limits<int>::min();
} else if (numeric_limits<int>::max() < lval) {
    err |= ios_base::failbit;
    val = numeric_limits<int>::max();
} else
    val = static_cast<int>(lval);
setstate(err);
```

### 31.7.4.3.3 `basic_istream::operator>>` [istream.extractors]

```cpp
1
basic_istream& operator>>(basic_istream& (*pf)(basic_istream&));
```

**Effects**: None. This extractor does not behave as a formatted input function (as described in 31.7.4.3.1).

**Returns**: `pf(*this)`.

```cpp
2
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 31.7.4.3.1).

**Returns**: `*this`.

```cpp
3
basic_istream& operator>>(ios_base& (*pf)(ios_base&));
```

**Effects**: Calls `pf(*this)`.

**Returns**: `*this`.

---

291) See, for example, the function signature `ws(basic_istream&)` (31.7.4.5).
292) See, for example, the function signature `dec(ios_base&)` (31.5.5.3).
template<class charT, class traits, size_t N>
    basic_istream<charT, traits>& operator>>(basic_istream<charT, traits>& in, charT (&s)[N]);

Effects: Behaves like a formatted input member (as described in 31.7.4.3.1) 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:

- n-1 characters are stored;
- end of file occurs on the input sequence;
- 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, it calls setstate(failbit), which may throw ios_base::failure (31.5.4.4).

Returns: in.

Effects: Behaves like a formatted input member (as described in 31.7.4.3.1) of in. After a sentry object is constructed a character is extracted from in, if one is available, and stored in c. Otherwise, the function calls in.setstate(failbit).

Returns: in.

Effects: Behaves as an unformatted input function (31.7.4.4). 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 inserts no characters, it calls setstate(failbit), which may throw ios_base::failure (31.5.4.4). If it inserted no characters because it caught an exception thrown while extracting characters from *this and failbit is set in exceptions() (31.5.4.4), then the caught exception is rethrown.

Returns: *this.

31.7.4.4 Unformatted input functions

Each unformatted input function begins execution by constructing 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 returns 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 an exception is thrown during input then
ios_base::badbit is turned on in *this’s error state. (Exceptions thrown from basic_ios<>::clear() are not caught or rethrown.) If (exceptions()&badbit) != 0 then the exception is rethrown. It also counts the number of characters extracted. If no exception has been thrown it ends by storing the count in a member object and returning the value specified. 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, the function calls setstate(failbit), which may throw ios_base::failure (31.5.4.4).

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. Otherwise, the function calls setstate(failbit) (which may throw ios_base::failure (31.5.4.4)).

Returns: *this.

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. 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 (in which case the function calls setstate(eofbit));
3. traits::eq(c, delim) for the next available input character c (in which case c is not extracted).

If the function stores no characters, it calls setstate(failbit) (which may throw ios_base::failure (31.5.4.4)). In any case, if n is greater than zero it then stores a null character into the next successive location of the array.

Returns: *this.

basic_istream& get(char_type* s, streamsize n);

Effects: Calls 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. 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, it calls setstate(failbit) (which may throw ios_base::failure (31.5.4.4)).

Notes:

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.
Returns: *this.

`basic_istream& get(basic_streambuf<char_type, traits>& sb);`

**Effects:** Calls `get(sb, widen('
'))`.

**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`. Characters are extracted and stored until one of the following occurs:

1. end-of-file occurs on the input sequence (in which case the function calls `setstate(eofbit)`);
2. `traits::eq(c, delim)` for the next available input character `c` (in which case the input character is extracted but not stored);
3. `n` is less than one or `n - 1` characters are stored (in which case the function calls `setstate(failbit)`).

These conditions are tested in the order shown.

If the function extracts no characters, it calls `setstate(failbit)` (which may throw `ios_base::failure` (31.5.4.4)).

In any case, if `n` is greater than zero, it then stores a null character (using `charT()`) into the next successive location of the array.

**Returns:** *this.

[Example 1:]
```cpp
#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;
  }
}
```

**Returns:** `getline(s, n, widen('\n'))`

---

296) Note that this function is not overloaded on types `signed char` and `unsigned char`.

297) Since the final input character is “extracted”, it is counted in the `gcount()`, even though it is not stored.

298) This allows an input line which exactly fills the buffer, without setting `failbit`. This is different behavior than the historical AT&T implementation.

299) This implies an empty input line will not cause `failbit` to be set.
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:

- \( n \neq \text{numeric\_limits<streamsize>::max()} \) (17.3.5) and \( n \) characters have been extracted so far
- 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));
- \( \text{traits::eq\_int\_type(traits::to\_int\_type(c), delim)} \) for the next available input character \( c \) (in which case \( c \) is extracted).

[Note 1: The last condition will never occur if \( \text{traits::eq\_int\_type(delim, traits::eof())} \). —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:

- \( n \) characters are stored;
- 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)).

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 \( \text{rdbuf() -> in\_avail()} == -1 \), calls setstate(eofbit) (which may throw ios_base::failure (31.5.4.4)), and extracts no characters; otherwise extracts \( \min(\text{rdbuf() -> in\_avail()}, n) \).

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 not null, calls rdbuf()->sungetc(). If rdbuf() (300) Note that this function is not overloaded on types signed char and unsigned char.
is null, or if `sungetc` 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.

```cpp
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.

```cpp
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()`.

Returns: After constructing a `sentry` object, if `fail() != false`, returns `pos_type(-1)` to indicate failure. Otherwise, returns `rdbuf()->pubseekoff(0, cur, in)`.

```cpp
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.

```cpp
basic_istream& seekg(off_type off, ios_base::seekdir dir);
```

**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`).

Returns: *this.

### 31.7.4.5 Standard basic_istream manipulators

Each instantiation of the function template specified in this subclause is a designated addressable function (16.4.5.2.1).

```cpp
template<class charT, class traits>
basic_istream<charT, traits>&& ws(basic_istream<charT, traits>&& is);
```

**Effects:** Behaves as an unformatted input function (31.7.4.4), 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` (31.7.4.2.4). If `ws` stops extracting characters because there are no more available it sets `eofbit`, but not `failbit`.

Returns: `is`.

### 31.7.4.6 Rvalue stream extraction

```cpp
template<class Istream, class T>
Istream&& operator>>(Istream&& is, T&& x);
```

**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`.

**Effects:** Equivalent to:
is >> std::forward<T>(x);
return std::move(is);

31.7.4.7  Class template basic_iostream

31.7.4.7.1  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;

  // 31.7.4.7.2, constructor
  explicit basic_iostream(basic_streambuf<charT, traits>* sb);

  // 31.7.4.7.3, destructor
  virtual ~basic_iostream();

private:

  // 31.7.4.7.2, constructor
  basic_iostream(const basic_iostream&) = delete;
  basic_iostream(basic_iostream&& rhs);

  // 31.7.4.7.4, assignment and swap
  basic_iostream& operator=(const basic_iostream& rhs);
  basic_iostream& operator=(basic_iostream&& rhs);
  void swap(basic_iostream& rhs);

};

}  // namespace std

1 The class template basic_iostream inherits a number of functions that allow reading input and writing output to sequences controlled by a stream buffer.

31.7.4.7.2  Constructors

explicit basic_iostream(basic_streambuf<charT, traits>* sb);

1 Effects: Initializes the base class subobjects with basic_istream<charT, traits>(sb) (31.7.4.2) and basic_ostream<charT, traits>(sb) (31.7.5.2).

2 Postconditions: rdbuf() == sb and gcount() == 0.

basic_iostream(basic_iostream&& rhs);

Effects: Move constructs from the rvalue rhs by constructing the basic_istream base class with move(rhs).

31.7.4.7.3  Destructor

virtual ~basic_iostream();

1 Remarks: Does not perform any operations on rdbuf().

31.7.4.7.4  Assignment and swap

basic_iostream& operator=(basic_iostream&& rhs);

1 Effects: Equivalent to: swap(rhs).

void swap(basic_iostream& rhs);

2 Effects: Calls basic_istream<charT, traits>::swap(rhs).
31.7.5 Output streams

31.7.5.1 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.

31.7.5.2 Class template basic_ostream

31.7.5.2.1 General

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;

        // 31.7.5.2.2, constructor/destructor
        explicit basic_ostream(basic_streambuf<char_type, traits>* sb);
        virtual ~basic_ostream();

        // 31.7.5.2.3, prefix/suffix
        class sentry;

        // 31.7.5.2.4, 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<<(const void* p);
        basic_ostream& operator<<(const volatile void* p);
        basic_ostream& operator<<(nullptr_t);
        basic_ostream& operator<<(basic_streambuf<char_type, traits>* sb);

        // 31.7.5.2.5, unformatted output
        basic_ostream& put(char_type c);
        basic_ostream& write(const char_type* s, streamsize n);
        basic_ostream& flush();

        // 31.7.5.2.6, seeks
        pos_type tellp();
        basic_ostream& seekp(pos_type);
        basic_ostream& seekp(off_type, ios_base::seekdir);

    protected:
        // 31.7.5.2.7, copy/move constructor
        basic_ostream(const basic_ostream&) = delete;
        basic_ostream(basic_ostream& rhs);
// 31.7.5.2.3, assignment and swap
basic_ostream basic_ostream\(\) = delete;
basic_ostream basic_ostream\& operator=(const basic_ostream\&) = delete;
void swap(basic_ostream\& rhs);
);

// 31.7.5.3.4, character inserters

// § 31.7.5.2.1 1527
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(), xsputn(), 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]

§ 31.7.5.2.2  Constructors
[ostream.cons]

---

§ 31.7.5.2.3  Assignment and swap
[ostream.assign]

---

§ 31.7.5.2.4  Class basic_ostream::sentry
[ostream.sentry]

---

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().

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)).

~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 propagating an exception.

explicit operator bool() const;

5 Effects: Returns ok_.

31.7.5.2.5 Seek members [ostream.seeks]

Each seek member function begins execution by constructing an object of class sentry. It returns by destroying the sentry object.

pos_type tellp();

2 Returns: If fail() != false, returns pos_type(-1) to indicate failure. Otherwise, returns rdbuf()->pubseekoff(0, cur, out).

basic_ostream& seekp(pos_type pos);

3 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).

4 Returns: *this.

basic_ostream& seekp(off_type off, ios_base::seekdir dir);

5 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).

6 Returns: *this.

31.7.5.3 Formatted output functions [ostream.formatted]

31.7.5.3.1 Common requirements [ostream.formatted.reqmts]

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 turned on 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.

3 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 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.

31.7.5.3.2 Arithmetic inserters [ostream.inserters.arithmetic]

basic_ostream& operator<<(bool val);

basic_ostream& operator<<(short val);

301) The call os.tie()->flush() does not necessarily occur if the function can determine that no synchronization is necessary.

302) The sentry constructor and destructor can also perform additional implementation-dependent operations.

303) This is done without causing an ios_base::failure to be thrown.
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 imbued 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:

```cpp
bool failed = use_facet<
    num_put<charT, ostreambuf_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, ostreambuf_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, ostreambuf_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, ostreambuf_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, ostreambuf_iterator<charT, traits>>
  >(getloc()).put(*this, *this, fill(),
      static_cast<long>(val)).failed();
```

The first argument provides an object of the ostreambuf_iterator<> class which is an iterator for class basic_ostream<. It bypasses ostream 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.

Returns: *this.
basic_ostream& operator<<(const volatile void* p);

Effects: Equivalent to: return operator<<(const_cast<const void*>(p));

31.7.5.3.3 basic_ostream::operator<<

basic_ostream& operator<<(basic_ostream& (*)(basic_ostream&));

Effects: None. Does not behave as a formatted output function (as described in 31.7.5.3.1).
Returns: *this.

basic_ostream& operator<<(basic_ios<charT, traits>& (*)(basic_ios<charT, traits>&));

Effects: Calls pf(*this). This inserter does not behave as a formatted output function (as described in 31.7.5.3.1).
Returns: *this.

basic_ostream& operator<<(ios_base& (*)(ios_base&));

Effects: Calls pf(*this). This inserter does not behave as a formatted output function (as described in 31.7.5.3.1).
Returns: *this.

basic_ostream& operator<<(basic_streambuf<charT, traits>* sb);

Effects: Behaves as an unformatted output function (31.7.5.4). 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:

(8.1) end-of-file occurs on the input sequence;
(8.2) inserting in the output sequence fails (in which case the character to be inserted is not extracted);
(8.3) 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). 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 (3.37).

31.7.5.3.4 Character inserter function templates

template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, charT c);

// specialization
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, char c);

// signed and unsigned
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, signed char c);

template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, unsigned char c);

Effects: Behaves as a formatted output function (31.7.5.3.1) of out. Constructs a character sequence seq. If c has type char and the character type of the stream is not char, then seq consists of

304) See, for example, the function signature endl(basic_ostream&) (31.7.5.5).
305) See, for example, the function signature dec(ios_base&) (31.5.5.3).
out.widen(c); otherwise seq consists of c. Determines padding for seq as described in 31.7.5.3.1. 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);
template<class charT, class traits>
    basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>& out, const char* s);
template<class traits>
    basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>& out, const signed char* s);
template<class traits>
    basic_ostream<char, traits>& operator<<(basic_ostream<char, traits>& out, const unsigned char* s);

Preconditions: s is not a null pointer.

Effects: Behaves like a formatted inserter (as described in 31.7.5.3.1) 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 31.7.5.3.1. Inserts seq into out. Calls width(0).

Returns: out.

31.7.5.4 Unformatted output functions [ostream.unformatted]

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 turned on 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.

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.307

Otherwise, calls setstate(badbit) (which may throw ios_base::failure (31.5.4.4)).

Returns: *this.

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.308 Characters are inserted until either of the following occurs:

(5.1) n characters are inserted;

(5.2) 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.

306) This is done without causing an ios_base::failure to be thrown.
307) Note that this function is not overloaded on types signed char and unsigned char.
308) Note that this function is not overloaded on types signed char and unsigned char.
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.

31.7.5.5 Standard manipulators [ostream.manip]
Each instantiation of any of the function templates specified in this subclause is a designated addressable function (16.4.5.2.1).

template<class charT, class traits>
basic_ostream<charT, traits>& endl(basic_ostream<charT, traits>& os);

Effects: Calls os.put(os.widen(’\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 (31.7.5.4) of os. After constructing a sentry object, calls buf->emit(). If that call returns false, calls os.setstate(ios_base::badbit).

Returns: os.

31.7.5.6 Rvalue stream insertion [ostream.rvalue]

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;
31.7.6 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.

```cpp
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:

```cpp
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`.

```cpp
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:

```cpp
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`.

```cpp
unspecified setbase(int base);
```

**Returns:** An object of unspecified type such that if `out` is an object of type `basic_ostream<charT, traits>` then the expression `out << setbase(base)` behaves as if it called `f(out, base)`, or if `in` is an object of type `basic_istream<charT, traits>` then the expression `in >> setbase(base)` behaves as if it called `f(in, base)`, where the function `f` is defined as:

```cpp
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 << 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`.

```cpp
unspecified setfill(char_type c);
```

**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:

---

309) The expression `cin >> resetiosflags(ios_base::skipws)` clears `ios_base::skipws` in the format flags stored in the `basic_istream<charT, traits>` object `cin` (the same as `cin >> noskipws`), and the expression `cout << resetiosflags(ios_base::showbase)` clears `ios_base::showbase` in the format flags stored in the `basic_ostream<charT, traits>` object `cout` (the same as `cout << noshowbase`).

§ 31.7.6
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 setprecision(int n);

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:

    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.

unspecified 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:

    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.

31.7.7 Extended manipulators [ext.manip]
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.

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 (31.7.4.3.1).

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:

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 $\gg$ get_money(mon, intl) has type basic_istream<charT, traits>& and value in.

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 $\ll$ put_money(mon, intl) behaves as a formatted output function (31.7.5.3.1) that calls f(out, mon, intl), where the function f is defined as:

```cpp
template<class charT, class traits, class moneyT>
void f(basic_ostream<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 $\ll$ put_money(mon, intl) has type basic_ostream<charT, traits>& and value out.

```cpp
template<class charT> unspecified get_time(tm* tmb, const charT* fmt);
```

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.

Returns: An object of unspecified type such that if in is an object of type basic_istream<charT, traits> then the expression in $\gg$ get_time(tmb, fmt) behaves as if it called f(in, tmb, fmt), where the function f is defined as:

```cpp
template<class charT, class traits>
void f(basic_istream<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 $\gg$ get_time(tmb, fmt) has type basic_istream<charT, traits>& and value in.

```cpp
template<class charT> unspecified put_time(const tm* tmb, const charT* fmt);
```

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.

Returns: An object of unspecified type such that if out is an object of type basic_ostream<charT, traits> then the expression out $\ll$ put_time(tmb, fmt) behaves as if it called f(out, tmb, fmt), where the function f is defined as:

```cpp
template<class charT, class traits>
void f(basic_ostream<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.

### 31.7.8 Quoted manipulators

**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.

#### 2 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 (31.7.5.3.1) of out. This forms a character sequence seq, initially consisting of the following elements:

1. **(2.1)** delim.
2. **(2.2)** 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. **(2.3)** delim.

Let x be the number of elements initially in seq. Then padding is determined for seq as described in 31.7.5.3.1, 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.

#### 3 Returns: An object of unspecified type such that:

1. **(3.1)** 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&): (31.7.4.3.3) which may throw ios_base::failure (31.5.2.2.1):

    1. **(3.1.1)** If the first character extracted is equal to delim, as determined by traits_type::eq, then:
        1. **(3.1.1.1)** Turn off the skipws flag.
        2. **(3.1.1.2)** s.clear()
        3. **(3.1.1.3)** 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. **(3.1.4)** Discard the final delim character.
    3. **(3.1.5)** Restore the skipws flag to its original value.
2. **(3.1.2)** Otherwise, in >> s.
If `out` is an instance of `basic_ostream` with member types `char_type` and `traits_type` the same as `charT` and `traits`, respectively, then the expression `out << quoted(s, delim, escape)` behaves as specified for the `const basic_string<charT, traits, Allocator>&` overload of the quoted function.

The expression `in >> quoted(s, delim, escape)` has type `basic_istream<charT, traits>&` and value `in`.

The expression `out << quoted(s, delim, escape)` has type `basic_ostream<charT, traits>&` and value `out`.

### 31.8 String-based streams

#### 31.8.1 Header `<sstream>` synopsis

```c++
namespace std {
    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>;

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>;

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);

using ostringstream = basic_ostringstream<char>;
using wostringstream = basic_ostringstream<wchar_t>;

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>;
}
```

1 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` [stringbuf]

31.8.2.1 General [stringbuf.general]

```cpp
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<
                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);
            basic_stringbuf<const basic_stringbuf&> = delete;
            basic_stringbuf& operator=(basic_stringbuf& rhs);
            void swap(basic_stringbuf& rhs) noexcept;

            // 31.8.2.3, 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<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);
    }
}
```
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

};

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.

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

#### [stringbuf.cons]

**explicit basic_stringbuf(ios_base::openmode which);**

1 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 Postconditions: str().empty() is true.

**explicit basic_stringbuf(const basic_string<charT, traits, Allocator>& s,
    ios_base::openmode which = ios_base::in | ios_base::out);**

3 Effects: Initializes the base class with basic_streambuf() (31.6.3.2), mode with which, and buf with s, then calls init_buf_ptrs().

**basic_stringbuf(ios_base::openmode which, const Allocator &a);**

4 Effects: Initializes the base class with basic_streambuf() (31.6.3.2), mode with which, and buf with a, then calls init_buf_ptrs().

5 Postconditions: str().empty() is true.

**explicit basic_stringbuf(**

**basic_string<charT, traits, Allocator>&& s,**

**ios_base::openmode which = ios_base::in | ios_base::out);**

6 Effects: Initializes the base class with basic_streambuf() (31.6.3.2), mode with which, and buf with std::move(s), then calls init_buf_ptrs().

**template<class SAlloc>**

**basic_stringbuf(**

**const basic_string<charT, traits, SAlloc>& s,**

% 31.8.2.2 1540
ios_base::openmode which, const Allocator &a);

Effects: Initializes the base class with basic_streambuf() (31.6.3.2), mode with which, and buf with {s,a}, then calls init_buf_ptrs().

template<class SAlloc>
explicit basic_stringbuf(
    const basic_string<charT, traits, SAlloc>& s,
    ios_base::openmode which = ios_base::in | ios_base::out);

Constraints: is_same_v<SAlloc, Allocator> is false.

Effects: Initializes the base class with basic_streambuf() (31.6.3.2), mode with which, and buf with s, then calls init_buf_ptrs().

basic_stringbuf(basic_stringbuf&& rhs);

basic_stringbuf(basic_stringbuf&& rhs, const Allocator& a);

Effects: Copy constructs the base class from rhs and initializes mode with rhs.mode. In the first form buf is initialized from std::move(rhs).str(). In the second form buf is initialized from {std::move(rhs).str(), a}. It is implementation-defined whether the sequence pointers in *this (eback(), gptr(), egptr(), pbase(), pptr(), epptr()) obtain the values which rhs had.

Postconditions: Let rhs_p refer to the state of rhs just prior to this construction and let rhs_a refer to the state of rhs just after this construction.

- str() == rhs_p.str()
- gptr() - eback() == rhs_p.gptr() - rhs_p.eback()
- egptr() - eback() == rhs_p.egptr() - rhs_p.eback()
- pptr() - pbase() == rhs_p.pptr() - rhs_p.pbase()
- epptr() - pbase() == rhs_p.epptr() - 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 (epptr()) epptr() != rhs_a.epptr()
- getloc() == rhs_p.getloc()
- rhs is empty but usable, as if std::move(rhs).str() was called.

31.8.2.3 Assignment and swap

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.

void swap(basic_stringbuf& rhs) noexcept(see below);

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:
 allocator_traits<Allocator>::propagate_on_container_swap::value ||
 allocator_traits<Allocator>::is_always_equal::value.

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

The member functions getting the underlying character sequence all refer to a high_mark value, where high_mark represents the position one past the highest initialized character in the buffer. Characters can be initialized by writing to the stream, by constructing the basic_stringbuf passing a basic_string argument, or by calling one of the str member functions passing a basic_string as an argument. In the latter case, all characters initialized prior to the call are now considered uninitialized (except for those characters re-initialized by the new basic_string).

```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 epitr() >= 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]

```cpp
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());
```

```cpp
template<class SAlloc>
basic_string<charT, traits, SAlloc> str(const SAlloc& sa) const;
```

Constraints: SAlloc is a type that qualifies as an allocator (24.2.2.1).

Effects: Equivalent to:

```
return basic_string<charT, traits, SAlloc>(view(), sa);
```

basic_string_view<charT, traits, Allocator> 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:

1. If ios_base::out is set in mode, then sv(pbase(), high_mark-pbase()) is returned.
2. Otherwise, if ios_base::in is set in mode, then sv(eback(), egptr()-eback()) is returned.
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]

```cpp
void str(const basic_string<charT, traits, Allocator>& s);
```

Effects: Equivalent to:
buf = s;
init_buf_ptrs();

```cpp
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();

## 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:

1. **(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. **(2.2)** 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.

3. **(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:

1. **(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.

2. **(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 122.

Table 122: seekoff positioning  [tab:stringbuf.seekoff.pos]

<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</td>
<td>positions both the input and the output sequences</td>
</tr>
<tr>
<td>way == ios_base::beg or</td>
<td></td>
</tr>
<tr>
<td>way == ios_base::end</td>
<td></td>
</tr>
<tr>
<td>Otherwise</td>
<td>the positioning operation fails.</td>
</tr>
</tbody>
</table>

For a sequence to be positioned, the function determines newoff as indicated in Table 123. If the sequence’s next pointer (either gptr() or pptr()) is a null pointer and newoff is nonzero, the positioning operation fails.

Table 123: newoff values  [tab:stringbuf.seekoff.newoff]

<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>

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.

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)).

pos_type seekpos(pos_type sp,
   ios_base::openmode which
   = ios_base::in | ios_base::out) override;

Effects: Equivalent to seekoff(off_type(sp), ios_base::beg, which).

Returns: sp to indicate success, or pos_type(off_type(-1)) to indicate failure.

basic_streambuf<charT, traits>* setbuf(charT* s, streamsize n);

Effects: implementation-defined, except that setbuf(0, 0) has no effect.

Returns: this.

31.8.3 Class template basic_istringstream  [istringstream]

31.8.3.1 General  [istringstream.general]

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>
    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);
basic_istringstream(const basic_istringstream&) = delete;
basic_istringstream(basic_istringstream&& rhs);

template<class SAlloc>
    basic_istringstream(
        const basic_string<charT, traits, SAlloc>& s,
        ios_base::openmode which = ios_base::in);
basic_istringstream& operator=(const basic_istringstream&) = delete;
basic_istringstream& operator=(basic_istringstream&& rhs);

// 31.8.3.3, swap
void swap(basic_istringstream& rhs);

// 31.8.3.4, 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 &;
    template<class SAlloc>
    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);
    template<class SAlloc>
    void str(basic_string<charT, traits, Allocator>&& s);

private:
    basic_stringbuf<charT, traits, Allocator> sb; // exposition only
};

1 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:

(1.1) — sb, the stringbuf object.
31.8.3.2 Constructors

explicit basic_istringstream(ios_base::openmode which);

Effects: Initializes the base class with basic_istream<charT, traits>(addressof(sb)) (31.7.4.2) and sb with basic_stringbuf<charT, traits, Allocator>(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)) (31.7.4.2) and sb with basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::in) (31.8.2.2).

explicit 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

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;

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));

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_string<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);
   basic_ostringstream(const basic_ostringstream&) = delete;
   basic_ostringstream(basic_ostringstream&& rhs);

§ 31.8.4.1
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:

1. `sb`, the `stringbuf` object.

### 31.8.4.2 Constructors

1. `explicit basic_ostringstream(ios_base::openmode which);`  
   **Effects:** Initializes the base class with `basic_ostream<charT, traits>(addressof(sb))` (31.7.5.2) and `sb` with `basic_stringbuf<charT, traits, Allocator>((which | ios_base::out))` (31.8.2.2).

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))` (31.7.5.2) and `sb` with `basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::out)` (31.8.2.2).

3. `basic_ostringstream(ios_base::openmode which, const Allocator& a);`  
   **Effects:** Initializes the base class with `basic_ostream<charT, traits>(addressof(sb))` (31.7.5.2) and `sb` with `basic_stringbuf<charT, traits, Allocator>(std::move(s), which | ios_base::out)` (31.8.2.2).

4. `template<class SAlloc> 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))` (31.7.5.2) and `sb` with `basic_stringbuf<charT, traits, Allocator>(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 = ios_base::out);

Constraints: is_same_v<SAlloc, Allocator> is false.

Effects: Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.5.2) and sb with basic_stringbuf<charT, traits, Allocator>(s, which | ios_base::out) (31.8.2.2).

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<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));

31.8.5 Class template basic_stringstream

31.8.5.1 General

namespace std {
    template<class charT, class traits = char_traits<charT>,
        class Allocator = allocator<charT>>
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

\( sb \), 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))` (31.7.4.7.2) 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))` (31.7.4.7.2) 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))` (31.7.4.7.2) 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))` (31.7.4.7.2) 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 = ios_base::out | ios_base::in);**

*Effects:* Initializes the base class with `basic_iostream<charT, traits>(addressof(sb))` (31.7.4.7.2) and `sb` with `basic_stringbuf<charT, traits, Allocator>(s, which)` (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))` (31.7.4.7.2) and `sb` with `basic_stringbuf<charT, traits, Allocator>(s, which, a)` (31.8.2.2). 

**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))`. 

§ 31.8.5.4 1551
namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_spanbuf;

    using spanbuf = basic_spanbuf<char>;
    using wspanbuf = basic_spanbuf<wchar_t>;

    template<class charT, class traits = char_traits<charT>>
    class basic_ispanstream;

    using ispanstream = basic_ispanstream<char>;
    using wispanstream = basic_ispanstream<wchar_t>;

    template<class charT, class traits = char_traits<charT>>
    class basic_ospanstream;

    using ospanstream = basic_ospanstream<char>;
    using wospanstream = basic_ospanstream<wchar_t>;

    template<class charT, class traits = char_traits<charT>>
    class basic_spanstream;

    using spanstream = basic_spanstream<char>;
    using wspanstream = basic_spanstream<wchar_t>;
}

§ 31.9.2 1552
31.9.3 Class template spanbuf

31.9.3.1 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
        }
    }

    template<class charT, class traits>
    void swap(basic_spanbuf<charT, traits>& x, basic_spanbuf<charT, traits>& y);
}

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);

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.

- span().data() == rhs_p.span().data()
- span().size() == rhs_p.span().size()
- eback() == rhs_p.eback()
- gptr() == rhs_p.gptr()
- egptr() == rhs_p.egptr()
- pbase() == rhs_p.pbase()
- pptr() == rhs_p.pptr()
- eppt() == rhs_p.epptr()
- getloc() == rhs_p.getloc()

31.9.3.3 Assignment and swap [spanbuf.assign]

basic_spanbuf basic_spanbuf& operator=(basic_spanbuf&& rhs);

Effects: Equivalent to:

```
basic_spanbuf tmp{std::move(rhs)};
*this->swap(tmp);
return *this;
```

void swap(basic_spanbuf& rhs);

Effects: Equivalent to:

```
basic_streambuf<charT, traits>::swap(rhs);
std::swap(mode, rhs.mode);
std::swap(buf, rhs.buf);
```

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 [spanbuf.members]

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:

- If `ios_base::out` is set in `mode`, `pbase() == s.data() && epptr() == pbase() + s.size()` is true;
- in addition, if `ios_base::ate` is set in `mode`, `pptr() == pbase() + s.size()` is true,
- otherwise `pptr() == pbase()` is true.
- If `ios_base::in` is set in `mode`, `eback() == s.data() && gptr() == eback() && egptr() == eback() + s.size()` is true.

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31.9.3.5 Overridden virtual functions

[Note 1: Because the underlying buffer is of fixed size, neither overflow, underflow, nor pbackfail can provide useful behavior. — end note]

```cpp
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:

- If `ios_base::in` is set in `which`, positions the input sequence; `xnext` is `gptr()`, `xbeg` is `eback()`.
- 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:

- When `way` is `ios_base::beg`:
- `(pptr() - pbase())` for the output sequence, or `(gptr() - eback())` for the input sequence when `way` is `ios_base::cur`;
- When `way` is `ios_base::end`:
  - `(pptr() - pbase())` if `ios_base::out` is set in `mode` and `ios_base::in` is not set in `mode`,
  - `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

```cpp
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.

```cpp
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);
```

```cpp
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

```cpp
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);
```

§ 31.9.4.1 1555
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
};

template<class charT, class traits>
void swap(basic_ispanstream<charT, traits>& x, basic_ispanstream<charT, traits>& y);

1 [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 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);

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

basic_spanbuf<charT, traits>* rdbuf() const noexcept;

Effects: Equivalent to:
  return const_cast<basic_spanbuf<charT, traits>*>(addressof(sb));

std::span<const charT> span() const noexcept;

Effects: Equivalent to: return rdbuf()->span();
31.9.5 Class template basic_ospanstream

31.9.5.1 General

namespace std {
    template<class charT, class traits = char_traits<charT>>
    class basic_ospanstream
        : 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;

            // 31.9.5.2, 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&& rhs);
            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;
            std::span<charT> span() const noexcept;
            void span(std::span<charT> s) noexcept;
            private:
                basic_spanbuf<charT, traits> sb;   // exposition only
                }

            template<class charT, class traits>
                void swap(basic_ospanstream<charT, traits>& x, basic_ospanstream<charT, traits>& y);

        } // basic_ospanstream

31.9.5.2 Constructors

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.
31.9.5.3 Swap

```cpp
void swap(basic_ospanstream& rhs);
```

**Effects:** Equivalent to:

```cpp
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).

31.9.5.4 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<charT> span() const noexcept;
```

**Effects:** Equivalent to:

```cpp
return rdbuf()->span();
```

```cpp
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

```cpp
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&&) = delete;
      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
    }
```

```cpp
template<class charT, class traits>
void swap(basic_spanstream<charT, traits>& x, basic_spanstream<charT, traits>& y);
```
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 {
    template<class charT, class traits = char_traits<charT>>
        class basic_filebuf;

template<class charT, class traits>
    void swap(basic_filebuf<charT, traits>& x, basic_filebuf<charT, traits>& y);

using filebuf = basic_filebuf<char>;
using wfilebuf = basic_filebuf<wchar_t>;

template<class charT, class traits = char_traits<charT>>
    class basic_ifstream;

template<class charT, class traits>
    void swap(basic_ifstream<charT, traits>& x, basic_ifstream<charT, traits>& y);

using ifstream = basic_ifstream<char>;
using wifstream = basic_ifstream<wchar_t>;

template<class charT, class traits = char_traits<charT>>
    class basic_ofstream;

template<class charT, class traits>
    void swap(basic_ofstream<charT, traits>& x, basic_ofstream<charT, traits>& y);
using ofstream = basic_ofstream<char>;
using wofstream = basic_ofstream<wchar_t>;

template<class charT, class traits = char_traits<charT>>
class basic_fstream;

template<class charT, class traits>
void swap(basic_fstream<charT, traits>& x, basic_fstream<charT, traits>& y);

using fstream = basic_fstream<char>;
using wfstream = basic_fstream<wchar_t>;

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 (31.12.6)` 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 Class template `basic_filebuf` [filebuf]
31.10.2.1 General [filebuf.general]
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;

        // 31.10.2.2, constructors/destructor
            basic_filebuf();
            basic_filebuf(const basic_filebuf&) = delete;
            basic_filebuf(basic_filebuf&& rhs);
            virtual ~basic_filebuf();

        // 31.10.2.3, assignment and swap
            basic_filebuf& operator=(const basic_filebuf&) = delete;
            basic_filebuf& operator=(basic_filebuf&& rhs);
            void swap(basic_filebuf& rhs);

        // 31.10.2.4, 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();

        protected:
            // 31.10.2.5, overridden virtual functions
            streamsize showmanyc() override;
            int_type underflow() override;
            int_type uflow() override;
    }
}
```cpp
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;
```

The class `basic_filebuf<charT, traits>` associates both the input sequence and the output sequence with a file.

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 `FILE`s.

In particular:

1. If the file is not open for reading the input sequence cannot be read.
2. If the file is not open for writing the output sequence cannot be written.
3. A joint file position is maintained for both the input sequence and the output sequence.

An instance of `basic_filebuf` behaves as described in 31.10.2 provided `traits::pos_type` is `fpos<typename traits::state_type>`. Otherwise the behavior is undefined.

In order to support file I/O and multibyte/wide character conversion, conversions are performed using members of a facet, referred to as `a_codecvt` in following subclauses, obtained as if by

```cpp
const codecvt<charT, char, typename traits::state_type>& a_codecvt =
use_facet<codecvt<charT, char, typename traits::state_type>>(getloc());
```

### 31.10.2.2 Constructors

- **basic_filebuf()**
  - **Effects**: Initializes the base class with `basic_streambuf<charT, traits>() (31.6.3.2).
  - **Postconditions**: `is_open() == false`.

- **basic_filebuf(basic_filebuf&& rhs)**
  - **Effects**: It is implementation-defined whether the sequence pointers in `*this (eback(), gptr(),
    egptr(), pbase(), pptr(), epptr())` obtain the values which `rhs` had. Whether they do or not, `*this
and `rhs` reference separate buffers (if any at all) after the construction. Additionally `*this` references
the file which `rhs` did before the construction, and `rhs` references no file after the construction. The
openmode, locale and any other state of `rhs` is also copied.
  - **Postconditions**: Let `rhs.p` refer to the state of `rhs` just prior to this construction and let `rhs.a` refer
to the state of `rhs` just after this construction.

  1. `is_open() == rhs_p.is_open()`
  2. `rhs_a.is_open() == false`.
  5. `pptr() - pbase() == rhs_p.pptr() - rhs_p.pbase()`.
  6. `epptr() - pbase() == rhs_p.epptr() - rhs_p.pbase()`.
  7. `if (eback()) eback() != rhs_a.eback()`.
  8. `if (gptr()) gptr() != rhs_a.gptr()`.
  9. `if (egptr()) egptr() != rhs_a.egptr()`.

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virtual ~basic_filebuf();

Effects: Calls close(). If an exception occurs during the destruction of the object, including the call to close(), the exception is caught but not rethrown (see 16.4.6.13).

31.10.2.3 Assignment and swap

basic_filebuf& operator=(basic_filebuf&& rhs);

Effects: Calls close() then move assigns from rhs. After the move assignment *this has the observable state it would have had if it had been move constructed from rhs (see 31.10.2.2).

Returns: *this.

void swap(basic_filebuf& rhs);

Effects: Exchanges the state of *this and rhs.

template<class charT, class traits>
  void swap(basic_filebuf<charT, traits>& x, basic_filebuf<charT, traits>& y);

Effects: Equivalent to: x.swap(y).

31.10.2.4 Member functions

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 (3.37).

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 124. If mode is not some combination of flags shown in the table then the open fails.

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).\(^{310}\)

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);

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.

\(^{310}\) 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).
Table 124: File open modes [tab:filebuf.open.modes]

<table>
<thead>
<tr>
<th>ios_base flag combination</th>
<th>stdio equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>binary in out trunc app</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>&quot;w&quot;</td>
</tr>
<tr>
<td>+</td>
<td>&quot;w&quot;</td>
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<tr>
<td>+</td>
<td>&quot;a&quot;</td>
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<tr>
<td>+</td>
<td>&quot;a&quot;</td>
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<tr>
<td>+</td>
<td>&quot;r&quot;</td>
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<tr>
<td>+</td>
<td>&quot;r+a&quot;</td>
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<tr>
<td>+</td>
<td>&quot;w+a&quot;</td>
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<td>+</td>
<td>&quot;ab&quot;</td>
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<tr>
<td>+</td>
<td>&quot;rb&quot;</td>
</tr>
<tr>
<td>+</td>
<td>&quot;r+b&quot;</td>
</tr>
<tr>
<td>+</td>
<td>&quot;w+b&quot;</td>
</tr>
<tr>
<td>+</td>
<td>&quot;a+b&quot;</td>
</tr>
</tbody>
</table>

Postconditions: is_open() == false.

Returns: this on success, a null pointer otherwise.

31.10.2.5 Overridden virtual functions [filebuf.virtuals]

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:

```cpp
codeconv_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:
— 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.

— 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.

int_type overflow(int_type c = traits::eof()) override;

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:

```
charT* b = pbase();
charT* p = pptr();
charT* 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.

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.

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 if 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 125.

Table 125: 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>

pos_type seekpos(pos_type sp,  
    ios_base::openmode which
    = ios_base::in | ios_base::out) override;

Alter 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 & ios_base::out) != 0, then update the output sequence and write any unshift sequence;
2. set the file position to sp as if by a call to fsetpos;
3. if (om & ios_base::in) != 0, then update the input sequence;

where om is the open mode passed to the last call to open(). The operation fails if is_open() returns 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 (seekoff or seekpos) on the same file the effects are undefined.

Returns: sp on success. Otherwise returns pos_type(off_type(-1)).

int sync() override;

Effects: If a put area exists, calls filebuf::overflow to write the characters to the file, then flushes the file as if by calling fflush(file). If a get area exists, the effect is implementation-defined.

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 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 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.

31.10.3 Class template basic_ifstream
31.10.3.1 General

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;

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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:

\[(1.1) \quad \text{sb, the filebuf object.}\]

### 31.10.3.2 Constructors

---

// 31.10.3.2, constructors

```cpp
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);
template<class T>
  explicit basic_ifstream(const T& s, ios_base::openmode mode = ios_base::in);
```

**Effects**: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.4.2.2) and `sb` with `basic_filebuf<charT, traits>()` (31.10.2.2).

```cpp
explicit basic_ifstream(const char* s,
  ios_base::openmode mode = ios_base::in);
```

**Effects**: Initializes the base class with `basic_istream<charT, traits>(addressof(sb))` (31.7.4.2.2) and `sb` with `basic_filebuf<charT, traits>()` (31.10.2.2), then calls `rdbuf()->open(s, mode | ios_base::in)`. If that function returns a null pointer, calls `setstate(failbit)`.

```cpp
explicit basic_ifstream(const string& s,
  ios_base::openmode mode = ios_base::in);
```

**Effects**: Equivalent to: `basic_ifstream(s.c_str(), mode)`.

```cpp
template<class T>
  explicit basic_ifstream(const T& s, ios_base::openmode mode = ios_base::in);
```

**Constraints**: `is_same_v<T, filesystem::path>` is true.

**Effects**: Equivalent to: `basic_ifstream(s.c_str(), mode)`. 

---

### 31.10.3.3 Swap

```cpp
void swap(basic_ifstream& rhs);
```
basic_ifstream(basic_ifstream&& 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.

31.10.3.3 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).

31.10.3.4 Member functions

basic_filebuf<charT, traits>* rdbuf() const;

Returns: const_cast<basic_filebuf<charT, traits>*>(addressof(sb)).

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, // wide systems only; see 31.10.1
  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).

31.10.4 Class template basic_ofstream

31.10.4.1 General

namespace std {

  template<class charT, class traits = char_traits<charT>>
  class basic_ofstream : public basic_ostream<charT, traits> { public:
    // 31.10.4.2, 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);
    template<class T>
    explicit basic_ofstream(const T& s, ios_base::openmode mode = ios_base::out);
    basic_ofstream(const basic_ofstream&) = delete;
    basic_ofstream(basic_ofstream&&) = delete;

    // 31.10.4.3, member functions
    basic_ofstream(const basic_ofstream&);
    basic_ofstream(basic_ofstream&& rhs);
  } // class basic_ofstream

} // namespace std

§ 31.10.4.1
basic_ofstream& operator=(const basic_ofstream& rhs);  
// 31.10.4.3, swap
void swap(basic_ofstream& rhs);

// 31.10.4.4, members
basic_filebuf<charT, traits>* rdbuf() const;

bool is_open() const;

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::out);
// wide systems only; see 31.10.1

void open(const string& s, ios_base::openmode mode = ios_base::out);

void open(const filesystem::path& s, ios_base::openmode mode = ios_base::out);

void close();

private:
  basic_filebuf<charT, traits> sb;  // exposition only
};

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) — sb, the filebuf object.

### 31.10.4.2 Constructors

**basic_ofstream();**

**Effects:** Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.5.2.2) and sb with basic_filebuf<charT, traits>() (31.10.2.2).

**explicit basic_ofstream(const char* s,**
  **ios_base::openmode mode = ios_base::out);**

**Effects:** Initializes the base class with basic_ostream<charT, traits>(addressof(sb)) (31.7.5.2.2) and sb with basic_filebuf<charT, traits>() (31.10.2.2), then calls rdbuf()->open(s, mode | ios_base::out). If that function returns a null pointer, calls setstate(failbit).

**explicit basic_ofstream(const string& s,**
  **ios_base::openmode mode = ios_base::out);**

**Effects:** Equivalent to: basic_ofstream(s.c_str(), mode).

**template<class T>**
  **explicit basic_ofstream(const Tk& s,**
    **ios_base::openmode mode = ios_base::out);**

  **Constraints:** is_same_v<T, filesystem::path> is true.

  **Effects:** Equivalent to: basic_ofstream(s.c_str(), mode).

**basic_ofstream(basic_ofstream&& rhs);**

**Effects:** Move constructs the base class, and the contained basic_filebuf. Then calls basic_ostream<charT, traits>::set_rdbuf(addressof(sb)) to install the contained basic_filebuf.

### 31.10.4.3 Swap

**void swap(basic_ofstream& rhs);**

**Effects:** Exchanges the state of *this and rhs by calling basic_ostream<charT, traits>::swap(rhs) 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).

31.10.4.4 Member functions

    basic_filebuf<charT, traits>* rdbuf() const;

        Returns: const_cast<basic_filebuf<charT, traits>*>(addressof(sb)).

    bool is_open() const;

        Returns: rdbuf()->is_open().

    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::out); // wide systems only; see 31.10.1

        Effects: Calls rdbuf()->open(s, mode | ios_base::out). 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 close();

        Effects: Calls rdbuf()->close() and, if that function fails (returns a null pointer), calls setstate(failbit) (which may throw ios_base::failure) (31.5.4.4).

    void open(const string& s, ios_base::openmode mode = ios_base::out);
    void open(const filesystem::path& s, ios_base::openmode mode = ios_base::out);

        Effects: Calls open(s.c_str(), mode).

31.10.5 Class template basic_fstream

31.10.5.1 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;

                        // 31.10.5.2, 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<typename 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);

                        // 31.10.5.3, swap
                        void swap(basic_fstream& rhs);
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:

\[(1.1)\] 

```
sb, the basic_filebuf object.
```

### 31.10.5.2 Constructors

[fstream.cons] 

```
basic_fstream();
```

1. **Effects**: Initializes the base class with `basic_iostream<charT, traits>(addressof(sb))` (31.7.4.7.2) and `sb` with `basic_filebuf<charT, traits>()`.

```
explicit basic_fstream( 
const char* s,  
ios_base::openmode mode = ios_base::in | ios_base::out);
```

2. **Effects**: Initializes the base class with `basic_iostream<charT, traits>(addressof(sb))` (31.7.4.7.2) 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 filesystem::path::value_type* s,  
ios_base::openmode mode = ios_base::in | ios_base::out);  
// wide systems only; see 31.10.1
```

2. **Effects**: Initializes the base class with `basic_iostream<charT, traits>(addressof(sb))` (31.7.4.7.2) 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);
```

3. **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);  
```

4. **Constraints**: `is_same_v<T, filesystem::path>` is true.

5. **Effects**: Equivalent to: `basic_fstream(s.c_str(), mode)`.

### 31.10.5.3 Swap

[fstream.swap] 

```
void swap(basic_fstream& rhs);
```

1. **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: \texttt{x.swap(y)}.

31.10.5.4 Member functions [fstream.members]

basic_filebuf<charT, traits>* rdbuf() const;
  
Returns: \texttt{const\_cast<basic\_filebuf<charT, traits>*>(addressof(sb))}.

bool is_open() const;
  
Returns: \texttt{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 \texttt{rdbuf()->open(s, mode)}. If that function does not return a null pointer calls \texttt{clear()}, otherwise calls \texttt{setstate(failbit)} (which may throw \texttt{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 \texttt{open(s.c\_str(), mode)}.

void close();
  
Effects: Calls \texttt{rdbuf()->close()} and, if that function returns a null pointer, calls \texttt{setstate(failbit)} (which may throw \texttt{ios\_base::failure}) (31.5.4.4).

31.11 Synchronized output streams [syncstream]

31.11.1 Header <syncstream> synopsis [syncstream.syn]

```cpp
#include <ostream>
// see 31.7.2

namespace std {
  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>& k,
              basic_syncbuf<charT, traits, Allocator>& t);

  using syncbuf = basic_syncbuf<char>;
  using wsyncbuf = basic_syncbuf<wchar_t>;

  template<class charT, class traits = char_traits<charT>, class Allocator = allocator<charT>>
    class basic_osyncstream;

  using osyncstream = basic_osyncstream<char>;
  using wosyncstream = basic_osyncstream<wchar_t>;
}
```

1 The header <syncstream> provides a mechanism to synchronize execution agents writing to the same stream.
31.11.2 Class template basic_syncbuf

31.11.2.1 Overview

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>;

            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();

        // 31.11.2.2, construction and destruction
        basic_syncbuf(streambuf_type* obuf, const Allocator& allocator);
        Effects: Sets \texttt{wrapped} to \texttt{obuf}.
        Postconditions: \texttt{get_wrapped()} == \texttt{obuf} and \texttt{get_allocator()} == \texttt{allocator} are true.
        Throws: Nothing unless an exception is thrown by the construction of a mutex or by memory allocation.
        Remarks: A copy of \texttt{allocator} is used to allocate memory for internal buffers holding the associated output.

    }  

};
basic_syncbuf(basic_syncbuf&& other);

Postconditions: The value returned by this->get_wrapped() is the value returned by other.get_wrapped() prior to calling this constructor. Output stored in other prior to calling this constructor will be stored in *this afterwards. other.pbase() == other.pptr() and other.get_wrapped() == nullptr are true.

Remarks: This constructor disassociates other from its wrapped stream buffer, ensuring destruction of other produces no output.

~basic_syncbuf();

Effects: Calls emit().

Throws: Nothing. If an exception is thrown from emit(), the destructor catches and ignores that exception.

31.11.2.3 Assignment and swap

basic_syncbuf& operator=(basic_syncbuf&& rhs);

Effects: Calls emit() then move assigns from rhs. After the move assignment *this has the observable state it would have had if it had been move constructed from rhs (31.11.2.2).

Postconditions:

(2.1) rhs.get_wrapped() == nullptr is true.
(2.2) this->get_allocator() == rhs.get_allocator() is true when allocator_traits<Allocator>::propagate_on_container_move_assignment::value is true; otherwise, the allocator is unchanged.

Returns: *this.

Remarks: This assignment operator disassociates rhs from its wrapped stream buffer, ensuring destruction of rhs produces no output.

void swap(basic_syncbuf& other);

Preconditions: Either allocator_traits<Allocator>::propagate_on_container_swap::value is true or this->get_allocator() == other.get_allocator() is true.

Effects: Exchanges the state of *this and other.

31.11.2.4 Member functions

bool emit();

Effects: Atomically transfers the associated output of *this to the stream buffer *wrapped, so that it appears in the output stream as a contiguous sequence of characters. *wrapped->pubsync() is called if and only if a call was made to sync() since the most recent call to emit(), if any.

Synchronization: All 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 emit() call synchronizes with subsequent 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:

(4.1) wrapped == nullptr is false.
(4.2) All of the characters in the associated output were successfully transferred.
(4.3) The call to wrapped->pubsync() (if any) succeeded.

Remarks: May call member functions of wrapped while holding a lock uniquely associated with 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()) {} // 31.11.3.2
            basic_osyncstream(basic_ostream<charT, traits>&& os, const Allocator& allocator)
                : basic_osyncstream(os.rdbuf(), allocator) {} // 31.11.3.2
            explicit basic_osyncstream(basic_ostream<charT, traits>&& os)
                : basic_osyncstream(os, Allocator()) {} // 31.11.3.2
            basic_osyncstream(basic_osyncstream&&) noexcept;
            basic_osyncstream(); // 31.11.3.2

            // assignment
            basic_osyncstream& operator=(basic_osyncstream&&) noexcept;

            // 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)); } // 31.11.3.2

            private:
                syncbuf_type sb; // exposition only
        }
    }
}

1 Allocator shall meet the Cpp17Allocator requirements (16.4.4.6.1).

2 [Example 1: A named variable can be used within a block statement for streaming.]
```cpp
{  
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

[bsynstream.osyncstream.cons]

basic_osyncstream(streambuf_type* buf, const Allocator& allocator);

1 Effects: Initializes sb from buf and allocator. Initializes the base class with basic_ostream<charT, traits>(addressof(sb)).

[Note 1: The member functions of the provided stream buffer can be called from emit() while a lock is held, which might result in a deadlock if used incautiously. — end note]

3 Postconditions: get_wrapped() == buf is true.

basic_osyncstream(basic_osyncstream&& other) noexcept;

4 Effects: Move constructs the base class and sb from the corresponding subobjects of other, and calls 
basic_ostream<charT, traits>::set_rdbuf(addressof(sb)).

5 Postconditions: The value returned by get_wrapped() is the value returned by os.get_wrapped() prior to calling this constructor. nullptr == other.get_wrapped() is true.

31.11.3.3 Member functions

[synstream.osyncstream.members]

void emit();

1 Effects: Behaves as an unformatted output function (31.7.5.4). 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();
} catch (...) {
  // handle exception
  }

}  // characters transferred; cout not flushed

— end example ]

streambuf_type* get_wrapped() const noexcept;

4 Returns: sb.get_wrapped().

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Example 3: Obtaining the wrapped stream buffer with get_wrapped() allows wrapping it again with an
osyncstream. For example,

```c
{ osyncstream bout1(cout);
  bout1 << "Hello, ";
  { osyncstream(bout1.get_wrapped()) << "Goodbye, " << "Planet!" << \n
    \n
};
  bout1 << "World!" << \n
    \n
};
```

produces the uninterleaved output

Goodbye, Planet!
Hello, World!

— end example]

31.12 File systems
31.12.1 General
Subclause 31.12 describes operations on file systems and their components, such as paths, regular files, and
directories.

A file system is a collection of files and their attributes.

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.

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.

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
31.12.2.1 General
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
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;

  // 31.12.11, 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 options);
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;

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);

} // 31.12.6.9, hash support
namespace std {
    template<class T> struct hash;
    template<> struct hash<filesystem::path>;
} // 31.12.4 1580

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  

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. Uses where file system errors are truly exceptional and indicate a serious failure. Throwing an exception is an appropriate response.
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]

Functions not having an argument of type error_code& handle errors as follows, unless otherwise specified:

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. Failure to allocate storage is reported by throwing an exception as described in 16.4.6.13.

3. Destructors throw nothing.

Functions having an argument of type error_code& handle errors as follows, unless otherwise specified:

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.

[Note 2: Pathnames “.” and “..” are relative paths. — end note]

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.
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;

            // 31.12.6.5.1, 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);
            ~path();

            // 31.12.6.5.2, assignments
            path& operator=(const path& p);
            path& operator=(path&& p) noexcept;
            path& assign(string_type&& source);
            template<class Source>
                path& operator=(const Source& source);
            template<class InputIterator>
                path& assign(InputIterator first, InputIterator last);

            // 31.12.6.5.3, appends
            path& operator/=(const path& p);
            template<class Source>
                path& operator/=(const Source& source);
            template<class InputIterator>
                path& append(InputIterator first, InputIterator 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<typename EcharT>
                path& operator+=(EcharT x);
            template<class InputIterator>
                path& concat(InputIterator first, InputIterator last);
        }
    }

[Example 1: POSIX specifies the mechanism in section 4.12, Pathname resolution. — end example]
// 31.12.6.5.5, 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;

// 31.12.6.5.10, query
[[nodiscard]] bool empty() const noexcept;
bool has_root_name() const;
bool has_root_directory() const;
bool has_root_path() const;
bool has_relative_path() const;
bool has_parent_path() const;
bool has_filename() const;
bool has_stem() const;
bool has_extension() const;
bool is_absolute() const;
bool is_relative() const;

// 31.12.6.5.11, generation
path lexically_normal() const;
path lexically_relative(const path& base) const;
path lexically_proximate(const path& base) const;

// 31.12.6.6, iterators
class iterator;
using const_iterator = iterator;

iterator begin() const;
iterator end() const;

// 31.12.6.7, path inserter and extractor
template<class charT, class traits>
friend basic_ostream<charT, traits>&
    operator<<(basic_ostream<charT, traits>& os, const path& p);
template<class charT, class traits>
friend basic_istream<charT, traits>&
    operator>>(basic_istream<charT, traits>& is, path& p);
};
}

7 value_type is a typedef for the operating system dependent encoded character type used to represent
pathnames.

8 The value of the preferred_separator member is the operating system dependent preferred-separator
character (31.12.6.2).

9 [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 [fs.path.generic]

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 /

1 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:
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]

The maximum permitted length.

Filenames that are not permitted.

Filenames that have special meaning.

Case awareness and sensitivity during path resolution.

Special rules that may apply to file types other than regular files, such as directories.

2 Except in a root-name, multiple successive directory-separator characters are considered to be the same as one directory-separator character.

3 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.

4 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]

5 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.
2 Several functions are defined to accept detected-format arguments, which are character sequences. A detected-format argument represents a path using either a pathname in the generic format (31.12.6.2) or a pathname 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.

[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. An implementation for an operating system where disambiguation is required is permitted to distinguish 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.

[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 (16.3.3.3.5).

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 `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:

1. **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 `path::value_type` is `char` so no conversion from `char` value type arguments or to `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. **wchar_t**: The encoding is the native wide encoding. The method of conversion is unspecified.

   [Note 3: For Windows-based operating systems `path::value_type` is `wchar_t` so no conversion from `wchar_t` value type arguments or to `wchar_t` value type return values is performed. — end note]

3. **char8_t**: The encoding is UTF-8. The method of conversion is unspecified.

4. **char16_t**: The encoding is UTF-16. The method of conversion is unspecified.

5. **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`. 

§ 31.12.6.3.2
31.12.6.4 Requirements  

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.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()`.`

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).

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

Arguments of type `Source` shall not be null pointers.

31.12.6.5 Members  

31.12.6.5.1 Constructors

path() noexcept;  
Postconditions: `empty() == 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:

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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.

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:

```cpp
namespace fs = std::filesystem;
std::string latin1_string = read_latin1_data();
codecvt_8859_1<wchar_t> latin1_facet;
std::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

```cpp
path& operator=(const path& p);
```

1. **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.

2. **Returns:** *this.

```cpp
path& operator=(path&& p) noexcept;
```

3. **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.

4. **Returns:** *this.

```cpp
path& operator=(string_type&& source);
push_back(string_type&& source);
```

5. **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.

6. **Returns:** *this.

```cpp
template<class Source>
path& operator=(const Source& source);
template<class Source>
path assign(const Source& source);
template<InputIterator>
path assign(InputIterator first, InputIterator last);
```

7. **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.

8. **Returns:** *this.

### 31.12.6.5.3 Appends

1. 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() || 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("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);
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

void clear() noexcept;

Postconditions: empty() == 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 << '
';
p.make_preferred();
std::cout << p << '
';
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:
p(path("foo/bar")).remove_filename(); // yields "foo/
p(path("foo/").remove_filename(); // yields "foo/
p(path("/foo")).remove_filename(); // yields "/
p(path("/")).remove_filename(); // yields "/
— end example]

path& replace_filename(const path& replacement);

Effects: Equivalent to:
remove_filename();
operator/=(replacement);

Returns: *this.

[Example 3:
p(path("/foo")).replace_filename("bar"); // yields "/bar" on POSIX
p(path("/")).replace_filename("bar"); // yields "/bar" on POSIX
— end example]

path& replace_extension(const path& replacement = path());

Effects:
(12.1) Any existing extension() (31.12.6.5.9) is removed from the pathname in the generic format, then
(12.2) 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
(12.3) operator+=(replacement);

Returns: *this.
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

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();`

operator string_type() const;

Returns: `native()`.

#### 31.12.6.5.7 Generic format observers

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.

```cpp
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 performed as specified by 31.12.6.3.
31.12.6.5.8 Compare

```cpp
int compare(const path& p) const noexcept;
```

1. **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.

2. **Effects:** Equivalent to: `return compare(path(s));`

31.12.6.5.9 Decomposition

```cpp
path root_name() const;
```

1. **Returns:** `root-name`, if the pathname in the generic format includes `root-name`, otherwise `path()`.

```cpp
path root_directory() const;
```

2. **Returns:** `root-directory`, if the pathname in the generic format includes `root-directory`, otherwise `path()`.

```cpp
path root_path() const;
```

3. **Returns:** `root_name() / root_directory()`.

```cpp
path relative_path() const;
```

4. **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()`.

```cpp
path parent_path() const;
```

5. **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.

```cpp
path filename() const;
```

6. **Returns:** `relative_path().empty() ? path() : *--end()`.

7. **[Example 1:]
   ```cpp
   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 "host"
   path("..").filename(); // yields "."
   path("...").filename(); // yields ".."
   ``` — end example]

```cpp
path stem() const;
```

8. **Returns:** Let `f` be the generic format pathname of `filename()`. Returns a path whose pathname in the generic format is

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— 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:

```cpp
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() << 'n';
    // 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:

```cpp
path("/foo/bar.txt").extension(); // yields ".txt" and stem() is "bar"
path("/foo/bar") .extension(); // yields "" and stem() is "bar"
path("/foo/.profile") .extension(); // yields "" and stem() is ".profile"
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().

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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 [fs.path.gen]

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:
— (3.1) root_name() != base.root_name() is true, or
— (3.2) is_absolute() != base.is_absolute() is true, or
— (3.3) !has_root_directory() && base.has_root_directory() is true, or
— (3.4) 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,
— (3.5) if a == end() and b == base.end(), returns path(""); otherwise
— (3.6) 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
— (3.7) if n == 0 and (a == end() || !a->empty()), returns path(""); otherwise
— (3.8) returns an object of class path that is default-constructed, followed by
— (3.8.1) application of operator/(path("..")) n times, and then
— (3.8.2) application of operator/= for each element in [a, end()).

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]
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.
(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 31.7.8. —end note]

Returns: os.

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 Hash support [fs.path.hash]

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 [fs.class.filesystem.error]

31.12.7.1 General [fs.class.filesystem.error.general]

namespace std::filesystem {
  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;
    };
  }
}

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 [fs.filesystem.error.members]

Constructors are provided that store zero, one, or two paths associated with an error.

filesystem_error(const string& what_arg, error_code ec);

Postconditions:
(2.1) — code() == ec,
(2.2) — path1().empty() == true,
(2.3) — path2().empty() == true, and
(2.4) — string_view(what()).find(what_arg.c_str()) != string_view::npos.
filesystem_error(const string& what_arg, const path& p1, error_code ec);

Postconditions:

- code() == ec,
- path1() returns a reference to the stored copy of p1,
- path2().empty() == true, and
- string_view(what()).find(what_arg.c_str()) != string_view::npos.

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 126.

<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 implementation-defined. The implementation may inspect the content of the character sequence to determine the format. Recommended practice: For POSIX-based systems, native and generic formats are equivalent and the character sequence should 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 127. 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 (16.3.3.3.4) 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 128. 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 127: Enum class file_type

<table>
<thead>
<tr>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</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>not_found</td>
<td>Pseudo-type indicating the file was not found.</td>
</tr>
<tr>
<td>regular</td>
<td>Regular file</td>
</tr>
<tr>
<td>directory</td>
<td>Directory file</td>
</tr>
<tr>
<td>symlink</td>
<td>Symbolic link file</td>
</tr>
<tr>
<td>block</td>
<td>Block special file</td>
</tr>
<tr>
<td>character</td>
<td>Character special file</td>
</tr>
<tr>
<td>fifo</td>
<td>FIFO or pipe file</td>
</tr>
<tr>
<td>socket</td>
<td>Socket file</td>
</tr>
<tr>
<td>implementation-defined</td>
<td>Implementations that support file systems having file types in addition to the above file_type types shall supply implementation-defined file_type constants to separately identify each of those additional file types</td>
</tr>
<tr>
<td>unknown</td>
<td>The file exists but the type cannot be determined</td>
</tr>
</tbody>
</table>

Table 128: Enum class copy_options

<table>
<thead>
<tr>
<th>Option group controlling copy_file function effects for existing target files</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>(Default) Error; file already exists.</td>
<td></td>
</tr>
<tr>
<td>skip_existing</td>
<td>Do not overwrite existing file, do not report an error.</td>
<td></td>
</tr>
<tr>
<td>overwrite_existing</td>
<td>Overwrite the existing file.</td>
<td></td>
</tr>
<tr>
<td>update_existing</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 copy function effects for sub-directories</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>(Default) Do not copy sub-directories.</td>
<td></td>
</tr>
<tr>
<td>recursive</td>
<td>Recursively copy sub-directories and their contents.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option group controlling copy function effects for symbolic links</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>(Default) Follow symbolic links.</td>
<td></td>
</tr>
<tr>
<td>copy_symlinks</td>
<td>Copy symbolic links as symbolic links rather than copying the files that they point to.</td>
<td></td>
</tr>
<tr>
<td>skip_symlinks</td>
<td>Ignore symbolic links.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option group controlling copy function effects for choosing the form of copying</th>
<th>Constant</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>(Default) Copy content.</td>
<td></td>
</tr>
<tr>
<td>directories_only</td>
<td>Copy directory structure only; do not copy non-directory files.</td>
<td></td>
</tr>
<tr>
<td>create_symlinks</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>create_hard_links</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 class type `perms` is a bitmask type (16.3.3.3.4) that specifies bitmask constants used to identify file permissions, with the meanings listed in Table 129.

<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>S_IRWXU</td>
<td>There are no permissions set for the file.</td>
</tr>
<tr>
<td>owner_read</td>
<td>040</td>
<td>S_IRUSR</td>
<td>Read permission, owner</td>
</tr>
<tr>
<td>owner_write</td>
<td>020</td>
<td>S_IWUSR</td>
<td>Write permission, owner</td>
</tr>
<tr>
<td>owner_exec</td>
<td>010</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;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>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;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>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;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>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 class type `perm_options` is a bitmask type (16.3.3.3.4) that specifies bitmask constants used to control the semantics of permissions operations, with the meanings listed in Table 130. The bitmask constants are bitmask elements. In Table 130 `perm` denotes a value of type `perms` passed to `permissions`.

<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>nofollow</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 class type `directory_options` is a bitmask type (16.3.3.3.4) that specifies bitmask constants used to identify directory traversal options, with the meanings listed in Table 131. The constant none represents the empty bitmask; every other constant in the table represents a distinct bitmask element.

§ 31.12.8.6
Table 131: Enum class directory_options  [tab:fs.enum.dir.opts]

<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  [fs.class.file.status]
31.12.9.1  General  [fs.class.file.status.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  [fs.file.status.cons]

explicit file_status(file_type ft, perms prms = perms::unknown) noexcept;

1  Postconditions: type() == ft and permissions() == prms.

31.12.9.3  Observers  [fs.file.status.obs]

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  [fs.file.status.mods]

void type(file_type ft) noexcept;

1  Postconditions: type() == ft.
void permissions(perms prms) noexcept;

Postconditions: permissions() == prms.

31.12.10 Class directory_entry

31.12.10.1 General

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 noexcept;
            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;

§ 31.12.10.1
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;

// 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]
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.
16  **Throws**: As specified in 31.12.5.

```cpp
bool is_socket() const;
bool is_socket(error_code& ec) const noexcept;
```

**Returns**: `is_socket(this->status())` or `is_socket(this->status(ec))`, respectively.

17  **Throws**: As specified in 31.12.5.

```cpp
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.

18  **Throws**: As specified in 31.12.5.

```cpp
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.

19  **Throws**: As specified in 31.12.5.

```cpp
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.

20  **Throws**: As specified in 31.12.5.

```cpp
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.

21  **Throws**: As specified in 31.12.5.

```cpp
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.

22  **Throws**: As specified in 31.12.5.

```cpp
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.

23  **Throws**: As specified in 31.12.5.

```cpp
bool operator==(const directory_entry& rhs) const noexcept;
```

**Returns**: `pathobject == rhs.pathobject`.

24  **Throws**: As specified in 31.12.5.

```cpp
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

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 sub-directories, see class recursive_directory_iterator (31.12.12). — end note]

```cpp
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);

            // other members as required by 25.3.5.3, input iterators
        }
    }
}
```

directory_iterator meets the Cpp17InputIterator requirements (25.3.5.3).

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.

The end iterator is not dereferenceable.

Two end iterators are always equal. An end iterator shall not be equal to a non-end iterator.

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 \texttt{operator/=}.

Directory iteration shall not yield directory entries for the current (dot) and parent (dot-dot) directories.

The order of directory entries obtained by dereferencing successive increments of a directory_iterator is unspecified.

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]
10 [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]

11 [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.

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);

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().
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;

        const directory_entry& operator*() const;
        const directory_entry* operator->() const;

        // 31.12.12.2, modifiers
        recursive_directory_iterator&
            operator=(const recursive_directory_iterator& rhs);
        recursive_directory_iterator&
            operator=(recursive_directory_iterator&& rhs) noexcept;
        recursive_directory_iterator& operator++();
        recursive_directory_iterator& increment(error_code& ec);

        void pop();
        void pop(error_code& ec);
        void disable_recursion_pending();

        // 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
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]

[Note 2: By default, recursive_directory_iterator does not follow directory symlinks. To follow directory symlinks, specify options as directory_options::follow_directory_symlink. — 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.

[Note 3: The initial directory is depth 0, its immediate subdirectories are depth 1, and so forth. — end note]

Throws: Nothing.

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]

31.12.13.2 Absolute [fs.op.absolute]

path filesystem::absolute(const path& p);
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);

Effects: Equivalent to copy(from, to, copy_options::none).

void filesystem::copy(const path& from, const path& to, error_code& ec);

Effects: Equivalent to copy(from, to, copy_options::none, ec).

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

(4.5.4) is_directory(f) && is_regular_file(t) is true.

(4.6) Otherwise, if is_symlink(f), then:

(4.6.1) If (options & copy_options::skip_symlinks) != copy_options::none then return.

(4.6.2) Otherwise if

!exists(t) && (options & copy_options::copy_symlinks) != copy_options::none

then copy_symlink(from, to).

(4.6.3) Otherwise report an error as specified in 31.12.5.

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— Otherwise, if \texttt{is\_regular\_file(f)}, then:

\begin{itemize}
\item If \((\texttt{options} \& \texttt{copy\_options::directories\_only}) \neq \texttt{copy\_options::none}\), then return.
\item Otherwise, if \((\texttt{options} \& \texttt{copy\_options::create\_symlinks}) \neq \texttt{copy\_options::none}\), then create a symbolic link to the source file.
\item Otherwise, if \((\texttt{options} \& \texttt{copy\_options::create\_hard\_links}) \neq \texttt{copy\_options::none}\), then create a hard link to the source file.
\item Otherwise, if \(\texttt{is\_directory(t)}\), then \texttt{copy\_file(from, to/from.filename(), options)}.
\item Otherwise, \texttt{copy\_file(from, to, options)}.
\end{itemize}

— Otherwise, if

\begin{itemize}
\item \(\texttt{is\_directory(f)} \& \& \left(\texttt{options} \& \texttt{copy\_options::create\_symlinks} \neq \texttt{copy\_options::none}\right)\)
\end{itemize}

then report an error with an \texttt{error\_code} argument equal to \texttt{make\_error\_code(errc::is\_a\_directory)}.

— Otherwise, if

\begin{itemize}
\item \(\texttt{is\_directory(f)} \& \& \left(\texttt{options} \& \texttt{copy\_options::recursive} \neq \texttt{copy\_options::none} || \texttt{options} == \texttt{copy\_options::none}\right)\)
\end{itemize}

then:

\begin{itemize}
\item If \(\texttt{exists(t)}\) is \texttt{false}, then \texttt{create\_directory(to, from)}.
\item Then, iterate over the files in \texttt{from}, as if by

\begin{verbatim}
for (const directory_entry& x : directory_iterator(from))
    copy(x.path(), to/x.path().filename(),
         options | copy_options::in-recursive-copy);
\end{verbatim}

where \texttt{in-recursive-copy} is a bitmask element of \texttt{copy\_options} that is not one of the elements in 31.12.8.3.
\end{itemize}

— Otherwise, for the signature with argument \texttt{ec}, \texttt{ec.clear()}.

— Otherwise, no effects.

\textit{Throses:} As specified in 31.12.5.

\textit{Remarks:} For the signature with argument \texttt{ec}, any library functions called by the implementation shall have an \texttt{error\_code} argument if applicable.

\[\text{Example 1:}\] Given this directory structure:

```
/dir1
 file1
 file2
 dir2
 file3
```

Calling \texttt{copy("/dir1", "/dir3")} would result in:

```
/dir1
 file1
 file2
 dir2
 file3
/dir3
 file1
 file2
```

Alternatively, calling \texttt{copy("/dir1", "/dir3", \texttt{copy\_options::recursive})} would result in:

```
/dir1
 file1
 file2
 dir2
 file3
/dir3
```
31.12.13.5 Copy file

bool filesystem::copy_file(const path& from, const path& to);
bool filesystem::copy_file(const path& from, const path& to, error_code& ec);

Returns: copy_file(from, to, copy_options::none) or copy_file(from, to, copy_options::none, ec), respectively.

Throws: As specified in 31.12.5.

bool filesystem::copy_file(const path& from, const path& to, copy_options options);
bool filesystem::copy_file(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: As follows:

(4.1) Report an error as specified in 31.12.5 if:

(4.1.1) is_regular_file(from) is false, or
(4.1.2) exists(to) is true and is_regular_file(to) is false, or
(4.1.3) exists(to) is true and equivalent(from, to) is true, or
(4.1.4) exists(to) is true and (options & (copy_options::skip_existing |
       copy_options::overwrite_existing | copy_options::update_existing)) == copy_options::none

(4.2) Otherwise, copy the contents and attributes of the file from resolves to, to the file to resolves to, if:

(4.2.1) exists(to) is false, or
(4.2.2) (options & copy_options::overwrite_existing) != copy_options::none, or
(4.2.3) (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).

(4.3) Otherwise, no effects.

Returns: true if the from file was copied, otherwise false. The signature with argument ec returns false if an error occurs.

Throws: As specified in 31.12.5.

Complexity: At most one direct or indirect invocation of status(to).

31.12.13.6 Copy symlink

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

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: θ(n) where n is the number of elements of `p`.

### 31.12.13.8 Create directory

```c++
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.

```c++
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

```c++
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

```c++
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;
```

**Effects:** Establishes the postcondition, as if by POSIX `link()`.

**Postconditions:**

1. `exists(to) && exists(new_hard_link) && equivalent(to, new_hard_link)`
2. The contents of the file or directory `to` resolves to are unchanged.

Throws: As specified in 31.12.5.

[Note 1: Some operating systems do not support hard links at all or support them only for regular files. Some file systems (such as the FAT file system) do not support hard links regardless of the operating system. Some file systems limit the number of links per file.

—end note]
31.12.13.11 Create symlink

```c++
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**: `new_symlink` resolves to a symbolic link file that contains an unspecified representation of `to`.
3. **Throws**: As specified in 31.12.5.
4. [Note 1: 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]

31.12.13.12 Current path

```c++
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 obtained as if by POSIX `getcwd()`. The signature with argument `ec` returns `path()` if an error occurs.
2. **Throws**: As specified in 31.12.5.
3. **Remarks**: The current working directory is the directory, associated with the process, that is used as the starting location in pathname resolution for relative paths.
4. [Note 1: The `current_path()` name was chosen to emphasize that the returned value is a path, not just a single directory name. — end note]
5. [Note 2: The current path as returned by many operating systems is a dangerous global variable and can be changed unexpectedly by third-party or system library functions, or by another thread. — end note]

```c++
void filesystem::current_path(const path& p);
void filesystem::current_path(const path& p, error_code& ec) noexcept;
```

1. **Effects**: Establishes the postcondition, as if by POSIX `chdir()`.
2. **Postconditions**: `equivalent(p, current_path())`.
3. **Throws**: As specified in 31.12.5.
4. [Note 3: The current path for many operating systems is a dangerous global state and can be changed unexpectedly by third-party or system library functions, or by another thread. — end note]

31.12.13.13 Equivalent

```c++
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 the same device at the same location.
2. **Returns**: `true`, if `p1` and `p2` resolve to the same file system entity, otherwise `false`. The signature with argument `ec` returns `false` if an error occurs.
3. **Throws**: As specified in 31.12.5.
4. **Remarks**: `!exists(p1) || !exists(p2)` is an error.

31.12.13.14 Exists

```c++
bool filesystem::exists(file_status s) noexcept;
```

1. **Returns**: `status_known(s) && s.type() != file_type::not_found`.

```c++
bool filesystem::exists(const path& p);
bool filesystem::exists(const path& p, error_code& ec) noexcept;
```

1. Let `s` be a `file_status`, determined as if by `status(p)` or `status(p, ec)`, respectively.
Effects: The signature with argument `ec` calls `ec.clear()` if `status_known(s)`.

Returns: `exists(s)`.

Throws: As specified in 31.12.5.

### 31.12.13.15 File size

```cpp
uintmax_t filesystem::file_size(const path& p);
uintmax_t filesystem::file_size(const path& p, error_code& ec) noexcept;
```

1. Effects: If `exists(p)` is `false`, an error is reported (31.12.5).
2. Returns:
   1. If `is_regular_file(p)`, the size in bytes of the file `p` resolves to, determined as if by the value of the POSIX `stat` class member `st_size` obtained as if by POSIX `stat()`.
   2. Otherwise, the result is implementation-defined.

The signature with argument `ec` returns `static_cast<uintmax_t>(-1)` if an error occurs.

Throws: As specified in 31.12.5.

### 31.12.13.16 Hard link count

```cpp
uintmax_t filesystem::hard_link_count(const path& p);
uintmax_t filesystem::hard_link_count(const path& p, error_code& ec) noexcept;
```

1. Returns: The number of hard links for `p`. The signature with argument `ec` returns `static_cast<uintmax_t>(-1)` if an error occurs.
2. Throws: As specified in 31.12.5.

### 31.12.13.17 Is block file

```cpp
bool filesystem::is_block_file(file_status s) noexcept;
```

1. Returns: `s.type() == file_type::block`.

```cpp
bool filesystem::is_block_file(const path& p);
bool filesystem::is_block_file(const path& p, error_code& ec) noexcept;
```

2. Returns: `is_block_file(status(p))` or `is_block_file(status(p, ec))`, respectively. The signature with argument `ec` returns `false` if an error occurs.
3. Throws: As specified in 31.12.5.

### 31.12.13.18 Is character file

```cpp
bool filesystem::is_character_file(file_status s) noexcept;
```

1. Returns: `s.type() == file_type::character`.

```cpp
bool filesystem::is_character_file(const path& p);
bool filesystem::is_character_file(const path& p, error_code& ec) noexcept;
```

2. 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.
3. Throws: As specified in 31.12.5.

### 31.12.13.19 Is directory

```cpp
bool filesystem::is_directory(file_status s) noexcept;
```

1. Returns: `s.type() == file_type::directory`.

```cpp
bool filesystem::is_directory(const path& p);
bool filesystem::is_directory(const path& p, error_code& ec) noexcept;
```

2. Returns: `is_directory(status(p))` or `is_directory(status(p, ec))`, respectively. The signature with argument `ec` returns `false` if an error occurs.
3. Throws: As specified in 31.12.5.
31.12.13.20  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

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

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);
bool filesystem::is_socket(const path& p, error_code& ec) noexcept;

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);
bool filesystem::is_symlink(const path& p, error_code& ec) noexcept;

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

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

path filesystem::proximate(const path& p, error_code& ec);

Returns: proximate(p, current_path(), ec).
2  Throws: As specified in 31.12.5.

   path filesystem::proximate(const path& p, const path& base = current_path());
   path filesystem::proximate(const path& p, const path& base, error_code& ec);

3  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));

5  or path() at the first error occurrence, if any.

4  Throws: As specified in 31.12.5.

31.12.13.29 Read symlink  [fs.op.read.symlink]

   path filesystem::read_symlink(const path& p);
   path filesystem::read_symlink(const path& p, error_code& ec);

1  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.

2  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  [fs.op.relative]

   path filesystem::relative(const path& p, error_code& ec);

1  Returns: relative(p, current_path(), ec).

2  Throws: As specified in 31.12.5.

path filesystem::relative(const path& p, const path& base = current_path());
path filesystem::relative(const path& p, const path& base, error_code& ec);

3  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));

5  or path() at the first error occurrence, if any.

4  Throws: As specified in 31.12.5.

31.12.13.31 Remove  [fs.op.remove]

   bool filesystem::remove(const path& p);
   bool filesystem::remove(const path& p, error_code& ec) noexcept;

1  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]

2  Postconditions: exists(symlink_status(p)) is false.

3  Returns: false if p did not exist, otherwise true. The signature with argument ec returns false if an error occurs.

4  Throws: As specified in 31.12.5.

31.12.13.32 Remove all  [fs.op.remove.all]

   uintmax_t filesystem::remove_all(const path& p);
   uintmax_t filesystem::remove_all(const path& p, error_code& ec);

1  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]

2  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:

```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]
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:

(6.1) If ec != error_code():

(6.1.1) 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).

(6.1.2) Otherwise, if the specific error indicates that p can be resolved but the attributes cannot be determined, returns file_status(file_type::unknown).

(6.1.3) 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]

(6.2) Otherwise,

(6.2.1) 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]

(6.2.2) 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]

(6.2.3) Otherwise, if the attributes indicate a block special file, as if by POSIX S_ISBLK, returns file_status(file_type::block, prms).

(6.2.4) Otherwise, if the attributes indicate a character special file, as if by POSIX S_ISCHR, returns file_status(file_type::character, prms).

(6.2.5) Otherwise, if the attributes indicate a fifo or pipe file, as if by POSIX S_ISFIFO, returns file_status(file_type::fifo, prms).

(6.2.6) Otherwise, if the attributes indicate a socket, as if by POSIX S_ISSOCK, returns file_status(file_type::socket, prms).

(6.2.7) 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.

(6.2.8) 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;

1. 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.

2. 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.

3. 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.


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);

1. Let p be an unspecified directory path suitable for temporary files.

2. Effects: If exists(p) is false or is_directory(p) is false, an error is reported (31.12.5).

3. Returns: The path p. The signature with argument ec returns path() if an error occurs.


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]

31.12.13.40 Weakly canonical

path filesystem::weakly_canonical(const path& p);
path filesystem::weakly_canonical(const path& p, error_code& ec);

1. Effects: Using status(p) or status(p, ec), respectively, to determine existence, return a path composed by operator/= from the result of calling canonical() with a path argument composed of the leading elements of p that exist, if any, followed by the elements of p that do not exist, if any. For the first form, canonical() is called without an error_code argument. For the second form, canonical() is called with ec as an error_code argument, and path() is returned at the first error occurrence, if any.

2. Postconditions: The returned path is in normal form (31.12.6.2).


5. Remarks: Implementations should avoid unnecessary normalization such as when canonical has already been called on the entirety of p.

31.13 C library files

31.13.1 Header <cstdio> synopsis

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

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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(char c, FILE* stream);
    int puts(const char* s);
    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 C 7.21
31.13.2 Header <cstdint> synopsis

```
#include <cstdint>        // see 17.4.2

namespace std {
    using imaxdiv_t = see below;

    intmax_t imaxabs(intmax_t j);
    imaxdiv_t imaxdiv(intmax_t numer, intmax_t denom);
    intmax_t strtoimax(const char* nptr, char** endptr, int base);
    uintmax_t strtoumax(const char* nptr, char** endptr, int base);
    intmax_t wcstoimax(const wchar_t* nptr, wchar_t** endptr, int base);
    uintmax_t wcstoumax(const wchar_t* nptr, wchar_t** endptr, int base);

    intmax_t abs(intmax_t);
    // optional, see below
    imaxdiv_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 PRIXN see below
#define SCNdN see below
#define SCNiN see below
#define SCNoN see below
#define SCNuN see below
#define SCNxN see below
#define PRIdLEAST see below
#define PRIiLEAST see below
#define PRIoLEAST see below
#define PRIuLEAST see below
#define PRIxLEAST see below
#define PRIXLEAST see below
#define SCNdLEAST see below
#define SCNiLEAST see below
#define SCNoLEAST see below
#define SCNuLEAST see below
#define SCNxLEAST 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 SCNiFAST see below
#define SCNoFAST see below
#define SCNuFAST see below
#define SCNxFAST see below
#define PRIdMAX see below
#define PRIiMAX see below
#define PRIoMAX see below
#define PRIuMAX see below
#define PRIxMAX see below
#define PRIXMAX see below
#define SCNdMAX see below
#define SCNiMAX see below
#define SCNoMAX see below
#define SCNuMAX see below
#define SCNxMAX see below
#define PRIdPTR see below
#define PRIiPTR see below
```
The contents and meaning of the header `<cinttypes>` are the same as the C standard library header `<inttypes.h>`, with the following changes:

(1.1) The header `<cinttypes>` includes the header `<cstdint>` (17.4.2) instead of `<stdint.h>`, and

(1.2) if and only if the type `intmax_t` designates an extended integer type (6.8.2), the following function signatures are added:

```c
intmax_t abs(intmax_t);
imaxdiv_t div(intmax_t, intmax_t);
```

which shall have the same semantics as the function signatures `intmax_t imaxabs(intmax_t)` and `imaxdiv_t imaxdiv(intmax_t, intmax_t)`, respectively.

**See also:** ISO C 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 17.4.2. Each of the SCN macros listed in this subclause is defined if and only if the implementation defines the corresponding `typedef-name` in 17.4.2 and has a suitable `fscanf` length modifier for the type.
# 32 Regular expressions library

## 32.1 General

This Clause describes components that C++ programs may use to perform operations involving regular expression matching and searching.

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 132.

### Table 132: Regular expressions library summary

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## 32.2 Requirements

This subclause defines requirements on classes representing regular expression traits.

1. 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`;
   - `cl` is an object of type `X::char_class_type` and
loc is an object of type X::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.

typename X::char_type

  Result: charT, the character container type used in the implementation of class template basic_regex.

typename X::string_type

  Result: basic_string<charT>

typename X::locale_type

  Result: A copy constructible type that represents the locale used by the traits class.

typename X::char_class_type

  Result: A bitmask type (16.3.3.3.4) representing a particular character classification.

X::length(p)

  Result: size_t

  Returns: The smallest i such that p[i] == 0.

  Complexity: Linear in i.

v.translate(c)

  Result: X::char_type

  Returns: A character such that for any character d that is to be considered equivalent to c then v.translate(c) == v.translate(d).

v.translate_nocase(c)

  Result: X::char_type

  Returns: For all characters C that are to be considered equivalent to c when comparisons are to be performed without regard to case, then v.translate_nocase(c) == v.translate_nocase(C).

v.transform(F1, F2)

  Result: X::string_type

  Returns: A sort key for the character sequence designated by the iterator range [F1,F2) such that if the character sequence [G1,G2) sorts before the character sequence [H1,H2) then v.transform(G1, G2) < v.transform(H1, H2).

v.transform_primary(F1, F2)

  Result: X::string_type

  Returns: A sort key for the character sequence designated by the iterator range [F1,F2) such that if the character sequence [G1,G2) sorts before the character sequence [H1,H2) when character case is not considered then v.transform_primary(G1, G2) < v.transform_primary(H1, H2).

v.lookup_collatename(F1, F2)

  Result: X::string_type

  Returns: A sequence of characters that represents the collating element consisting of the character sequence designated by the iterator range [F1,F2). Returns an empty string if the character sequence is not a valid collating element.

v.lookup_classname(F1, F2, b)

  Result: X::char_class_type

  Returns: Converts the character sequence designated by the iterator range [F1,F2) into a value of a bitmask type that can subsequently be passed to isctype. Values returned from lookup_classname can be bitwise OR'ed together; the resulting value represents membership in either of the corresponding character classes. If b is true, the returned bitmask is suitable for matching characters without regard

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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.

\texttt{v.isctype(c, cl)}

\textit{Result: bool}

\textit{Returns:} Returns \texttt{true} if character \texttt{c} is a member of one of the character classes designated by \texttt{cl}, \texttt{false} otherwise.

\texttt{v.value(c, I)}

\textit{Result: int}

\textit{Returns:} Returns the value represented by the digit \texttt{c} in base \texttt{I} if the character \texttt{c} is a valid digit in base \texttt{I}; otherwise returns \texttt{-1}.

[\textit{Note 2:} The value of \texttt{I} will only be 8, 10, or 16. — \textit{end note}]

\texttt{u.imbue(loc)}

\textit{Result: X::locale_type}

\textit{Effects:} Imbues \texttt{u} with the locale \texttt{loc} and returns the previous locale used by \texttt{u} if any.

\texttt{v.getloc()}

\textit{Result: X::locale_type}

\textit{Returns:} Returns the current locale used by \texttt{v}, if any.

[\textit{Note 3:} Class template \texttt{regex_traits} meets the requirements for a regular expression traits class when it is specialized for \texttt{char} or \texttt{wchar_t}. This class template is described in the header \texttt{<regex>}, and is described in \texttt{32.6}. — \textit{end note}]

### 32.3 Header <regex> synopsis

```c
#include <compare>  // see 17.11.1
#include <initializer_list>  // see 17.10.2

namespace std {
  namespace regex_constants {
    using syntax_option_type = T1;
    using match_flag_type = T2;
    using error_type = T3;
  }

  namespace regex_traits {
    template<class charT> struct regex_traits;
    template<class charT, class traits = regex_traits<charT>> class basic_regex;
    using regex = basic_regex<char>;
    using wregex = basic_regex<wchar_t>;
  }

  class regex_error;

  template<class charT, class traits> void swap(basic_regex<charT, traits>& e1, basic_regex<charT, traits>& e2);
}
```

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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 BiIter, 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>

// 32.9, class template match_results

template<class BiDirectionalIterator, class Allocator = allocator<sub_match<BiDirectionalIterator>>>>
class match_results;

// 32.9.8, match_results swap

template<class BiDirectionalIterator, class Allocator = allocator<sub_match<BiDirectionalIterator>>>>
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,
template<
class charT, class Allocator, 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);

template<class ST, class SA, class Allocator, 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);

// 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 traits>
bool regex_search(const charT* str,
const basic_regex<charT, traits>& e,
regex_constants::match_flag_type flags = regex_constants::match_default);

template<class ST, class SA, class Allocator, 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);

// § 32.3 1629
// 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);

// 32.10.4, function template regex_replace
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);

// 32.3, 1630
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 (16.3.3.3.4). Setting its elements has the effects listed in Table 133. 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 (16.3.3.3.4). 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 134 for any bitmask elements set.
**Table 133: syntax_option_type effects**  

<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 <code>match_results</code> 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>
</tbody>
</table>
| ECMAScript | Specifies that the grammar recognized by the regular expression engine shall be that used by ECMA-262, as modified in 32.12.  
*See also:* ECMA-262 15.10 |
| basic    | 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 |
| extended | 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 |
| awk      | Specifies that the grammar recognized by the regular expression engine shall be that used by the utility awk in POSIX. |
| grep     | Specifies that the grammar recognized by the regular expression engine shall be that used by the utility grep in POSIX. |
| egrep    | 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. |
| multiline | Specifies that ^ shall match the beginning of a line and $ shall match the end of a line, if the ECMAScript engine is selected. |

**Table 134: regex_constants::match_flag_type effects when obtaining a match against a character container sequence `[first, last)`**  

<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 <code>[first, last)</code> shall be treated as though it is not at the beginning of a line, so the character ^ in the regular expression shall not match <code>[first, first)</code>.</td>
</tr>
<tr>
<td>match_not_eol</td>
<td>The last character in the sequence <code>[first, last)</code> 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 <code>[last, last)</code>.</td>
</tr>
<tr>
<td>match_not_bow</td>
<td>The expression &quot;\b&quot; shall not match the sub-sequence <code>[first, first)</code>.</td>
</tr>
<tr>
<td>match_not_eow</td>
<td>The expression &quot;\b&quot; shall not match the sub-sequence <code>[last, last)</code>.</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><code>--first</code> 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>
<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>
</tbody>
</table>
Table 134: regex_constants::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_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

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_brace = 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 (16.3.3.3.3). Values of type error_type represent the error conditions described in Table 135:

Table 135: 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_brace</td>
<td>The expression contains mismatched { and }</td>
</tr>
<tr>
<td>error_badbrace</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>
<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>

32.5 Class regex_error

namespace std {
    class regex_error : public runtime_error {
    public:
        explicit regex_error(regex_constants::error_type ecode);
        regex_constants::error_type code() const;
    }
}

§ 32.5 1633
The class `regex_error` defines the type of objects thrown as exceptions to report errors from the regular expression library.

```cpp
regex_error(regex_constants::error_type ecode);
```

**Postconditions:** `ecode == code()`.

```cpp
regex_constants::error_type code() const;
```

**Returns:** The error code that was passed to the constructor.

### 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;
        int value(charT ch, int radix) const;
        locale_type imbue(locale_type l);
        locale_type getloc() const;
    };
}
```

The specializations `regex_traits<char>` and `regex_traits<wchar_t>` meet the requirements for a regular expression traits class (32.2).

```cpp
using char_class_type = bitmask_type;
```

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`.

```cpp
static size_t length(const char_type* p);
```

**Returns:** `char_traits<charT>::length(p)`.

```cpp
charT translate(charT c) const;
```

**Returns:** `c`.

```cpp
charT translate_nocase(charT c) const;
```

**Returns:** `use_facet<ctype<charT>>(getloc()).tolower(c)`.

```cpp
template<class ForwardIterator>
string_type transform(ForwardIterator first, ForwardIterator last) const;
```

**Effects:** As if by:
```cpp
string_type str(first, last);
return use_facet<collate<charT>>(
    getloc()).transform(str.data(), str.data() + str.length());
```

```cpp
template<class ForwardIterator>
string_type transform_primary(ForwardIterator first, ForwardIterator last) const;
```

**Effects:** If

```cpp
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.

```cpp
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.

```cpp
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.\(^{311}\) 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()`.\(^{311}\)

**Remarks:** For `regex_traits<char>`, at least the narrow character names in Table 136 shall be recognized. For `regex_traits<wchar_t>`, at least the wide character names in Table 136 shall be recognized.

```cpp
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`.

```cpp
// 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 136 is set, then the result is determined as if by:

```cpp
cctype_base::mask m = convert<charT>(f);
const cctype<charT>& ct = use_facet<cctype<charT>>(getloc());
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:**

```cpp
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());
```

\(^{311}\) For example, if the parameter `icase` is `true` then `[:lower:]` is the same as `[:alpha:]`.\(^{311}\)
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;
13 Preconditions: The value of radix is 8, 10, or 16.
14 Returns: The value represented by the digit ch in base radix if the character ch is a valid digit in base
radix; otherwise returns -1.

locale_type imbue(locale_type loc);
15 Effects: Imbues this with a copy of the locale loc.
16 [Note 1: Calling imbue with a different locale than the one currently in use invalidates all cached data held by
*this. — end note]
17 Postconditions: getloc() == loc.
18 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;
18 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.

Table 136: 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>

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]

The functions described in 32.7 report errors by throwing exceptions of type `regex_error`.

```cpp
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&);
            basic_regex(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();

            // 32.7.3, assign
            basic_regex& operator=(const basic_regex& e);
            basic_regex& operator=(basic_regex&& e) noexcept;
            basic_regex& operator=(const charT* p);
            basic_regex& operator=(const character_list<charT> il);
            template<class ST, class SA>
                basic_regex& operator=(const basic_string<charT, ST, SA>& s);

            template<class ST, class SA>
                basic_regex& assign(const basic_string<charT, ST, SA>& s,
                                    flag_type f = regex_constants::ECMAScript);
        }
    }
```
template<class InputIterator>
    basic_regex& assign(InputIterator first, InputIterator last,
    flag_type f = regex_constants::ECMAScript);
basic_regex& assign(initializer_list<charT>,
    flag_type f = regex_constants::ECMAScript);

// 32.7.4, const operations
unsigned mark_count() const;
flag_type flags() const;

// 32.7.5, locale
locale_type imbue(locale_type loc);
locale_type getloc() const;

// 32.7.6, swap
void swap(basic_regex&);
};

template<class ForwardIterator>
basic_regex(ForwardIterator, ForwardIterator,
    regex_constants::syntax_option_type = regex_constants::ECMAScript)
    -> basic_regex<typename iterator_traits<ForwardIterator>::value_type>;

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 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 [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.

\[
\text{template<typename ForwardIterator>}
\]
\[
\text{basic_regex(ForwardIterator first, ForwardIterator last,}
\]
\[
\text{flag_type f = regex_constants::ECMAScript);}
\]

Effects: The object’s internal finite state machine is constructed from the regular expression contained in the sequence of characters \([\text{first, last}]\), 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 \([\text{first, last}]\) is not a valid regular expression.

\[
\text{basic_regex(initializer_list<charT> il, flag_type f = regex_constants::ECMAScript);}
\]

Effects: Same as basic_regex(il.begin(), il.end(), \( f \)).

### 32.7.3 Assignment

\[
\text{basic_regex& operator=(const basic_regex& e);}\]

Postconditions: flags() and mark_count() return \( e.\text{flags()} \) and \( e.\text{mark_count()} \), respectively.

\[
\text{basic_regex& operator=(basic_regex&& e) noexcept;}
\]

Postconditions: flags() and mark_count() return the values that \( e.\text{flags()} \) and \( e.\text{mark_count()} \), respectively, had before assignment. \( e \) is in a valid state with unspecified value.

\[
\text{basic_regex& operator=(const charT* p);}\]

Effects: Equivalent to: return assign(p);

\[
\text{basic_regex& operator=(initializer_list<charT> il);}\]

Effects: Equivalent to: return assign(il.begin(), il.end());

\[
\text{template<typename ST, class SA>}
\]
\[
\text{basic_regex& operator=(const basic_string<charT, ST, SA>& s);}\]

Effects: Equivalent to: return assign(s);

\[
\text{basic_regex& assign(const basic_regex& e);}\]

Effects: Equivalent to: return *this = e;

\[
\text{basic_regex& assign(basic_regex&& e) noexcept;}
\]

Effects: Equivalent to: return *this = std::move(e);

\[
\text{basic_regex& assign(const charT* p, flag_type f = regex_constants::ECMAScript);}\]

Effects: Equivalent to: return assign(string_type(p), \( f \));

\[
\text{basic_regex& assign(const charT* p, size_t len, flag_type f = regex_constants::ECMAScript);}\]

Effects: Equivalent to: return assign(string_type(p, len), \( f \));

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

unsigned mark_count() const;

    Effects: Returns the number of marked sub-expressions within the regular expression.

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

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.

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

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

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;

§ 32.8.1

1 Class template sub_match denotes the sequence of characters matched by a particular marked sub-expression.
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;
}

32.8.2 Members

constexpr sub_match();

Effects: Value-initializes the pair base class subobject and the member matched.

difference_type length() const;

Returns: matched ? distance(first, second) : 0.

operator string_type() const;

Returns: matched ? string_type(first, second) : string_type().

string_type str() const;

Returns: matched ? string_type(first, second) : string_type().

int compare(const sub_match& s) const;

Returns: str().compare(s.str()).

int compare(const string_type& s) const;

Returns: str().compare(s).

int compare(const value_type* s) const;

Returns: str().compare(s).

32.8.3 Non-member operators

Let SM-CAT(I) be

\text{compare\_three\_way\_result\_t}<\text{basic\_string<typename iterator\_traits<I>::value\_type}>$

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().

32.9 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 and of a sequence container (24.2.2.1, 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&);
    match_results(const match_results& m);
    match_results(match_results&& m) noexcept;
    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;
    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 137 lists the postconditions of \texttt{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.

\begin{enumerate}
\item explicit \texttt{match_results}(const Allocator& a);
  \begin{itemize}
  \item Postconditions: \texttt{ready()} returns \texttt{false}. \texttt{size()} returns 0.
  \end{itemize}
\item \texttt{match_results}(const match_results& m);
  \begin{itemize}
  \item Postconditions: As specified in Table 137.
  \end{itemize}
\item \texttt{match_results(match_results&& m)} noexcept;
  \begin{itemize}
  \item Effects: The stored \texttt{Allocator} value is move constructed from \texttt{m.get_allocator()}.
  \item Postconditions: As specified in Table 137.
  \end{itemize}
\item \texttt{match_results& operator=(const match_results& m)};
  \begin{itemize}
  \item Postconditions: As specified in Table 137.
  \end{itemize}
\item \texttt{match_results& operator=(match_results&& m)};
  \begin{itemize}
  \item Postconditions: As specified in Table 137.
  \end{itemize}
\end{enumerate}

Table 137: \texttt{match_results} copy/move operation postconditions

\begin{tabular}{|l|l|}
\hline
Element & Value \\
\hline
\texttt{ready()} & \texttt{m.ready()} \\
\texttt{size()} & \texttt{m.size()} \\
\texttt{str(n)} & \texttt{m.str(n)} for all non-negative integers \( n < \texttt{m.size()} \) \\
\texttt{prefix()} & \texttt{m.prefix()} \\
\texttt{suffix()} & \texttt{m.suffix()} \\
\texttt{(*this)[n]} & \texttt{m[n]} for all non-negative integers \( n < \texttt{m.size()} \) \\
\texttt{length(n)} & \texttt{m.length(n)} for all non-negative integers \( n < \texttt{m.size()} \) \\
\texttt{position(n)} & \texttt{m.position(n)} for all non-negative integers \( n < \texttt{m.size()} \) \\
\hline
\end{tabular}

32.9.3 State

\begin{itemize}
\item bool \texttt{ready()} const;
  \begin{itemize}
  \item Returns: \texttt{true} if \texttt{*this} has a fully established result state, otherwise \texttt{false}.
  \end{itemize}
\end{itemize}

32.9.4 Size

\begin{itemize}
\item size_type \texttt{size()} const;
  \begin{itemize}
  \item Returns: One plus the number of marked sub-expressions in the regular expression that was matched if \texttt{*this} represents the result of a successful match. Otherwise returns 0.
  \end{itemize}
\end{itemize}
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 \([\text{fmt\_first, fmt\_last}]\) to OutputIter \(\text{out}\). Replaces each format specifier or escape sequence in the copied range with either the character(s) it represents or the sequence of characters within \(*\text{this}\) to which it refers. The bitmasks specified in flags determine which format specifiers and escape sequences are recognized.

Returns: \(\text{out}\).

```cpp
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:

\[
\text{return format(out, fmt.data(), fmt.data() + fmt.size(), flags)};
\]

```cpp
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;
```

Effects: Constructs an empty string result of type basic_string<char_type, ST, SA> and calls:

\[
\text{format(back inserter(result), fmt, flags)};
\]

Returns: result.

```cpp
string_type format(
    const char_type* fmt,
    regex_constants::match_flag_type flags = regex_constants::format_default) const;
```

Effects: Constructs an empty string result of type string_type and calls:

\[
\text{format(back inserter(result), fmt + char_traits<char_type>::length(fmt), flags)};
\]

Returns: result.

### 32.9.7 Allocator

```cpp
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

```cpp
void swap(match_results& that);
```

Effects: Swaps the contents of the two sequences.

Postconditions: \(*\text{this}\) contains the sequence of matched sub-expressions that were in \(\text{that}\), \(\text{that}\) contains the sequence of matched sub-expressions that were in \(*\text{this}\).

Complexity: Constant time.

```cpp
template<class BidirectionalIterator, class Allocator>
void swap(match_results<BidirectionalIterator, Allocator>& m1,
    match_results<BidirectionalIterator, Allocator>& m2);
```

Effects: As if by \(m1\).\(\text{swap}(m2)\).

### 32.9.9 Non-member functions

```cpp
template<class BidirectionalIterator, class Allocator>
bool operator==(const match_results<BidirectionalIterator, Allocator>& m1,
    const match_results<BidirectionalIterator, Allocator>& m2);
```

Returns: \(\text{true}\) if neither match result is ready, \(\text{false}\) if one match result is ready and the other is not. If both match results are ready, returns \(\text{true}\) only if:
— m1.empty() && m2.empty(), or
— !m1.empty() && !m2.empty(), and the following conditions are satisfied:
— m1.prefix() == m2.prefix(),
— m1.size() == m2.size() && equal(m1.begin(), m1.end(), m2.begin()), and
— 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

```cpp
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);
```

1 Preconditions: BidirectionalIterator meets the Cpp17BidirectionalIterator requirements (25.3.5.6).

Effect: 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:
```cpp
std::regex re("Get\|GetValue");
std::cmatch m;
regex_search("GetValue", m, re); // returns true, and m[0] contains "Get"
regex_match ("Get\|Value", 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
```
— end example]

3 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 138.

Table 138: 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>
</tbody>
</table>
### Table 138: Effects of `regex_match` algorithm (continued)

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>m[n].second</code></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 <code>last</code>.</td>
</tr>
<tr>
<td><code>m[n].matched</code></td>
<td>For all integers $0 &lt; n &lt; m.size()$, <code>true</code> if sub-expression $n$ participated in the match, <code>false</code> otherwise.</td>
</tr>
</tbody>
</table>

```cpp
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);
```

**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)`.

```cpp
template<class charT, class Allocator, 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);
```

**Returns:** `regex_match(str, str + char_traits<charT>::length(str), m, e, flags)`.

```cpp
template<class ST, class SA, 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)`.

```cpp
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)`.

```cpp
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`  

```cpp
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` meets the `Cpp17BidirectionalIterator` requirements (25.3.5.6).

**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 139.
Table 139: Effects of `regex_search` algorithm  

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>m.size()</td>
<td><code>1 + e.mark_count()</code></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><code>m[0].first</code></td>
</tr>
<tr>
<td>m.prefix().matched</td>
<td><code>m.prefix().first != m.prefix().second</code></td>
</tr>
<tr>
<td>m.suffix().first</td>
<td><code>m[0].second</code></td>
</tr>
<tr>
<td>m.suffix().second</td>
<td>last</td>
</tr>
<tr>
<td>m.suffix().matched</td>
<td><code>m.suffix().first != m.suffix().second</code></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 <code>0 &lt; n &lt; m.size()</code>, 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 <code>0 &lt; n &lt; m.size()</code>, 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 <code>0 &lt; n &lt; m.size()</code>, true if sub-expression n participated in the match, false 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);

4 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);

5 Returns: `regex_search(s.begin(), s.end(), m, e, flags)`. 

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);

7 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);

8 Returns: `regex_search(s.begin(), s.end(), e, flags)`. 

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### 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);

**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);

**Effects:** Constructs a regex_iterator object \( i \) as if by

\[
\text{regex_iterator<BidirectionalIterator, charT, traits> } i\text{(first, last, e, flags)}
\]

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 \(!\text{(flags & regex_constants::format_no_copy)}\)
then calls
\[
\text{out = copy(first, last, out)}
\]

If any matches are found then, for each such match:

1. If \(!\text{(flags & regex_constants::format_no_copy)}\), calls
   \[
   \text{out = copy(m.prefix().first, m.prefix().second, out)}
   \]

2. Then calls
   \[
   \text{out = m.format(out, fmt, flags)}
   \]
   for the first form of the function and
   \[
   \text{out = m.format(out, fmt, fmt + char_traits<charT>::length(fmt), flags)}
   \]
   for the second.

Finally, if such a match is found and \(!\text{(flags & regex_constants::format_no_copy)}\), calls
\[
\text{out = copy(last_m.suffix().first, last_m.suffix().second, out)}
\]

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:

\[
\text{regex_replace(back_inserter(result), s.begin(), s.end(), e, fmt, flags)}
\]

**Returns:** result.
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.

### 32.11 Regular expression iterators

#### 32.11.1 Class template regex_iterator

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>*` is returned. It is impossible to store things into `regex_iterator`s. 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.

```cpp
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 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;
            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
};

2 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'`). —end note]

32.11.1.2 Constructors [re.regiter.cnstr]

regex_iterator();
1
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);
2
Effects: Initializes begin and end to a and b, respectively, sets pregex to addressof(re), sets flags
to m, then calls regex_search(begin, end, match, *pregex, flags). If this call returns false the
constructor sets *this to the end-of-sequence iterator.

32.11.1.3 Comparisons [re.regiter.comp]

bool operator==(const regex_iterator& right) const;
1
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) — pregex == right.pregex,
(1.4) — flags == right.flags, and
(1.5) — match[0] == right.match[0];
otherwise false.

32.11.1.4 Indirection [re.regiter.deref]

const value_type& operator*() const;
1
Returns: match.

const value_type* operator->() const;
2
Returns: addressof(match).

32.11.1.5 Increment [re.regiter.incr]

regex_iterator& operator++();
1
Effects: Constructs a local variable start of type BidirectionalIterator and initializes it with the
value of match[0].second.
2
If the iterator holds a zero-length match and start == end the operator sets *this to the end-of-
sequence iterator and returns *this.
3
Otherwise, if the iterator holds a zero-length match, the operator calls:

regex_search(start, end, match, *pregex,
flags | regex_constants::match_not_null | regex_constants::match_continuous)
4
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_consts-
tants::match_prev_avail and calls regex_search(start, end, match, *pregex, flags). If
the call returns false the iterator sets *this to the end-of-sequence iterator. The iterator then returns *this.
5
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).
6
[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]
7
It is unspecified how the implementation makes these adjustments.
8
[Note 2: This means that an implementation can call an implementation-specific search function, in which case
a program-defined specialization of regex_search will not be called. — end note]

regex_iterator operator++(int);
9
Effects: As if by:
   regex_iterator tmp = *this;
   ++(*this);
   return tmp;
32.11.2 Class template regex_token_iterator
[re.tokiter]
32.11.2.1 General
[re.tokiter.general]
1
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.
2
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.
3
After it is constructed, the iterator finds and stores a value regex_iterator<BidirectionalIterator>
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.
4
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.
5
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_match<BidirectionalIterator>& is returned. The result of
operator-> on an end-of-sequence iterator is not defined. For any other iterator value a const sub_match
BidirectionalIterator>* is returned.
6
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 value_type = sub_match<BidirectionalIterator>;
         using difference_type = ptrdiff_t;
         using pointer = const value_type*;

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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);
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,
    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(const regex_token_iterator&);
regex_token_iterator& operator=(const regex_token_iterator&);
bool operator==(const regex_token_iterator& const);
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; // exposition only
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++();
```

1. **Effects**: Constructs a local variable `prev` of type `position_iterator`, initialized with the value of `position`.
2. If `*this` is a suffix iterator, sets `*this` to an end-of-sequence iterator.
3. Otherwise, if `N + 1 < subs.size()`, increments `N` and sets `result` to the address of the current match.
4. Otherwise, sets `N` to 0 and increments `position`. If `position` is not an end-of-sequence iterator the operator sets `result` to the address of the current match.
5. Otherwise, if any of the values stored in `subs` is equal to −1 and `prev->suffix().length()` is not 0 the operator sets `*this` to a suffix iterator that points to the range `[prev->suffix().first, prev->suffix().second)`.
6. Otherwise, sets `*this` to an end-of-sequence iterator.
7. **Returns**: `*this`

```
regex_token_iterator& operator++(int);
```

1. **Effects**: Constructs a copy `tmp` of `*this`, then calls `++(*this)`.
2. **Returns**: `tmp`.

32.12 Modified ECMAScript regular expression grammar

```
The regular expression grammar recognized by `basic_regex` objects constructed with the ECMAScript flag is that specified by ECMA-262, except as specified below.
```

1. Objects of type specialization of `basic_regex` store within themselves a default-constructed instance of their `traits` template parameter, henceforth referred to as `traits_inst`. This `traits_inst` object is used to support localization of the regular expression; `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.
2. The following productions within the ECMAScript grammar are modified as follows:

   - **ClassAtom**::
     - `ClassAtomNoDash`
     - `ClassAtomExClass`
     - `ClassAtomCollatingElement`
     - `ClassAtomEquivalence`

   - **IdentityEscape**::
     - `SourceCharacter but not c`

3. The following new productions are then added:

   - **ClassAtomExClass**::
     - `[ : ClassName :]`
   - **ClassAtomCollatingElement**::
     - `[ . ClassName ]`
   - **ClassAtomEquivalence**::
     - `[ = ClassName = ]`

   - **ClassName**::
     - `ClassNameCharacter`
     - `ClassNameCharacter ClassName`

4. The productions `ClassAtomExClass`, `ClassAtomCollatingElement` and `ClassAtomEquivalence` provide functionality equivalent to that of the same features in regular expressions in POSIX.

5. The regular expression grammar may be modified by any `regex_constants::syntax_option_type` flags specified when constructing an object of type specialization of `basic_regex` according to the rules in Table 133.
A `ClassName` production, when used in `ClassAtomExtClass`, is not valid if `traits_inst.lookup_classname` returns zero for that name. The names recognized as valid `ClassNames` are determined by the type of the traits class, but at least the following names shall be recognized: `alnum`, `alpha`, `blank`, `cntrl`, `digit`, `graph`, `lower`, `print`, `punct`, `space`, `upper`, `xdigit`, `d`, `s`, `w`. In addition the following expressions shall be equivalent:

\d and `[:digit:]`
\D and `[^[:digit:]]`
\s and `[:space:]`
\S and `[^[:space:]]`
\w and `[[:alnum:]]`
\W and `[^[:alnum:]]`

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`.

[Note 1: This means that values of the form “uxxxx” that do not fit in a character are invalid. — end note]

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 `c` is matched in accordance with the following algorithm:

```c
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 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 [first, last) if traits_-
inst.isctype(c, traits_inst.lookup_classname(first, last, flags() & icase)) is true.

See also: ECMA-262 15.10
33  Concurrency support library [thread]

33.1  General [thread.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 140.

Table 140: Thread support library summary [tab:thread.summary]

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header</th>
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</thead>
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33.2  Requirements [thread.req]

33.2.1  Template parameter names [thread.req.paramname]

Throughout this Clause, the names of template parameters are used to express type requirements. If a template parameter is named **Predicate**, `operator()` applied to the template argument shall return a value that is convertible to `bool`. 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 [thread.req.exception]

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 [thread.req.native]

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 [thread.req.timing]

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.

3 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.\(^3\) Given a duration argument $D_t$, the real-time duration of the timeout is $D_t + D_i + D_m$.

4 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:

\[(4.1)\] 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.

\[(4.2)\] If $C_a \leq C_t$, the waiting function should not time out until `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.

5 [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]

6 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.

7 Implementation-provided clocks that are used for these functions meet the `Cpp17TrivialClock` requirements (29.3).

8 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 In general

1 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.

2 [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.

312) Implementations for which standard time units are meaningful will typically have a steady clock within their hardware implementation.
A lock on an object \( m \) is said to be

- 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
- 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 [thread.req.lockable.basic]

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 \( L \)).

\[
m.\text{lock}()
\]

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.

\[
m.\text{unlock}()
\]

Preconditions: The current execution agent holds a non-shared lock on \( m \).

Effects: Releases a non-shared lock on \( m \) held by the current execution agent.

Throws: Nothing.

### 33.2.5.3 **Cpp17Lockable** requirements [thread.req.lockable.req]

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 \( L \)).

\[
m.\text{try_lock}()
\]

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: \text{true} if the lock was acquired, otherwise \text{false}.

### 33.2.5.4 **Cpp17TimedLockable** requirements [thread.req.lockable.timed]

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 `duration` (29.5), and \( \text{abs\_time} \) denotes a value of an instantiation of `time_point` (29.6)).

\[
m.\text{try_lock_for}(<\text{rel\_time})
\]

Effects: Attempts to acquire a lock for the current execution agent within the relative timeout (33.2.4) specified by \( \text{rel\_time} \). The function will not return within the timeout specified by \( \text{rel\_time} \) 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: \text{true} if the lock was acquired, otherwise \text{false}.

\[
m.\text{try_lock_until}(<\text{abs\_time})
\]

Effects: Attempts to acquire a lock for the current execution agent before the absolute timeout (33.2.4) specified by \( \text{abs\_time} \). The function will not return before the timeout specified by \( \text{abs\_time} \) 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: \text{true} if the lock was acquired, otherwise \text{false}.
33.2.5.5  **Cpp17SharedLockable requirements**  

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`):

```cpp
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.

```cpp
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.

```cpp
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**  

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`).

```cpp
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.

```cpp
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**  

33.3.1  **Introduction**  

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

1. actively poll the token to check if there has been a stop request, or
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 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]
33.3.3 Members

[[nodiscard]] bool stop_requested() const noexcept;

Returns: true if *this has ownership of a stop state that has received a stop request; otherwise, false.

[[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.

33.3.4 Non-member functions

[[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.

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
   stop_source();
   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 [stopsource.cons]

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).
   Returns: *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;

    private:
        Callback callback; // exposition only
    };

§ 33.3.5.1 1666
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

33.4 Threads

33.4.1 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]
33.4.3 Class thread

33.4.3.1 General

The class `thread` provides a mechanism to create a new thread of execution, to join with a thread (i.e., wait for a thread to complete), and to perform other operations that manage and query the state of a thread. A `thread` object uniquely represents a particular thread of execution. That representation may be transferred to other `thread` objects in such a way that no two `thread` objects simultaneously represent the same thread of execution. A thread of execution is detached when no `thread` object represents that thread. Objects of class `thread` can be in a state that does not represent a thread of execution.

[Note 1: A `thread` object does not represent a thread of execution after default construction, after being moved from, or after a successful call to `detach` or `join`. — end note]

```cpp
namespace std {

// 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;
};

33.4.3.2 Class thread::id

namespace std {
    class thread::id {
        id() noexcept;
    };

    bool operator==(thread::id x, thread::id y) noexcept;
    strong_ordering operator<=>(thread::id x, thread::id y) noexcept;

    template<class charT, class traits>
    basic_ostream<charT, traits>&
        operator<<(basic_ostream<charT, traits>& out, thread::id id);

```

§ 33.4.3.2
// hash support

```cpp
template<class T> struct hash;
```

```cpp
template<> struct hash<thread::id>;
```

1. 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.

2. `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.

3. [Note 1: Relational operators allow `thread::id` objects to be used as keys in associative containers. — end note]

```cpp
id() noexcept;
```

4. **Postconditions:** The constructed object does not represent a thread of execution.

```cpp
bool operator==(thread::id x, thread::id y) noexcept;
```

5. **Returns:** `true` only if `x` and `y` represent the same thread of execution or neither `x` nor `y` represents a thread of execution.

```cpp
strong_ordering operator<=>(thread::id x, thread::id y) noexcept;
```

6. Let `P(x,y)` be an unspecified total ordering over `thread::id` as described in 27.8.

7. **Returns:** `strong_ordering::less` if `P(x,y)` is `true`. Otherwise, `strong_ordering::greater` if `P(y,x)` is `true`. Otherwise, `strong_ordering::equal`.

```cpp
template<class charT, class traits>
basic_ostream<charT, traits>& operator<<(basic_ostream<charT, traits>& out, thread::id id);
```

8. **Effects:** Inserts an unspecified text representation of `id` into `out`. For two objects of type `thread::id` `x` and `y`, if `x == y` the `thread::id` objects have the same text representation and if `x != y` the `thread::id` objects have distinct text representations.

9. **Returns:** `out`.

10. The specialization is enabled (22.10.19).

### 33.4.3.3 Constructors

[thread.thread.constr]

```cpp
thread() noexcept;
```

1. **Effects:** The object does not represent a thread of execution.

```cpp
template<class F, class... Args> explicit thread(F&& f, Args&&... args);
```

2. **Constraints:** `remove_cvref_t<F>` is not the same type as `thread`.

3. **Mandates:** The following are all `true`:

   ```cpp
   (is_constructible_v<decay_t<F>, F>,
   (is_constructible_v<decay_t<Args>, Args> && ...), and
   (is_invocable_v<decay_t<F>, decay_t<Args>...>.
   ```

4. **Effects:** The new thread of execution executes `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 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:**

- `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.

```cpp
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

```cpp
~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

```cpp
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

```cpp
void swap(thread& x) noexcept;
```

**Effects:** Swaps the state of `*this` and `x`.

```cpp
bool joinable() const noexcept;
```

**Returns:** `get_id() != id()`.

```cpp
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:**

- `resource_deadlock_would_occur` — if deadlock is detected or `get_id() == this_thread::get_id()`.
- `no_such_process` — if the thread is not valid.
- `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.

Postconditions: get_id() == id().

Throws: system_error when an exception is required (33.2.2).

Error conditions:

— no_such_process — if the thread is not valid.
— 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.

33.4.3.7 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 x.swap(y).

33.4.4 Class jthread

33.4.4.1 General

The class jthread provides a mechanism to create a new thread of execution. The functionality is the same as for class thread (33.4.3) with the additional abilities to provide a 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;

        // 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;

        // 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
    }
// 33.4.4.4, stop token handling
[[nodiscard]] stop_source get_stop_source() noexcept;
[[nodiscard]] stop_token get_stop_token() const noexcept;
bool request_stop() noexcept;

// 33.4.4.5, specialized algorithms
friend void swap(jthread& lhs, jthread& rhs) noexcept;

// 33.4.4.6, static members
[[nodiscard]] static unsigned int hardware_concurrency() noexcept;

private:
    stop_source ssource;  // exposition only
};

33.4.4.2 Constructors, move, and assignment

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.

template<class F, class... Args> explicit jthread(F&& f, Args&&... args);

Constraints: remove_cvref_t<F> is not the same type as jthread.

Mandates: The following are all true:
(4.1) is_constructible_v<decay_t<F>, F>,
(4.2) (is_constructible_v<decay_t<Args>, Args> && ...), and
(4.3) is_invocable_v<decay_t<F>, decay_t<Args>...> ||
      is_invocable_v<decay_t<F>, stop_token, decay_t<Args>...>.

Effects: Initializes ssource. The new thread of execution executes
      invoke(auto(std::forward<F>(f)), get_stop_token(),
            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 ssource.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.

jthread(jthread&& x) noexcept;

Postconditions: x.get_id() == id() and get_id() returns the value of x.get_id() prior to the
start of construction. ssource has the value of x.ssource prior to the start of construction and
x.ssource.stop_possible() is false.
Effects: If joinable() is true, calls request_stop() and then join().

[Note 3: Operations on *this are not synchronized. — end note]

jthread& operator=(jthread&& x) noexcept;

Effects: If joinable() is true, calls request_stop() and then join(). 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. ssource has the value of x.ssource prior to the assignment and x.ssource.stop_possible() is false.

Returns: *this.

33.4.4.3 Members

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.

Postconditions: get_id() == id().

Throws: system_error when an exception is required (33.2.2).

Error conditions:

(11.1) — no_such_process — if the thread is not valid.
(11.2) — 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 ssource;
[[nodiscard]] stop_token get_stop_token() const noexcept;

Effects: Equivalent to: return ssource.get_token();

bool request_stop() noexcept;

Effects: Equivalent to: return ssource.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. No other thread of execution has this id and this thread of execution always has this id. 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;
}
template<class T>
    T kill_dependency(T y) noexcept;
}

// 33.5.5, lock-free property
#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_INT_LOCK_FREE unspecified
#define ATOMIC_LONG_LOCK_FREE unspecified
#define ATOMIC_LLONG_LOCK_FREE unspecified
#define ATOMIC_POINTER_LOCK_FREE unspecified

namespace std {
    // 33.5.7, class template atomic_ref
    template<class T> struct atomic_ref;
    // 33.5.7.5, partial specialization for pointers
    template<class T> struct atomic_ref<T*>;

    // 33.5.8, class template atomic
    template<class T> struct atomic;
    // 33.5.8.5, partial specialization for pointers
    template<class T> struct atomic<T*>;

    // 33.5.9, non-member functions
    template<class T>
    bool atomic_is_lock_free(const volatile atomic<T>*) noexcept;
    template<class T>
    bool atomic_is_lock_free(const atomic<T>*) noexcept;
    template<class T>
    void atomic_store(volatile atomic<T>*, typename atomic<T>::value_type) noexcept;
    template<class T>
    void atomic_store(atomic<T>*, typename atomic<T>::value_type) noexcept;
    template<class T>
    void atomic_store_explicit(volatile atomic<T>*, typename atomic<T>::value_type, memory_order) noexcept;
    template<class T>
    void atomic_store_explicit(atomic<T>*, typename atomic<T>::value_type, memory_order) noexcept;
    template<class T>
    T atomic_load(const volatile atomic<T>*) noexcept;
    template<class T>
    T atomic_load(const atomic<T>*) noexcept;
    template<class T>
    T atomic_load_explicit(const volatile atomic<T>*, memory_order) noexcept;
    template<class T>
    T atomic_load_explicit(const atomic<T>*, memory_order) noexcept;
    template<class T>
    T atomic_exchange(volatile atomic<T>*, typename atomic<T>::value_type) noexcept;
    template<class T>
    T atomic_exchange(atomic<T>*, typename atomic<T>::value_type) noexcept;
    template<class T>
    T atomic_exchange_explicit(volatile atomic<T>*, typename atomic<T>::value_type, memory_order) noexcept;
    template<class T>
    T atomic_exchange_explicit(atomic<T>*, typename atomic<T>::value_type, memory_order) noexcept;
    template<class T>
    bool atomic_compare_exchange_weak(volatile atomic<T>*,
                                      typename atomic<T>::value_type*,
                                      typename atomic<T>::value_type*,
                                      memory_order) noexcept;
    } /* end of std namespace */
template<
class T>
typename atomic<T>::value_type) noexcept;

bool atomic_compare_exchange_weak(atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type) noexcept;

template<
class T>
bool atomic_compare_exchange_strong(atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type) noexcept;

template<
class T>
bool atomic_compare_exchange_strong(atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type) noexcept;

template<
class T>
bool atomic_compare_exchange_weak_explicit(volatile atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type,
memory_order, memory_order) noexcept;

template<
class T>
bool atomic_compare_exchange_weak_explicit(atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type,
memory_order, memory_order) noexcept;

template<
class T>
bool atomic_compare_exchange_strong_explicit(volatile atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type,
memory_order, memory_order) noexcept;

template<
class T>
bool atomic_compare_exchange_strong_explicit(atomic<T>*,
typename atomic<T>::value_type*,
typename atomic<T>::value_type,
memory_order, memory_order) noexcept;

template<
class T>
T atomic_fetch_add(volatile atomic<T>*, typename atomic<T>::difference_type) noexcept;

template<
class T>
T atomic_fetch_add(atomic<T>*, typename atomic<T>::difference_type) noexcept;

template<
class T>
T atomic_fetch_add_explicit(volatile atomic<T>*, typename atomic<T>::difference_type,
memory_order) noexcept;

template<
class T>
T atomic_fetch_add_explicit(atomic<T>*, typename atomic<T>::difference_type,
memory_order) noexcept;

template<
class T>
T atomic_fetch_sub(volatile atomic<T>*, typename atomic<T>::difference_type) noexcept;

template<
class T>
T atomic_fetch_sub(atomic<T>*, typename atomic<T>::difference_type) noexcept;

template<
class T>
T atomic_fetch_sub_explicit(volatile atomic<T>*, typename atomic<T>::difference_type,
memory_order) noexcept;

template<
class T>
T atomic_fetch_sub_explicit(atomic<T>*, typename atomic<T>::difference_type,
memory_order) noexcept;

template<
class T>
T atomic_fetch_and(volatile atomic<T>*, typename atomic<T>::value_type) noexcept;

template<
class T>
T atomic_fetch_and(atomic<T>*, typename atomic<T>::value_type) noexcept;

template<
class T>
T atomic_fetch_and_explicit(volatile atomic<T>*, typename atomic<T>::value_type,
memory_order) noexcept;

template<
class T>
T atomic_fetch_and_explicit(atomic<T>*, typename atomic<T>::value_type,
memory_order) noexcept;
template<class T>
T atomic_fetch_or(volatile atomic<T>*, typename atomic<T>::value_type) noexcept;
template<class T>
T atomic_fetch_or(atomic<T>*, typename atomic<T>::value_type) noexcept;
template<class T>
T atomic_fetch_or_explicit(volatile atomic<T>*, typename atomic<T>::value_type,
memory_order) noexcept;
template<class T>
T atomic_fetch_or_explicit(atomic<T>*, typename atomic<T>::value_type,
memory_order) noexcept;
template<class T>
T atomic_fetch_xor(volatile atomic<T>*, typename atomic<T>::value_type) noexcept;
template<class T>
T atomic_fetch_xor(atomic<T>*, typename atomic<T>::value_type) noexcept;
template<class T>
T atomic_fetch_xor_explicit(volatile atomic<T>*, typename atomic<T>::value_type,
memory_order) noexcept;
template<class T>
T atomic_fetch_xor_explicit(atomic<T>*, typename atomic<T>::value_type,
memory_order) noexcept;

template<class T>
void atomic_wait(const volatile atomic<T>*, typename atomic<T>::value_type);
template<class T>
void atomic_wait(const atomic<T>*, typename atomic<T>::value_type);
template<class T>
void atomic_wait_explicit(const volatile atomic<T>*, typename atomic<T>::value_type,
memory_order);
template<class T>
void atomic_wait_explicit(const atomic<T>*, typename atomic<T>::value_type,
memory_order);

template<class T>
void atomic_notify_one(volatile atomic<T>*);
template<class T>
void atomic_notify_one(atomic<T>*);
template<class T>
void atomic_notify_all(volatile atomic<T>*);
template<class T>
void atomic_notify_all(atomic<T>*);

// 33.5.3, type aliases
using atomic_bool = atomic<bool>;
using atomic_char = atomic<char>;
using atomic_schar = atomic<signed char>;
using atomic_uchar = atomic<unsigned char>;
using atomic_short = atomic<short>;
using atomic_ushort = atomic<unsigned short>;
using atomic_int = atomic<int>;
using atomic_uint = atomic<unsigned int>;
using atomic_long = atomic<long>;
using atomic_ulong = atomic<unsigned long>;
using atomic_llong = atomic<long long>;
using atomic_ullong = atomic<unsigned long long>;
using atomic_char8_t = atomic<char8_t>;
using atomic_char16_t = atomic<char16_t>;
using atomic_char32_t = atomic<char32_t>;
using atomic_wchar_t = atomic<wchar_t>;
using atomic_int8_t = atomic<int8_t>;
using atomic_uint8_t = atomic<uint8_t>;
using atomic_int16_t = atomic<int16_t>;
using atomic_uint16_t = atomic<uint16_t>;
using atomic_int32_t = atomic<int32_t>;
using atomic_uint32_t = atomic<uint32_t>;

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using atomic_int64_t = atomic<int64_t>;
using atomic_uint64_t = atomic<uint64_t>;
using atomic_int_least8_t = atomic<int_least8_t>;
using atomic_uint_least8_t = atomic<uint_least8_t>;
using atomic_int_least16_t = atomic<int_least16_t>;
using atomic_uint_least16_t = atomic<uint_least16_t>;
using atomic_int_least32_t = atomic<int_least32_t>;
using atomic_uint_least32_t = atomic<uint_least32_t>;
using atomic_int_least64_t = atomic<int_least64_t>;
using atomic_uint_least64_t = atomic<uint_least64_t>;
using atomic_int_fast8_t = atomic<int_fast8_t>;
using atomic_uint_fast8_t = atomic<uint_fast8_t>;
using atomic_int_fast16_t = atomic<int_fast16_t>;
using atomic_uint_fast16_t = atomic<uint_fast16_t>;
using atomic_int_fast32_t = atomic<int_fast32_t>;
using atomic_uint_fast32_t = atomic<uint_fast32_t>;
using atomic_int_fast64_t = atomic<int_fast64_t>;
using atomic_uint_fast64_t = atomic<uint_fast64_t>;
using atomic intptr_t = atomic<intptr_t>;
using atomic uintptr_t = atomic<uintptr_t>;
using atomic_size_t = atomic<size_t>;
using atomic ptrdiff_t = atomic<ptrdiff_t>;
using atomic intmax_t = atomic<intmax_t>;
using atomic uintmax_t = atomic<uintmax_t>;

using atomic_signed_lock_free = see below;
using atomic unsigned_lock_free = see below;

// 33.5.10, flag type and operations
struct atomic_flag;

bool atomic_flag_test(const volatile atomic_flag*) noexcept;
bool atomic_flag_test(const atomic_flag*) noexcept;
bool atomic_flag_test_explicit(const volatile atomic_flag*, memory_order) noexcept;
bool atomic_flag_test_explicit(const atomic_flag*, memory_order) noexcept;
bool atomic_flag_test_and_set(volatile atomic_flag*) noexcept;
bool atomic_flag_test_and_set(atomic_flag*) noexcept;
bool atomic_flag_test_and_set_explicit(volatile atomic_flag*, memory_order) noexcept;
bool atomic_flag_test_and_set_explicit(atomic_flag*, memory_order) noexcept;
void atomic_flag_clear(volatile atomic_flag*) noexcept;
void atomic_flag_clear(atomic_flag*) noexcept;
void atomic_flag_clear_explicit(volatile atomic_flag*, memory_order) noexcept;
void atomic_flag_clear_explicit(atomic_flag*, memory_order) noexcept;
void atomic_flag_wait(const volatile atomic_flag*, bool) noexcept;
void atomic_flag_wait(const atomic_flag*, bool) noexcept;
void atomic_flag_wait_explicit(const volatile atomic_flag*,
    bool, memory_order) noexcept;
void atomic_flag_wait_explicit(const atomic_flag*,
    bool, memory_order) noexcept;
void atomic_flag_notify_one(volatile atomic_flag*) noexcept;
void atomic_flag_notify_one(atomic_flag*) noexcept;
void atomic_flag_notify_all(volatile atomic_flag*) noexcept;
void atomic_flag_notify_all(atomic_flag*) noexcept;

// 33.5.11, fences
extern "C" void atomic_thread_fence(memory_order) noexcept;
extern "C" void atomic_signal_fence(memory_order) noexcept;
}
### 33.5.3 Type aliases

The type aliases `atomic_int N_t`, `atomic_uint N_t`, `atomic_intptr_t`, and `atomic_uintptr_t` are defined if and only if `int N_t`, `uint N_t`, `intptr_t`, and `uintptr_t` are defined, respectively.

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 (16.4.2.4). — 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

```
namespace std {
  enum class memory_order : unspecified {
    relaxed, consume, acquire, release, acq_rel, seq_cst
  };
  inline constexpr memory_order memory_order_relaxed = memory_order::relaxed;
  inline constexpr memory_order memory_order_consume = memory_order::consume;
  inline constexpr memory_order memory_order_acquire = memory_order::acquire;
  inline constexpr memory_order memory_order_release = memory_order::release;
  inline constexpr memory_order memory_order_acq_rel = memory_order::acq_rel;
  inline constexpr memory_order memory_order_seq_cst = memory_order::seq_cst;
}
```

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. `memory_order::relaxed`: no operation orders memory.
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.
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]
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]

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`.

An atomic operation `A` on some atomic object `M` is coherence-ordered before another atomic operation `B` on `M` if

1. `A` is a modification, and `B` reads the value stored by `A`, or
2. `A` precedes `B` in the modification order of `M`, or
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
4. there exists an atomic modification `X` of `M` such that `A` is coherence-ordered before `X` and `X` is coherence-ordered before `B`.

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`:
— if \( A \) and \( B \) are both `memory_order::seq_cst` operations, then \( A \) precedes \( B \) in \( S \); and

— if \( A \) is a `memory_order::seq_cst` operation and \( B \) happens before a `memory_order::seq_cst` fence \( Y \), then \( A \) precedes \( Y \) in \( S \); and

— if a `memory_order::seq_cst` fence \( X \) happens before \( A \) and \( B \) is a `memory_order::seq_cst` operation, then \( X \) precedes \( B \) in \( S \); and

— if a `memory_order::seq_cst` fence \( X \) happens before \( A \) and \( B \) happens before a `memory_order::seq_cst` fence \( Y \), then \( X \) precedes \( Y \) in \( S \).


\[ \text{Note 3: This definition ensures that } S \text{ is consistent with the modification order of any atomic object } M. \text{ It also ensures that a `memory_order::seq_cst` load } A \text{ of } M \text{ gets its value either from the last modification of } M \text{ that precedes } A \text{ in } S \text{ or from some non-`memory_order::seq_cst` modification of } M \text{ that does not happen before any modification of } M \text{ that precedes } A \text{ in } S. \quad \text{—end note} \]


\[ \text{Note 4: We do not require that } S \text{ be consistent with “happens before” (6.9.2.2). This allows more efficient implementation of `memory_order::acquire` and `memory_order::release` on some machine architectures. It can produce surprising results when these are mixed with `memory_order::seq_cst` accesses. —end note} \]


\[ \text{Note 5: `memory_order::seq_cst` ensures sequential consistency only for a program that is free of data races and uses exclusively `memory_order::seq_cst` atomic operations. Any use of weaker ordering will invalidate this guarantee unless extreme care is used. In many cases, `memory_order::seq_cst` atomic operations are reorderable with respect to other atomic operations performed by the same thread. —end note} \]

Implementations should ensure that no “out-of-thin-air” values are computed that circularly depend on their own computation.

\[ \text{Note 6: For example, with } x \text{ and } y \text{ initially zero,} \]

```
// 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]

\[ \text{Note 7: The recommendation similarly disallows } r1 == r2 == 42 \text{ in the following example, with } x \text{ and } y \text{ again initially zero:} \]

```
// 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.

Implementations should make atomic stores visible to atomic loads within a reasonable amount of time.

```
template<class T>
T kill_dependency(T y) noexcept;
```

\[ \text{Effects: The argument does not carry a dependency to the return value (6.9.2).} \]

\[ \text{Returns: } y. \]

33.5.5 Lock-free property

```c
#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
```
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.

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.

>Note 1: This requirement is optional in freestanding implementations (16.4.2.4). — end note

The functions `atomic<T>::is_lock_free` and `atomic_is_lock_free` 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.

Atomic operations that are not lock-free are considered to potentially block (6.9.2.3).

>Recommended practice: Operations that are lock-free should also be address-free. The implementation of these operations should not depend on any per-process state.

>Note 2: 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

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

>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

>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

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

(4.3) — `Y` happens before the call to the atomic notifying operation.

---

313) That is, atomic operations on the same memory location via two different addresses will communicate atomically.
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 atomic_ref objects 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]
static constexpr bool is_always_lock_free;

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;

Returns: true if operations on all objects of the type atomic_ref<T> are lock-free, false otherwise.

atomic_ref(T& obj);

Preconditions: The referenced object is aligned to required_alignment.

Postconditions: *this references obj.

Throws: Nothing.

atomic_ref(const atomic_ref&amp; ref) noexcept;

Postconditions: *this refers to the object referenced by ref.

void store(T desired, memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: The order argument is neither memory_order::consume, memory_order::acquire, nor memory_order::acq_rel.

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;

Effects: Equivalent to:

store(desired);
return desired;

T load(memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: The order argument is neither memory_order::release nor memory_order::acq_rel.

Effects: Memory is affected according to the value of order.

Returns: Atomically returns the value referenced by *ptr.

operator T() const noexcept;

Effects: Equivalent to: return load();

T exchange(T desired, memory_order order = memory_order::seq_cst) const noexcept;

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&amp; expected, T desired,
memory_order success, memory_order failure) const noexcept;

bool compare_exchange_strong(T&amp; expected, T desired,
memory_order success, memory_order failure) const noexcept;

bool compare_exchange_weak(T&amp; expected, T desired,
memory_order order = memory_order::seq_cst) const noexcept;

bool compare_exchange_strong(T&amp; expected, T desired,
memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: The failure argument is neither memory_order::release nor memory_order::acq_rel.

Effects: Retrieves the value in expected. It then atomically compares the value represented by *ptr for equality with that previously retrieved from expected, and if true, replaces the value referenced 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]

```cpp
void wait(T old, memory_order order = memory_order::seq_cst) const noexcept;
```

Preconditions: order is neither memory_order::release nor memory_order::acq_rel.

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.

```cpp
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.

```cpp
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> (17.4.2). For each such type integral, the specialization atomic_ref<integral> provides additional atomic operations appropriate to integral types.

[Note 1: The specialization atomic_ref<bool> uses the primary template (33.5.7). —end note]

```cpp
namespace std {
    template<> struct atomic_ref<integral> {
        private:
            integral* ptr; // exposition only
        public:
            using value_type = integral;
            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&);
atomic_ref(const atomic_ref&) noexcept;
atomic_ref& operator=(const atomic_ref&) = delete;

void store(integral, memory_order = memory_order::seq_cst) const noexcept;
integral operator=(integral) const noexcept;
integral load(memory_order = memory_order::seq_cst) const noexcept;
operator integral() const noexcept;

integral exchange(integral,
    memory_order = memory_order::seq_cst) const noexcept;
bool compare_exchange_weak(integral&, integral,
    memory_order, memory_order) const noexcept;
bool compare_exchange_strong(integral&, integral,
    memory_order, memory_order) const noexcept;
bool compare_exchange_weak(integral&, integral,
    memory_order = memory_order::seq_cst) const noexcept;
bool compare_exchange_strong(integral&, integral,
    memory_order = memory_order::seq_cst) const noexcept;

integral fetch_add(integral,
    memory_order = memory_order::seq_cst) const noexcept;
integral fetch_sub(integral,
    memory_order = memory_order::seq_cst) const noexcept;
integral fetch_and(integral,
    memory_order = memory_order::seq_cst) const noexcept;
integral fetch_or(integral,
    memory_order = memory_order::seq_cst) const noexcept;
integral fetch_xor(integral,
    memory_order = memory_order::seq_cst) const noexcept;

integral operator++(int) const noexcept;
integral operator--(int) const noexcept;
integral operator++() const noexcept;
integral operator--() const noexcept;
integral operator+=(integral) const noexcept;
integral operator-=(integral) const noexcept;
integral operator&=(integral) const noexcept;
integral operator|=(integral) const noexcept;
integral operator^=(integral) const noexcept;

void wait(integral, 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 141.

integral fetch_key(integral operand, memory_order_order = memory_order::seq_cst) const noexcept;

4 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).
5 Returns: Atomically, the value referenced by *ptr immediately before the effects.
6 Remarks: 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]
integral operator \( \text{op}=(\text{integral operand}) \) const noexcept;

\[\text{Effects: Equivalent to: return } \text{fetch_key(operand)} \text{ op operand;}\]

### 33.5.7.4 Specializations for floating-point types

There are specializations of the `atomic_ref` class template for the floating-point types `float`, `double`, and `long double`. For each such type `floating-point`, the specialization `atomic_ref<floating-point>` provides additional atomic operations appropriate to floating-point types.

```cpp
namespace std {
  template<> struct atomic_ref<floating-point> {
    private:
      floating-point* ptr; // exposition only
    public:
      using value_type = floating-point;
      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&);
      atomic_ref(const atomic_ref&) noexcept;
      atomic_ref& operator=(const atomic_ref&) = delete;
      void store(floating-point, memory_order = memory_order::seq_cst) const noexcept;
      floating-point operator=(floating-point) const noexcept;
      floating-point load(memory_order = memory_order::seq_cst) const noexcept;
      operator floating-point() const noexcept;
      floating-point exchange(floating-point,
        memory_order = memory_order::seq_cst) const noexcept;
      bool compare_exchange_weak(floating-point&, floating-point,
        memory_order, memory_order) const noexcept;
      bool compare_exchange_strong(floating-point&, floating-point,
        memory_order, memory_order) const noexcept;
      bool compare_exchange_weak(floating-point&, floating-point,
        memory_order = memory_order::seq_cst) const noexcept;
      bool compare_exchange_strong(floating-point&, floating-point,
        memory_order = memory_order::seq_cst) const noexcept;
      floating-point fetch_add(floating-point,
        memory_order = memory_order::seq_cst) const noexcept;
      floating-point fetch_sub(floating-point,
        memory_order = memory_order::seq_cst) const noexcept;
      floating-point operator+=(floating-point) const noexcept;
      floating-point operator-=(floating-point) const noexcept;
      void wait(floating-point, 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 141.

```cpp
floating-point fetch_key(floating-point operand,
  memory_order = memory_order::seq_cst) const noexcept;
```

4 \[\text{Effects: Atomically replaces the value referenced by } \ast \text{ptr} \text{ with the result of the computation applied to the value referenced by } \ast \text{ptr} \text{ and the given operand. Memory is affected according to the value of } \text{order}. \text{ These operations are atomic read-modify-write operations (6.9.2.2).}\]
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 should conform to the \texttt{std::numeric\_limits<floating-point>} traits associated with the floating-point type (17.3.3). The floating-point environment (28.3) for atomic arithmetic operations on floating-point may be different than the calling thread's floating-point environment.

\texttt{floating-point} operator \texttt{op}(\texttt{floating-point}\ operand) const noexcept;

Effects: Equivalent to: return \texttt{fetch\_key}\ (operand) \texttt{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;
            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;
            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* operator++(int) const noexcept;
            T* operator--(int) const noexcept;
            T* operator++() const noexcept;
            T* operator--() 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 142.
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.

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;

§ 33.5.8.1
bool compare_exchange_strong(T& t, T, memory_order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_strong(T& 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

(1.1) — is_trivially_copyable_v<T>,
(1.2) — is_copy_constructible_v<T>,
(1.3) — is_move_constructible_v<T>,
(1.4) — is_copy_assignable_v<T>, or
(1.5) — 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.

3 [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>);  
1 Mandates: is_default_constructible_v<T> is true.

constexpr atomic(T desired) noexcept;
2 Effects: Initializes the object with the value desired. Initialization is not an atomic operation (6.9.2).

static constexpr bool is_always_lock_free = implementation-defined;
4 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;
5 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;
6 Constraints: For the volatile overload of this function, is_always_lock_free is true.

Preconditions: The order argument is neither memory_order::consume, memory_order::acquire, nor memory_order::acq_rel.
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: The order argument is neither memory_order::release nor memory_order::acq_rel.

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: The failure argument is neither memory_order::release nor memory_order::acq_rel.

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).
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]

```c
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.]

```c
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:]

```c
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/IEEE 60559, floating-point -0.0 and +0.0 will not compare equal with memcmp but will compare equal with operator==, and NaNs with the same payload will compare equal with memcmp 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]

```c
void wait(T old, memory_order order = memory_order::seq_cst) const volatile noexcept;
void wait(T old, memory_order order = memory_order::seq_cst) const noexcept;
```

29  **Preconditions:** order is neither `memory_order::release` nor `memory_order::acq_rel`.

30  **Effects:** Repeatedly performs the following steps, in order:

1. Evaluates `load(order)` and compares its value representation for equality against that of `old`.
2. If they compare unequal, returns.
3. Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

31  **Remarks:** This function is an atomic waiting operation (33.5.6).

```c
void notify_one() volatile noexcept;
void notify_one() noexcept;
```

32  **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.

33  **Remarks:** This function is an atomic notifying operation (33.5.6).

```c
void notify_all() volatile noexcept;
void notify_all() noexcept;
```

34  **Effects:** Unblocks the execution of all atomic waiting operations that are eligible to be unblocked (33.5.6) by this call.

35  **Remarks:** This function is an atomic notifying operation (33.5.6).

### 33.5.8.3 Specializations for integers

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`, `char8_t`, `char16_t`, `char32_t`, `wchar_t`, and any other types needed by the typedefs in the header `<cstdint>` (17.4.2). For each such type `integral`, the specialization `atomic<integral>` provides additional atomic operations appropriate to integral types.

[Note 1: The specialization `atomic<bool>` uses the primary template (33.5.8).]
atomic\& operator=(const atomic\&) volatile = delete;

void store(integral, memory_order = memory_order::seq_cst) volatile noexcept;
void store(integral, memory_order = memory_order::seq_cst) noexcept;
integral operator=(integral) volatile noexcept;
integral operator=(integral) noexcept;
integral load(memory_order = memory_order::seq_cst) const volatile noexcept;
integral load(memory_order = memory_order::seq_cst) const noexcept;
operator integral() const volatile noexcept;
operator integral() const noexcept;

integral exchange(integral, memory_order = memory_order::seq_cst) volatile noexcept;
integral exchange(integral, memory_order = memory_order::seq_cst) noexcept;
bool compare_exchange_weak(integral\&, integral, memory_order, memory_order) volatile noexcept;
bool compare_exchange_weak(integral\&, integral, memory_order, memory_order) noexcept;
bool compare_exchange_strong(integral\&, integral, memory_order, memory_order) volatile noexcept;
bool compare_exchange_strong(integral\&, integral, memory_order, memory_order) noexcept;

bool compare_exchange_weak(integral\&, integral, memory_order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_weak(integral\&, integral, memory_order = memory_order::seq_cst) noexcept;
bool compare_exchange_strong(integral\&, integral, memory_order = memory_order::seq_cst) volatile noexcept;
bool compare_exchange_strong(integral\&, integral, memory_order = memory_order::seq_cst) noexcept;

integral fetch_add(integral, memory_order = memory_order::seq_cst) volatile noexcept;
integral fetch_add(integral, memory_order = memory_order::seq_cst) noexcept;
integral fetch_sub(integral, memory_order = memory_order::seq_cst) volatile noexcept;
integral fetch_sub(integral, memory_order = memory_order::seq_cst) noexcept;
integral fetch_and(integral, memory_order = memory_order::seq_cst) volatile noexcept;
integral fetch_and(integral, memory_order = memory_order::seq_cst) noexcept;
integral fetch_or(integral, memory_order = memory_order::seq_cst) volatile noexcept;
integral fetch_or(integral, memory_order = memory_order::seq_cst) noexcept;
integral fetch_xor(integral, memory_order = memory_order::seq_cst) volatile noexcept;
integral fetch_xor(integral, memory_order = memory_order::seq_cst) noexcept;

integral operator++(int) volatile noexcept;
integral operator++(int) noexcept;
integral operator--(int) volatile noexcept;
integral operator--(int) noexcept;
integral operator++() volatile noexcept;
integral operator++() noexcept;
integral operator--() volatile noexcept;
integral operator--() noexcept;
integral operator+=(integral) volatile noexcept;
integral operator+=(integral) noexcept;
integral operator-=(integral) volatile noexcept;
integral operator-=(integral) noexcept;
integral operator&=(integral) volatile noexcept;
integral operator&=(integral) noexcept;
integral operator|=(integral) volatile noexcept;
integral operator|=(integral) noexcept;
integral operator^=(integral) volatile noexcept;
integral operator^=(integral) noexcept;

void wait(integral, memory_order = memory_order::seq_cst) const volatile noexcept;
void wait(integral, memory_order = memory_order::seq_cst) const noexcept;
void notify_one() volatile noexcept;
void notify_one() noexcept;
The atomic integral specializations 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 arithmetic computations. The correspondence among key, operator, and computation is specified in Table 141.

<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>or</td>
<td></td>
<td>bitwise inclusive or</td>
</tr>
<tr>
<td>and</td>
<td>&amp;</td>
<td>bitwise and</td>
</tr>
<tr>
<td>sub</td>
<td>-</td>
<td>subtraction</td>
</tr>
<tr>
<td>xor</td>
<td>^</td>
<td>bitwise exclusive or</td>
</tr>
</tbody>
</table>

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: 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]

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;

### Specializations for floating-point types

There are specializations of the atomic class template for the floating-point types float, double, and long double. For each such type floating-point, the specialization atomic<floating-point> provides additional atomic operations appropriate to floating-point types.

namespace std {
    template<>
    struct atomic<floating-point> {
        using value_type = floating-point;
        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) noexcept;
        atomic(const atomic&) = delete;
        atomic& operator=(const atomic&) = delete;
        atomic& operator=(const atomic&) volatile = delete;

        void store(floating-point, memory_order order = memory_order::seq_cst) volatile noexcept;
        void store(floating-point, memory_order order = memory_order::seq_cst) noexcept;
        floating-point operator=(floating-point) volatile noexcept;
        floating-point operator=(floating-point) noexcept;
    }
}

§ 33.5.8.4
The atomic floating-point specializations 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 arithmetic addition and subtraction computations. The correspondence among key, operator, and computation is specified in Table 141.

\[ T \text{ fetch}_{-}\text{key}(T \text{ operand}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ T \text{ fetch}_{-}\text{key}(T \text{ operand}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ exchange}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ exchange}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{weak}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{weak}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{strong}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{strong}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{weak}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{weak}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{strong}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{bool compare}_{-}\text{exchange}_{-}\text{strong}(\text{volatile float}_{-}\text{ing-point}, \text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ fetch}_{-}\text{add}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ fetch}_{-}\text{add}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ fetch}_{-}\text{sub}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ fetch}_{-}\text{sub}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ operator}+=\text{(volatile float}_{-}\text{ing-point}) \text{ volatile noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ operator}+=\text{(volatile float}_{-}\text{ing-point}) \text{ noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ operator}-=\text{(volatile float}_{-}\text{ing-point}) \text{ volatile noexcept}; \]

\[ \text{volatile float}_{-}\text{ing-point} \text{ operator}-=\text{(volatile float}_{-}\text{ing-point}) \text{ noexcept}; \]

\[ \text{void wait}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ const volatile noexcept}; \]

\[ \text{void wait}(\text{volatile float}_{-}\text{ing-point}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ const noexcept}; \]

\[ \text{void notify}_{-}\text{one()} \text{ volatile noexcept}; \]

\[ \text{void notify}_{-}\text{one()} \text{ noexcept}; \]

\[ \text{void notify}_{-}\text{all()} \text{ volatile noexcept}; \]

\[ \text{void notify}_{-}\text{all()} \text{ noexcept}; \]

\};

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 141.

\[ \text{T fetch}_{-}\text{key}(\text{T operand}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ volatile noexcept}; \]

\[ \text{T fetch}_{-}\text{key}(\text{T operand}, \text{memory_order} = \text{memory_order::seq_cst}) \text{ noexcept}; \]

5 Constraints: For the volatile overload of this function, is_always_lock_free is true.

6 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).

7 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` should conform to the `std::numeric_limits` traits associated with the floating-point type (17.3.3). The floating-point environment (28.3) for atomic arithmetic operations on `floating-point` may be different than the calling thread’s floating-point environment.

```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;`

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` should conform to the `std::numeric_limits` traits associated with the floating-point type (17.3.3). The floating-point environment (28.3) for atomic arithmetic operations on `floating-point` may be different than the calling thread’s floating-point environment.

### 33.5.8.5 Partial specialization for pointers

[atomics.types.pointer]

```cpp
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, T*, memory_order, memory_order) volatile noexcept;
        bool compare_exchange_weak(T*& T, T*, memory_order, memory_order) noexcept;
        bool compare_exchange_strong(T*& T, T*, memory_order, memory_order) volatile noexcept;
        bool compare_exchange_strong(T*& T, T*, memory_order, memory_order) noexcept;
        bool compare_exchange_weak(T*& T, T*, memory_order = memory_order::seq_cst) volatile noexcept;
        bool compare_exchange_weak(T*& T, T*, memory_order = memory_order::seq_cst) noexcept;
        bool compare_exchange_strong(T*& T, T*, memory_order = memory_order::seq_cst) volatile noexcept;
        bool compare_exchange_strong(T*& 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* 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 142.

<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>sub</td>
<td>-</td>
<td>subtraction</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 onvoid* or function pointers is ill-formed. — end note]
Effects: Atomically replaces the value pointed to bythis with the result of the computation applied to the value pointed to bythis and the givenoperand. Memory is affected according to the value oforder. These operations are atomic read-modify-write operations (6.9.2).

Returns: Atomically, the value pointed to bythis immediately before the effects.
Remarks: The result may be an undefined address, but the operations otherwise have no undefined behavior.

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

33.5.8.7.1 General

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:
    auto find(T t) const {
        auto p = head.load();
        while (p && p->t != t)
            p = p->next;
        return shared_ptr<node>(move(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`

```cpp
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;
        constexpr atomic() noexcept;
        constexpr atomic(nullptr_t) noexcept : atomic() { }
        atomic(shared_ptr<T> desired) noexcept;
        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;
        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 success, memory_order failure) noexcept;
        bool compare_exchange_strong(shared_ptr<T>& expected, shared_ptr<T> desired,
                                       memory_order success, memory_order failure) 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;
    }
}
```

1. **Effects**: Initializes `p`.
2. **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]
3. **Preconditions**: `order` is neither `memory_order::consume`, `memory_order::acquire`, nor `memory_order::acq_rel`.
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`.
5. **Effects**: Equivalent to `store(desired)`.
6. **Preconditions**: `order` is neither `memory_order::release` nor `memory_order::acq_rel`.
7. **Effects**: Memory is affected according to the value of `order`. 

§ 33.5.8.7.2

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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 neither memory_order::release nor memory_order::acq_rel.

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 neither memory_order::release nor memory_order::acq_rel.

Effects: Repeatedly performs the following steps, in order:

   (20.1) Evaluates load(order) and compares it to old.
   (20.2) If the two are not equivalent, returns.
   (20.3) 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).
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).

33.5.8.7.3 Partial specialization for weak_ptr

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;
        bool compare_exchange_weak(weak_ptr<T>& expected, weak_ptr<T> desired,
                                    memory_order order = memory_order::seq_cst) noexcept;
        bool compare_exchange_strong(weak_ptr<T>& expected, weak_ptr<T> desired,
                                      memory_order order = memory_order::seq_cst) 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
    };
}

constexpr atomic() noexcept;

Effects: Initializes p{}.

atomic(weak_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(weak_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;

Preconditions: order is neither memory_order::consume, memory_order::acquire, nor memory_order::acq_rel.

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=(weak_ptr<T> desired) noexcept;

Effects: Equivalent to store(desired).

weak_ptr<T> load(memory_order order = memory_order::seq_cst) const noexcept;

Preconditions: order is neither memory_order::release nor memory_order::acq_rel.

Effects: Memory is affected according to the value of order.

Returns: Atomically returns p.

operator weak_ptr<T>() const noexcept;

Effects: Equivalent to: return load();

weak_ptr<T> exchange(weak_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(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;

Preconditions: failure is neither memory_order::release nor memory_order::acq_rel.

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 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.

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(weak_ptr<T>& expected, weak_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(weak_ptr<T>& expected, weak_ptr<T> desired, memory_order order = memory_order::seq_cst) noexcept;

Effects: Equivalent to:

return compare_exchange_strong(expected, desired, order, fail_order);
where \texttt{fail\_order} is the same as \texttt{order} except that a value of \texttt{memory\_order::acq\_rel} shall be replaced by the value \texttt{memory\_order::acquire} and a value of \texttt{memory\_order::release} shall be replaced by the value \texttt{memory\_order::relaxed}.

```cpp
void wait(weak_ptr<T> old, memory_order order = memory_order::seq_cst) const noexcept;
```

\textbf{Preconditions:} \texttt{order} is neither \texttt{memory\_order::release} nor \texttt{memory\_order::acq\_rel}.

\textbf{Effects:} Repeatedly performs the following steps, in order:

- Evaluates \texttt{load(order)} and compares it to \texttt{old}.
- If the two are not equivalent, returns.
- Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

\textbf{Remarks:} Two \texttt{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).

```cpp
void notify_one() noexcept;
```

\textbf{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.

\textbf{Remarks:} This function is an atomic notifying operation (33.5.6).

```cpp
void notify_all() noexcept;
```

\textbf{Effects:} Unblocks the execution of all atomic waiting operations that are eligible to be unblocked (33.5.6) by this call.

\textbf{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 \texttt{atomic\_f} or the pattern \texttt{atomic\_f\_}\texttt{-}\texttt{explicit} invokes the member function \texttt{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 \texttt{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

```cpp
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;
};

}
```

\textbf{1} The \texttt{atomic\_flag} type provides the classic test-and-set functionality. It has two states, set and clear.

\textbf{2} Operations on an object of type \texttt{atomic\_flag} shall be lock-free. The operations should also be address-free.
3 The atomic_flag type is a standard-layout struct. It has a trivial destructor.

```cpp
constexpr atomic_flag::atomic_flag() noexcept;
```

4 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) const volatile noexcept;
bool atomic_flag::test(memory_order order = memory_order::seq_cst) const noexcept;
```

5 For atomic_flag_test, let order be memory_order::seq_cst.

6 Preconditions: order is neither memory_order::release nor memory_order::acq_rel.

7 Effects: Memory is affected according to the value of order.

8 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;
```

9 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).

10 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;
```

11 Preconditions: The order argument is neither memory_order::consume, memory_order::acquire, nor memory_order::acq_rel.

12 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;
```

13 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.

14 Preconditions: order is neither memory_order::release nor memory_order::acq_rel.

15 Effects: Repeatedly performs the following steps, in order:

15.1 Evaluates flag->test(order) != old.

15.2 If the result of that evaluation is true, returns.

15.3 Blocks until it is unblocked by an atomic notifying operation or is unblocked spuriously.

16 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).

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 $X$ headed by $A$.

extern "C" void atomic_thread_fence(memory_order order) noexcept;

Effects: Depending on the value of order, this operation:

1. has no effects, if order == memory_order::relaxed;
2. is an acquire fence, if order == memory_order::acquire or order == memory_order::consume;
3. is a release fence, if order == memory_order::release;
4. is both an acquire fence and a release fence, if order == memory_order::acq_rel;
5. 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:

```cpp
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_u1long; // see below
using std::atomic_char8_t; // see below
using std::atomic_char16_t; // see below
using std::atomic_char32_t; // see below
using std::atomic_wchar_t; // 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_fast8_t; // see below
using std::atomic_uint_fast8_t; // see below
using std::atomic_int_fast16_t; // see below
using std::atomic_uint_fast16_t; // see below
using std::atomic_int_fast32_t; // see below
using std::atomic_uint_fast32_t; // see below
using std::atomic_int_fast64_t; // see below
using std::atomic_uint_fast64_t; // see below
using std::atomic_intp_t; // see below
using std::atomic_uintp_t; // see below
using std::atomic_size_t; // see below
using std::atomic_ptrdiff_t; // see below
using std::atomic_intmax_t; // see below
using std::atomic_uintmax_t; // see below
using std::atomic_is_lock_free; // see below
using std::atomic_load; // see below
using std::atomic_load_explicit; // see below
using std::atomic_store; // see below
using std::atomic_store_explicit; // see below
using std::atomic_exchange; // see below
using std::atomic_exchange_explicit; // see below
using std::atomic_compare_exchange_strong; // see below
using std::atomic_compare_exchange_strong_explicit; // see below
using std::atomic_compare_exchange_weak; // see below
using std::atomic_compare_exchange_weak_explicit; // see below
using std::atomic_fetch_add; // see below
using std::atomic_fetch_add_explicit; // see below
using std::atomic_fetch_sub; // see below
using std::atomic_fetch_sub_explicit; // see below
using std::atomic_fetch_or; // see below
using std::atomic_fetch_or_explicit; // see below
using std::atomic_fetch_and; // see below
using std::atomic_fetch_and_explicit; // see below
using std::atomic_flag_test_and_set; // see below
using std::atomic_flag_test_and_set_explicit; // see below
using std::atomic_flag_clear; // see below
using std::atomic_flag_clear_explicit; // 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 \( \text{std::}\!A \) 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 int\(N\)_t, uint\(N\)_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

1 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

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

/*
 * Copyright © 2021 International Organization for Standardization
 * and/or other contributors as indicated by the @copyright notice
 * in the file(s) distributed with this work.
 */

template<class Mutex> class lock_guard;
template<class... MutexTypes> class scoped_lock;
template<class Mutex> class unique_lock;

// 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);

} // namespace std

33.6.3 Header <shared_mutex> synopsis

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;

} // namespace std

33.6.4 Mutex requirements

33.6.4.1 In 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

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.

[Note 2: 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.
— end note]
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 appear 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:**

- `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.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;
            ~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
};

1 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. Implementations are required to handle such scenarios correctly, as long as thread A doesn’t 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]

2 The class mutex meets all of the mutex requirements (33.6.4). It is a standard-layout class (11.2).

3 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]

4 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

namespace std {
    class recursive_mutex {
    public:
        recursive_mutex();
        ~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
    };
}

1 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.

2 The class recursive_mutex meets all of the mutex requirements (33.6.4). It is a standard-layout class (11.2).

3 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.

4 The behavior of a program is undefined if:

   (4.1) it destroys a recursive_mutex object owned by any thread or
   (4.2) a thread terminates while owning a recursive_mutex object.
33.6.4.3 Timed mutex types

33.6.4.3.1 General

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).

[Note 1: The timed mutex types meet the `Cpp17TimedLockable` requirements (33.2.5.4). — end note]

The expression `m.try_lock_for(rel_time)` is well-formed and has the following semantics:

3. **Preconditions:** If `m` is of type `timed_mutex` or `shared_timed_mutex`, the calling thread does not own the mutex.

4. **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]

5. **Synchronization:** If `try_lock_for()` returns `true`, prior `unlock()` operations on the same object synchronize with (6.9.2) this operation.

6. **Return type:** `bool`.

7. **Returns:** `true` if ownership was obtained, otherwise `false`.

8. **Throws:** Timeout-related exceptions (33.2.4).

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.

[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]

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();  // blocking
            ~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();
    }
```
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:

1. it destroys a `timed_mutex` object owned by any thread,
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. a thread terminates while owning a `timed_mutex` object.

### 33.6.4.3.3 Class `recursive_timed_mutex`

```cpp
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 object will fail (for `try_lock()`) or block (for `lock()`, `try_lock_for()`, and `try_lock_until()`) until the owning thread has completely released ownership or the call to `try_lock_for()` or `try_lock_until()` times out (having failed to obtain ownership).

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:

1. 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 \( m\)\texttt{.lock\_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 \( m\)\texttt{.unlock\_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 \( m\)\texttt{.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();
    }
```
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:

- it destroys a `shared_mutex` object owned by any thread,
- a thread attempts to recursively gain any ownership of a `shared_mutex`, or
- 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 \texttt{abs\_time} has already passed, the function attempts to obtain shared ownership without blocking (as if by calling \texttt{try\_lock\_shared()}). The function returns before the absolute timeout (33.2.4) specified by \texttt{abs\_time} only if it has obtained shared ownership of the mutex object.

[Note 3: As with \texttt{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 \texttt{try\_lock\_shared\_until()} returns \texttt{true}, prior \texttt{unlock()} operations on the same object synchronize with (6.9.2) this operation.

Return type: \texttt{bool}.

Returns: \texttt{true} if the shared lock was acquired, otherwise \texttt{false}.

Throws: Timeout-related exceptions (33.2.4).

### 33.6.4.5.2 Class \texttt{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();
    };
}
```

1 The class \texttt{shared\_timed\_mutex} provides a non-recursive mutex with shared ownership semantics.

2 The class \texttt{shared\_timed\_mutex} meets all of the shared timed mutex requirements (33.6.4.5). It is a standard-layout class (11.2).

3 The behavior of a program is undefined if:

   (3.1) — it destroys a \texttt{shared\_timed\_mutex} object owned by any thread,

   (3.2) — a thread attempts to recursively gain any ownership of a \texttt{shared\_timed\_mutex}, or

   (3.3) — a thread terminates while possessing any ownership of a \texttt{shared\_timed\_mutex}.

### 33.6.5 Locks

#### 33.6.5.1 General

1 A \texttt{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 \textit{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]

2 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
  struct adopt_lock_t { }; // assume the calling thread has already
                           // obtained mutex ownership and manage it

  inline constexpr defer_lock_t defer_lock { };   
  inline constexpr try_to_lock_t try_to_lock { }; 
  inline constexpr adopt_lock_t adopt_lock { };   
}
```

### 33.6.5.2 Class template lock_guard

```cpp
namespace std {

  template<class Mutex>
  class lock_guard {
  public:
    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
  };
}
```

1 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).

2 **Effects**: Initializes `pm` with `m`. Calls `m.lock()`.

3 **Preconditions**: The calling thread holds a non-shared lock on `m`.

4 **Effects**: Initializes `pm` with `m`.

5 **Throws**: Nothing.

6 **Effects**: Equivalent to: `pm.unlock()`

### 33.6.5.3 Class template scoped_lock

```cpp
namespace std {

  template<class... MutexTypes>
  class scoped_lock {
  public:
    using mutex_type = see below; // Only if sizeof...(MutexTypes) == 1 is true
  }
```

§ 33.6.5.3
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`.

### 33.6.5.4 Class template unique_lock

> `unique_lock` is a class template that provides a unique lock on a `Mutex`. It is used to acquire and release a lock in a thread-safe manner.

```cpp
namespace std {
    template<class Mutex>
    class unique_lock {
    public:
        using mutex_type = Mutex;

        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&) = delete;
        unique_lock(unique_lock&& u) noexcept;
        unique_lock& operator=(unique_lock&& u);
    };

    // 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&) = delete;
    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.
—end note]

33.6.5.4.2 Constructors, destructor, and assignment [thread.lock.unique.cons]
unique_lock() noexcept;

1 Postconditions: pm == 0 and owns == false.

explicit unique_lock(mutex_type& m);

2 Effects: Calls m.lock().
3 Postconditions: pm == addressof(m) and owns == true.

unique_lock(mutex_type& m, defer_lock_t) noexcept;

4 Postconditions: pm == addressof(m) and owns == false.

unique_lock(mutex_type& m, try_to_lock_t);

5 Preconditions: The supplied Mutex type meets the Cpp17Lockable requirements (33.2.5.3).
6 Effects: Calls m.try_lock().
7 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);

8 Preconditions: The calling thread holds a non-shared lock on m.
9 Postconditions: pm == addressof(m) and owns == true.
10 Throws: Nothing.

§ 33.6.5.4.2 1718
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:
(4.1) operation_not_permitted — if pm is nullptr.
(4.2) resource_deadlock_would_occur — if on entry owns is true.

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 the call to try_lock().
Returns: The value returned by the call to try_lock().
Throws: Any exception thrown by pm->try_lock(). system_error when an exception is required (33.2.2).

Error conditions:
(10.1) operation_not_permitted — if pm is nullptr.
(10.2) resource_deadlock_would_occur — if on entry owns is true.

§ 33.6.5.4.3
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 the call to try_lock_until(abs_time).

Returns: The value returned by the call to try_lock_until(abs_time).

Throws: Any exception thrown by pm->try_lock_until(). 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: 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 the call to try_lock_for(rel_time).

Returns: The value returned by the call to try_lock_for(rel_time).

Throws: Any exception thrown by pm->try_lock_for(). 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.

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.

template<class Mutex>
void swap(unique_lock<Mutex>& x, unique_lock<Mutex>& y) noexcept;

Effects: As if by x.swap(y).

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);
        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();
        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;

        // 33.6.5.5.5, 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
    }
}

1 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).

2 [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 == false`.

- **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()`.

---

§ 33.6.5.5.3
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:
— operation_not_permitted — if pm is nullptr.
— 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:
— 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

**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;
    };
}
```

**Note:** The class `once_flag` is an opaque data structure that `call_once` uses to initialize data without causing a data race or deadlock.
constexpr once_flag() noexcept;

Synchronization: The construction of a once_flag object is not synchronized.

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

[thread.once.callonce]

template<class Callable, class... Args>
void call_once(once_flag& flag, Callable&& func, Args&&... args);

Mandates: is_invocable_v<Callable, Args...> is true.

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 calls INVOKE( std::forward<Callable>(func), std::forward<Args>(args)...). 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]

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.

Throws: system_error when an exception is required (33.2.2), or any exception thrown by func.

[Example 1:

// 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

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.
Condition variables permit concurrent invocation of the `wait`, `wait_for`, `wait_until`, `notify_one` and `notify_all` member functions.

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.

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.

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);
```

**Preconditions:** `lk` is locked by the calling thread and either

1. no other thread is waiting on `cond`, or
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:

```cpp
lk.unlock();
cond.notify_all();
```

**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 erroneously 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;
    }
}```
The class `condition_variable` is a standard-layout class (11.2).

```cpp
condition_variable();
```

**Throws:** `system_error` when an exception is required (33.2.2).

**Error conditions:**

1. `resource_unavailable_try_again` — if some non-memory resource limitation prevents initialization.

```cpp
~condition_variable();
```

**Preconditions:** There is no thread blocked on `*this`.

1. 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

```cpp
void notify_one() noexcept;
void notify_all() noexcept;
void wait(unique_lock<mutex>& lock);
```

**Effects:** If any threads are blocked waiting for `*this`, unblocks one of those threads.

```cpp
void notify_one() noexcept;
void notify_all() noexcept;
void wait(unique_lock<mutex>& lock);
```

**Effects:** Unblocks all threads that are blocked waiting for `*this`.

```cpp
void wait_for(unique_lock<mutex>& lock, const chrono::duration<Rep, Period>& rel_time);
```

**Effects:**

1. Atomically calls `lock.unlock()` and blocks on `*this`.
2. When unblocked, calls `lock.lock()` (possibly blocking on the lock), then returns.
3. The function will unblock when signaled by a call to `notify_one()` or a call to `notify_all()`, or spuriously.

§ 33.7.4
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.
— If the function exits via an exception, `lock.lock()` is called prior to exiting the function.

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]

template<class Rep, class Period>
cv_status 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:

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: \( \text{cv\_status::timeout} \) if the relative timeout (33.2.4) specified by \( \text{rel\_time} \) expired, otherwise \( \text{cv\_status::no\_timeout} \).

Throws: Timeout-related exceptions (33.2.4).

Remarks: If the function fails to meet the postcondition, \text{terminate} is invoked (14.6.2).

[Note 5: This can happen if the re-locking of the mutex throws an exception. — end note]

\[
\text{template<class Clock, class Duration, class Predicate>}
\text{bool wait\_until(unique\_lock<mutex>& lock,}
\text{ const \text{chrono::time\_point<Clock, Duration>}& abs\_time,}
\text{ Predicate pred);}\]

Preconditions: \text{lock.owns\_lock()} is \text{true} and \text{lock.mutex()} is locked by the calling thread, and either

(29.1) — no other thread is waiting on this \text{condition\_variable} object or

(29.2) — \text{lock.mutex()} returns the same value for each of the \text{lock} arguments supplied by all concurrently waiting (via \text{wait, wait\_for, or wait\_until}) threads.

Effects: Equivalent to:

\[
\text{while (!pred())}
\text{if (wait\_until(lock, abs\_time) == cv\_status::timeout)}
\text{return pred();}
\text{return true;}\]

Postconditions: \text{lock.owns\_lock()} is \text{true} and \text{lock.mutex()} is locked by the calling thread.

[Note 6: The returned value indicates whether the predicate evaluated to \text{true} regardless of whether the timeout was triggered. — end note]

Throws: Timeout-related exceptions (33.2.4) or any exception thrown by \text{pred}.

Remarks: If the function fails to meet the postcondition, \text{terminate()} is invoked (14.6.2).

[Note 7: This can happen if the re-locking of the mutex throws an exception. — end note]

\[
\text{template<class Rep, class Period, class Predicate>}
\text{bool wait\_for(unique\_lock<mutex>& lock,}
\text{ const \text{chrono::duration<Rep, Period>}& rel\_time,}
\text{ Predicate pred);}\]

Preconditions: \text{lock.owns\_lock()} is \text{true} and \text{lock.mutex()} is locked by the calling thread, and either

(35.1) — no other thread is waiting on this \text{condition\_variable} object or

(35.2) — \text{lock.mutex()} returns the same value for each of the \text{lock} arguments supplied by all concurrently waiting (via \text{wait, wait\_for, or wait\_until}) threads.

Effects: Equivalent to:

\[
\text{return wait\_until(lock, \text{chrono::steady\_clock::now()} + rel\_time, std::move(pred));}\]

Postconditions: \text{lock.owns\_lock()} is \text{true} and \text{lock.mutex()} is locked by the calling thread.

[Note 8: There is no blocking if \text{pred()} is initially \text{true}, even if the timeout has already expired. — end note]

Throws: Timeout-related exceptions (33.2.4) or any exception thrown by \text{pred}.

Remarks: If the function fails to meet the postcondition, \text{terminate()} is invoked (14.6.2).

[Note 10: This can happen if the re-locking of the mutex throws an exception. — end note]
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:

- resource_unavailable_try_again — if some non-memory resource limitation prevents initialization.

- operation_not_permitted — if the thread does not have the privilege to perform the operation.

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.

§ 33.7.5.1
33.7.5.2 Noninterruptible waits

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]

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]
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]

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.

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).

[Note 2: This can happen if the re-locking of the mutex throws an exception. — end note]

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:

```cpp
return wait_until(lock, std::move(stoken), chrono::steady_clock::now() + rel_time,
    std::move(pred));
```

### 33.8 Semaphore

#### 33.8.1 General

Semaphore 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

```cpp
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

```cpp
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:
            pptrdiff_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;

Returns: The maximum value of counter. This value is greater than or equal to least_max_value.

cconstexpr explicit counting_semaphore(ptrdiff_t desired);

Preconditions: desired >= 0 is true, and desired <= max() is true.

Effects: Initializes counter with desired.

Throws: Nothing.

void release(ptrdiff_t update = 1);

Preconditions: update >= 0 is true, and update <= max() - counter is true.

Effects: Atomically execute counter += update. Then, unblocks any threads that are waiting for counter to be greater than zero.

Synchronization: Strongly happens before invocations of try_acquire that observe the result of the effects.

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).

bool try_acquire() noexcept;

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.

Returns: true if counter was decremented, otherwise false.

void acquire();

Effects: Repeatedly performs the following steps, in order:

— Evaluates try_acquire. If the result is true, returns.

— Blocks on *this until counter is greater than 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).

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);

Effects: Repeatedly performs the following steps, in order:

— Evaluates try_acquire(). If the result is true, returns true.

— 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).

Throws: Timeout-related exceptions (33.2.4), or system_error when a non-timeout-related exception is required (33.2.2).

Error conditions: Any of the error conditions allowed for mutex types (33.6.4.2).

33.9 Coordination types

33.9.1 General

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.
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.

### Header `<latch>` synopsis

```cpp
namespace std {
    class latch;
}
```

### 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:
            ptdiff_t counter;  // exposition only
    };
}
```

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.

#### `max()`

```
static constexpr ptrdiff_t max() noexcept;
```

**Returns:** The maximum value of `counter` that the implementation supports.

```
constexpr explicit latch(ptrdiff_t expected);
```

**Preconditions:** `expected >= 0` is true and `expected <= max()` is true.

**Effects:** Initializes `counter` with `expected`.

**Throws:** Nothing.

```
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).

```
bool try_wait() const noexcept;
```

**Returns:** With very low probability `false`. Otherwise `counter == 0`.

§ 33.9.2.3
```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).

void arrive_and_wait(ptrdiff_t update = 1);
  Effects: Equivalent to:
    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) When the expected count reaches zero, the phase completion step is run. For the specialization with
   the default value of the CompletionFunction template parameter, the completion step is run as part
   of the call to `arrive` or `arrive_and_drop` that caused the expected count to reach zero. For other
   specializations, the completion step is run on one of the threads that arrived at the barrier during the
   phase.

§ 33.9.3.3
— When the completion step finishes, the expected count is reset to what was specified by the \texttt{expected} argument to the constructor, possibly adjusted by calls to \texttt{arrive\_and\_drop}, and the next phase starts.

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 \texttt{wait}, and will remain blocked until the phase completion step is run.

The phase completion step that is executed at the end of each phase has the following effects:

— Invokes the completion function, equivalent to \texttt{completion()}.

— 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 \texttt{CompletionFunction} template parameter, the behavior is undefined if any of the barrier object’s member functions other than \texttt{wait} are called while the completion step is in progress.

Concurrent invocations of the member functions of \texttt{barrier}, other than its destructor, do not introduce data races. The member functions \texttt{arrive} and \texttt{arrive\_and\_drop} execute atomically.

\texttt{CompletionFunction} shall meet the \texttt{Cpp17MoveConstructible} (Table 30) and \texttt{Cpp17Destructible} (Table 34) requirements. \texttt{is\_nothrow\_invocable\_v<CompletionFunction\&>} shall be \texttt{true}.

The default value of the \texttt{CompletionFunction} template parameter is an unspecified type, such that, in addition to satisfying the requirements of \texttt{CompletionFunction}, it meets the \texttt{Cpp17DefaultConstructible} requirements (Table 29) and \texttt{completion()} has no effects.

\texttt{barrier::arrival\_token} is an unspecified type, such that it meets the \texttt{Cpp17MoveConstructible} (Table 30), \texttt{Cpp17MoveAssignable} (Table 32), and \texttt{Cpp17Destructible} (Table 34) requirements.

\begin{verbatim}
static constexpr ptrdiff_t max() noexcept;
\end{verbatim}

Returns: The maximum expected count that the implementation supports.

\begin{verbatim}
constexpr explicit barrier(ptrdiff_t expected, 
CompletionFunction f = CompletionFunction());
\end{verbatim}

Preconditions: \texttt{expected} \(\geq 0\) is \texttt{true} and \texttt{expected} \(\leq\) \texttt{max()} is \texttt{true}.

Effects: Sets both the initial expected count for each barrier phase and the current expected count for the first phase to \texttt{expected}. Initializes \texttt{completion} with \texttt{std::move(f)}. Starts the first phase.

[Note 1: If \texttt{expected} is 0 this object can only be destroyed. — end note]

 Throws: Any exception thrown by \texttt{CompletionFunction}’s move constructor.

\begin{verbatim}
[[nodiscard]] arrival\_token arrive(ptrdiff_t update = 1);
\end{verbatim}

Preconditions: \texttt{update} > 0 is \texttt{true}, and \texttt{update} is less than or equal to the expected count for the current barrier phase.

Effects: Constructs an object of type \texttt{arrival\_token} that is associated with the phase synchronization point for the current phase. Then, decrements the expected count by \texttt{update}.

Synchronization: The call to \texttt{arrive} strongly happens before the start of the phase completion step for the current phase.

Returns: The constructed \texttt{arrival\_token} object.

Throws: \texttt{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]

\begin{verbatim}
void wait(arrival\_token&& arrival) const;
\end{verbatim}

Preconditions: \texttt{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 \texttt{std::move(arrival)} until the phase completion step of the synchronization point’s phase is run.

[Note 3: If \texttt{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 decrement 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

#### 33.10.1 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

```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> class packaged_task;
// not defined
template<class R, class... ArgTypes>
class packaged_task<R(ArgTypes...)>; // not defined

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 (16.3.3.3.4) 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]

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); // not defined
        
        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 \texttt{ec_} with \texttt{make_error_code(e)}.

const error_code& code() const noexcept;

Returns: \texttt{ec_}.

const char* what() const noexcept;

Returns: An \texttt{ntbs} incorporating \texttt{code().message()}.

\section{Shared state} \label{futures.state}

Many of the classes introduced in subclause \ref{futures.state} use some state to communicate results. This \textit{shared state} consists of some state information and some (possibly not yet evaluated) \textit{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 \texttt{async} when \texttt{policy} is \texttt{launch::deferred}. — end note]

An \textit{asynchronous return object} is an object that reads results from a shared state. A \textit{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 (\ref{futures.schedule}), then it is a \textit{timed waiting function}, otherwise it is a \textit{non-timed waiting function}.

An \textit{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.

[Note 3: Such as promises or tasks. — end note]

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:

1. if the return object or provider holds the last reference to its shared state, the shared state is destroyed;
2. the return object or provider gives up its reference to its shared state; and
3. 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 \texttt{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:

1. first, the provider marks its shared state as ready; and
2. 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:

1. first, if that state is not ready, the provider
   1. stores an exception object of type \texttt{future_error} with an error condition of \texttt{broken_promise} within its shared state; and then
   2. makes its shared state ready;
2. second, the provider releases its shared state.

A shared state is \textit{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 (\ref{futures.temporary}) 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 4: 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 {
    class promise {
        public:
            promise();
            template<class Allocator>
                promise(allocator_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> : true_type { };
}
```

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.

4 Preconditions: Alloc meets the Cpp17Allocator requirements (16.4.4.6.1).

promise();
template<class Allocator>
    promise(allocation_arg_t, const Allocator& a);

Effects: Creates a shared state. The second constructor uses the allocator \( a \) to allocate memory for the shared state.

promise(promise&& rhs) noexcept;

Effects: Transfers ownership of the shared state of \( rhs \) (if any) to the newly-constructed object.

Postconditions: \( rhs \) has no shared state.

\~promise();

Effects: Abandons any shared state (33.10.5).

promise operator=(promise&& rhs) noexcept;

Effects: Abandons any shared state (33.10.5) and then as if \( \text{promise(std::move(rhs)).swap(*this)} \).

Returns: \*this.

void swap(promise& other) noexcept;

Effects: Exchanges the shared state of \*this and other.

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();

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();

Effects: Atomically stores the value \( r \) in the shared state and makes that state ready (33.10.5).

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.

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);

Preconditions: \( p \) is not null.

Effects: Atomically stores the exception pointer \( p \) in the shared state and makes that state ready (33.10.5).

Throws: future_error if its shared state already has a stored value or exception.

Error conditions:

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promise_already_satisfied if its shared state already has a stored value or exception.

no_state if *this has no shared state.

```cpp
void promise::set_value_at_thread_exit(const R& r);
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();
```

**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.

**Throws:**
- future_error if its shared state already has a stored value or exception, or
- for the first version, any exception thrown by the constructor selected to copy an object of \( R \), or
- for the second version, any exception thrown by the constructor selected to move an object of \( R \).

**Error conditions:**
- promise_already_satisfied if its shared state already has a stored value or exception.
- no_state if *this has no shared state.

```cpp
void set_exception_at_thread_exit(exception_ptr p);
```

**Preconditions:** \( p \) is not null.

**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.

**Throws:** future_error if an error condition occurs.

**Error conditions:**
- promise_already_satisfied if its shared state already has a stored value or exception.
- no_state if *this has no shared state.

```cpp
template<class R>
void swap(promise<R>& x, promise<R>& y) noexcept;
```

**Effects:** As if by \( x.swap(y) \).

### 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(future& x, future& y) noexcept;
        future(const future& x, future& y) noexcept;
        future(const future& x) noexcept;
        future(const future& x) = 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;
};

4 For the primary template, $R$ shall be an object type that meets the Cpp17Destructible requirements.

5 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:

(9.1) `valid()` returns the same value as `rhs.valid()` prior to the constructor invocation.

(9.2) `rhs.valid() == false`.

future();

Effects:

(10.1) Releases any shared state (33.10.5);

(10.2) destroys *this.

future& operator=(future&& rhs) noexcept;

Effects:

(11.1) Releases any shared state (33.10.5).

(11.2) move assigns the contents of `rhs` to *this.

Postconditions:

(12.1) `valid()` returns the same value as `rhs.valid()` prior to the assignment.

(12.2) `rhs.valid() == false`.

shared_future<R> share() noexcept;

Postconditions: valid() == false.

Returns: shared_future<R>(std::move(*this)).

R future::get();
R& future<R&>::get();
void future<void>::get();

[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]

Effects:
— wait()s until the shared state is ready, then retrieves the value stored in the shared state;
— releases any shared state (33.10.5).

Postconditions: valid() == false.

Returns:
— future::get() returns the value v stored in the object’s shared state as std::move(v).
— future<R&>::get() returns the reference stored as value in the object’s shared state.
— 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.

template<class Rep, class Period>
future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;

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).

template<class Clock, class Duration>
future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;

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

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]
The effect of calling any member function other than the destructor, the move-assignment operator, the copy-assignment operator, or \texttt{valid()} on a \texttt{shared_future} object for which \texttt{valid()} == \texttt{false} is undefined.

[Note 2: It is valid to copy or move from a \texttt{shared_future} object for which \texttt{valid()} is \texttt{false}. — end note]

\textbf{Recommended practice:} Implementations should detect this case and throw an object of type \texttt{future_error} with an error condition of \texttt{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>&& rhs) 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;
    };
}
```

For the primary template, \texttt{R} shall be an object type that meets the \texttt{Cpp17Destructible} requirements.

The implementation provides the template \texttt{shared_future} and two specializations, \texttt{shared_future<R&>} and \texttt{shared_future<void>}. These differ only in the return type and return value of the member function \texttt{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.
```

```cpp
shared_future(const shared_future& rhs) noexcept;
Effects: The object refers to the same shared state as \texttt{rhs} (if any).
Postconditions: valid() returns the same value as \texttt{rhs.valid()}.
```

```cpp
shared_future(future<R>&& rhs) noexcept;
shared_future(shared_future&& rhs) noexcept;
Effects: Move constructs a \texttt{shared_future} object that refers to the shared state that was originally referred to by \texttt{rhs} (if any).
Postconditions:
(11.1) valid() returns the same value as \texttt{rhs.valid()} returned prior to the constructor invocation.
(11.2) \texttt{rhs.valid()} == false.
```

```cpp
~shared_future();
Effects:
(12.1) Releases any shared state (33.10.5);
(12.2) destroys \texttt{*this}.
```
shared_future& operator=(shared_future&& rhs) noexcept;

Effects:
— Releases any shared state (33.10.5);
— move assigns the contents of rhs to *this.

Postconditions:
— valid() returns the same value as rhs.valid() returned prior to the assignment.
— rhs.valid() == false.

shared_future& operator=(const shared_future& rhs) noexcept;

Effects:
— Releases any shared state (33.10.5);
— assigns the contents of rhs to *this.

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:
— 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]

— shared_future<R&>::get() returns the reference stored as value in the object’s shared state.

— 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.

template<class Rep, class Period>
future_status wait_for(const chrono::duration<Rep, Period>& rel_time) const;

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).

template<class Clock, class Duration>
future_status wait_until(const chrono::time_point<Clock, Duration>& abs_time) const;
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.

```cpp
template<class F, class... Args>
[[nodiscard]] future<invoke_result_t<decay_t<F>, decay_t<Args>...>> async(F&& f, Args&&... args);
```

Mandates: The following are all true:

- (is_constructible_v<decay_t<F>, F>, F),
- (is_constructible_v<decay_t<Args>, Args> && ...), and
- (is_invocable_v<decay_t<F>, decay_t<Args>...>.

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))...) (22.10.4, 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 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.

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.
If the implementation chooses the `launch::async` policy,

---

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);

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.

**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`.

---

**Throws:** `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.

**Error conditions:**

---

**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

---

### 33.10.10 Class template `packaged_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 [futures.task.members]

packaged_task() noexcept;
   Effects: The object has no shared state and no stored task.

template<class F>
packaged_task(F&& f);
   Constraints: remove_cvref_t<F> is not the same type as packaged_task<R(ArgTypes...)>
.
   Mandates: is_invocable_r_v<R, F&, ArgTypes...> is true.
   Preconditions: Invoking a copy of f behaves the same as invoking f.
   Effects: Constructs a new packaged_task object with a shared state and initializes the object’s stored
task with std::forward<F>(f).
   Throws: Any exceptions thrown by the copy or move constructor of f, or bad_alloc if memory for the
internal data structures cannot be allocated.

template<class F> packaged_task(F) -> packaged_task<see below>;
   Constraints: &F::operator() is well-formed when treated as an unevaluated operand (7.2.3) and
decltype(&F::operator()) is of the form R(G::*)(A...) ev &opt noexcept for a class type G.
   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.

§ 33.10.10.2
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, t₁, t₂, ..., tₙ) (22.10.4), where f is the stored task of *this and t₁, t₂, ..., tₙ 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, t₁, t₂, ..., tₙ) (22.10.4), where f is the stored task and t₁, t₂, ..., tₙ 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:

(25.1) — promise_already_satisfied if the stored task has already been invoked.

(25.2) — 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:

(27.1) — bad_alloc if memory for the new shared state cannot be allocated.

(27.2) — any exception thrown by the move constructor of the task stored in the shared state.

(27.3) — future_error with an error condition of no_state if *this has no shared state.

33.10.10.3 Globals

template<class R, class... ArgTypes>

§ 33.10.10.3 1751
```cpp
void swap(packaged_task<R(ArgTypes...)> & x, packaged_task<R(ArgTypes...)> & y) noexcept;

1

Effects: As if by x.swap(y).
```
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.

typedef-name:
  identifier
  simple-template-id

namespace-name:
  identifier
  namespace-alias

namespace-alias:
  identifier

class-name:
  identifier
  simple-template-id

enum-name:
  identifier

template-name:
  identifier

A.3 Lexical conventions

hex-quad:
  hexadecimal-digit hexadecimal-digit hexadecimal-digit hexadecimal-digit

universal-character-name:
  \u hex-quad
  \U hex-quad hex-quad

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-TI

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

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

identifier:
   identifier-start
   identifier identifier-continue

identifier-start:
   nondigit
   an element of the translation character set of class XID_Start

identifier-continue:
   digit
   nondigit
   an element of the translation character set of class 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 _

digit: one of
   0 1 2 3 4 5 6 7 8 9

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
closeprint-literal
floating-point-literal
string-literal
boolean-literal
pointer-literal
user-defined-literal

integer-literal:
binary-literal integer-suffixopt
octal-literal integer-suffixopt
decimal-literal integer-suffixopt
hexadecimal-literal integer-suffixopt

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
	onal-digit: one of
0 1 2 3 4 5 6 7
	onal-digit: one of
0 1 2 3 4 5 6 7 8 9
	onal-digit: one of
0x 0X
	onal-digit-sequence: hexadecimal-digit
	onal-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-suffixopt
unsigned-suffix long-long-suffixopt
unsigned-suffix size-suffixopt
long-suffix unsigned-suffixopt
long-long-suffix unsigned-suffixopt
size-suffix unsigned-suffixopt
**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

**character-literal**: encoding-prefix opt `c-char-sequence`

encoding-prefix: one of
  - `u8` `u` U `L` c-char-sequence

**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

octal-escape-sequence:
  - \ octal-digit
  - \ octal-digit octal-digit
  - \ octal-digit octal-digit octal-digit

hexadecimal-escape-sequence:
  - \x hexadecimal-digit
  - hexadecimal-escape-sequence hexadecimal-digit

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 `u, U, or x`

**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
  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 F L

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 PARENTHESES 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 PARENTHESES, U+0029 RIGHT PARENTHESES, U+005C REVERSE SOLIDUS,
    U+0009 CHARACTER TABULATION, U+000B LINE TABULATION, U+000C FORM FEED, and new-line

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

unqualified-id:
    identifier
    operator-function-id
    conversion-function-id
    literal-operator-id
    ~ type-name
    ~ decltype-specifier
    template-id

qualified-id:
    nested-name-specifier template opt unqualified-id

nested-name-specifier:
    ::
    type-name ::
    namespace-name ::
    decltype-specifier ::
    nested-name-specifier identifier ::
    nested-name-specifier template opt simple-template-id ::

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
c    constexpr
c    mutable

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

delta-capture:
    identifier . . . opt
    & identifier . . . opt
    this
    *= this

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-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

delta-requirement:
    expression ;
type-requirement:
  typename nested-name-specifier_{opt} type-name;

compound-requirement:
  { expression } noexcept_{opt} return-type-requirement_{opt};

return-type-requirement:
  -> type-constraint

nested-requirement:
  requires constraint-expression;

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

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\textsubscript{opt}

assignment-expression:
  conditional-expression
  yield-expression
  throw-expression
  logical-or-expression assignment-operator initializer-clause

assignment-operator: one of
  = *= /= %= += -= >>= <<= &= ^= |=

data-type:
  data-type
  \texttt{char | wchar_t | short | int | long | long long | float | double | complex | std::vector | std::map | std::list | std::set | std::unordered_set | std::unordered_map | std::string | std::shared_ptr | std::unique_ptr | std::make_shared | std::make_unique | std::move}

A.6 Statements

statement:
  labeled-statement
  attribute-specifier-seq\textsubscript{opt} expression-statement
  attribute-specifier-seq\textsubscript{opt} compound-statement
  attribute-specifier-seq\textsubscript{opt} selection-statement
  attribute-specifier-seq\textsubscript{opt} iteration-statement
  attribute-specifier-seq\textsubscript{opt} jump-statement
  declaration-statement
  attribute-specifier-seq\textsubscript{opt} try-block

init-statement:
  expression-statement
  simple-declaration
  alias-declaration

condition:
  expression
  attribute-specifier-seq\textsubscript{opt} decl-specifier-seq declorator brace-or-equal-initializer

labeled-statement:
  attribute-specifier-seq\textsubscript{opt} identifier : statement
  attribute-specifier-seq\textsubscript{opt} case constant-expression : statement
  attribute-specifier-seq\textsubscript{opt} default : statement

expression-statement:
  expression\textsubscript{opt} ;

compound-statement:
  \{ statement-seq\textsubscript{opt} \}

statement-seq:
  statement
  statement-seq statement

selection-statement:
  if constexpr\textsubscript{opt} ( init-statement\textsubscript{opt} condition ) statement
  if constexpr\textsubscript{opt} ( init-statement\textsubscript{opt} condition ) statement else statement
  if \textsubscript{opt} consteval compound-statement
  if \textsubscript{opt} consteval compound-statement else statement
  switch ( init-statement\textsubscript{opt} condition ) statement
iteration-statement:
  while ( condition ) statement
  do statement while ( expression ) ;
  for ( init-statement conditionopt ; expressionopt ) statement
  for ( init-statementopt for-range-declaration : for-range-initializer ) statement

for-range-declaration:
  attribute-specifier-seqopt decl-specifier-seq declarator
  attribute-specifier-seqopt decl-specifier-seq ref-qualifieropt [ identifier-list ]

for-range-initializer:
  expr-or-braced-init-list

jump-statement:
  break ;
  continue ;
  return expr-or-braced-init-listopt ;
  coroutine-return-statement
  goto identifier ;

coroutine-return-statement:
  co_return expr-or-braced-init-listopt ;

declaration-statement:
  block-declaration

A.7 Declarations

declaration-seq:
  declaration
  declaration-seq declaration

declaration:
  block-declaration
  noddeclspec-function-declaration
  function-definition
  template-declaration
  deduction-guide
  explicit-instantiation
  explicit-specialization
  export-declaration
  linkage-specification
  namespace-definition
  empty-declaration
  attribute-declaration
  module-import-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

noddeclspec-function-declaration:
  attribute-specifier-seqopt decl declarator ;

alias-declaration:
  using identifier attribute-specifier-seqopt = defining-type-id ;

simple-declaration:
  decl-specifier-seq init-declarator-listopt ;
  attribute-specifier-seq decl-specifier-seq init-declarator-list ;
  attribute-specifier-seqopt decl-specifier-seq ref-qualifieropt [ identifier-list ] initializer ;
static_assert-declaration:
  static_assert ( constant-expression );
  static_assert ( constant-expression, string-literal );

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
dcltype-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
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
elaborated-enum-specifier
elaborated-enum-specifier:
  enum nested-name-specifier\_opt identifier
dcltype-specifier:
  dcltype ( expression )
placeholder-type-specifier:
  type-constraint\_opt auto
type-constraint\_opt dcltype ( auto )
init-declarator-list:
  init-declarator
  init-declarator-list , init-declarator
init-declarator:
  declarator initializer\_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-qualifier-seq\_opt
  ref-qualifier\_opt noexcept-specifier\_opt attribute-specifier-seq\_opt
trailing-return-type:
  \rightarrow 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:
  &
  &&

deaclarator-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}

nopr-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

nopr-abstract-pack-declarator:
  noptr-abstract-pack-declarator parameters-and-qualifiers
  noptr-abstract-pack-declarator\textsubscript{opt} [ constant-expression\textsubscript{opt} ] attribute-specifier-seq\textsubscript{opt}
  \ldots

parameter-declaration-clause:
  parameter-declaration-list\textsubscript{opt} \ldots \textsubscript{opt}
  parameter-declaration-list , \ldots

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} this\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} this\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

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 decl-specifier-seq_opt declarator virt-specifier-seq_opt function-body
    attribute-specifier-seq_opt decl-specifier-seq_opt declarator requires-clause function-body

function-body:
    ctor-initializer_opt compound-statement
    function-try-block
    = default ;
    = delete ;

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

using-enum-declaration:
    using elaborated-enum-specifier ;

namespace-name:
    identifier
    namespace-alias
namespace-definition:
  named-namespace-definition
  unnamed-namespace-definition
  nested-namespace-definition

named-namespace-definition:
  inline_opt namespace attribute-specifier-seq_opt identifier { namespace-body }

unnamed-namespace-definition:
  inline_opt namespace attribute-specifier-seq_opt { namespace-body }

nested-namespace-definition:
  namespace enclosing-namespace-specifier :: inline_opt identifier { namespace-body }

enclosing-namespace-specifier:
  identifier
  enclosing-namespace-specifier :: inline_opt 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 ... opt
  using-declarator-list , using-declarator ... opt

using-declarator:
  typename_opt nested-name-specifier unqualified-id

asm-declaration:
  attribute-specifier-seq_opt asm ( string-literal ) ;

linkage-specification:
  extern string-literal { declaration-seq_opt }
  extern string-literal declaration

attribute-specifier-seq:
  attribute-specifier-seq_opt attribute-specifier

attribute-specifier:
  [ [ attribute-using-prefix_opt attribute-list ] ]

alignment-specifier:
  alignas ( type-id ... opt )
  alignas ( constant-expression ... opt )

attribute-using-prefix:
  using attribute-namespaced :

attribute-list:
  attribute_opt
  attribute-list , attribute_opt
  attribute ...
  attribute-list , attribute ...

attribute:
  attribute-using-prefix_opt

attribute-token:
  identifier
  attribute-scoped-token

§ A.7
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 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-virtSpecifier_opt base-clause_opt
  class-key attribute-specifier-seq_opt base-clause_opt

class-head-name:
  nested-name-specifier_opt class-name

class-virtSpecifier:
  final
class-key:
  class
  struct
  union
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
  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
deaclarator requires-clause
deaclarator brace-or-equal-initializer_opt
  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

collection-function-id:
  operator conversion-type-id

collection-type-id:
  type-specifier-seq conversion-clauser_opt

collection-declarator:
  ptr-operator conversion-declarator_opt

base-clause:
  : base-specifier-list

base-specifier-list:
  base-specifier ..._opt
  base-specifier-list , base-specifier ..._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
  decltype-specifier

access-specifier:
  private
  protected
  public

ctor-initializer:
  : mem-initializer-list
A.10 Overloading

operator-function-id:
  operator operator

operator: one of
  new delete new[] delete[] co_await () [ ] -> ->*
  ~ ! + - * / % ^ &
  | = += -= ** /= %= ^= &=
  || << >> <<= >>= ++ -- ,

literal-operator-id:
  operator string-literal identifier
  operator user-defined-string-literal

A.11 Templates

template-declaration:
  template-head declaration
  template-head concept-definition

template-head:
  template < template-parameter-list > requires-clause_opt

template-parameter-list:
  template-parameter
  template-parameter-list , template-parameter

requires-clause:
  requires constraint-logical-or-expression

constraint-logical-or-expression:
  constraint-logical-and-expression
  constraint-logical-and-expression || constraint-logical-and-expression

constraint-logical-and-expression:
  primary-expression
  constraint-logical-and-expression && primary-expression

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 >
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 , template-argument ... opt

template-argument:
  constant-expression
  type-id
  id-expression

constraint-expression:
  logical-or-expression

deduction-guide:
  explicit-specifier_opt template-name ( parameter-declaration-clause ) -> simple-template-id ;

concept-definition:
  concept concept-name = constraint-expression ;

calendar-name:
  identifier

typename-specifier:
  typename nested-name-specifier identifier
  typename nested-name-specifier template_opt simple-template-id

explicit-instantiation:
  extern_opt template declaration

explicit-specialization:
  template <> declaration

A.12 Exception handling

try-block:
  try compound-statement handler-seq

function-try-block:
  try ctor-initializer_opt compound-statement handler-seq

handler-seq:
  handler handler-seq_opt

handler:
  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

pp-private-module-fragment:
  module : private ; new-line group

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 ) 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
  # pragma pp-tokens new-line
  # new-line

if-section:
  if-group elif-groups , else-group endif-line

if-group:
  # if constant-expression new-line group
  # ifdef identifier new-line group
  # ifndef identifier new-line group

eelif-groups:
  elif-group
eelif-groups elif-group

eelif-group:
  # elif constant-expression new-line group
  # elifdef constant-expression new-line group
  # elifndef constant-expression new-line group

eelse-group:
  # else new-line group

dendif-line:
  # endif new-line

text-line:
  pp-tokens new-line

conditionally-supported-directive:
  pp-tokens new-line

lparen:
  a ( character not immediately preceded by whitespace

identifier-list:
  identifier
  identifier-list , identifier

replacement-list:
  pp-tokens

pp-tokens:
  preprocessing-token
  pp-tokens preprocessing-token

new-line:
  the new-line character
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 )

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  (normative)
Implementation quantities [implimits]

1 Because computers are finite, C++ implementations are inevitably limited in the size of the programs they can successfully process. Every implementation shall document those limitations where known. This documentation may cite fixed limits where they exist, say how to compute variable limits as a function of available resources, or say that fixed limits do not exist or are unknown.

2 The limits may constrain quantities that include those described below or others. The bracketed number following each quantity is recommended as the minimum for that quantity. However, these quantities are only guidelines and do not determine compliance.

(2.1) Nesting levels of compound statements (8.4), iteration control structures (8.6), and selection control structures (8.5) [256].
(2.2) Nesting levels of conditional inclusion (15.2) [256].
(2.3) Pointer (9.3.4.2), array (9.3.4.5), and function (9.3.4.6) declarators (in any combination) modifying a class, arithmetic, or incomplete type in a declaration [256].
(2.4) Nesting levels of parenthesized expressions (7.5.3) within a full-expression [256].
(2.5) Number of characters in an internal identifier (5.10) or macro name (15.6) [1024].
(2.6) Number of characters in an external identifier (5.10, 6.6) [1024].
(2.7) External identifiers (6.6) in one translation unit [65536].
(2.8) Identifiers with block scope declared in one block (6.4.3) [1024].
(2.9) Structured bindings (9.6) introduced in one declaration [256].
(2.10) Macro identifiers (15.6) simultaneously defined in one translation unit [65536].
(2.11) Parameters in one function definition (9.5.1) [256].
(2.12) Arguments in one function call (7.6.1.3) [256].
(2.13) Parameters in one macro definition (15.6) [256].
(2.14) Arguments in one macro invocation (15.6) [256].
(2.15) Characters in one logical source line (5.2) [65536].
(2.16) Characters in a string-literal (5.13.5) (after concatenation (5.2)) [65536].
(2.17) Size of an object (6.7.2) [262144].
(2.18) Nesting levels for #include files (15.3) [256].
(2.19) Case labels for a switch statement (8.5.3) (excluding those for any nested switch statements) [16384].
(2.20) Non-static data members (including inherited ones) in a single class (11.4) [16384].
(2.21) Lambda-captures in one lambda-expression (7.5.5.3) [256].
(2.22) Enumeration constants in a single enumeration (9.7.1) [4096].
(2.23) Levels of nested class definitions (11.4.12) in a single member-specification [256].
(2.24) Functions registered by atexit() (17.5) [32].
(2.25) Functions registered by at_quick_exit() (17.5) [32].
(2.26) Direct and indirect base classes (11.7) [16384].
(2.27) Direct base classes for a single class (11.7) [1024].
(2.28) Class members declared in a single member-specification (including member functions) (11.4) [4096].
(2.29) Final overriding virtual functions in a class, accessible or not (11.7.3) [16384].
(2.30) Direct and indirect virtual bases of a class (11.7.2) [1024].
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
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<tbody>
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<td>Static data members of a class (11.4.9.3) [1024].</td>
</tr>
<tr>
<td>(2.32)</td>
<td>Friend declarations in a class (11.8.4) [4096].</td>
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<td>(2.33)</td>
<td>Access control declarations in a class (11.8.2) [4096].</td>
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<td>(2.34)</td>
<td>Member initializers in a constructor definition (11.9.3) [6144].</td>
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<td>(2.37)</td>
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<td>Recursive constexpr function invocations (9.2.6) [512].</td>
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<td>Recursively nested template instantiations (13.9.2), including substitution during template argument deduction (13.10.3) [1024].</td>
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<td>(2.42)</td>
<td>Handlers per try block (14.4) [256].</td>
</tr>
<tr>
<td>(2.43)</td>
<td>Number of placeholders (22.10.15.5) [10].</td>
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</table>
Annex C  (informative)
Compatibility

C.1  C++ and ISO C++ 2020

C.1.1 General

Subclause C.1 lists the differences between C++ and ISO C++ 2020 (ISO/IEC 14882:2020, Programming Languages — C++), by the chapters of this document.

C.1.2 Clause 5: lexical conventions

1. Affected subclause: 5.10
   Change: Previously valid identifiers containing characters not present in UAX #44 properties XID_Start or XID_Continue, or not in Normalization Form C, are now rejected.
   Rationale: Prevent confusing characters in identifiers. Requiring normalization of names ensures consistent linker behavior.
   Effect on original feature: Some identifiers are no longer well-formed.

2. Affected subclause: 5.13.5
   Change: Concatenated string-literals can no longer have conflicting encoding-prefixes.
   Rationale: Removal of unimplemented conditionally-supported feature.
   Effect on original feature: Concatenation of string-literals with different encoding-prefixes is now ill-formed.

   [Example 1:
    auto c = L"a" U"b";
    // was conditionally-supported; now ill-formed
   — end example]

C.1.3 Clause 7: expressions

1. 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. For example:

   arr[1, 2]
   // was equivalent to arr[(1, 2)],
   // now equivalent to arr.operator[](1, 2) or ill-formed

C.1.4 Clause 16: library introduction

1. 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), <stdatomic.h> (33.5.12), <spanstream> (31.9.2), and <stacktrace> (19.6.2). Valid C++ 2020 code that #includes headers with these names may be invalid in this revision of C++.

C.1.5 Clause 22: general utilities library

1. 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. For example:

   auto s = std::format("{:d}", "I am not a number");  // ill-formed,
   // previously threw format_error

   2. Affected subclause: 22.14
      Change: Signature changes: format, format_to, format_to_n, formatted_size.

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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. For example:

```cpp
struct tiny {
    int bit: 1;
};

auto t = tiny();
std::format("{t.bit}");     // ill-formed, previously returned "0"
```

C.1.6 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++. For example:

```cpp
struct B {
    auto operator<=>(const B&) const = default;
};

struct D : private B {
    void f(std::set<B, std::less<>>& s) {
        s.erase(*this);      // ill formed; previously well-formed
    }
};
```

C.2 C++ and ISO C++ 2017

C.2.1 General

Subclause C.2 lists the differences between C++ and ISO C++ 2017 (ISO/IEC 14882:2017, Programming Languages — C++), by the chapters of this document.

C.2.2 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
```

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.

- The `char8_t` keyword is added to differentiate the types of ordinary and UTF-8 literals (5.13.5).
- The `concept` keyword is added to enable the definition of concepts (13.7.9).
- The `constexpr` keyword is added to declare immediate functions (9.2.6).
- The `constinit` keyword is added to prevent unintended dynamic initialization (9.2.7).
- The `co_await`, `co_yield`, and `co_return` keywords are added to enable the definition of coroutines (9.5.4).
- The `requires` keyword is added to introduce constraints through a `requires-clause` (13.1) or a `requires-expression` (7.5.7).

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++:

```cpp
namespace N {
  struct X {};
  bool operator<=(X, X);
  template<bool(X, X)> struct Y {};
  Y<operator<=> y; // ill-formed; previously well-formed
}
```

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++.

```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
```

C.2.3 Clause 6: basics

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:
```cpp
int f() {
  int a = 123;
} [diff.cpp17.basic]"
using T = int;
a. -T();
return a; // undefined behavior; previously returned 123
}
— end example]  

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.2.4 Clause 7: expressions  

Affected subclause: 7.5.5.3  
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.2.5 Clause 9: declarations  

Affected subclause: 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++.

typedef struct {
    void f() {}
} S;  

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.

// 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

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++.

struct A {
    A() = delete;
};  

struct B {
    B() = default;
    int i = 0;
};

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struct C { // not an aggregate; previously an aggregate
    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 {
    // not an aggregate; previously an aggregate
    Y(const Y&) = default;
    X x;
};

Y y(x()); // copy constructor call; previously aggregate-initialization

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++. For example:

```cpp
bool y[] = { "bc" }; // ill-formed; previously well-formed
```

C.2.6 Clause 11: classes [diff.cpp17.class]

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++. For example:

```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
};
```

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++. For example:

```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
};
```

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++. For example:

```cpp
struct base {
    base();
    base(base const &); ```

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private:
    base(base &&);
};

struct derived : base {};

base f(base b) {
    throw b; // error: base(base &&) is private
    derived d; // error: base(base &&) is private
    return d;
}

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.2.7 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: Equality and inequality expressions between two objects of different types, where one is convertible to the other, could invoke a different operator. Equality and inequality expressions between two objects of the same type could become ambiguous.

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
}

C.2.8 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.

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.2.9 Clause 14: exception handling [diff.cpp17.except]

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.2.10 Clause 16: library introduction [diff.cpp17.library]

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), <cmath> (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), <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++.

Affected subclause: 16.4.2.3
Change: Remove vacuous C++ header files.
Rationale: The empty headers implied a false requirement to achieve C compatibility with the C++ headers.
Effect on original feature: A valid C++ 2017 program that #includes any of the following headers may fail to compile: <ccomplex>, <ciso646>, <cstdlibalign>, <cstdlibbool>, and <ctgmath>. To retain the same behavior:

(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>, <cstdlibalign>, or <cstdlibbool> can simply be removed.

C.2.11 Clause 24: containers library [diff.cpp17.containers]

Affected subclauses: 24.3.9 and 24.3.10
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.2.12 Clause 25: iterators library [diff.cpp17.iterators]

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.2.13 Clause 27: algorithms library

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.2.14 Clause 31: input/output library

Affected subclause: 31.7.4.3.3
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++:

```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
```

Affected subclause: 31.7.5.3.4
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, ...>::operator<< or basic_ostream<wchar_t, ...>::operator<< is now ill-formed.

```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
```

Affected subclause: 31.7.5.3.4
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, ...>::operator<< or that passes char16_t or char32_t characters or strings to basic_ostream<wchar_t, ...>::operator<< is now ill-formed.

```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
```

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++.

```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.2.15 Annex D: compatibility features

Affected subclause: 31.4.3.3
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.

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.

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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 directly makes use of the `pointer`, `const_pointer`, `reference`, `const_reference`, `rebind`, `address`, `construct`, `destroy`, or `max_size` members of `std::allocator`, or that directly calls `allocate` with an additional hint argument, may fail to compile.

4 Change: Remove `raw_storage_iterator`.
Rationale: The iterator encouraged use of algorithms that might throw exceptions, but did not return the number of elements successfully constructed that might need to be destroyed in order to avoid leaks.
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 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.15
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 could not report the result of a regular function type. 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.3 C++ and ISO C++ 2014

C.3.1 General

Subclause C.3 lists the differences between C++ and ISO C++ 2014 (ISO/IEC 14882:2014, Programming Languages — C++), in addition to those listed above, by the chapters of this document.

C.3.2 Clause 5: lexical conventions

1 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 physical source file characters to the translation character set.

2 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++. For example:
C.3.3 Clause 7: expressions

1. 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++. Note that this might occur when the lvalue has a type given by a template parameter.

2. 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.3.4 Clause 9: declarations

1. 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.

2. Affected subclause: 9.2.9.6
   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++. For example:
   ```
   auto x1{1}; // was std::initializer_list<int>, now int
   auto x2{1, 2}; // was std::initializer_list<int>, now ill-formed
   ```

3. 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++. For example:
   ```
   void g1() noexcept;
   void g2();
   template<class T> int f(T *, T *);
   int x = f(g1, g2); // ill-formed; previously well-formed
   ```

4. 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. For example:
   ```
   struct derived;
   struct base {
     friend struct derived;
     private:
     base();
   };
   struct derived : base {};
   derived d1{}; // error; the code was well-formed in C++ 2014
   derived d2; // still OK
   ```

§ C.3.4
C.3.5 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.

```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).
```

C.3.6 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++. For example:

```cpp
template <int N> struct A;
template <typename T, T N> int foo(A<N> *) = delete;
void foo(void *);
void bar(A<0> *p) {
    foo(p);    // ill-formed; previously well-formed
}
```

C.3.7 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, or function reference declaration, or function reference 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.3.8 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++.

Affected subclause: 16.4.5.2.3
Change: New reserved namespaces.
Rationale: Reserve namespaces for future revisions of the standard library that might otherwise be incompatible with existing programs.

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Effect on original feature: The global namespaces `std` followed by an arbitrary sequence of digits (5.10) are reserved for future standardization. Valid C++ 2014 code that uses such a top-level namespace, e.g., `std2`, may be invalid in this revision of C++.

C.3.9 Clause 22: general utilities library [diff.cpp14.utilities]

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++.

Affected subclause: 20.3.2.2
Change: Different constraint on conversions from `unique_ptr`.
Rationale: Adding array support to `shared_ptr`, via the syntax `shared_ptr<T[]>` and `shared_ptr<T[N]>`.
Effect on original feature: Valid C++ 2014 code may fail to compile or may change meaning in this revision of C++. For example:

```cpp
#include <memory>
std::unique_ptr<int[]> arr(new int[1]);
std::shared_ptr<int> ptr(std::move(arr)); // error: int(*)[] is not compatible with int*
```

C.3.10 Clause 23: strings library [diff.cpp14.string]

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++. For example:

```cpp
int f(char *) = delete;
int f(const char *);
string s;
int x = f(s.data()); // ill-formed; previously well-formed
```

C.3.11 Clause 24: containers library [diff.cpp14.containers]

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++:

```cpp
#include <set>
struct compare
{
    bool operator()(int a, int b)
    {
        return a < b;
    }
};

int main()
{
    const std::set<int, compare> s;
    s.find(0);
}
```


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.4 C++ and ISO C++ 2011

C.4.1 General

Subclause C.4 lists the differences between C++ and ISO C++ 2011 (ISO/IEC 14882:2011, Programming Languages — C++), in addition to those listed above, by the chapters of this document.

C.4.2 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++:

```c++
#define M(x, ...) _VA_ARGS_
// int x[2] = { 3'4, 5 }; — this revision of C++
```

C.4.3 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:

```c++
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.4.4 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++:

```c++
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, \(f(\text{true})\) returns 1. In this revision of C++, it returns 2.

```cpp
sizeof(true ? "" : throw 0)
```

In C++ 2011, the expression yields `sizeof(const char*)`. In this revision of C++, it yields `sizeof(const char[1])`.

### C.4.5 Clause 9: declarations

1. **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++. For example, the following 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:

   ```cpp
   struct S {
   constexpr const int &f();
   int &f();
   };
   ```

2. **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++. For example:

   ```cpp
   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++
   ```

### C.4.6 Clause 16: library introduction

1. **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 includes a header with that name may be invalid in this revision of C++.

### C.4.7 Clause 31: input/output library

1. **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.5 C++ and ISO C++ 2003

1. **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. For example:

```c
#define u8 "abc"
const char* s = u8"def";    // Previously "abcdef", now "def"
```

2 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++. For example:

```c
#define _x "there"
"hello"_x    // #1
```

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.

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.5.3 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++. For example:

```c
void f(void *);    // #1
void f(...);       // #2
template<int N> void g() {
    f(0*N);   // calls #2; used to call #1
}
```

2 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.

3 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++. For example:

```c
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
```

C.5.4 Clause 9: declarations

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++. For example, the following code is valid in C++ 2003 but invalid in this revision of C++ because `double` to `int` is a narrowing conversion:

```c++
int x[] = { 2.0 };
```

### C.5.5 Clause 11: classes

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.5.6 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. For example, the following code is valid in C++ 2003 because “>>” is a right-shift operator, but invalid in this revision of C++ because “>>” closes two templates.

```c++
template <class T> struct X { };  
template <int N> struct Y { };  
X<< Y<< 1 >> 2 >> x;
```

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 could get a different result than in this revision of C++.

### C.5.7 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), <codecvt> (D.22.2), <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), <type-index> (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> (17.4.2), 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.5.8 Clause 17: language support library

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.5.9 Clause 19: diagnostics library

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.5.10 Clause 22: general utilities library

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.5.11 Clause 23: strings library

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.5.12 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.

2 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:

(2.1) — not all containers provide size(); use empty() instead of size() == 0;
(2.2) — not all containers are empty after construction (array);
(2.3) — not all containers have constant complexity for swap() (array).

3 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.

4 Affected subclauses: 24.2.4 and 24.2.7
Change: Signature changes: from 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:

(4.1) — erase(iter) for set, multiset, map, multimap
(4.2) — erase(begin, end) for set, multiset, map, multimap
(4.3) — insert(pos, num, val) for vector, deque, list, forward_list
(4.4) — insert(pos, beg, end) for vector, deque, list, forward_list

Valid C++ 2003 code that relies on these functions returning 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++.

5 Affected subclauses: 24.2.4 and 24.2.7
Change: Signature changes: from iterator to const_iterator parameters.
Rationale: Overspecification.
Effect on original feature: The signatures of the following member functions changed from taking an iterator to taking a const_iterator:

(5.1) — insert(iter, val) for vector, deque, list, set, multiset, map, multimap
(5.2) — insert(pos, beg, end) for vector, deque, list, forward_list
(5.3) — erase(begin, end) for set, multiset, map, multimap
(5.4) — all forms of list::splice
(5.5) — all forms of list::merge

Valid C++ 2003 code that uses these functions may fail to compile with this revision of C++.

6 Affected subclauses: 24.2.4 and 24.2.7
Change: Signature changes: resize.
Rationale: Performance, compatibility with move semantics.
Effect on original feature: For vector, deque, and list the fill value passed to resize is now passed by reference instead of by value, and an additional overload of resize has been added. Valid C++ 2003 code that uses this function may fail to compile with this revision of C++.

C.5.13 Clause 27: algorithms library  [diff.cpp03.algorithms]

1 Affected subclause: 27.1
Change: Result state of inputs after application of some algorithms.
Rationale: Required by new feature.
Effect on original feature: A valid C++ 2003 program may detect that an object with a valid but unspecified state has a different valid but unspecified state with this revision of C++. For example, std::remove and std::remove_if may leave the tail of the input sequence with a different set of values than previously.

C.5.14 Clause 28: numerics library  [diff.cpp03.numerics]

1 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.5.15 Clause 30: localization library  [diff.cpp03.locale]

1 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.5.16 Clause 31: input/output library  [diff.cpp03.input.output]

1 Affected subclauses: 31.7.4.2.4, 31.7.5.2.4, 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:

(1.1) — passing a value to a function that takes an argument of type bool;
(1.2) — using operator== to compare to false or true;
(1.3) — returning a value from a function with a return type of bool;
(1.4) — initializing members of type bool via aggregate initialization;
(1.5) — initializing a const bool& which would bind to a temporary object.

2 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++.

3 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++. For example:

```cpp
#include <iostream>

int main() {
    int flag = std::ios_base::hex;
    std::cout.setf(flag); // error: setf does not take argument of type int
}
```
C.6  C++ and ISO C

C.6.1  General

Subclause C.6 lists the differences between C++ and ISO C, in addition to those listed above, by the chapters of this document.

C.6.2  Clause 5: lexical conventions

1  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 ISO 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. For example:
   ```c
   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.
   Effect on original feature: Change to semantics of well-defined feature. ISO 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 UTF-32 string literal is changed from “array of some-integer-type” to “array of const char32_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:
   ```c
   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.6.3 Clause 6: basics

1 Affected subclause: 6.2
Change: C++ does not have “tentative definitions” as in C.
E.g., at file scope,

```c
int i;
int i;
```
is valid in C, invalid in C++. 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. For example,

```c
struct X { int i; struct X* next; };

static struct X a;
static struct X b = { 0, &a };  // Error: &a is undefined in C++
static struct X a = { 1, &b };
```

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. For example,

```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`.

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.6.4 Clause 7: expressions

Affected subclause: 7.3.12
Change: Converting `void*` to a pointer-to-object type requires casting.

```c
char a[10];
void* b = a;
void foo() {
    char* c = b;
}
```

ISO C accepts this usage of pointer to `void` being assigned to a pointer to object type. C++ does not.

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. For example:

```c
char* c = (char*) b;
```

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 ISO C translators will give a warning if the cast is not used.

---

Affected subclause: 7.6.1.3
Change: Implicit declaration of functions is not allowed.

Rationale: The type-safe nature of C++.

Effect on original feature: Deletion of semantically well-defined feature. Note: the original feature was labeled as “obsolete” in ISO C.

Difficulty of converting: Syntactic transformation. Facilities for producing explicit function declarations are fairly widespread commercially.

How widely used: Common.

---

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 ISO 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. For example,

```c
p = (void*)(struct x {int i;}) *0;
```

defines a new type, struct x.

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 lvalue-to-rvalue conversions will yield different results. For example,

```c
char arr[100];
sizeof(0, arr)
```

yields 100 in C++ and `sizeof(char*)` in C.

Difficulty of converting: Programs must add explicit casts to the appropriate rvalue.

How widely used: Rare.

C.6.5 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
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, any use of the uninitialized object could be a disaster. 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.

Affected subclause: 8.7.4
Change: It is now invalid to return (explicitly or implicitly) from a function which is declared to return a value without actually returning a value.

Rationale: The caller and callee may assume fairly elaborate return-value mechanisms for the return of class objects. If some flow paths execute a return without specifying any value, the implementation must embody many more complications. Besides, promising to return a value of a given type, and then not returning such a value, has always been recognized to be a questionable practice, tolerated only because very-old C had no distinction between functions with void and int return types.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. Add an appropriate return value to the source code, such as zero.

How widely used: Seldom. For several years, many existing C implementations have produced warnings in this case.

C.6.6 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:

```c
static struct S {
    int i;
};
```

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. Allowing storage class specifiers on type declarations could render the code confusing for users.

Effect on original feature: Deletion of semantically well-defined feature.

Difficulty of converting: Semantic transformation. Add an appropriate return value to the source code, such as zero.

How widely used: Seldom.

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: Semantic transformation.

How widely used: Common.

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:

```c
typedef struct namel { /* ... */ } namel;       // valid C and C++
struct name { /* ... */ };                  // valid C, invalid C++
typedef int name;                         // valid C, invalid C++
```

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:

```c
class name { /* ... */ };
```
name i;         // i has type class name

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.

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.

Affected subclause: 9.2.9
Change: Banning implicit int.
In C++ a decl-specifier-seq must contain a type-specifier, unless it is followed by a declarator for a constructor, a destructor, or a conversion function. In the following example, the left-hand column presents valid C; the right-hand column presents equivalent C++:

```
void f(const parm);    void f(const int parm);
const n = 3;           const int n = 3;
main()                int main()
    /* ... */          /* ... */
```

Rationale: In C++, implicit int creates several opportunities for ambiguity between expressions involving function-like casts and declarations. Explicit declaration is increasingly considered to be proper style. Liaison with WG14 (C) indicated support for (at least) deprecating implicit int in the next revision of C.
Effect on original feature: Deletion of semantically well-defined feature.
Difficulty of converting: Syntactic transformation. Can be automated.
How widely used: Common.

Affected subclause: 9.2.9.6
Change: The keyword auto cannot be used as a storage class specifier.

```
void f() {
    auto int x;    // valid C, invalid C++
}
```

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.

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:

```
int f();    // means int f(void) in C++
            // int f( unknown ) in C
```

Rationale: This is to avoid erroneous function calls (i.e., 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.

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:
void f( struct S { int a; } arg ) {}  // valid C, invalid C++
enum E { A, B, C } f() {}           // valid C, invalid C++

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.

9  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 “obsolescent”.

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.

10 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:
struct A { int x, y; };
struct B { struct A a; };
struct A a = {.y = 1, .x = 2};  // valid C, invalid C++
int arr[3] = {{1} = 5};         // valid C, invalid C++
struct B b = {.a.x = 0};        // valid C, invalid C++
struct A c = {.x = 1, 2};       // valid C, invalid C++

Rationale: In C++, members are destroyed in reverse construction order and the elements of an initializer list are evaluated in lexical order, so field 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.

11 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:
char array[4] = "abcd";           // valid C, invalid C++

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.

12 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:
enum color { red, blue, green };
enum color c = 1;                 // valid C, invalid C++

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:

```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) */
```

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.

C.6.7 Clause 11: classes

Affected subclause: 11.3 [see also 9.2.4]
Change: In C++, a class declaration introduces the class name into the scope where it is declared and hides any object, function or other declaration of that name in an enclosing scope. In C, an inner scope declaration of a struct tag name never hides the name of an object or function in an outer scope.

Example:

```c
int x[99];
void f() {
    struct x { int a; };
    sizeof(x);  // size of the array in C
    /* size of the struct in C++ */
}
```

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.

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. For example, the following is valid in ISO 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++
```

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
\texttt{const\_cast} can be used.

\textbf{How widely used:} Seldom.

\textbf{3 Affected subclause: 11.4.10}

\textbf{Change:} Bit-fields of type plain \texttt{int} are signed.

\textbf{Rationale:} Leaving the choice of signedness to implementations could lead to inconsistent definitions of
template specializations. For consistency, the implementation freedom was eliminated for non-dependent
types, too.

\textbf{Effect on original feature:} The choice is implementation-defined in C, but not so in C++.

\textbf{Difficulty of converting:} Syntactic transformation.

\textbf{How widely used:} Seldom.

\textbf{4 Affected subclause: 11.4.12}

\textbf{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.

\textbf{Example:}

\begin{verbatim}
struct X {
    struct Y { /* ... */ } y;
};
struct Y yy;              // valid C, invalid C++
\end{verbatim}

\textbf{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.

\textbf{Effect on original feature:} Change to semantics of well-defined feature.

\textbf{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:

\begin{verbatim}
struct Y;                   // struct Y and struct X are at the same scope
struct X {
    struct Y { /* ... */ } y;
};
\end{verbatim}

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.

\textbf{How widely used:} Seldom.

\textbf{5 Affected subclause: 6.5.2}

\textbf{Change:} In C++, a \texttt{typedef-name} may not be redeclared in a class definition after being used in that
definition.

\textbf{Example:}

\begin{verbatim}
typedef int I;
struct S {
    I i;
    int I;          // valid C, invalid C++
};
\end{verbatim}

\textbf{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 \texttt{I} really is.

\textbf{Effect on original feature:} Deletion of semantically well-defined feature.

\textbf{Difficulty of converting:} Semantic transformation. Either the type or the struct member has to be
renamed.

\textbf{How widely used:} Seldom.

\section{Clause 15: preprocessing directives

\textbf{[diff.cpp]}

\textbf{1 Affected subclause: 15.11}

\textbf{Change:} Whether \texttt{__STDC__} is defined and if so, what its value is, are implementation-defined.

\textbf{Rationale:} C++ is not identical to ISO C. Mandating that \texttt{__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.7 C standard library [diff.library]

C.7.1 General [diff.library.general]

Subclause C.7 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.7.2 Modifications to headers [diff.mods.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.7.3 Modifications to definitions [diff.mods.to.declarations]

C.7.3.1 Types char16_t and char32_t [diff.char16]

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.7.3.2 Type wchar_t [diff.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.7.3.3 Header <assert.h> [diff.header.assert.h]

1 The token static_assert is a keyword in C++. It does not appear as a macro name defined in <cassert> (19.3.2).

C.7.3.4 Header <iso646.h> [diff.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.7.3.5 Header <stdalign.h> [diff.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.7.3.6 Header <stdbool.h> [diff.headerstdbool.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.7.3.7 Macro NULL [diff.null]

1 The macro NULL, defined in any of <locale> (30.5.1), <cstdlib> (17.2.1), <cstdio> (31.13.1), <cstdlib> (17.2.2), <cstring> (23.5.3), <ctime> (29.14), or <cwchar> (23.5.4), is an implementation-defined null pointer constant in C++ (17.2).

C.7.4 Modifications to declarations [diff.mods.to.declarations]

1 Header <cstring> (23.5.3): The following functions have different declarations:

- strchr
- strpbrk
- strrchr
C.7.5 Modifications to behavior

C.7.5.1 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.7.5.2 Macro `offsetof(type, member-designator)`

1 The macro `offsetof`, defined in `<cassert>` (17.2.1), accepts a restricted set of `type` arguments in C++. Subclause 17.2.4 describes the change.

C.7.5.3 Memory allocation functions

1 The functions `aligned_alloc`, `calloc`, `malloc`, and `realloc` are restricted in C++. Subclause 20.2.11 describes the changes.
Annex D  (normative)
Compatibility features  [depr]

D.1 General  [depr.general]
1 This Annex describes features of the C++ Standard 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 (9.12.4).

D.2 Arithmetic conversion on enumerations  [depr.arith.conv.enum]
1 The ability to apply the usual arithmetic conversions (7.4) on operands where one is of enumeration type and the other is of a different enumeration type or a floating-point type is deprecated.

[Note 1: Three-way comparisons (7.6.8) between such operands are ill-formed. — end note]

[Example 1:
enum E1 { e };
enum E2 { f };
bool b = e <= 3.7; // deprecated
int k = f - e; // deprecated
auto cmp = e <=> f; // error
—end example]

D.3 Implicit capture of *this by reference  [depr.capture.this]
1 For compatibility with prior revisions of C++, a lambda-expression with capture-default = (7.5.5.3) may implicitly capture *this by reference.

[Example 1:
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.4 Array comparisons  [depr.array.comp]
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:
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.5 Deprecated volatile types  [depr.volatile.type]
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:
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:
  int neck, tail;
  volatile int brachiosaur;
  brachiosaur = neck;  // OK
  tail = brachiosaur;  // OK
  tail = brachiosaur = neck;  // deprecated
  brachiosaur += neck;  // deprecated
  brachiosaur = brachiosaur + neck;  // OK
—end example]

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:
  volatile struct amber jurassic();  // deprecated
  void trex(volatile short left_arm, volatile short right_arm);  // deprecated
  void fly(volatile struct pterosaur* pteranodon);  // OK
—end example]

4 A structured binding (9.6) of a volatile-qualified type is deprecated.

[Example 4:
  struct linhenykus { short forelimb; };
  void park(linhenykus alvarezsauroid) {
    volatile auto [what_is_this] = alvarezsauroid;  // deprecated
    // ...
  }
—end example]

D.6 Redeclaration of static constexpr data members [depr.static.constexpr]

For compatibility with prior revisions of C++, a constexpr static data member may be redundantly redeclared outside the class with no initializer. This usage is deprecated.

[Example 1:
  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.7 Non-local use of TU-local entities [depr.local]

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:
  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.8 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.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.

D.10 Requires paragraph

In addition to the elements specified in 16.3.2.4, descriptions of function semantics may also contain a Requires: element to denote the preconditions for calling a function.

2 Violation of any preconditions specified in a function’s Requires: element results in undefined behavior unless the function’s Throws: element specifies throwing an exception when the precondition is violated.

D.11 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&);
}
```

2 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);
Requires: Type T is Cpp17EqualityComparable (Table 27).
Returns: !(x == y).
```

```cpp
template<class T> bool operator>(const T& x, const T& y);
Requires: Type T is Cpp17LessThanComparable (Table 28).
Returns: y < x.
```

```cpp
template<class T> bool operator<=(const T& x, const T& y);
Requires: Type T is Cpp17LessThanComparable (Table 28).
Returns: !(y < x).
```

```cpp
template<class T> bool operator>=(const T& x, const T& y);
Requires: Type T is Cpp17LessThanComparable (Table 28).
Returns: !(x < y).
```

D.12 char* streams

D.12.1 Header <strstream> synopsis

The header <strstream> defines types that associate stream buffers with character array objects and assist reading and writing such objects.

```cpp
namespace std {
    class strstreambuf;
    class istrstream;
    class ostrstream;
    class strstream;
}
```
D.12.2 Class strstreambuf

D.12.2.1 General

namespace std {
    class strstreambuf : public basic_streambuf<char> {
        public:
            strstreambuf() : strstreambuf(0) {}
            explicit strstreambuf(streamsize alsize_arg);
            strstreambuf(void* (*palloc_arg)(size_t), void (*pfree_arg)(void*));
            strstreambuf(char* gnext_arg, streamsize n, char* pbeg_arg = nullptr);
            strstreambuf(const char* gnext_arg, streamsize n);
            strstreambuf(signed char* gnext_arg, streamsize n,
                         signed char* pbeg_arg = nullptr);
            strstreambuf(const signed char* gnext_arg, streamsize n,
                          unsigned char* pbeg_arg = nullptr);
            strstreambuf(const unsigned char* gnext_arg, streamsize n);
            virtual ~strstreambuf();

            void freeze(bool freezefl = true);
            char* str();
            int pcount();

        protected:
            int_type overflow (int_type c = EOF) override;
            int_type pbackfail(int_type c = EOF) override;
            int_type underflow() 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;
            streambuf* setbuf(char* s, streamsize n) override;

        private:
            using strstate = T1;  // exposition only
            static const strstate allocated;  // exposition only
            static const strstate constant;  // exposition only
            static const strstate dynamic;  // exposition only
            static const strstate frozen;  // exposition only
            strstate strmode;  // exposition only
            streamsize alsize;  // exposition only
            void* (*palloc)(size_t);  // exposition only
            void (*pfree)(void*);  // exposition only
    };  // end of class strstreambuf

1 The class strstreambuf associates the input sequence, and possibly the output sequence, with an object of some character array type, whose elements store arbitrary values. The array object has several attributes.

2 [Note 1: For the sake of exposition, these are represented as elements of a bitmask type (indicated here as T1) called strstate. The elements are:

(2.1) — allocated, set when a dynamic array object has been allocated, and hence will be freed by the destructor for the strstreambuf object;
(2.2) — constant, set when the array object has const elements, so the output sequence cannot be written;
(2.3) — dynamic, set when the array object is allocated (or reallocated) as necessary to hold a character sequence that can change in length;
(2.4) — frozen, set when the program has requested that the array object not be altered, reallocated, or freed.

— end note]

3 [Note 2: For the sake of exposition, the maintained data is presented here as:

(3.1) — strstate strmode, the attributes of the array object associated with the strstreambuf object;]
— int alsize, the suggested minimum size for a dynamic array object;
— void* (*palloc)(size_t), points to the function to call to allocate a dynamic array object;
— void (*pfree)(void*), points to the function to call to free a dynamic array object.

— end note]

Each object of class strstreambuf has a seekable area, delimited by the pointers seeklow and seekhigh. If

gnext is a null pointer, the seekable area is undefined. Otherwise, seeklow equals gbeg and seekhigh is

either pend, if pend is not a null pointer, or gend.

D.12.2.2 strstreambuf constructors

explicit strstreambuf(streamsize alsize_arg);

1 Effects: Initializes the base class with streambuf(). The postconditions of this function are indicated

in Table 143.

Table 143: strstreambuf(streamsize) effects  [tab:depr.strstreambuf.cons.sz]

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strmode</td>
<td>dynamic</td>
</tr>
<tr>
<td>alsize</td>
<td>alsize_arg</td>
</tr>
<tr>
<td>palloc</td>
<td>a null pointer</td>
</tr>
<tr>
<td>pfree</td>
<td>a null pointer</td>
</tr>
</tbody>
</table>

strstreambuf(void* (*palloc_arg)(size_t), void (*pfree_arg)(void*));

2 Effects: Initializes the base class with streambuf(). The postconditions of this function are indicated

in Table 144.

Table 144: strstreambuf(void* (*)(size_t), void (*)(void*)) effects  [tab:depr.strstreambuf.cons.alloc]

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strmode</td>
<td>dynamic</td>
</tr>
<tr>
<td>alsize</td>
<td>an unspecified value</td>
</tr>
<tr>
<td>palloc</td>
<td>palloc_arg</td>
</tr>
<tr>
<td>pfree</td>
<td>pfree_arg</td>
</tr>
</tbody>
</table>

strstreambuf(char* gnext_arg, streamsize n, char* pbeg_arg = nullptr);
strstreambuf(signed char* gnext_arg, streamsize n,

signed char* pbeg_arg = nullptr);
strstreambuf(unsigned char* gnext_arg, streamsize n,

unsigned char* pbeg_arg = nullptr);

3 Effects: Initializes the base class with streambuf(). The postconditions of this function are indicated

in Table 145.

Table 145: strstreambuf(charT*, streamsize, charT*) effects  [tab:depr.strstreambuf.cons.ptr]

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strmode</td>
<td>0</td>
</tr>
<tr>
<td>alsize</td>
<td>an unspecified value</td>
</tr>
<tr>
<td>palloc</td>
<td>a null pointer</td>
</tr>
<tr>
<td>pfree</td>
<td>a null pointer</td>
</tr>
</tbody>
</table>

gnext_arg shall point to the first element of an array object whose number of elements N is determined

as follows:

— If n > 0, N is n.
If \( n == 0 \), \( N \) is \( \text{std::strlen(gnext_arg)} \).

If \( n < 0 \), \( N \) is \( \text{INT_MAX} \).\(^{314}\)

If \( \text{pbeg_arg} \) is a null pointer, the function executes:

\[
\text{setg(gnext_arg, gnext_arg, gnext_arg + N)};
\]

Otherwise, the function executes:

\[
\text{setg(gnext_arg, gnext_arg, pbeg_arg)};
\]

\[
\text{setp(pbeg_arg, pbeg_arg + N)};
\]

**strstreambuf(const char* gnext_arg, streamsize n);**

**strstreambuf(const signed char* gnext_arg, streamsize n);**

**strstreambuf(const unsigned char* gnext_arg, streamsize n);**

**Effects:** Behaves the same as \( \text{strstreambuf((char*)gnext_arg,n)} \), except that the constructor also sets \text{constant} in \text{strmode}.

**virtual ~strstreambuf();**

**Effects:** Destroys an object of class \text{strstreambuf}. The function frees the dynamically allocated array object only if \((\text{strmode} & \text{allocated}) != 0 \text{ and } (\text{strmode} & \text{frozen}) == 0\). (D.12.2.4 describes how a dynamically allocated array object is freed.)

### D.12.2.3 Member functions

void \text{freeze(bool freezefl = true);} \[\text{[depr.strstreambuf.members]}\]

**Effects:** If \text{strmode} \& \text{dynamic} is nonzero, alters the freeze status of the dynamic array object as follows:

1. (1.1) If \text{freezefl} is \text{true}, the function sets \text{frozen} in \text{strmode}.
2. (1.2) Otherwise, it clears \text{frozen} in \text{strmode}.

char* \text{str();} \[\text{Effects: Calls freeze()}, \text{then returns the beginning pointer for the input sequence, gbeg.}\]

\[\text{Remarks: The return value can be a null pointer.}\]

int \text{pcount() const;} \[\text{Effects: The next pointer for the output sequence, pnext, is a null pointer, returns zero. Otherwise, returns the current effective length of the array object as the next pointer minus the beginning pointer for the output sequence, pnext - pbeg.}\]

### D.12.2.4 strstreambuf overridden virtual functions

int_type \text{overflow(int_type c = EOF) override;} \[\text{[depr.strstreambuf.virtuals]}\]

**Effects:** Appends the character designated by \( c \) to the output sequence, if possible, in one of two ways:

1. (1.1) If \( c != \text{EOF} \) and if either the output sequence has a write position available or the function makes a write position available (as described below), assigns \( c \) to \(*\text{pnext}++\).

   Returns \((\text{unsigned char})c\).

2. (1.2) If \( c == \text{EOF} \), there is no character to append.

   Returns a value other than \text{EOF}.

**Remarks:** The function can alter the number of write positions available as a result of any call.

To make a write position available, the function reallocates (or initially allocates) an array object with a sufficient number of elements \( n \) to hold the current array object (if any), plus at least one additional write position. How many additional write positions are made available is otherwise unspecified. If \text{palloc} is not a null pointer, the function calls \((\text{*palloc})(n)\) to allocate the new dynamic array object.

---

\(^{314}\)The function signature \text{strlen(const char*)} is declared in \text{<cstring> (23.5.3)}. The macro \text{INT_MAX} is defined in \text{<climits> (17.3.6)}.
Otherwise, it evaluates the expression `new charT[n]`. In either case, if the allocation fails, the function returns `EOF`. Otherwise, it sets `allocated` in `strmode`.

To free a previously existing dynamic array object whose first element address is `p`: If `pfree` is not a null pointer, the function calls `(*pfree)(p)`. Otherwise, it evaluates the expression `delete[]p`.

If `(strmode & dynamic) == 0`, or if `(strmode & frozen) != 0`, the function cannot extend the array (reallocating it with greater length) to make a write position available.

*Recommended practice:* An implementation should consider `alsize` in making the decision how many additional write positions to make available.

```cpp
int_type pbackfail(int_type c = EOF) override;
```

Puts back the character designated by `c` to the input sequence, if possible, in one of three ways:

(8.1) If `c != EOF`, if the input sequence has a putback position available, and if `(char)c == gnext[-1]`, assigns `gnext - 1` to `gnext`.

Returns `c`.

(8.2) If `c != EOF`, if the input sequence has a putback position available, and if `strmode & constant` is zero, assigns `c` to `*--gnext`.

Returns `c`.

(8.3) If `c == EOF` and if the input sequence has a putback position available, assigns `gnext - 1` to `gnext`.

Returns a value other than `EOF`.

Returns `EOF` to indicate failure.

*Remarks:* 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.

```cpp
int_type underflow() override;
```

*Effects:* Reads a character from the input sequence, if possible, without moving the stream position past it, as follows:

(11.1) If the input sequence has a read position available, the function signals success by returning `(unsigned char)*gnext`.

(11.2) Otherwise, if the current write next pointer `pnext` is not a null pointer and is greater than the current read end pointer `gend`, makes a read position available by assigning to `gend` a value greater than `gnext` and no greater than `pnext`.

Returns `(unsigned char)*gnext`.

Returns `EOF` to indicate failure.

*Remarks:* The function can alter the number of read positions available as a result of any call.

```cpp
pos_type seekoff(off_type off, seekdir way, openmode which = in | out) override;
```

*Effects:* Alters the stream position within one of the controlled sequences, if possible, as indicated in Table 146.

Table 146: `seekoff` positioning  
[tab:depr.strstreambuf.seekoff.pos]

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>(which &amp; ios::in) != 0</code></td>
<td>positions the input sequence</td>
</tr>
<tr>
<td><code>(which &amp; ios::out) != 0</code></td>
<td>positions the output sequence</td>
</tr>
<tr>
<td>`(which &amp; (ios::in</td>
<td>ios::out)) == (ios::in</td>
</tr>
<tr>
<td>Otherwise</td>
<td>the positioning operation fails.</td>
</tr>
</tbody>
</table>

For a sequence to be positioned, if its next pointer is a null pointer, the positioning operation fails. Otherwise, the function determines `newoff` as indicated in Table 147.
Table 147: \texttt{newoff} values  

<table>
<thead>
<tr>
<th>Condition</th>
<th>\texttt{newoff} Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{way == ios::beg}</td>
<td>0</td>
</tr>
<tr>
<td>\texttt{way == ios::cur}</td>
<td>the next pointer minus the beginning pointer ($xnext - xbeg$).</td>
</tr>
<tr>
<td>\texttt{way == ios::end}</td>
<td>seekhigh minus the beginning pointer ($seekhigh - xbeg$).</td>
</tr>
</tbody>
</table>

If $(\texttt{newoff} + \texttt{off}) < (\texttt{seeklow} - xbeg)$ or $(\texttt{seekhigh} - xbeg) < (\texttt{newoff} + \texttt{off})$, the positioning operation fails. Otherwise, the function assigns $xbeg + \texttt{newoff} + \texttt{off}$ to the next pointer $xnext$.

Returns: \texttt{pos_type(newoff)}, constructed from the resultant offset \texttt{newoff} (of type \texttt{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 \texttt{pos_type(off_type(-1))}.

\begin{verbatim}
pos_type seekpos(pos_type sp, ios_base::openmode which = ios_base::in | ios_base::out) override;
\end{verbatim}

Effects: Alters the stream position within one of the controlled sequences, if possible, to correspond to the stream position stored in \texttt{sp} (as described below).

1. If $(\text{which} & \text{ios::in}) \neq 0$, positions the input sequence.
2. If $(\text{which} & \text{ios::out}) \neq 0$, positions the output sequence.
3. If the function positions neither sequence, the positioning operation fails.

For a sequence to be positioned, if its next pointer is a null pointer, the positioning operation fails. Otherwise, the function determines \texttt{newoff} from \texttt{sp.offset}():

1. If \texttt{newoff} is an invalid stream position, has a negative value, or has a value greater than $(\texttt{seekhigh} - \texttt{seeklow})$, the positioning operation fails
2. Otherwise, the function adds \texttt{newoff} to the beginning pointer $xbeg$ and stores the result in the next pointer $xnext$.

Returns: \texttt{pos_type(newoff)}, constructed from the resultant offset \texttt{newoff} (of type \texttt{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 \texttt{pos_type(off_type(-1))}.

\begin{verbatim}
streambuf<char*>* setbuf(char* s, streamsize n) override;
\end{verbatim}

Effects: Behavior is implementation-defined, except that \texttt{setbuf(0, 0)} has no effect.

D.12.3 Class istrstream

D.12.3.1 General

The class istrstream supports the reading of objects of class strstreambuf. It supplies a strstreambuf object to control the associated array object. For the sake of exposition, the maintained data is presented here as:
D.12.3.2 **istream constructors**

```cpp
explicit istrstream(const char* s);
explicit istrstream(char* s);
```

1. **Effects**: Initializes the base class with `istream(&sb)` and `sb` with `strstreambuf(s, 0)`. `s` shall designate the first element of an `ntbs`.

```cpp
istrstream(const char* s, streamsize n);
istrstream(char* s, streamsize n);
```

2. **Effects**: Initializes the base class with `istream(&sb)` and `sb` with `strstreambuf(s, n)`. `s` shall designate the first element of an array whose length is `n` elements, and `n` shall be greater than zero.

D.12.3.3 **Member functions**

```cpp
strstreambuf* rdbuf() const;
```

1. **Returns**: `const_cast<strstreambuf*>(&sb)`.

```cpp
char* str();
```

2. **Returns**: `rdbuf()->str()`.

D.12.4 **Class ostrstream**

D.12.4.1 **General**

```cpp
namespace std {
    class ostrstream : public basic_ostream<char> {
        public:
            ostrstream();
            ostrstream(char* s, int n, ios_base::openmode mode = ios_base::out);
            virtual ~ostrstream();

            strstreambuf* rdbuf() const;
            void freeze(bool freezefl = true);
            char* str();
            int pcount() const;
        private:
            strstreambuf sb; // exposition only
    };
}
```

1. The class `ostrstream` supports the writing of objects of class `strstreambuf`. It supplies a `strstreambuf` object to control the associated array object. For the sake of exposition, the maintained data is presented here as:

(1.1) — `sb`, the `strstreambuf` object.

D.12.4.2 **ostrstream constructors**

```cpp
ostrstream();
```

1. **Effects**: Initializes the base class with `ostream(&sb)` and `sb` with `strstreambuf()`.

```cpp
ostrstream(char* s, int n, ios_base::openmode mode = ios_base::out);
```

2. **Effects**: Initializes the base class with `ostream(&sb)`, and `sb` with one of two constructors:

(2.1) — If `(mode & app) == 0`, then `s` shall designate the first element of an array of `n` elements. The constructor is `strstreambuf(s, n, s)`.

(2.2) — If `(mode & app) != 0`, then `s` shall designate the first element of an array of `n` elements that contains an `ntbs` whose first element is designated by `s`. The constructor is `strstreambuf(s, n, s + std::strlen(s))`.\(^{315}\)

---

\(^{315}\) The function signature `strlen(const char*)` is declared in `<cstring>` (23.5.3).
D.12.4.3 Member functions

strstreambuf* rdbuf() const;
1
Returns: (strstreambuf*)&sb.

void freeze(bool freezefl = true);
2
Effects: Calls rdbuf()->freeze(freezefl).

char* str();
3
Returns: rdbuf()->str().

int pcount() const;
4
Returns: rdbuf()->pcount().

D.12.5 Class strstream

D.12.5.1 General

namespace std {

class strstream
   : public basic_iostream<char> {

   public:
   // types
   using char_type = char;
   using int_type = char_traits<char>::int_type;
   using pos_type = char_traits<char>::pos_type;
   using off_type = char_traits<char>::off_type;

   // constructors/destructor
   strstream();
   strstream(char* s, int n,
         ios_base::openmode mode = ios_base::in|ios_base::out);
   virtual ~strstream();

   // members
   strstreambuf* rdbuf() const;
   void freeze(bool freezefl = true);
   int pcount() const;
   char* str();

   private:
   strstreambuf sb; // exposition only
   }
}

1 The class strstream supports reading and writing from objects of class strstreambuf. It supplies a strstreambuf object to control the associated array object. For the sake of exposition, the maintained data is presented here as:

   (1.1) — sb, the strstreambuf object.

D.12.5.2 strstream constructors

strstream();
1
Effects: Initializes the base class with iostream(&sb).

strstream(char* s, int n,
         ios_base::openmode mode = ios_base::in|ios_base::out);
2
Effects: Initializes the base class with iostream(&sb), and sb with one of the two constructors:

(2.1) — If (mode & app) == 0, then s shall designate the first element of an array of n elements. The constructor is strstreambuf(s,n,s).

(2.2) — If (mode & app) != 0, then s shall designate the first element of an array of n elements that contains an NTBS whose first element is designated by s. The constructor is strstreambuf(s,n,s + std::strlen(s)).
D.12.5.3 `strstream` destructor

virtual ~strstream();

Effects: Destroys an object of class `strstream`.

D.12.5.4 `strstream` operations

`strstreambuf* rdbuf() const;`

Returns: `const_cast<strstreambuf*>(&sb)`.

void freeze(bool freezefl = true);

Effects: Calls `rdbuf() -> freeze(freezefl)`.

`char* str();`

Returns: `rdbuf() -> str()`.

`int pcount() const;`

Returns: `rdbuf() -> pcount()`.

D.13 The default allocator

The following member is defined in addition to those specified in 20.2.9:

```c
namespace std {
    template<class T> class allocator {
        public:
            using is_always_equal = true_type;
    }
}
```

D.14 Deprecated polymorphic_allocator member function

The following member is declared in addition to those members specified in 20.4.3.3:

```c
namespace std::pmr {
    template<class Tp = byte>
    class polymorphic_allocator {
        public:
            template <class T>
            void destroy(T* p);
    }
}
```

template<class T>
void destroy(T* p);

Effects: As if by `p -> T()`.

D.15 Deprecated type traits

The header `<type_traits>` (21.3.3) has the following addition:

```c
namespace std {
    template<class T> struct is_pod;
    template<class T> inline 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>
    struct aligned_union;
    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.

```cpp
template<class T> struct is_pod;

Requires: remove_all_extents_t<T> shall be a complete type or cv void.

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. 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.

[Note 1: It is unspecified whether a closure type (7.5.5.2) is a POD type. — end note]
```

```cpp
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. Align is equal to alignof(T) for some type T or to default-alignment.

The member typedef type is 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 aligned_storage as:

```cpp
template<size_t Len, size_t Alignment>
struct aligned_storage {
    typedef struct {
        alignas(Alignment) unsigned char __data[Len];
    } type;
};
```

— end note]
```

```cpp
template<size_t Len, class... Types>
struct aligned_union;

Mandates: At least one type is provided. Each type in the template parameter pack Types is a complete object type.

The member typedef type is a trivial standard-layout type suitable for use as uninitialized storage for any object whose type is listed in Types; its size shall be at least Len. The static member alignment_value is an integral constant of type size_t whose value is the strictest alignment of all types listed in Types.
```

D.16 Tuple

[depr.tuple]

The header <tuple> (22.4.2) has the following additions:

```cpp
namespace std {
    template<class T> class tuple_size<volatile T>;
    template<class T> class tuple_size<const volatile T>;

    template<size_t I, class T> class tuple_element<I, volatile T>;
    template<size_t I, class T> class tuple_element<I, const volatile T>;
}
```

```cpp
template<class T> class tuple_size<volatile T>;
template<class T> class tuple_size<const volatile 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 specializations of each of the two templates meet the Cpp17TransformationTrait requirements with a base characteristic of integral_constant<size_t, TS::value>. Otherwise, they have 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.
In addition to being available via inclusion of the `<tuple>` (22.4.2) header, the two templates are 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> class tuple_element<I, volatile T>;
template<size_t I, class T> class tuple_element<I, const volatile T>;
```

Let \( \text{TE} \) denote `tuple_element_t<I, T>` of the cv-unqualified type \( T \). Then specializations of each of the two templates meet the `Cpp17TransformationTrait` requirements with a member typedef `type` that names the following type:

1. For the first specialization, `add_volatile_t<TE>`, and
2. For the second specialization, `add_cv_t<TE>`.

In addition to being available via inclusion of the `<tuple>` (22.4.2) header, the two templates are available when any of the headers `<array>` (24.3.2), `<ranges>` (26.2), or `<utility>` (22.2.1) are included.

### D.17 Variant

The header `<variant>` (22.6.2) has the following additions:

```cpp
namespace std {
  template<class T> struct variant_size<volatile T>;
  template<class T> struct variant_size<const volatile T>;

  template<size_t I, class T> struct variant_alternative<I, volatile T>;
  template<size_t I, class T> struct variant_alternative<I, const volatile T>;
}
```

Let \( \text{VS} \) denote `variant_size<T>` of the cv-unqualified type \( T \). Then specializations of each of the two templates meet the `Cpp17UnaryTypeTrait` requirements with a base characteristic of `integral_constant<size_t, \text{VS}::value>`.

```cpp
template<size_t I, class T> class variant_alternative<I, volatile T>;
template<size_t I, class T> class variant_alternative<I, const volatile T>;
```

Let \( \text{VA} \) denote `variant_alternative<I, T>` of the cv-unqualified type \( T \). Then specializations of each of the two templates meet the `Cpp17TransformationTrait` requirements with a member typedef `type` that names the following type:

1. For the first specialization, `add_volatile_t<\text{VA}::type>`, and
2. For the second specialization, `add_cv_t<\text{VA}::type>`.

### D.18 Deprecated iterator class template

The header `<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 `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 `double` and such that it works on a large memory model of the implementation, it can do so with:]
class MyIterator :
public iterator<bidirectional_iterator_tag, double, long, T*, T&> {
    // code implementing ++, etc.
};
—end example]

D.19 Deprecated move_iterator access [depr.move.iter.elem]
1 The following member is declared in addition to those members specified in 25.5.3.6:

```cpp
namespace std {
    template<class Iterator>
    class move_iterator {
    public:
        constexpr pointer operator->() const;
    }
}
```

2 
`constexpr pointer operator->() const;`

Returns: current.

D.20 Deprecated shared_ptr atomic access [depr.util.smartptr.shared.atomic]
1 The header `<memory>` (20.2.2) has the following additions:

```cpp
namespace std {
    template<class T>
    bool atomic_is_lock_free(const shared_ptr<T>* p);
    template<class T>
    shared_ptr<T> atomic_load(const shared_ptr<T>* p);
    template<class T>
    shared_ptr<T> atomic_load_explicit(const shared_ptr<T>* p, memory_order mo);
    template<class T>
    void atomic_store(shared_ptr<T>* p, shared_ptr<T> r);
    template<class T>
    void atomic_store_explicit(shared_ptr<T>* p, shared_ptr<T> r, memory_order mo);
    template<class T>
    shared_ptr<T> atomic_exchange(shared_ptr<T>* p, shared_ptr<T> r);
    template<class T>
    shared_ptr<T> atomic_exchange_explicit(shared_ptr<T>* p, shared_ptr<T> r, memory_order mo);
    template<class T>
    bool atomic_compare_exchange_weak(shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w);
    template<class T>
    bool atomic_compare_exchange_strong(shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w);
    template<class T>
    bool atomic_compare_exchange_weak_explicit(
        shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w,
        memory_order success, memory_order failure);
    template<class T>
    bool atomic_compare_exchange_strong_explicit(
        shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w,
        memory_order success, memory_order failure);
}
```

2 Concurrent access to a shared_ptr object from multiple threads does not introduce a data race if the access is done exclusively via the functions in this subclause and the instance is passed as their first argument.

3 The meaning of the arguments of type memory_order is explained in 33.5.4.

```cpp
template<class T> bool atomic_is_lock_free(const shared_ptr<T>* p);
```

4 Requires: p shall not be null.

5 Returns: true if atomic access to *p is lock-free, false otherwise.
template<class T> shared_ptr<T> atomic_load(const shared_ptr<T>* p);

Requires: p shall not be null.

Returns: atomic_load_explicit(p, memory_order::seq_cst).

Throws: Nothing.

template<class T> shared_ptr<T> atomic_load_explicit(const shared_ptr<T>* p, memory_order mo);

Requires: p shall not be null.

Requires: mo shall not be memory_order::release or memory_order::acq_rel.

Returns: *p.

Throws: Nothing.

template<class T> void atomic_store(shared_ptr<T>* p, shared_ptr<T> r);

Requires: p shall not be null.

Effects: As if by atomic_store_explicit(p, r, memory_order::seq_cst).

Throws: Nothing.

template<class T> void atomic_store_explicit(shared_ptr<T>* p, shared_ptr<T> r, memory_order mo);

Requires: p shall not be null.

Requires: mo shall not be memory_order::acquire or memory_order::acq_rel.

Effects: As if by p->swap(r).

Throws: Nothing.

template<class T> shared_ptr<T> atomic_exchange(shared_ptr<T>* p, shared_ptr<T> r);

Requires: p shall not be null.

Returns: atomic_exchange_explicit(p, r, memory_order::seq_cst).

Throws: Nothing.

template<class T>

shared_ptr<T> atomic_exchange_explicit(shared_ptr<T>* p, shared_ptr<T> r, memory_order mo);

Requires: p shall not be null.

Effects: As if by p->swap(r).

Returns: The previous value of *p.

Throws: Nothing.

template<class T>

bool atomic_compare_exchange_weak(shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w);

Requires: p shall not be null and v shall not be null.

Returns:

atomic_compare_exchange_weak_explicit(p, v, w, memory_order::seq_cst, memory_order::seq_cst)

Throws: Nothing.

template<class T>

bool atomic_compare_exchange_strong(shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w);

Returns:

atomic_compare_exchange_strong_explicit(p, v, w, memory_order::seq_cst, memory_order::seq_cst)

template<class T>

bool atomic_compare_exchange_weak_explicit(
    shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w,
    memory_order success, memory_order failure);
template<class T>
bool atomic_compare_exchange_strong_explicit(
    shared_ptr<T>* p, shared_ptr<T>* v, shared_ptr<T> w,
    memory_order success, memory_order failure);

Requires: p shall not be null and v shall not be null. The failure argument shall not be memory_
order::release nor memory_order::acq_rel.

Effects: If *p is equivalent to *v, assigns w to *p and has synchronization semantics corresponding to
the value of success, otherwise assigns *p to *v and has synchronization semantics corresponding to
the value of failure.

Returns: true if *p was equivalent to *v, false otherwise.

Throws: Nothing.

Remarks: Two shared_ptr objects are equivalent if they store the same pointer value and share
ownership. The weak form may fail spuriously. See 33.5.8.2.

D.21 Deprecated basic_string capacity

The following member is declared in addition to those members specified in 23.4.3.5:

namespace std {
    template<class charT, class traits = char_traits<charT>,
    class Allocator = allocator<charT>>
    class basic_string {
    public:
        void reserve();
    };  // end class basic_string
}

void reserve();

Effects: After this call, capacity() has an unspecified value greater than or equal to size().

[Note 1: This is a non-binding shrink to fit request. — end note]

D.22 Deprecated standard code conversion facets

D.22.1 General

The header <codecvt> provides code conversion facets for various character encodings.

D.22.2 Header <codecvt> synopsis

namespace std {
    enum codecvt_mode {
        consume_header = 4,
        generate_header = 2,
        little_endian = 1
    };

    template<class Elem, unsigned long Maxcode = 0x10ffff, codecvt_mode Mode = (codecvt_mode)0>
    class codecvt_utf8 : public codecvt<Elem, char, mbstate_t> {
    public:
        explicit codecvt_utf8(size_t refs = 0);  
        ~codecvt_utf8();
    };

    template<class Elem, unsigned long Maxcode = 0x10ffff, codecvt_mode Mode = (codecvt_mode)0>
    class codecvt_utf16 : public codecvt<Elem, char, mbstate_t> {
    public:
        explicit codecvt_utf16(size_t refs = 0);  
        ~codecvt_utf16();
    };

    template<class Elem, unsigned long Maxcode = 0x10ffff, codecvt_mode Mode = (codecvt_mode)0>
    class codecvt_utf8_utf16 : public codecvt<Elem, char, mbstate_t> {
    public:
        explicit codecvt_utf8_utf16(size_t refs = 0);  
    };
}
D.22.3 Requirements

1 For each of the three code conversion facets `codecvt_utf8`, `codecvt_utf16`, and `codecvt_utf8_utf16`:

   (1.1) `Elem` is the wide-character type, such as `wchar_t`, `char16_t`, or `char32_t`.
   (1.2) `Maxcode` is the largest wide-character code that the facet will read or write without reporting a conversion error.
   (1.3) If `(Mode & consume_header)`, the facet shall consume an initial header sequence, if present, when reading a multibyte sequence to determine the endianness of the subsequent multibyte sequence to be read.
   (1.4) If `(Mode & generate_header)`, the facet shall generate an initial header sequence when writing a multibyte sequence to advertise the endianness of the subsequent multibyte sequence to be written.
   (1.5) If `(Mode & little_endian)`, the facet shall generate a multibyte sequence in little-endian order, as opposed to the default big-endian order.

2 For the facet `codecvt_utf8`:

   (2.1) The facet shall convert between UTF-8 multibyte sequences and UCS-2 or UTF-32 (depending on the size of `Elem`) within the program.
   (2.2) Endianness shall not affect how multibyte sequences are read or written.
   (2.3) The multibyte sequences may be written as either a text or a binary file.

3 For the facet `codecvt_utf16`:

   (3.1) The facet shall convert between UTF-16 multibyte sequences and UCS-2 or UTF-32 (depending on the size of `Elem`) within the program.
   (3.2) Multibyte sequences shall be read or written according to the `Mode` flag, as set out above.
   (3.3) The multibyte sequences may be written only as a binary file. Attempting to write to a text file produces undefined behavior.

4 For the facet `codecvt_utf8_utf16`:

   (4.1) The facet shall convert between UTF-8 multibyte sequences and UTF-16 (one or two 16-bit codes) within the program.
   (4.2) Endianness shall not affect how multibyte sequences are read or written.
   (4.3) The multibyte sequences may be written as either a text or a binary file.

5 The encoding forms UTF-8, UTF-16, and UTF-32 are specified in ISO/IEC 10646. The encoding form UCS-2 is specified in ISO/IEC 10646:2003.\(^\text{316}\)

D.23 Deprecated convenience conversion interfaces

D.23.1 General

The header `<locale>`\(^\text{(30.2)}\) has the following additions:

```cpp
namespace std {
    template<class Codecvt, class Elem = wchar_t,
             class WideAlloc = allocator<Elem>,
             class ByteAlloc = allocator<char>>
    class wstring_convert;

    template<class Codecvt, class Elem = wchar_t,
             class Tr = char_traits<Elem>>
    class wbuffer_convert;
}
```

\(^{316}\) Cancelled and replaced by ISO/IEC 10646:2017.
D.23.2 Class template **wstring_convert**  

Class template **wstring_convert** performs conversions between a wide string and a byte string. It lets you specify a code conversion facet (like class template `codecvt`) to perform the conversions, without affecting any streams or locales.

**[Example 1]** If you want to use the code conversion facet `codecvt_utf8` to output to `cout` a UTF-8 multibyte sequence corresponding to a wide string, but you don’t want to alter the locale for `cout`, you can write something like:

```cpp
wstring_convert<std::codecvt_utf8<wchar_t>> myconv;
std::string mbstring = myconv.to_bytes(L"Hello\n");
std::cout << mbstring;
```

--- end example ---

```cpp	namespace std {
  template<class Codecvt, class Elem = wchar_t,
           class WideAlloc = allocator<Elem>,
           class ByteAlloc = allocator<char>>
  class wstring_convert {
    public:
    using byte_string = basic_string<char, char_traits<char>, ByteAlloc>;
    using wide_string = basic_string<Elem, char_traits<Elem>, WideAlloc>;
    using state_type = typename Codecvt::state_type;
    using int_type = typename wide_string::traits_type::int_type;

    wstring_convert() : wstring_convert(new Codecvt) {}  
    explicit wstring_convert(Codecvt* pcvt);
    wstring_convert(Codecvt* pcvt, state_type state);
    explicit wstring_convert(const byte_string& byte_err,
                               const wide_string& wide_err = wide_string());
    ~wstring_convert();

    wstring_convert(const wstring_convert&) = delete;
    wstring_convert& operator=(const wstring_convert&) = delete;

    wide_string from_bytes(char byte);
    wide_string from_bytes(const char* ptr);
    wide_string from_bytes(const byte_string& str);
    wide_string from_bytes(const Elem* first, const Elem* last);

    byte_string to_bytes(Elem wchar);
    byte_string to_bytes(const Elem* wptr);
    byte_string to_bytes(const wide_string& wstr);
    byte_string to_bytes(const Elem* first, const Elem* last);

    size_t converted() const noexcept;
    state_type state() const;
  }
  private:
    byte_string byte_err_string;  // exposition only
    wide_string wide_err_string;  // exposition only
    Codecvt* cvtptr;              // exposition only
    state_type cvtstate;          // exposition only
    size_t cvtcount;              // exposition only
  }
```
(3.2) — wide_err_string — a wide string to display on errors
(3.3) — cvtptr — a pointer to the allocated conversion object (which is freed when the wstring_convert
object is destroyed)
(3.4) — cvtstate — a conversion state object
(3.5) — cvtcount — a conversion count

using byte_string = basic_string<char, char_traits<char>, ByteAlloc>;
The type shall be a synonym for basic_string<char, char_traits<char>, ByteAlloc>.

size_t converted() const noexcept;
Returns: cvtcount.

wide_string from_bytes(char byte);
wide_string from_bytes(const char* ptr);
wide_string from_bytes(const byte_string& str);
wide_string from_bytes(const char* first, const char* last);
Effects: The first member function shall convert the single-element sequence byte to a wide string.
The second member function shall convert the null-terminated sequence beginning at ptr to a wide
string. The third member function shall convert the sequence stored in str to a wide string. The
fourth member function shall convert the sequence defined by the range [first, last) to a wide string.
In all cases:
(7.1) — If the cvtstate object was not constructed with an explicit value, it shall be set to its default value
(the initial conversion state) before the conversion begins. Otherwise it shall be left unchanged.
(7.2) — The number of input elements successfully converted shall be stored in cvtcount.
Returns: If no conversion error occurs, the member function shall return the converted wide string.
Otherwise, if the object was constructed with a wide-error string, the member function shall return the
wide-error string. Otherwise, the member function throws an object of class range_error.

using int_type = typename wide_string::traits_type::int_type;
The type shall be a synonym for wide_string::traits_type::int_type.

state_type state() const;
Returns: cvtstate.

using state_type = typename Codecvt::state_type;
The type shall be a synonym for Codecvt::state_type.

byte_string to_bytes(Elem wchar);
byte_string to_bytes(const Elem* wptr);
byte_string to_bytes(const wide_string& wstr);
byte_string to_bytes(const Elem* first, const Elem* last);
Effects: The first member function shall convert the single-element sequence wchar to a byte string.
The second member function shall convert the null-terminated sequence beginning at wptr to a byte
string. The third member function shall convert the sequence stored in wstr to a byte string. The
fourth member function shall convert the sequence defined by the range [first, last) to a byte string.
In all cases:
(13.1) — If the cvtstate object was not constructed with an explicit value, it shall be set to its default value
(the initial conversion state) before the conversion begins. Otherwise it shall be left unchanged.
(13.2) — The number of input elements successfully converted shall be stored in cvtcount.
Returns: If no conversion error occurs, the member function shall return the converted byte string.
Otherwise, if the object was constructed with a byte-error string, the member function shall return the
byte-error string. Otherwise, the member function shall throw an object of class range_error.

using wide_string = basic_string<Elem, char_traits<Elem>, WideAlloc>;
The type shall be a synonym for basic_string<Elem, char_traits<Elem>, WideAlloc>.

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explicit wstring_convert(Codecvt* pcvt);
wstring_convert(Codecvt* pcvt, state_type state);
explicit wstring_convert(const byte_string& byte_err,
    const wide_string& wide_err = wide_string());

Requires: For the first and second constructors, pcvt != nullptr.

Effects: The first constructor shall store pcvt in cvtptr and default values in cvtstate, byte_-
    err_string, and wide_err_string. The second constructor shall store pcvt in cvtptr, state in
cvtstate, and default values in byte_err_string and wide_err_string; moreover the stored state
shall be retained between calls to from_bytes and to_bytes. The third constructor shall store new
Codecvt in cvtptr, state_type() in cvtstate, byte_err in byte_err_string, and wide_err in
wide_err_string.

~wstring_convert();

Effects: The destructor shall delete cvtptr.

D.23.3 Class template wbuffer_convert [depr.conversions.buffer]

Class template wbuffer_convert looks like a wide stream buffer, but performs all its I/O through an
underlying byte stream buffer that you specify when you construct it. Like class template wstring_convert,
it lets you specify a code conversion facet to perform the conversions, without affecting any streams or locales.

namespace std {
    template<class Codecvt, class Elem = wchar_t, class Tr = char_traits<Elem>>
    class wbuffer_convert : public basic_streambuf<Elem, Tr> {
        public:
            using state_type = typename Codecvt::state_type;

            wbuffer_convert() : wbuffer_convert(nullptr) {}
        explicit wbuffer_convert(streambuf* bytebuf,
            Codecvt* pcvt = new Codecvt,
            state_type state = state_type());

        ~wbuffer_convert();

        wbuffer_convert(const wbuffer_convert&) = delete;
wbuffer_convert& operator=(const wbuffer_convert&) = delete;

        streambuf* rdbuf() const;
        streambuf* rdbuf(streambuf* bytebuf);

        state_type state() const;

    private:
        streambuf* bufptr;    // exposition only
        Codecvt* cvtptr;      // exposition only
        state_type cvtstate;  // exposition only
    };
}

The class template describes a stream buffer that controls the transmission of elements of type Elem, whose
character traits are described by the class Tr, to and from a byte stream buffer of type streambuf. Conversion
between a sequence of Elem values and multibyte sequences is performed by an object of class Codecvt, which
shall meet the requirements of the standard code-conversion facet codecvt<Elem, char, mbstate_t>.

An object of this class template stores:

(3.1) — bufptr — a pointer to its underlying byte stream buffer
(3.2) — cvtptr — a pointer to the allocated conversion object (which is freed when the wbuffer_convert
        object is destroyed)
(3.3) — cvtstate — a conversion state object

state_type state() const;

Returns: cvtstate.
streambuf* rdbuf() const;
Returns: bufptr.

streambuf* rdbuf(streambuf* bytebuf);
Effects: Stores bytebuf in bufptr.
Returns: The previous value of bufptr.

using state_type = typename Codecvt::state_type;
The type shall be a synonym for Codecvt::state_type.

explicit wbuffer_convert(
streambuf* bytebuf,
Codecvt* pcvt = new Codecvt,
state_type state = state_type());
Requires: pcvt != nullptr.
Effects: The constructor constructs a stream buffer object, initializes bufptr to bytebuf, initializes cvtptr to pcvt, and initializes cvtstate to state.
~wbuffer_convert();
Effects: The destructor shall delete cvtptr.

D.24 Deprecated locale category facets [depr.locale.category]
The ctype locale category includes the following facets as if they were specified in table Table 100 of 30.3.1.2.1.
- codecvt<char16_t, char, mbstate_t>
- codecvt<char32_t, char, mbstate_t>

The ctype locale category includes the following facets as if they were specified in table Table 101 of 30.3.1.2.1.
- codecvt_byname<char16_t, char, mbstate_t>
- codecvt_byname<char32_t, char, mbstate_t>

The following class template specializations are required in addition to those specified in 30.4.2.5. The specialization codecvt<char16_t, char, mbstate_t> converts between the UTF-16 and UTF-8 encoding forms, and the specialization codecvt<char32_t, char, mbstate_t> converts between the UTF-32 and UTF-8 encoding forms.

D.25 Deprecated filesystem path factory functions [depr.fs.path.factory]
template<class Source>
path u8path(const Source& source);
template<class InputIterator>
path u8path(InputIterator first, InputIterator last);
Requires: The source and [first, last) sequences are UTF-8 encoded. The value type of Source and InputIterator is char or char8_t. Source meets the requirements specified in 31.12.6.4.
Returns:
(2.1) — If 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,
(2.2) — if value_type is wchar_t and the native wide encoding is UTF-16, or if value_type is char16_t or char32_t, convert source or [first, last) to a temporary, tmp, of type string_type and return path(tmp); otherwise,
(2.3) — 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:
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.26 Deprecated atomic operations[ depr.atomics]

D.26.1 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>*, typename atomic<T>::value_type) noexcept;
    template<class T>
    void atomic_init(atomic<T>*, typename atomic<T>::value_type) noexcept;

    #define ATOMIC_VAR_INIT(value) see below

    #define ATOMIC_FLAG_INIT see below
}
```

D.26.2 Volatile access[ depr.atomics.volatile]

1 If an atomic 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.26.3 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;
```

Effects: Equivalent to: atomic_store_explicit(object, desired, memory_order::relaxed);

D.26.4 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]

D.26.5 Flag type and operations

#define ATOMIC_FLAG_INIT see below

1 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.
Annex E  (informative)
Conformance with UAX #31

E.1 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 C++. In terms of UAX #31, C++ conforms by meeting the requirements R1 “Default Identifiers” and R4 “Equivalent Normalized Identifiers”. The other requirements, also listed below, are either alternatives not taken or do not apply to C++.

E.2 R1 Default identifiers

E.2.1 General

UAX #31 specifies a default syntax for identifiers based on properties from the Unicode Character Database, UAX #44. The general syntax is

<Identifier> := <Start> <Continue>* (<Medial> <Continue>)*

where <Start> has the XID_Start property, <Continue> has the XID_Continue property, and <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 <Start> characters, the <Medial> set is empty, and the <Continue> characters are unmodified. In the grammar used in UAX #31, this is

<Identifier> := <Start> <Continue>*
<Start> := XID_Start + u+005F
<Continue> := <Start> + XID_Continue

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

If an implementation of UAX #31 wishes to allow format characters such as ZERO WIDTH JOINER or ZERO WIDTH NON-JOINER it must define a profile allowing them, or describe precisely which combinations are permitted.

C++ does not allow format characters in identifiers, so this does not apply.

E.2.3 R1b Stable identifiers

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.

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

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.

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

UAX #31 describes how languages that use or interpret patterns of characters, such as regular expressions or number formats, may describe that syntax with Unicode properties.

C++ does not do this as part of the language, deferring to library components for such usage of patterns. This requirement does not apply to C++.
E.5 R4 Equivalent normalized identifiers  

1 UAX #31 requires that implementations describe how identifiers are compared and considered equivalent.

2 C++ 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 C++ considers case to be significant in identifier comparison, and does not do any case folding. This requirement does not apply to C++.

E.7 R6 Filtered normalized identifiers  

1 If any characters are excluded from normalization, UAX #31 requires a precise specification of those exclusions.

2 C++ does not make any such exclusions.

E.8 R7 Filtered case-insensitive identifiers  

1 C++ identifiers are case sensitive, and therefore this requirement does not apply.

E.9 R8 Hashtag identifiers  

1 There are no hashtags in C++, so this requirement does not apply.
Bibliography

— ISO 4217:2015, *Codes for the representation of currencies*
— IANA Time Zone Database. Available from: https://www.iana.org/time-zones

The arithmetic specification described in ISO/IEC 10967-1:2012 is called *LIA-1* in this document.
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All clause and subclause labels from ISO C++ 2020 (ISO/IEC 14882:2020, Programming Languages — C++) are present in this document, with the exceptions described below.

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