Working Draft, C++ Extensions for Ranges

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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1 Scope

Naturally the villagers were intrigued and soon a fire was put to the town’s greatest kettle as the soldiers dropped in three smooth stones.

“Now this will be a fine soup”, said the second soldier; “but a pinch of salt and some parsley would make it wonderful!”

—Author Unknown

This Technical Specification describes extensions to the C++ Programming Language (2) that permit operations on ranges of data. These extensions include changes and additions to the existing library facilities as well as the extension of one core language facility. In particular, changes and extensions to the Standard Library include:

1. The formulation of the foundational and iterator concept requirements using the syntax of the Concepts TS (2).
2. Analogues of the Standard Library algorithms specified in terms of the new concepts.
3. The loosening of the algorithm constraints to permit the use of sentinels to denote the end of a range and corresponding changes to algorithm return types where necessary.
4. The addition of new concepts describing range and view abstractions; that is, objects with a begin iterator and an end sentinel.
5. New algorithm overloads that take range objects.
6. Support of callable objects (as opposed to function objects) passed as arguments to the algorithms.
7. The addition of optional projection arguments to the algorithms to permit on-the-fly data transformations.
8. Analogues of the iterator primitives and new primitives in support of the addition of sentinels to the library.
9. Constrained analogues of the standard iterator adaptors and stream iterators that satisfy the new iterator concepts.
10. New iterator adaptors (counted_iterator and common_iterator) and sentinels (unreachable).

Changes to the core language include:

1. The extension of the range-based for statement to support the new iterator range requirements (9.10).

This document does not specify constrained analogues of other parts of the Standard Library (e.g., the numeric algorithms), nor does it add range support to all the places that could benefit from it (e.g., the containers).

This document does not specify any new range views, actions, or facade or adaptor utilities; all are left as future work.
2 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 14882:2014, Programming Languages - C++

(1.2) ISO/IEC TS 19217:2015, Programming Languages - C++ Extensions for Concepts

(1.3) JTC1/SC22/WG21 N4128, Ranges for the Standard Library, Revision 1

(1.4) JTC1/SC22/WG21 N3351, A Concept Design for the STL

ISO/IEC 14882:2014 is herein called the C++ Standard, N3351 is called the “The Palo Alto” report, and ISO/IEC TS 19217:2015 is called the Concepts TS.
3 Terms and definitions [intro.defs]

Terms defined in ISO/IEC 14882:2014 §17.3 are used in this document with the same meaning.

3.1 projection [defs.projection]

A (function object argument) used by an algorithm to examine the values of elements. This enables algorithms to behave based on the projected values rather than the actual element values.

[Example:

```cpp
std::pair<int, const char*> pairs[] = {{2, "foo"}, {1, "bar"}, {0, "baz"}};
ranges::sort(pairs, std::less<{}>, [] (auto const & p) { return p.first; });
```

sorts the pairs in increasing order of their first members:

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

— end example]
4 General principles

4.1 Implementation compliance

Conformance requirements for this specification are the same as those defined in ISO/IEC 14882:2014 §1.4.

[Note: Conformance is defined in terms of the behavior of programs. — end note]

4.2 Namespaces, headers, and modifications to standard classes

Since the extensions described in this technical specification are experimental and not part of the C++ standard library, they should not be declared directly within namespace std. Unless otherwise specified, all components described in this document either:

(1.1) modify an existing interface in the C++ Standard Library in-place,

(1.2) are declared in namespace std::experimental::ranges::v1.

The International Standard, ISO/IEC 14882, together with ISO/IEC TS 19217:2015 (the Concepts TS), provide important context and specification for this document. In places, this document suggests changes to be made to components in namespace std in-place. In other places, entire chapters and sections are copied from ISO/IEC 14882 and modified so as to define similar but different components in namespace std::experimental::ranges::v1.

Instructions to modify or add paragraphs are written as explicit instructions. Modifications made to existing text from the International Standard use underlining to represent added text and strikethrough to represent deleted text.

This document assumes that the contents of the std::experimental::ranges::v1 namespace will become a new constrained version of the C++ Standard Library that will be delivered alongside the existing unconstrained version.

Unless otherwise specified, references to other entities described in this document are assumed to be qualified with std::experimental::ranges::, and references to entities described in the International Standard are assumed to be qualified with std::.

New header names are prefixed with experimental/ranges/. Where the final element of a new header name is the same as an existing standard header name (e.g., <experimental/ranges/algorithm>), the new header shall include the standard header as if by

#include <algorithm>
5 Statements

5.1 Iteration statements

5.1.1 The range-based for statement

[Editor’s note: Modify ISO/IEC 14882:2014 §6.5.4/p1 to allow differently typed begin and end iterators, like in C++17.]

For a range-based for statement of the form

\[\text{for ( for-range-declaration : expression ) statement}\]

let range-init be equivalent to the expression surrounded by parentheses

\( ( \text{expression} ) \)

and for a range-based for statement of the form

\[\text{for ( for-range-declaration : braced-init-list ) statement}\]

let range-init be equivalent to the \textit{braced-init-list}. In each case, a range-based for statement is equivalent to

\[
\begin{aligned}
&\{} \\
&\text{auto } &\_\text{range} &= \text{range-init}; \\
&\text{for ( auto } &\_\text{begin} &= \text{begin-expr}, \\
& &\_\text{end} &= \text{end-expr}; \\
& &\_\text{begin} &\neq \_\text{end}; \\
& &++\_\text{begin} ) \{} \\
& &\text{for-range-declaration} &= *\_\text{begin}; \\
& &\text{statement} \\
&\}\end{aligned}
\]

\[
\begin{aligned}
&\{} \\
&\text{auto } &\_\text{range} &= \text{range-init}; \\
&\text{auto } &\_\text{begin} &= \text{begin-expr}; \\
&\text{auto } &\_\text{end} &= \text{end-expr}; \\
&\text{for ( } &; &\_\text{begin} &\neq \_\text{end}; &++\_\text{begin} ) \{} \\
& &\text{for-range-declaration} &= *\_\text{begin}; \\
& &\text{statement} \\
&\}\end{aligned}
\]

where \_\text{range}, \_\text{begin}, and \_\text{end} are variables defined for exposition only, and \_\text{Range}T is the type of the expression, and \text{begin-expr} and \text{end-expr} are determined as follows:

(1.1) if \_\text{Range}T is an array type, \text{begin-expr} and \text{end-expr} are \_\text{range} and \_\text{range} + \_\text{bound}, respectively, where \_\text{bound} is the array bound. If \_\text{Range}T is an array of unknown size or an array of incomplete type, the program is ill-formed;

(1.2) if \_\text{Range}T is a class type, the \textit{unqualified-ids} \text{begin} and \text{end} are looked up in the scope of class \_\text{Range}T as if by class member access lookup (3.4.5), and if either (or both) finds at least one declaration, \text{begin-expr} and \text{end-expr} are \_\text{range}.\text{begin()} and \_\text{range}.\text{end()}, respectively;

(1.3) otherwise, \text{begin-expr} and \text{end-expr} are \text{begin(\_\text{range})} and \text{end(\_\text{range})}, respectively, where \text{begin} and \text{end} are looked up in the associated namespaces (3.4.2). [Note: Ordinary unqualified lookup (3.4.1) is not performed. —end note]
Example:

```c
int array[5] = { 1, 2, 3, 4, 5 };
for (int& x : array)
    x *= 2;
```

— end example ]

In the `decl-specifier-seq` of a `for-range-declaration`, each `decl-specifier` shall be either a `type-specifier` or `constexpr`. The `decl-specifier-seq` shall not define a class or enumeration.

§ 5.1.1
6 Library introduction

6.1 General

This Clause describes the contents of the Ranges library, how a well-formed C++ program makes use of the library, and how a conforming implementation may provide the entities in the library.

Clause 6.3, Clauses 7 through 11, and Annex A specify the contents of the library, as well as library requirements and constraints on both well-formed C++ programs and conforming implementations.

Detailed specifications for each of the components in the library are in Clauses 7–11, as shown in Table 1.

Table 1 — Library categories

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<tr>
<th>Clause</th>
<th>Category</th>
</tr>
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<td>8</td>
<td>General utilities library</td>
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<tr>
<td>9</td>
<td>Iterators library</td>
</tr>
<tr>
<td>10</td>
<td>Algorithms library</td>
</tr>
<tr>
<td>11</td>
<td>Numerics library</td>
</tr>
</tbody>
</table>

The concepts library (Clause 7) describes library components that C++ programs may use to perform compile-time validation of template parameters and perform function dispatch based on properties of types.

The general utilities library (Clause 8) includes components used by other library elements and components used as infrastructure in C++ programs, such as function objects.

The iterators library (Clause 9) describes components that C++ programs may use to perform iterations over containers (Clause ISO/IEC 14882:2014 §23), streams (ISO/IEC 14882:2014 §27.7), stream buffers (ISO/IEC 14882:2014 §27.6), and ranges (9.9).

The algorithms library (Clause 10) describes components that C++ programs may use to perform algorithmic operations on containers (Clause ISO/IEC 14882:2014 §23) and other sequences

The numerics library (Clause 11) provides concepts that are useful to constrain numeric algorithms.

6.2 Method of description (Informative)

This subclause describes the conventions used to specify the Ranges library. 6.2.1 describes the structure of the normative Clauses 7 through 11 and Annex A. 6.2.2 describes other editorial conventions.

6.2.1 Structure of each clause

Each library clause contains the following elements, as applicable:

1. Summary
2. Requirements
3. Detailed specifications

1) 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.
6.2.1.2 Summary

1 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 Paragraphs labeled “Note(s):” or “Example(s):” are informative, other paragraphs are normative.

3 The contents of the summary and the detailed specifications include:

- (3.1) macros
- (3.2) values
- (3.3) types
- (3.4) classes and class templates
- (3.5) functions and function templates
- (3.6) objects
- (3.7) concepts

6.2.1.3 Requirements

1 Requirements describe constraints that shall be met by a C++ program that extends the Ranges library. Such extensions are generally one of the following:

- (1.1) Template arguments
- (1.2) Derived classes
- (1.3) Containers, iterators, and algorithms that meet an interface convention or satisfy a concept

2 Interface convention requirements are stated as generally as possible. Instead of stating “class X has to define a member function \texttt{operator++()},” the interface requires “for any object \texttt{x} of class \texttt{X}, ++\texttt{x} is defined.” That is, whether the operator is a member is unspecified.

3 Requirements are stated in terms of concepts (Concepts TS [dcl.spec.concept]). Concepts are stated in terms of well-defined expressions that define valid terms of the types that satisfy the concept. For every set of well-defined expression requirements there is a named concept that specifies an initial set of the valid expressions and their semantics. Any generic algorithm (Clause 10) that uses the well-defined expression requirements is described in terms of the valid expressions for its formal type parameters.

4 Template argument requirements are sometimes referenced by name. See ISO/IEC 14882:2014 §17.5.2.1.

5 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.2

6 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 satisfied. [ Example: The required \texttt{<} operator of the \texttt{StrictTotallyOrdered} concept (7.4.4) does not meet the semantic requirements of that concept when operating on NaNs. — end example] This does not affect whether a type satisfies the concept.

7 A declaration may explicitly impose requirements through its associated constraints (Concepts TS [temp.constr.decl]). When the associated constraints refer to a concept (Concepts TS [dcl.spec.concept]), additional semantic requirements are imposed on the use of the declaration.

2) Although in some cases the code given is unambiguously the optimum implementation.
If the semantic requirements of a declaration are not satisfied at the point of use, the program is ill-formed, no diagnostic required.

6.2.1.4 Detailed specifications

The detailed specifications of each entity defined in Clauses 7–11 follows the conventions established by ISO/IEC 14882:2014 §17.5.1.4.

6.2.2 Other conventions

This subclause describes several editorial conventions used to describe the contents of the Ranges library. These conventions are for describing member functions (6.2.2.1), private members (6.2.2.2), and customization point objects (6.2.2.3).

6.2.2.1 Functions within classes

This document follows the same conventions as specified in ISO/IEC 14882:2014 §17.5.2.2.

6.2.2.2 Private members

This document follows the same conventions as specified in ISO/IEC 14882:2014 §17.5.2.3.

6.2.2.3 Customization Point Objects

A customization point object is a function object (8.3) with a literal class type that interacts with user-defined types while enforcing semantic requirements on that interaction.

1 The type of a customization point object shall satisfy Semiregular (7.5.8).

2 All instances of a specific customization point object type shall be equal (7.1.1).

3 The type of a customization point object T shall satisfy Invocable<const T, Args...>() (7.6.2) when the types of Args... meet the requirements specified in that customization point object’s definition. Otherwise, T shall not have a function call operator that participates in overload resolution.

4 Each customization point object type constrains its return type to satisfy a particular concept.

5 The library defines several named customization point objects. In every translation unit where such a name is defined, it shall refer to the same instance of the customization point object.

6 [Note: Many of the customization point objects in the library evaluate function call expressions with an unqualified name which results in a call to a user-defined function found by argument dependent name lookup (ISO/IEC 14882:2014 §3.4.2). To preclude such an expression resulting in a call to unconstrained functions with the same name in namespace 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 std. When the deleted overloads are viable, user-defined overloads must be more specialized (ISO/IEC 14882:2014 §14.5.6.2) or more constrained (Concepts TS [temp.constr.order]) to be used by a customization point object. — end note]

6.3 Library-wide requirements

This subclause specifies requirements that apply to the entire Ranges library. Clauses 7 through 11 and Annex A specify the requirements of individual entities within the library.

2 Requirements specified in terms of interactions between threads do not apply to programs having only a single thread of execution.

3 Within this subclause, 6.3.1 describes the library’s contents and organization, 6.3.3 describes how well-formed C++ programs gain access to library entities, 6.3.4 describes constraints on well-formed C++ programs, and 6.3.5 describes constraints on conforming implementations.
6.3.1 Library contents and organization

6.3.1.1 Library contents

The Ranges library provides definitions for the entities and macros specified in the Ranges library headers (6.3.2).

All library entities are defined within an inline namespace `v1` within the namespace `std::experimental::ranges` or namespaces nested within namespace `std::experimental::ranges::v1`. It is unspecified whether names declared in a specific namespace are declared directly in that namespace or in an inline namespace inside that namespace.

6.3.2 Headers

Each element of the Ranges library is declared or defined (as appropriate) in a header.

The Ranges library provides the Ranges library headers, shown in Table 2.

Table 2 — Ranges TS library headers

<table>
<thead>
<tr>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>&lt;experimental/ranges/algorithm&gt;</code></td>
</tr>
<tr>
<td><code>&lt;experimental/ranges/random&gt;</code></td>
</tr>
<tr>
<td><code>&lt;experimental/ranges/concepts&gt;</code></td>
</tr>
<tr>
<td><code>&lt;experimental/ranges/tuple&gt;</code></td>
</tr>
<tr>
<td><code>&lt;experimental/ranges/functional&gt;</code></td>
</tr>
<tr>
<td><code>&lt;experimental/ranges/utility&gt;</code></td>
</tr>
</tbody>
</table>

6.3.3 Using the library

6.3.3.1 Overview

This section describes how a C++ program gains access to the facilities of the Ranges library. 6.3.3.2 describes effects during translation phase 4, while 6.3.3.3 describes effects during phase 8 (ISO/IEC 14882:2014 §2.2).

6.3.3.2 Headers

The entities in the Ranges library are defined in headers, the use of which is governed by the same requirements as specified in ISO/IEC 14882:2014 §17.6.2.2.

6.3.3.3 Linkage

Entities in the C++ standard library have external linkage (ISO/IEC 14882:2014 §3.5). Unless otherwise specified, objects and functions have the default `extern "C++"` linkage (ISO/IEC 14882:2014 §7.5).

6.3.4 Constraints on programs

6.3.4.1 Overview

This section describes restrictions on C++ programs that use the facilities of the Ranges library. The following subclauses specify constraints on the program’s use of Ranges library classes as base classes (6.3.4.2) and other constraints.

6.3.4.2 Derived classes

Virtual member function signatures defined for a base class in the Ranges library may be overridden in a derived class defined in the program (ISO/IEC 14882:2014 §10.3).

6.3.4.3 Other functions

In certain cases (operations on types used to instantiate Ranges library template components), the Ranges 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.

§ 6.3.4.3
In particular, the effects are undefined if an incomplete type (ISO/IEC 14882:2014 §3.9) is used as a template argument when instantiating a template component or evaluating a concept, unless specifically allowed for that component.

6.3.4.4 Function arguments

The constraints on arguments passed to C++ standard library function as specified in ISO/IEC 14882:2014 §17.6.4.9 also apply to arguments passed to functions in the Ranges library.

6.3.4.5 Library object access

The constraints on object access by C++ standard library functions as specified in ISO/IEC 14882:2014 §17.6.4.10 also apply to object access by functions in the Ranges library.

6.3.4.6 Requires paragraph

Violation of the preconditions specified in a function’s Requires: paragraph results in undefined behavior unless the function’s Throws: paragraph specifies throwing an exception when the precondition is violated.

6.3.5 Conforming implementations

The constraints upon, and latitude of, implementations of the Ranges library follow the same constraints and latitudes for implementations of the C++ standard library as specified in ISO/IEC 14882:2014 §17.6.5.
7 Concepts library

7.1 General

This Clause describes library components that C++ programs may use to perform compile-time validation of template parameters 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 core language concepts, comparison concepts, object concepts, and function concepts as summarized in Table 3.

Table 3 — Fundamental concepts library summary

<table>
<thead>
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<th>Header(s)</th>
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<td></td>
</tr>
</tbody>
</table>

7.1.1 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.

Not all input values must be valid for a given expression; e.g., 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. The domain of an expression is the set of input values for which the expression is required to be well-defined.

Expressions required by this specification to be equality preserving are further required to be stable: two evaluations of such an expression with the same input objects must have equal outputs absent any explicit intervening modification of those input objects. [Note: 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 this document 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. This document uses 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 must not be modified.

Where a requires-expression declares an expression that is non-modifying for some constant lvalue operand, additional variants 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 variant is explicitly required with differing semantics. Such implicit expression variants must meet the semantic requirements of the declared
expression. The extent to which an implementation validates the syntax of these implicit expression variants is unspecified.

[Example:

```cpp
template <class T>
concept bool C() {
    return requires(T a, T b, const T c, const T d) {
        c == d;  // #1
        a = std::move(b); // #2
        a = c;  // #3
    };
}
```

Expression #1 does not modify either of its operands, #2 modifies both of its operands, and #3 modifies only its first operand a.

Expression #1 implicitly requires additional expression variants that meet the requirements for c == d (including non-modification), as if the expressions

```cpp
a == d;    a == b;    a == move(b);    a == d;
c == a;    c == move(a);    c == move(d);
move(a) == d; move(a) == b; move(a) == move(b); move(a) == move(d);
move(c) == b; move(c) == move(b); move(c) == d; move(c) == move(d);
```

had been declared as well.

Expression #3 implicitly requires additional expression variants that meet the requirements for a = c (including non-modification of the second operand), as if the expressions a = b and a = move(c) had been declared. Expression #3 does not implicitly require an expression variant with a non-constant rvalue second operand, since expression #2 already specifies exactly such an expression explicitly. — end example]

[Example: 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 C<T>() is not satisfied. Since implementations are not required to validate the syntax of implicit requirements, it is unspecified whether or not an implementation diagnoses as ill-formed a program which requires C<T>(). — end example]

7.2 Header <experimental/ranges/concepts> synopsis [concepts.lib.synopsis]

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    // 7.3, core language concepts:
    // 7.3.2, Same:
    template <class T, class U>
    concept bool Same() {
        return see below;
    }

    // 7.3.3, DerivedFrom:
    template <class T, class U>
    concept bool DerivedFrom() {
        return see below;
    }
}}}
```

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// 7.3.4, ConvertibleTo:
template <class T, class U>
concept bool ConvertibleTo() {
    return see below;
}

// 7.3.5, CommonReference:
template <class T, class U>
concept bool CommonReference() {
    return see below;
}

// 7.3.6, Common:
template <class T, class U>
concept bool Common() {
    return see below;
}

// 7.3.7, Integral:
template <class T>
concept bool Integral() {
    return see below;
}

// 7.3.8, SignedIntegral:
template <class T>
concept bool SignedIntegral() {
    return see below;
}

// 7.3.9, UnsignedIntegral:
template <class T>
concept bool UnsignedIntegral() {
    return see below;
}

// 7.3.10, Assignable:
template <class T, class U>
concept bool Assignable() {
    return see below;
}

// 7.3.11, Swappable:
template <class T>
concept bool Swappable() {
    return see below;
}

template <class T, class U>
concept bool Swappable() {
    return see below;
}

// 7.4, comparison concepts:
// 7.4.2, Boolean:
template <class B>
concept bool Boolean() { return see below; }

// 7.4.3, EqualityComparable:
template <class T, class U>
concept bool WeaklyEqualityComparable() { return see below; }

template <class T>
concept bool EqualityComparable() { return see below; }

template <class T, class U>
concept bool EqualityComparable() { return see below; }

// 7.4.4, StrictTotallyOrdered:
template <class T>
concept bool StrictTotallyOrdered() { return see below; }

template <class T, class U>
concept bool StrictTotallyOrdered() { return see below; }

// 7.5, object concepts:
// 7.5.1, Destructible:
template <class T>
concept bool Destructible() { return see below; }

// 7.5.2, Constructible:
template <class T, class... Args>
concept bool Constructible() { return see below; }

// 7.5.3, DefaultConstructible:
template <class T>
concept bool DefaultConstructible() { return see below; }

// 7.5.4, MoveConstructible:
template <class T>
concept bool MoveConstructible() {
return see below;
}

// 7.5.5, CopyConstructible:
template <class T>
concept bool CopyConstructible() {
  return see below;
}

// 7.5.6, Movable:
template <class T>
concept bool Movable() {
  return see below;
}

// 7.5.7, Copyable:
template <class T>
concept bool Copyable() {
  return see below;
}

// 7.5.8, Semiregular:
template <class T>
concept bool Semiregular() {
  return see below;
}

// 7.5.9, Regular:
template <class T>
concept bool Regular() {
  return see below;
}

// 7.6, callable concepts:
// 7.6.2, Invocable:
template <class F, class... Args>
concept bool Invocable() {
  return see below;
}

// 7.6.3, RegularInvocable:
template <class F, class... Args>
concept bool RegularInvocable() {
  return see below;
}

// 7.6.4, Predicate:
template <class F, class... Args>
concept bool Predicate() {
  return see below;
}

// 7.6.5, Relation:
template <class R, class T>
concept bool Relation() {

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return see below;
);

template <class R, class T, class U>
concept bool Relation() {
  return see below;
}

// 7.6.6, StrictWeakOrder:
template <class R, class T>
concept bool StrictWeakOrder() {
  return see below;
}

template <class R, class T, class U>
concept bool StrictWeakOrder() {
  return see below;
}
}]]

7.3 Core language concepts [concepts.lib.corelang]

7.3.1 In general [concepts.lib.corelang.general]

1 This section contains the definition of concepts corresponding to language features. These concepts express relationships between types, type classifications, and fundamental type properties.

7.3.2 Concept Same [concepts.lib.corelang.same]

template <class T, class U>
concept bool Same() {
  return see below;
}

1 Same<T, U>() is satisfied if and only if T and U denote the same type.

2 Remarks: For the purposes of constraint checking, Same<T, U>() implies Same<U, T>().

7.3.3 Concept DerivedFrom [concepts.lib.corelang.derived]

template <class T, class U>
concept bool DerivedFrom() {
  return see below;
}

1 DerivedFrom<T, U>() is satisfied if and only if is_base_of<U, T>::value is true.

7.3.4 Concept ConvertibleTo [concepts.lib.corelang.convertibleto]

template <class T, class U>
concept bool ConvertibleTo() {
  return see below;
}

1 ConvertibleTo<T, U>() is satisfied if and only if is_convertible<T, U>::value is true.

7.3.5 Concept CommonReference [concepts.lib.corelang.commonref]

1 For two types T and U, if common_reference_t<T, U> is well-formed and denotes a type C such that both ConvertibleTo<T, C>() and ConvertibleTo<U, C>() are satisfied, then T and U share a common reference

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type, C. [Note: C could be the same as T, or U, or it could be a different type. C may be a reference type. C need not be unique. — end note]

template <class T, class U>
concept bool CommonReference() {
    return requires(T (&t)(), U (&u)()) {
        typename common_reference_t<T, U>;
        typename common_reference_t<U, T>;
        requires Same<common_reference_t<T, U>,
            common_reference_t<U, T>>();
        common_reference_t<T, U>(t());
        common_reference_t<T, U>(u());
    };
}

Let C be common_reference_t<T, U>. Let t be a function whose return type is T, and let u be a function whose return type is U. CommonReference<T, U>() is satisfied if and only if:

(2.1) — C(t()) equals C(t()) if and only if t() is an equality preserving expression (7.1.1).

(2.2) — C(u()) equals C(u()) if and only if u() is an equality preserving expression.

[Note: Users can customize the behavior of CommonReference by specializing the basic_common_reference class template (8.4.3). — end note]

7.3.6 Concept Common

[concepts.lib.corelang.common]

If T and U can both be explicitly converted to some third type, C, then T and U share a common type, C. [Note: C could be the same as T, or U, or it could be a different type. C may not be unique. — end note]

template <class T, class U>
concept bool Common() {
    return CommonReference<const T&, const U&>() &&
    requires(T (&t)(), U (&u)()) {
        typename common_type_t<T, U>;
        typename common_type_t<U, T>;
        requires Same<common_type_t<T, U>, common_type_t<U, T>>();
        common_type_t<T, U>(t());
        common_type_t<T, U>(u());
        requires CommonReference<add_lvalue_reference_t<common_type_t<T, U>>,
            common_type_t<T, add_lvalue_reference_t<common_type_t<const T>>,
            add_lvalue_reference_t<common_type_t<const U>>>();
    };
}

Let C be common_type_t<T, U>. Let t be a function whose return type is T, and let u be a function whose return type is U. Common<T, U>() is satisfied if and only if:

(2.1) — C(t()) equals C(t()) if and only if t() is an equality preserving expression (7.1.1).

(2.2) — C(u()) equals C(u()) if and only if u() is an equality preserving expression.

[Note: Users can customize the behavior of Common by specializing the common_type class template (8.4.2). — end note]

7.3.7 Concept Integral

[concepts.lib.corelang.integral]
template <class T>
concept bool Integral() {
    return is_integral<T>::value;
}

7.3.8 Concept SignedIntegral

template <class T>
concept bool SignedIntegral() {
    return Integral<T>() && is_signed<T>::value;
}

[Note: SignedIntegral<T>() may be satisfied even for types that are not signed integral types (ISO/IEC 14882:2014 §3.9.1); for example, char. — end note]

7.3.9 Concept UnsignedIntegral

template <class T>
concept bool UnsignedIntegral() {
    return Integral<T>() && !SignedIntegral<T>();
}

[Note: UnsignedIntegral<T>() may be satisfied even for types that are not unsigned integral types (ISO/IEC 14882:2014 §3.9.1); for example, char. — end note]

7.3.10 Concept Assignable

Let t be an lvalue of type T, and R be the type remove_reference_t<U>. If U is an lvalue reference type, let v be an lvalue of type R; otherwise, let v be an rvalue of type R. Let uu be a distinct object of type R such that uu is equal to v. Then Assignable<T, U>() is satisfied if and only if

1. addressof(t = v) == addressof(t).
2. After evaluating t = v, t is equal to uu and:
   1.2.1. If v is a non-const rvalue, its resulting state is valid but unspecified (ISO/IEC 14882:2014 §17.6.5.15).
   1.2.2. Otherwise, v is not modified.

7.3.11 Concept Swappable

template <class T>
concept bool Swappable() {
    return requires(T& a, T& b) {
        ranges::swap(std::forward<T>(a), std::forward<T>(b));
    };
}

template <class T, class U>
concept bool Swappable() {
    return Swappable<T>() &&
    Swappable<U>() &&
    CommonReference<const T&, const U&>() &&
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 \( U \).

An object \( t \) is swappable with an object \( u \) if and only if \( \text{Swappable}\langle T, U \rangle() \) is satisfied. \( \text{Swappable}\langle T, U \rangle() \) is satisfied if and only if given distinct objects \( t_2 \) equal to \( t \) and \( u_2 \) equal to \( u \), after evaluating either \( \text{ranges}\langle\text{swap}(t, u) \rangle \) or \( \text{ranges}\langle\text{swap}(u, t) \rangle \), \( t_2 \) is equal to \( u \) and \( u_2 \) is equal to \( t \).

An rvalue or lvalue \( t \) is swappable if and only if \( t \) is swappable with any rvalue or lvalue, respectively, of type \( T \).

[Example: 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 <utility>

// Requires: \( \text{std}\langle\text{forward}\langle T \rangle(t) \rangle \) shall be swappable with \( \text{std}\langle\text{forward}\langle U \rangle(u) \rangle \).
template <class T, class U>
void value_swap(T&& t, U&& u) {
    using std::experimental::ranges::swap;
    swap(std::forward<T>(t), std::forward<U>(u)); // OK: uses “swappable with” conditions
    // for rvalues and lvalues
}

// Requires: lvalues of \( T \) shall be swappable.
template <class T>
void lv_swap(T& t1, T& t2) {
    using std::experimental::ranges::swap;
    swap(t1, t2); // OK: uses swappable conditions for lvalues of type \( T \)
}

namespace N {
    struct A { int m; }
    struct Proxy { A* a; }
    Proxy proxy(A& a) { return Proxy{ &a }; }

    void swap(A& x, Proxy p) {
        std::experimental::ranges::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);
}```
7.4 Comparison concepts [concepts.lib.compare]

7.4.1 In general [concepts.lib.compare.general]

This section describes concepts that establish relationships and orderings on values of possibly differing object types.

7.4.2 Concept Boolean [concepts.lib.compare.boolean]

The Boolean concept specifies the requirements on a type that is usable in Boolean contexts.

```cpp
template <class B>
concept bool Boolean() {
    return MoveConstructible<B>() && // (see 7.5.4)
    requires(const B b1, const B b2, const bool a) {
        bool(b1);
        { b1 } -> bool;
        bool(!b1);
        { !b1 } -> bool;
        { b1 && b2 } -> Same<bool>;
        { b1 && a } -> Same<bool>;
        { a && b1 } -> Same<bool>;
        { b1 || b2 } -> Same<bool>;
        { b1 || a } -> Same<bool>;
        { a || b1 } -> Same<bool>;
        { b1 == b2 } -> bool;
        { b1 != b2 } -> bool;
        { b1 == a } -> bool;
        { a == b1 } -> bool;
        { b1 != a } -> bool;
        { a != b1 } -> bool;
    };
}
```

Given values \(b_1\) and \(b_2\) of type \(B\), then \(\text{Boolean}<B>()\) is satisfied if and only if

(2.1) \(-\) \(\text{bool}(b_1) == [](\text{bool} x) \{ \text{return } x; \}(b_1)\).

(2.2) \(-\) \(\text{bool}(b_1) == !\text{bool}(!b_1)\).

(2.3) \(-\) \((b_1 && b_2), (b_1 && \text{bool}(b_2)), \text{and } (\text{bool}(b_1) && b_2)\) are all equal to \((\text{bool}(b_1) && \text{bool}(b_2))\), and have the same short-circuit evaluation.

(2.4) \(-\) \((b_1 || b_2), (b_1 || \text{bool}(b_2)), \text{and } (\text{bool}(b_1) || b_2)\) are all equal to \((\text{bool}(b_1) || \text{bool}(b_2))\), and have the same short-circuit evaluation.

(2.5) \(-\) \(\text{bool}(b_1 == b_2), \text{bool}(b_1 == \text{bool}(b_2)), \text{and } \text{bool}(\text{bool}(b_1) == b_2)\) are all equal to \((\text{bool}(b_1) == \text{bool}(b_2))\).

(2.6) \(-\) \(\text{bool}(b_1 != b_2), \text{bool}(b_1 != \text{bool}(b_2)), \text{and } \text{bool}(\text{bool}(b_1) != b_2)\) are all equal to \((\text{bool}(b_1) != \text{bool}(b_2))\).

[Example: The types \text{bool}, \text{std::true\_type}, \text{and std::bitset<N>::reference} are Boolean types. Pointers, smart pointers, and types with explicit conversions to \text{bool} are not Boolean types. —end example]
7.4.3 Concept EqualityComparable

```cpp
template <class T, class U>
concept bool WeaklyEqualityComparable() {
    return requires(const T& t, const U& u) {
        { t == u } -> Boolean;
        { u == t } -> Boolean;
        { t != u } -> Boolean;
        { u != t } -> Boolean;
    };
}
```

Let $t$ and $u$ be objects of types $T$ and $U$ respectively. $\text{WeaklyEqualityComparable}<T, U>()$ is satisfied if and only if:

1. $t == u$, $u == t$, $t != u$, and $u != t$ have the same domain.
2. $\text{bool}(u == t) == \text{bool}(t == u)$.
3. $\text{bool}(t != u) == !\text{bool}(t == u)$.
4. $\text{bool}(u != t) == \text{bool}(t != u)$.

```cpp
template <class T>
concept bool EqualityComparable() {
    return WeaklyEqualityComparable<T, T>();
}
```

Let $a$ and $b$ be objects of type $T$. $\text{EqualityComparable}<T>()$ is satisfied if and only if:

1. $\text{bool}(a == b)$ if and only if $a$ is equal to $b$.
2. [Note: The requirement that the expression $a == b$ is equality preserving implies that $==$ is reflexive, transitive, and symmetric. — end note]

```cpp
template <class T, class U>
concept bool EqualityComparable() {
    return CommonReference<const T&, const U&>() &&
            EqualityComparable<T>() &&
            EqualityComparable<U>() &&
            EqualityComparable<
                remove_cv_t<remove_reference_t<common_reference_t<const T&, const U&>>>() &&
            WeaklyEqualityComparable<T, U>();
}
```

Let $t$ be an object of type $T$, $u$ be an object of type $U$, and $C$ be $\text{common_reference_t<const T&, const U&}>$. Then $\text{EqualityComparable}<T, U>()$ is satisfied if and only if:

1. $\text{bool}(t == u) == \text{bool}(C(t) == C(u))$.

7.4.4 Concept StrictTotallyOrdered

```cpp
template <class T>
concept bool StrictTotallyOrdered() {
    return EqualityComparable<T>() &&
            requires(const T a, const T b) {
                { a < b } -> Boolean;
                { a > b } -> Boolean;
                { a <= b } -> Boolean;
                { a >= b } -> Boolean;
            };
}
```

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Let \(a, b,\) and \(c\) be objects of type \(T\). Then \text{StrictTotallyOrdered}<T>() is satisfied if and only if

1. Exactly one of \(\text{bool}(a < b), \text{bool}(a > b),\) or \(\text{bool}(a == b)\) is true.
2. If \(\text{bool}(a < b)\) and \(\text{bool}(b < c)\), then \(\text{bool}(a < c)\).
3. \(\text{bool}(a > b) == \text{bool}(b < a)\).
4. \(\text{bool}(a <= b) == !\text{bool}(b < a)\).
5. \(\text{bool}(a >= b) == !\text{bool}(a < b)\).

```cpp
template <class T, class U>
concept bool StrictTotallyOrdered() {
    return CommonReference<const T&, const U&>() &&
    StrictTotallyOrdered<T>() &&
    StrictTotallyOrdered<U>() &&
    StrictTotallyOrdered<
        remove_cv_t<remove_reference_t<common_reference_t<const T&, const U&>>>() &&
    EqualityComparable<T, U>() &&
    requires(const T t, const U u) {
        { t < u } -> Boolean;
        { t > u } -> Boolean;
        { t <= u } -> Boolean;
        { t >= u } -> Boolean;
        { u < t } -> Boolean;
        { u > t } -> Boolean;
        { u <= t } -> Boolean;
        { u >= t } -> Boolean;
    };
}
```

Let \(t\) be an object of type \(T\), \(u\) be an object of type \(U\), and \(C\) be \text{common_reference_t<const T&, const U&>}. Then \text{StrictTotallyOrdered<T, U>()} is satisfied if and only if

1. \(\text{bool}(t < u) == \text{bool}(C(t) < C(u))\).
2. \(\text{bool}(t > u) == \text{bool}(C(t) > C(u))\).
3. \(\text{bool}(t <= u) == \text{bool}(C(t) <= C(u))\).
4. \(\text{bool}(t >= u) == \text{bool}(C(t) >= C(u))\).
5. \(\text{bool}(u < t) == \text{bool}(C(u) < C(t))\).
6. \(\text{bool}(u > t) == \text{bool}(C(u) > C(t))\).
7. \(\text{bool}(u <= t) == \text{bool}(C(u) <= C(t))\).
8. \(\text{bool}(u >= t) == \text{bool}(C(u) >= C(t))\).

### 7.5 Object concepts

This section describes concepts that specify the basis of the value-oriented programming style on which the library is based.

#### 7.5.1 Concept Destructible

The Destructible concept is the base of the hierarchy of object concepts. It specifies properties that all such object types have in common.

```cpp
template <class T>
concept bool Destructible() {
    return requires(T t, const T ct, T* p) {
        { t.~T() } noexcept;
    };
}
```
The expression requirement \( \&ct \) does not require implicit expression variants.

Given a (possibly const) lvalue \( t \) of type \( T \) and pointer \( p \) of type \( T* \), \texttt{Destructible<T>()} is satisfied if and only if

\begin{align}
&\text{(3.1)} & \text{After evaluating the expression } t.\sim T(), \text{ delete } p, \text{ or delete[] } p, \text{ all resources owned by the denoted object(s) are reclaimed.} \\
&\text{(3.2)} & \&t == \text{addressof}(t). \\
&\text{(3.3)} & \text{The expression } \&t \text{ is non-modifying.}
\end{align}

\[ \text{Note: Unlike the } \texttt{Destructible} \text{ library concept in the C++ Standard (ISO/IEC 14882:2014 §17.6.3.1), this concept forbids destructors that are noexcept(false), even if non-throwing.} \]

### 7.5.2 Concept Constructible

The \texttt{Constructible} concept is used to constrain the type of a variable to be either an object type constructible from a given set of argument types, or a reference type that can be bound to those arguments.

```cpp
template <class T, class... Args>
concept bool __ConstructibleObject = // exposition only
    Destructible<T>() && requires(Args&&... args) {
        T{std::forward<Args>(args)...}; // not required to be equality preserving
        new T{std::forward<Args>(args)...}; // not required to be equality preserving
    };

template <class T, class... Args>
concept bool __BindableReference = // exposition only
    is_reference<T>::value && requires(Args&&... args) {
        T{std::forward<Args>(args)...};
    };

template <class T, class... Args>
concept bool Constructible() {
    return __ConstructibleObject<T, Args...> ||
        __BindableReference<T, Args...>;
}
```

### 7.5.3 Concept DefaultConstructible

```cpp
template <class T>
concept bool DefaultConstructible() {
    return Constructible<T>() &&
        requires(const size_t n) {
            new T[n]{}; // not required to be equality preserving
        };
}
```

\[ \text{Note: The array allocation expression } \texttt{new T[n]{} } \text{ implicitly requires that } T \text{ has a non-explicit default constructor.} \]

### 7.5.4 Concept MoveConstructible

```cpp
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```
Let U be the type remove_cv_t<T>, rv be an rvalue of type U, and u2 be a distinct object of type T equal to rv. Then MoveConstructible<T>() is satisfied if and only if

1. After the definition T u = rv;, u is equal to u2.
2. T{rv} or *new T{rv} is equal to u2.

rv’s resulting state is valid but unspecified (ISO/IEC 14882:2014 §17.6.5.15).

### 7.5.5 Concept CopyConstructible

Let v be an lvalue of type (possibly const) remove_cv_t<T> or an rvalue of type const remove_cv_t<T>. Then CopyConstructible<T>() is satisfied if and only if

1. After the definition T u = v;, u is equal to v.
2. T{v} or *new T{v} is equal to v.

### 7.5.6 Concept Movable

### 7.5.7 Concept Copyable

### 7.5.8 Concept Semiregular

[Note: The Semiregular concept is satisfied by types that behave similarly to built-in types like int, except that they may not be comparable with ==. — end note]
7.5.9 Concept Regular

```
template <class T>
concept bool Regular() {
    return Semiregular<T>() &&
        EqualityComparable<T>();
}
```

[Note: The Regular concept is satisfied by types that behave similarly to built-in types like int and that are comparable with ==. — end note]

7.6 Callable concepts

7.6.1 In general

The concepts in this section describe the requirements on function objects (8.3) and their arguments.

7.6.2 Concept Invocable

```
template <class F, class... Args>
concept bool Invocable() {
    return requires(F&& f, Args&&... args) {
        invoke(std::forward<F>(f), std::forward<Args>(args)...); // not required to be equality preserving
    };
}
```

[Note: Since the invoke function call expression is not required to be equality-preserving (7.1.1), a function that generates random numbers may satisfy Invocable. — end note]

7.6.3 Concept RegularInvocable

```
template <class F, class... Args>
concept bool RegularInvocable() {
    return Invocable<F, Args...>();
}
```

[Note: The invoke function call expression shall be equality-preserving (7.1.1). [Note: This requirement supersedes the annotation in the definition of Invocable. — end note]

[Note: A random number generator does not satisfy RegularInvocable. — end note]

[Note: The distinction between Invocable and RegularInvocable is purely semantic. — end note]

7.6.4 Concept Predicate

```
template <class F, class... Args>
concept bool Predicate() {
    return RegularInvocable<F, Args...>() &&
        Boolean<result_of_t<F&(Args&&...)>>();
}
```

7.6.5 Concept Relation

```
template <class R, class T>
concept bool Relation() {
    return Predicate<R, T, T>();
}
```

§ 7.6.5
template <class R, class T, class U>
concept bool Relation() {
    return Relation<R, T>() &&
    Relation<R, U>() &&
    CommonReference<const T&, const U&>() &&
    Relation<R,
    common_reference_t<const T&, const U&>() &&
    Predicate<R, T, U>() &&
    Predicate<R, U, T>();
}

Let \( r \) be any object of type \( R \), \( t \) be any object of type \( T \), \( u \) be any object of type \( U \), and \( C \) be \texttt{common\_reference\_t<const T&, const U&>}. Then \( \text{Relation}<R, T, U>() \) is satisfied if and only if

\[
\begin{align*}
(1.1) & \quad \text{bool}(r(t, u)) == \text{bool}(r(C(t), C(u))). \\
(1.2) & \quad \text{bool}(r(u, t)) == \text{bool}(r(C(u), C(t))).
\end{align*}
\]

### 7.6.6 Concept StrictWeakOrder

**Template**

```cpp
template <class R, class T>
concept bool StrictWeakOrder() {
    return Relation<R, T>();
}
```

**Template**

```cpp
template <class R, class T, class U>
concept bool StrictWeakOrder() {
    return Relation<R, T, U>();
}
```

A Relation satisfies **StrictWeakOrder** if and only if it imposes a strict weak ordering on its arguments. The term **strict** refers to the requirement of an irreflexive relation (\(!\text{comp}(x, x)\) for all \( x \)), and the term **weak** to requirements that are not as strong as those for a total ordering, but stronger than those for a partial ordering. If we define \texttt{equiv}(a, b) as \texttt{!comp}(a, b) \&\& \texttt{!comp}(b, a), then the requirements are that \texttt{comp} and \texttt{equiv} both be transitive relations:

\[
\begin{align*}
(2.1) & \quad \text{comp}(a, b) \&\& \text{comp}(b, c) \implies \text{comp}(a, c) \\
(2.2) & \quad \text{equiv}(a, b) \&\& \text{equiv}(b, c) \implies \text{equiv}(a, c) \quad [\text{Note: Under these conditions, it can be shown that}]
\end{align*}
\]

\[
\begin{align*}
(2.2.1) & \quad \text{equiv} \text{ is an equivalence relation} \\
(2.2.2) & \quad \text{comp} \text{ induces a well-defined relation on the equivalence classes determined by equiv} \\
(2.2.3) & \quad \text{The induced relation is a strict total ordering.} \quad [\text{end note}] \\
\end{align*}
\]


8 General utilities library

8.1 General

This Clause describes utilities that are generally useful in C++ programs; some of these utilities are used by other elements of the Ranges library. These utilities are summarized in Table 4.

Table 4 — General utilities library summary

<table>
<thead>
<tr>
<th>Subclause</th>
<th>Header(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>&lt;experimental/ranges/utility&gt;</td>
</tr>
<tr>
<td>8.3</td>
<td>&lt;experimental/ranges/functional&gt;</td>
</tr>
<tr>
<td>8.4</td>
<td>&lt;type_traits&gt;</td>
</tr>
<tr>
<td>8.5</td>
<td>&lt;experimental/ranges/utility&gt; &amp;</td>
</tr>
<tr>
<td></td>
<td>&lt;experimental/ranges/tuple&gt;</td>
</tr>
</tbody>
</table>

8.2 Utility components

This subclause contains some basic function and class templates that are used throughout the rest of the library.

Header <experimental/ranges/utility> synopsis

The header <experimental/ranges/utility> defines several types, function templates, and concepts that are described in this Clause. It also defines the templates tagged and tagged_pair and various function templates that operate on tagged_pair objects.

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    // 8.2.1, swap:
    namespace {
        constexpr unspecified swap = unspecified ;
    }

    // 8.2.2, exchange:
    template <MoveConstructible T, class U=T>
    requires Assignable<T&, U>()
    T exchange(T& obj, U& new_val);

    // 8.5.2, struct with named accessors
    template <class T>
    concept bool TagSpecifier() {
        return see below;
    }

    template <class F>
    concept bool TaggedType() {
        return see below;
    }

    template <class Base, TagSpecifier... Tags>
    requires sizeof...(Tags) <= tuple_size<Base>::value
    struct tagged;

```
// 8.5.4, tagged pairs
template <TaggedType T1, TaggedType T2> using tagged_pair = see below;

// 8.5.3, tuple-like access to tagged
namespace std {
    // 8.5.3, tuple-like access to tagged
    template <class Base, class... Tags>
    struct tuple_size<experimental::ranges::tagged<Base, Tags...>>;

    template <size_t N, class Base, class... Tags>
    struct tuple_element<N, experimental::ranges::tagged<Base, Tags...>>;
} // end std namespace

Any entities declared or defined directly in namespace std in header <utility> that are not already defined in namespace std::experimental::ranges::v1 in header <experimental/ranges/utility> are imported with using-declarations (ISO/IEC 14882:2014 §7.3.3). [Example:

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    using std::pair;
    using std::make_pair;
    // ... others
}}}}

—end example]

8.2.1 swap [utility.swap]

The name swap denotes a customization point object (6.2.2.3). The effect of the expression ranges::swap(E1, E2) for some expressions E1 and E2 is equivalent to:

(1.1) — (void)swap(E1, E2), if that expression is valid, with overload resolution performed in a context that includes the declarations

    template <class T>
    void swap(T&, T&) = delete;
    template <class T, size_t N>
    void swap(T(&)[N], T(&)[N]) = delete;

and does not include a declaration of ranges::swap. If the function selected by overload resolution does not exchange the values referenced by E1 and E2, the program is ill-formed with no diagnostic required.

(1.2) — Otherwise, (void)swap_ranges(E1, E2) if E1 and E2 are lvalues of array types (ISO/IEC 14882:2014 §3.9.2) of equal extent and ranges::swap(*(E1), *(E2)) is a valid expression, except that noexcept(ranges::swap(E1, E2)) is equal to noexcept(ranges::swap(*(E1), *(E2))).

(1.3) — Otherwise, if E1 and E2 are lvalues of the same type T which meets the syntactic requirements of MoveConstructible<T>() and Assignable<T&, T>(), exchanges the referenced values. ranges::swap(E1, E2) is a constant expression if the constructor selected by overload resolution for T{std::move(E1)} is a constexpr constructor and the expression E1 = std::move(E2) can appear in a constexpr function. noexcept(ranges::swap(E1, E2)) is equal to is_nothrow_move_constructible<T>::value && is_nothrow_move_assignable<T>::value. If either MoveConstructible or Assignable is not satisfied, the program is ill-formed with no diagnostic required.
Otherwise, `ranges::swap(E1, E2)` is ill-formed.

*Remark:* Whenever `ranges::swap(E1, E2)` is a valid expression, it exchanges the values referenced by `E1` and `E2` and has type `void`.

### 8.2.2 exchange

```cpp
template <MoveConstructible T, class U=T>
requires Assignable<T&, U>()
T exchange(T& obj, U&& new_val);
```

*Effects:* Equivalent to:

```cpp
T old_val = std::move(obj);
obj = std::forward<U>(new_val);
return old_val;
```

### 8.3 Function objects

#### Header `<experimental/ranges/functional>` synopsis

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    // 8.3.1, invoke:
    template <class F, class... Args>
    result_of_t<F&&(Args&&...)> invoke(F&& f, Args&&... args);

    // 8.3.2, comparisons:
    template <class T = void>
    requires EqualityComparable<T>() || Same<T, void>()
    struct equal_to;

    template <class T = void>
    requires EqualityComparable<T>() || Same<T, void>()
    struct not_equal_to;

    template <class T = void>
    requires StrictTotallyOrdered<T>() || Same<T, void>()
    struct greater;

    template <class T = void>
    requires StrictTotallyOrdered<T>() || Same<T, void>()
    struct less;

    template <class T = void>
    requires StrictTotallyOrdered<T>() || Same<T, void>()
    struct greater_equal;

    template <class T = void>
    requires StrictTotallyOrdered<T>() || Same<T, void>()
    struct less_equal;

    template <> struct equal_to<void>;
    template <> struct not_equal_to<void>;
    template <> struct greater<void>;
    template <> struct less<void>;
    template <> struct greater_equal<void>;
    template <> struct less_equal<void>;
```
Any entities declared or defined directly in namespace `std` in header `<functional>` that are not already defined in namespace `std::experimental::ranges` in header `<experimental/ranges/functional>` are imported with `using-declarations` (ISO/IEC 14882:2014 §7.3.3). [Example:

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    using std::reference_wrapper;
    using std::ref;
    // ... others
}}}}

—end example]

Any nested namespaces defined directly in namespace `std` in header `<functional>` that are not already defined in namespace `std::experimental::ranges` in header `<experimental/ranges/functional>` are aliased with a `namespace-alias-definition` (ISO/IEC 14882:2014 §7.3.2). [Example:

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    namespace placeholders = std::placeholders;
}}}}

—end example]

8.3.1 Function template `invoke` [func.invoke]

template <class F, class... Args>
result_of_t<F&&(Args&&...)> invoke(F&& f, Args&&... args);

Effects: Equivalent to:
```cpp
default invokes (std::forward<F>(f), std::forward<Args>(args)...); (ISO/IEC 14882:2014 §20.9.2).
```

8.3.2 Comparisons [comparisons]

The library provides basic function object classes for all of the comparison operators in the language (ISO/IEC 14882:2014 §5.9, ISO/IEC 14882:2014 §5.10).

```cpp
template <class T = void>
requires EqualityComparable<T>() || Same<T, void>()
struct equal_to {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

Effects: `operator()` returns `x == y`.

```cpp
template <class T = void>
requires EqualityComparable<T>() || Same<T, void>()
struct not_equal_to {
    constexpr bool operator()(const T& x, const T& y) const;
};
```

Effects: `operator()` returns `x != y`.

```cpp
template <class T = void>
requires StrictTotallyOrdered<T>() || Same<T, void>()
struct greater {
```
constexpr bool operator()(const T& x, const T& y) const;

operator() returns x > y.

template <class T = void>
  requires StrictTotallyOrdered<T>() || Same<T, void>()
  struct less {
    constexpr bool operator()(const T& x, const T& y) const;
  };

operator() returns x < y.

template <class T = void>
  requires StrictTotallyOrdered<T>() || Same<T, void>()
  struct greater_equal {
    constexpr bool operator()(const T& x, const T& y) const;
  };

operator() returns x >= y.

template <class T = void>
  requires StrictTotallyOrdered<T>() || Same<T, void>()
  struct less_equal {
    constexpr bool operator()(const T& x, const T& y) const;
  };

operator() returns x <= y.

template <> struct equal_to<void> {
  template <class T, class U>
    requires EqualityComparable<T, U>()
    constexpr auto operator()(T&& t, U&& u) const
      -> decltype(std::forward<T>(t) == std::forward<U>(u));

typedef unspecified is_transparent;
};

operator() returns std::forward<T>(t) == std::forward<U>(u).

template <> struct not_equal_to<void> {
  template <class T, class U>
    requires EqualityComparable<T, U>()
    constexpr auto operator()(T&& t, U&& u) const
      -> decltype(std::forward<T>(t) != std::forward<U>(u));

typedef unspecified is_transparent;
};

operator() returns std::forward<T>(t) != std::forward<U>(u).

template <> struct greater<void> {
  template <class T, class U>
    requires StrictTotallyOrdered<T, U>()
    constexpr auto operator()(T&& t, U&& u) const
      -> decltype(std::forward<T>(t) > std::forward<U>(u));

typedef unspecified is_transparent;
};

§ 8.3.2
operator() returns std::forward<T>(t) > std::forward<U>(u).

```
template <> struct less<void> {
  template <class T, class U>
  requires StrictTotallyOrdered<T, U>()
  constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) < std::forward<U>(u));

typedef unspecified is_transparent;
};
```

operator() returns std::forward<T>(t) < std::forward<U>(u).

```
template <> struct greater_equal<void> {
  template <class T, class U>
  requires StrictTotallyOrdered<T, U>()
  constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) >= std::forward<U>(u));

typedef unspecified is_transparent;
};
```

operator() returns std::forward<T>(t) >= std::forward<U>(u).

```
template <> struct less_equal<void> {
  template <class T, class U>
  requires StrictTotallyOrdered<T, U>()
  constexpr auto operator()(T&& t, U&& u) const
    -> decltype(std::forward<T>(t) <= std::forward<U>(u));

typedef unspecified is_transparent;
};
```

operator() returns std::forward<T>(t) <= std::forward<U>(u).

For templates greater, less, greater_equal, and less_equal, the specializations for any pointer type yield a total order, even if the built-in operators <,>, <=, >= do not.

### 8.3.3 Class identity

```
struct identity {
  template <class T>
  constexpr T&& operator()(T&& t) const noexcept;

  typedef unspecified is_transparent;
};
```

operator() returns std::forward<T>(t).

### 8.4 Metaprogramming and type traits

#### 8.4.1 Header <type_traits> synopsis

[Editor's note: Change the <type_traits> synopsis (ISO/IEC 14882:2014 §20.10.2) as follows. Note: this change is intended to be made in namespace std.]

```
namespace std {
  [...]
  // 20.10.4.3, type properties:
}
```
[...]  
```cpp
template <class T> struct is_move_assignable;
```

```cpp
template <class T, class U> struct is_swappable_with:
```

```cpp
template <class T> struct is_destructible;
```

[...]  
```cpp
template <class T> struct is_nothrow_move_assignable;
```

```cpp
template <class T, class U> struct is_nothrow_swappable_with:
```

```cpp
template <class T> struct is_nothrow_destructible;
```

[...]  
```cpp```

// 20.10.7.6, other transformations:  
[...]  
```cpp
template <class... T> struct common_type;
```

```cpp
template <class T, class U, template <class> class TQual, template <class> class UQual>
```

```cpp
struct basic_common_reference {};
```

```cpp
template <class... T> struct common_reference;
```

```cpp
template <class T> struct underlying_type;
```

[...]  
```cpp```

// 20.15.4.3, type properties  
[...]  
```cpp
template <class T, class U> constexpr bool is_swappable_with_v
```

```cpp
= is_swappable_with<T, U>::value;
```

```cpp
template <class T> constexpr bool is_swappable_v
```

```cpp
= is_swappable<T>::value;
```

[...]  
```cpp
template <class T, class U> constexpr bool is_nothrow_swappable_with_v
```

```cpp
= is_nothrow_swappable_with<T, U>::value;
```

```cpp
template <class T> constexpr bool is_nothrow_swappable_v
```

```cpp
= is_nothrow_swappable<T>::value;
```

[...]  
```cpp```

8.4.2 Type properties [meta.unary.prop]  
[Editor’s note: Change [meta.unary.prop], Table 49 – “Type property predicates” in ISO/IEC 14882:2014 as indicated. The following is taken from the current Working Draft of C++17.]  

Table 49 — Type property predicates

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
</table>

...
<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;    </code></td>
<td><code>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 in an overload-resolution context for swappable values (7.3.11). Access checking is performed as if in a context unrelated to T and U. Only the validity of the immediate context of the <code>swap</code> expressions is considered. [Note: The compilation of the expressions can result in side effects such as the instantiation of class template specializations and function template specializations, the generation of implicitly-defined functions, and so on. Such side effects are not in the &quot;immediate context&quot; and can result in the program being ill-formed. — end note]`</td>
</tr>
<tr>
<td><code>template &lt;class T&gt;             </code></td>
<td><code>struct is_swappable;</code></td>
<td>For a referenceable type T, the same result as <code>is_swappable_with_v&lt;T&amp;, T&amp;&gt;</code>, otherwise false.</td>
</tr>
<tr>
<td><code>template &lt;class T, class U&gt;    </code></td>
<td><code>struct is_nothrow_swappable_with;</code></td>
<td><code>is_swappable_with_v&lt;T, U&gt;</code> is true and each <code>swap</code> expression of the definition of <code>is_swappable_with&lt;T, U&gt;</code> is known not to throw any exceptions (ISO/IEC 14882:2014 §5.3.7).</td>
</tr>
</tbody>
</table>
Table 49 — Type property predicates (continued)

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Preconditions</th>
</tr>
</thead>
</table>
| template `<class T>`
struct is_nothrow_swappable;
| For a referenceable type T, the same result as `is_nothrow_swappable` with `v<T&, T&>`, otherwise false. | T shall be a complete type, (possibly cv-qualified) void, or an array of unknown bound. |

8.4.3 Other transformations

[Editor’s note: Change Table 57 – “Other Transformations” in ISO/IEC 14882:2014 as follows:]

Table 57 — Other transformations

<table>
<thead>
<tr>
<th>Template</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| template `<class... T>`
struct common_type; | The member typedef type shall be defined or omitted as specified below. If it is omitted, there shall be no member type. All types in the parameter pack T shall be complete or (possibly cv) void. A program may specialize this trait if at least one template parameter in the specialization depends on a user-defined type and `sizeof...(T) == 2`. [Note: Such specializations are needed when only explicit conversions are desired among the template arguments. — end note] |
| template `<class T, class U,`
`template <class> class TQual,`
`template <class> class UQual>`
struct basic_common_reference; | The primary template shall have no member typedef type. A program may specialize this trait if at least one template parameter in the specialization depends on a user-defined type. In such a specialization, a member typedef type may be defined or omitted. If it is omitted, there shall be no member type. [Note: Such specializations may be used to influence the result of common_reference. — end note] |
| template `<class... T>`
struct common_reference; | The member typedef type shall be defined or omitted as specified below. If it is omitted, there shall be no member type. Each type in the parameter pack T shall be complete or (possibly cv) void. |

§ 8.4.3
Let \( \text{CREF}(A) \) be \( \text{add	extunderscore lvalue	extunderscore reference}_t<\text{const remove	extunderscore reference}_t<A> \). Let \( \text{UNCVREF}(A) \) be \( \text{remove	extunderscore cv}_t<\text{remove	extunderscore reference}_t<A> \). Let \( \text{XREF}(A) \) denote a unary template \( T \) such that \( T<\text{UNCVREF}(A)> \) denotes the same type as \( A \). Let \( \text{COPYCV}(\text{FROM}, \text{TO}) \) be an alias for type \( \text{TO} \) with the addition of \( \text{FROM} \)’s top-level \textit{cv}-qualifiers. \[ \text{Example: } \text{COPYCV}(\text{const int}, \text{volatile short}) \text{ is an alias for } \text{const volatile short}. \] Let \( \text{COND	extunderscore RES}(X, Y) \) be \( \text{decltype}(\text{declval<bool>() ? declval<X>() : declval<Y>()}) \). Given types \( A \) and \( B \), let \( X \) be \( \text{remove	extunderscore reference}_t<A> \), let \( Y \) be \( \text{remove	extunderscore reference}_t<B> \), and let \( \text{COMMON	extunderscore REF}(A, B) \) be:

1. If \( A \) and \( B \) are both lvalue reference types, \( \text{COMMON	extunderscore REF}(A, B) \) is \( \text{COND	extunderscore RES}(\text{COPYCV}(X, Y) \& \& \text{COPYCV}(Y, X) \& \&) \).
2. Otherwise, let \( C \) be \( \text{RREF	extunderscore RES}(\text{COMMON	extunderscore REF}(X\&\&, Y\&\&)). \) If \( A \) and \( B \) are both rvalue reference types, and \( C \) is well-formed, and \( \text{is	extunderscore convertible}_t<A, C>::\text{value} \) and \( \text{is	extunderscore convertible}_t<B, C>::\text{value} \) are true, then \( \text{COMMON	extunderscore REF}(A, B) \) is \( C \).
3. Otherwise, let \( D \) be \( \text{COMMON	extunderscore REF}(\text{const } X\&, Y\&\&). \) If \( A \) is an rvalue reference and \( B \) is an lvalue reference and \( D \) is well-formed and \( \text{is	extunderscore convertible}_t<A, D>::\text{value} \) is true, then \( \text{COMMON	extunderscore REF}(A, B) \) is \( D \).
4. Otherwise, if \( A \) is an lvalue reference and \( B \) is an rvalue reference, then \( \text{COMMON	extunderscore REF}(A, B) \) is \( \text{COMMON	extunderscore REF}(B, A) \).
5. Otherwise, \( \text{COMMON	extunderscore REF}(A, B) \) is \( \text{decay	extunderscore t}<\text{COND	extunderscore RES}(\text{CREF}(A), \text{CREF}(B))> \).

If any of the types computed above are ill-formed, then \( \text{COMMON	extunderscore REF}(A, B) \) is ill-formed.

2. For the \textit{common	extunderscore type} trait applied to a parameter pack \( T \) of types, the member \texttt{type} shall be either defined or not present as follows:

1. If \( \text{sizeof...}(T) \) is zero, there shall be no member \texttt{type}.
2. Otherwise, if \( \text{sizeof...}(T) \) is one, let \( T_0, T_1 \) denote the sole type in the pack \( T \). The member typedef \texttt{type} shall denote the same type as \( \text{decay	extunderscore t}<T_0 T_1> \).
3. Otherwise, if \( \text{sizeof...}(T) \) is two, let \( T_1 \) and \( T_2 \) denote the two types in the pack \( T \), and let \( D_1 \) and \( D_2 \) be \( \text{decay	extunderscore t}<T_1>T_2 \) and \( \text{decay	extunderscore t}<T_2>T_1 \) respectively. Then

   a. If \( D_1 \) and \( T_1 \) denote the same type and \( D_2 \) and \( T_2 \) denote the same type, then
      a. If \( \text{COMMON	extunderscore REF}(T_1, T_2) \) is well-formed, then the member typedef \texttt{type} denotes that type.
      b. Otherwise, there shall be no member \texttt{type}.
   b. Otherwise, if \( \text{common	extunderscore type}_t<D_1, D_2> \) is well-formed, then the member typedef \texttt{type} denotes that type.
   c. Otherwise, there shall be no member \texttt{type}.

4. Otherwise, if \( \text{sizeof...}(T) \) is greater than two, let \( T_1, T_2, \) and \( \text{Rest} \), respectively, denote the first, second, and (pack of) remaining types comprising \( T \). \[ \text{Note: } \text{sizeof...}(\text{Rest}) \text{ may be zero.} \] Let \( C \) denote the type, if any, of an unevaluated conditional expression (5.16) whose first operand is an arbitrary value of type \( \text{bool} \), whose second operand is an \texttt{xvalue} of type \( T_1 \), and whose third operand is an \texttt{xvalue} of type \( T_2 \) to be the type \( \text{common	extunderscore type}_t<T_1, T_2> \). Then:

   a. If there is such a type \( C \), the member typedef \texttt{type} shall denote the same type, if any, as \( \text{common	extunderscore type}_t<C, \text{Rest}...> \).

\[ \text{§ 8.4.3} \]
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:

1. If sizeof...(T) is zero, there shall be no member type.
2. Otherwise, if sizeof...(T) is one, let T1 denote the sole type in the pack T. The member typedef type shall denote the same type as T1.
3. Otherwise, if sizeof...(T) is two, let T1 and T2 denote the two types in the pack T. Then
   1. If COMMON_REF(T1, T2) is well-formed and denotes a reference type then the member typedef type denotes that type.
   2. Otherwise, if basic_common_reference<UNCVREF(T1), UNCVREF(T2), XREF(T1), XREF(T2)>::type is well-formed, then the member typedef type denotes that type.
   3. Otherwise, if common_type_t<T1, T2> is well-formed, then the member typedef type denotes that type.
   4. Otherwise, there shall be no member type.
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:
   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...>.
   2. Otherwise, there shall be no member type.

8.5 Tagged tuple-like types

8.5.1 In general

The library provides a template for augmenting a tuple-like type with named element accessor member functions. The library also provides several templates that provide access to tagged objects as if they were tuple objects (see ISO/IEC 14882:2014 §20.4.2.6).

8.5.2 Class template tagged

Class template tagged augments a tuple-like class type (e.g., pair (ISO/IEC 14882:2014 §20.3), tuple (ISO/IEC 14882:2014 §20.4)) by giving it named accessors. It is used to define the alias templates tagged_pair (8.5.4) and tagged_tuple (8.5.5).

In the class synopsis below, let i be in the range [0, sizeof...(Tags)) and Ti be the ith type in Tags, where indexing is zero-based.

```cpp
// defined in header <experimental/ranges/utility>
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <class T>
    concept bool TagSpecifier() {
        return implementation-defined;
    }

    template <class F>
    concept bool TaggedType() {
```
return implementation-defined;
}

template <class Base, TagSpecifier... Tags>
  requires sizeof...(Tags) <= tuple_size<Base>::value
struct tagged :
  Base, TAGGET(tagged<Base, Tags...>, T, i)... { // see below
    using Base::Base;
    tagged() = default;
    tagged(tagged&) = default;
    tagged(const tagged&) = default;
    tagged &operator=(tagged&) = default;
    tagged &operator=(const tagged&) = default;
    template <class Other>
      requires Constructible<Base, Other>()
      tagged(tagged<Other, Tags...>&& that) noexcept(see below);
    template <class Other>
      requires Constructible<Base, const Other&>()
      tagged(const tagged<Other, Tags...>& that);
    template <class Other>
      requires Assignable<Base&, Other&>()
      tagged& operator=(tagged<Other, Tags...>&& that) noexcept(see below);
    template <class Other>
      requires Assignable<Base&, const Other&>()
      tagged& operator=(const tagged<Other, Tags...>& that);
    template <class U>
      requires Assignable<Base&, U>() & !Same<decay_t<U>, tagged>()
      tagged& operator=(U&& u) noexcept(see below);
    void swap(tagged& that) noexcept(see below)
      requires Swappable<Base&>();
    friend void swap(tagged&, tagged&) noexcept(see below)
      requires Swappable<Base&>();
  };
};

3 A tagged getter is an empty trivial class type that has a named member function that returns a reference to a member of a tuple-like object that is assumed to be derived from the getter class. The tuple-like type of a tagged getter is called its DerivedCharacteristic. The index of the tuple element returned from the getter’s member functions is called its ElementIndex. The name of the getter’s member function is called its ElementName.

4 A tagged getter class with DerivedCharacteristic D, ElementIndex N, and ElementName name shall provide the following interface:

    struct __TAGGED_GETTER {
      constexpr decltype(auto) name() const & { return get<N>(static_cast<D&>(*this)); }
      constexpr decltype(auto) name() && { return get<N>(static_cast<D&&>(*this)); }
      constexpr decltype(auto) name() const { return get<N>(static_cast<const D&>(*this)); }
    };

5 A tag specifier is a type that facilitates a mapping from a tuple-like type and an element index into a tagged getter that gives named access to the element at that index. TagSpecifier<T>() is satisfied if and only if T is a tag specifier. The tag specifiers in the Tags parameter pack shall be unique. [Note: The mapping mechanism from tag specifier to tagged getter is unspecified. — end note]

6 Let TAGGET(D, T, N) name a tagged getter type that gives named access to the N-th element of the
tuple-like type D.

It shall not be possible to delete an instance of class template tagged through a pointer to any base other than Base.

TaggedType<\( F \)>() is satisfied if and only if \( F \) is a unary function type with return type \( T \) which satisfies TagSpecifier<\( T \)>(). Let \( \text{TAGSPEC}(F) \) name the tag specifier of the TaggedType \( F \), and let \( \text{TAGELEM}(F) \) name the argument type of the TaggedType \( F \).

\[
\text{template } <\text{class Other}>
\text{requires Constructible<Base, Other>()}
\text{tagged(tagged<Other, Tags...> &\&that) noexcept(see below)};
\]

\( Remarks: \) The expression in the noexcept is equivalent to:

\[
\text{is_nothrow_constructible<Base, Other>::value}
\]

\( Effects: \) Initializes Base with static\_cast<Other&>(that).

\[
\text{template } <\text{class Other}>
\text{requires Constructible<Base, const Other&>()}
\text{tagged(const tagged<Other, Tags...>& that)};
\]

\( Effects: \) Initializes Base with static\_cast<const Other&>(that).

\[
\text{template } <\text{class Other}>
\text{requires Assignable<Base&, Other&>()}
\text{tagged\& operator=(tagged<Other, Tags...>&& that) noexcept(see below)};
\]

\( Remarks: \) The expression in the noexcept is equivalent to:

\[
\text{is_nothrow_assignable<Base&, Other>::value}
\]

\( Effects: \) Assigns static\_cast<Other&>(that) to static\_cast<Base&>(*\this).

\( Returns: \) *\this.

\[
\text{template } <\text{class Other}>
\text{requires Assignable<Base&, const Other&>()}
\text{tagged\& operator=(const tagged<Other, Tags...>& that)};
\]

\( Effects: \) Assigns static\_cast<const Other&>(that) to static\_cast<Base&>(*\this).

\( Returns: \) *\this.

\[
\text{template } <\text{class U}>
\text{requires Assignable<Base&, U&>() && !Same<decay_t<U>, tagged>()}
\text{tagged\& operator=(U&& u) noexcept(see below)};
\]

\( Remarks: \) The expression in the noexcept is equivalent to:

\[
\text{is_nothrow_assignable<Base&, U>::value}
\]

\( Effects: \) Assigns std::\_forward\<\U\>(u) to static\_cast<Base&>(*\this).

\( Returns: \) *\this.

\[
\text{void swap(tagged\& rhs) noexcept(see below)}
\text{requires Swappable<Base&>()};
\]

\( Remarks: \) The expression in the noexcept is equivalent to:

\[
\text{noexcept(swap(declval<Base&>(), declval<Base&>()))}
\]
Effects: Calls \texttt{swap} on the result of applying \texttt{static\_cast} to \(*\texttt{this}\) and \texttt{that}.

\textbf{Throws:} Nothing unless the call to \texttt{swap} on the \texttt{Base} sub-objects throws.

\begin{verbatim}
friend void swap(tagged& lhs, tagged& rhs) noexcept(see below)
  requires Swappable<Base&>();
\end{verbatim}

\textbf{Remarks}: The expression in the \texttt{noexcept} is equivalent to:

\begin{verbatim}
  noexcept(lhs.swap(rhs))
\end{verbatim}

Effects: Equivalent to \texttt{lhs.swap(rhs)}.

8.5.3 Tuple-like access to \texttt{tagged} [tagged.astuple]

\begin{verbatim}
namespace std {
  template <class Base, class... Tags>
  struct tuple_size<experimental::ranges::tagged<Base, Tags...>>
    : tuple_size<Base> { };

  template <size_t N, class Base, class... Tags>
  struct tuple_element<N, experimental::ranges::tagged<Base, Tags...>>
    : tuple_element<N, Base> { };
}
\end{verbatim}

8.5.4 Alias template \texttt{tagged\_pair} [tagged.pairs]

\begin{verbatim}
// defined in header <experimental/ranges/utility>
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  // ...
  template <TaggedType T1, TaggedType T2>
  using tagged_pair = tagged<pair<TAGELEM(T1), TAGELEM(T2)>,
    TAGSPEC(T1), TAGSPEC(T2)>;
}}}}
\end{verbatim}

\begin{itemize}
\item \texttt{Example:}
  \begin{verbatim}
  // See 10.2:
  tagged_pair<tag::min(int), tag::max(int)> p{0, 1};
  assert(&p.min() == &p.first);
  assert(&p.max() == &p.second);
  
  // end example
\end{verbatim}
\end{itemize}

8.5.4.1 Tagged pair creation functions [tagged.pairs.creation]

\begin{verbatim}
// defined in header <experimental/ranges/utility>

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  // ...
  template <TagSpecifier Tag1, TagSpecifier Tag2, class T1, class T2>
  constexpr
  see below make_tagged_pair(T1&& x, T2&& y);
}}}}
\end{verbatim}

\begin{itemize}
\item Let \( P \) be the type of \texttt{make\_pair(std::forward<T1>(x), std::forward<T2>(y))}. Then the return type is \texttt{tagged}\_\texttt{P, Tag1, Tag2}.
\item \textbf{Returns}: \texttt{std::forward<T1>(x), std::forward<T2>(y)}.
\item \texttt{Example}: In place of:
  \begin{verbatim}
    return tagged_pair<tag::min(int), tag::max(double)>(5, 3.1415926); // explicit types
  \end{verbatim}
\end{itemize}
a C++ program may contain:

```cpp
    return make_tagged_pair<tag::min, tag::max>(5, 3.1415926); // types are deduced
```

— end example]

8.5.5 Alias template tagged_tuple

[tagged.tuple]

1 Header <experimental/ranges/tuple> synopsis

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {

    template <TaggedType... Types>
    using tagged_tuple = tagged<tuple<TAGELEM(Types)...>,
    TAGSPEC(Types)...>;

    template <TagSpecifier... Tags, class... Types>
    requires sizeof...(Tags) == sizeof...(Types)
    constexpr
    see below make_tagged_tuple(Types&&... t);
}}}}
```

2 Any entities declared or defined in namespace std in header <tuple> that are not already defined in
   namespace std::experimental::ranges in header <experimental/ranges/tuple> are imported with
   using-declarations (ISO/IEC 14882:2014 §7.3.3).

   ```cpp
   namespace std { namespace experimental { namespace ranges { inline namespace v1 {
       using std::tuple;
       using std::make_tuple;
       // ... others
   }}}}
   ```

   — end example]

```

3

```cpp
    template <TaggedType... Types>
    using tagged_tuple = tagged<tuple<TAGELEM(Types)...>,
    TAGSPEC(Types)...>;
```

4

   [Example:

   ```cpp
   // See 10.2:
   tagged_tuple<tag::in(char*), tag::out(char*)> t{0, 0};
   assert(&t.in() == &get<0>(t));
   assert(&t.out() == &get<1>(t));
   ```

   — end example]

8.5.5.1 Tagged tuple creation functions

[tagged.tuple.creation]

```cpp
    template <TagSpecifier... Tags, class... Types>
    requires sizeof...(Tags) == sizeof...(Types)
    constexpr
    see below make_tagged_tuple(Types&&... t);
```

1 Let T be the type of make_tuple(std::forward<Types>(t)...). Then the return type is tagged<T, Tags...>.

2 Returns: tagged<T, Tags...>(std::forward<Types>(t)...).

3 [Example:

   ```cpp
   int i; float j;
   make_tagged_tuple<tag::in1, tag::in2, tag::out>(i, ref(i), cref(j))
   ```

§ 8.5.5.1
creates a tagged tuple of type

```
tagged_tuple<tag::in1(int), tag::in2(int&), tag::out(const float&)>
```

— end example]
9 Iterators library [iterators]

9.1 General [iterators.general]

1 This Clause describes components that C++ programs may use to perform iterations over containers (Clause ISO/IEC 14882:2014 §23), streams (ISO/IEC 14882:2014 §27.7), stream buffers (ISO/IEC 14882:2014 §27.6), and ranges (9.9).

2 The following subclauses describe iterator requirements, and components for iterator primitives, predefined iterators, and stream iterators, as summarized in Table 5.

Table 5 — Iterators library summary

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9.2 Header <experimental/ranges/iterator> synopsis [iterator.synopsis]

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  template <class T> concept bool dereferenceable // exposition only
    = requires(T& t) { {*t} -> auto&&; };

  // 9.3, iterator requirements:
  // 9.3.2, customization points:
  namespace {
    // 9.3.2.1, iter_move:
    constexpr unspecified iter_move = unspecified;

    // 9.3.2.2, iter_swap:
    constexpr unspecified iter_swap = unspecified;
  }

  // 9.3.3, associated types:
  // 9.3.3.1, difference_type:
  template <class> struct difference_type;
  template <class T> using difference_type_t
    = typename difference_type<T>::type;

  // 9.3.3.2, value_type:
  template <class> struct value_type;
  template <class T> using value_type_t
    = typename value_type<T>::type;

  // 9.3.3.3, iterator_category:
  template <class> struct iterator_category;
```
template <class T> using iterator_category_t
  = typename iterator_category<T>::type;

template <dereferenceable T> using reference_t
  = decltype(*declval<T&>());

template <dereferenceable T>
  requires see below using rvalue_reference_t
  = decltype(ranges::iter_move(declval<T&>()));

// 9.3.4, Readable:
template <class In>
concept bool Readable() {
  return see below;
}

// 9.3.5, Writable:
template <class Out, class T>
concept bool Writable() {
  return see below;
}

// 9.3.6, WeaklyIncrementable:
template <class I>
concept bool WeaklyIncrementable() {
  return see below;
}

// 9.3.7, Incrementable:
template <class I>
concept bool Incrementable() {
  return see below;
}

// 9.3.8, Iterator:
template <class I>
concept bool Iterator() {
  return see below;
}

// 9.3.9, Sentinel:
template <class S, class I>
concept bool Sentinel() {
  return see below;
}

// 9.3.10, SizedSentinel:
template <class S, class I>
constexpr bool disable_sized_sentinel = false;

template <class S, class I>
concept bool SizedSentinel() {
  return see below;
}
// 9.3.11, InputIterator:
template <class I>
concept bool InputIterator() {
    return see below;
}

// 9.3.12, OutputIterator:
template <class I>
concept bool OutputIterator() {
    return see below;
}

// 9.3.13, ForwardIterator:
template <class I>
concept bool ForwardIterator() {
    return see below;
}

// 9.3.14, BidirectionalIterator:
template <class I>
concept bool BidirectionalIterator() {
    return see below;
}

// 9.3.15, RandomAccessIterator:
template <class I>
concept bool RandomAccessIterator() {
    return see below;
}

// 9.4, indirect callable requirements:
// 9.4.2, indirect callables:
template <class F>
concept bool IndirectInvocable() {
    return see below;
}

template <class F, class I>
concept bool IndirectInvocable() {
    return see below;
}

template <class F, class I1, class I2>
concept bool IndirectInvocable() {
    return see below;
}

template <class F>
concept bool IndirectRegularInvocable() {
    return see below;
}

template <class F, class I>
concept bool IndirectRegularInvocable() {
    return see below;
}

template <class F, class I1, class I2>
concept bool IndirectRegularInvocable() {
    return see below;
}
return see below;
}

template <class F, class I>
concept bool IndirectPredicate() {
    return see below;
}

template <class F, class I1, class I2>
concept bool IndirectPredicate() {
    return see below;
}

template <class F, class I1, class I2 = I1>
concept bool IndirectRelation() {
    return see below;
}

template <class F, class I1, class I2 = I1>
concept bool IndirectStrictWeakOrder() {
    return see below;
}

template <class> struct indirect_result_of;

template <class F, class... Is>
    requires IndirectInvocable<decay_t<F>, Is...>()
struct indirect_result_of<F(Is...)>
{
    template <class F>
    using indirect_result_of_t
        = typename indirect_result_of<F>::type;

    // 9.4.3, projected:
    template <Readable I, IndirectRegularInvocable<I> Proj>
    struct projected;

    template <WeaklyIncrementable I, class Proj>
    struct difference_type<projected<I, Proj>>;

    // 9.5, common algorithm requirements:
    // 9.5.2 IndirectlyMovable:
    template <class In, class Out>
    concept bool IndirectlyMovable() {
        return see below;
    }

    template <class In, class Out>
    concept bool IndirectlyMovableStorable() {
        return see below;
    }

    // 9.5.3 IndirectlyCopyable:
    template <class In, class Out>
    concept bool IndirectlyCopyable() {
        return see below;
    }

§ 9.2
template <class In, class Out>
concept bool IndirectlyCopyableStorable() {
    return see below;
}

// 9.5.4 IndirectlySwappable:
template <class I1, class I2 = I1>
concept bool IndirectlySwappable() {
    return see below;
}

// 9.5.5 IndirectlyComparable:
template <class I1, class I2, class R = equal_to<>, class P1 = identity, class P2 = identity>
concept bool IndirectlyComparable() {
    return see below;
}

// 9.5.6 Permutable:
template <class I>
concept bool Permutable() {
    return see below;
}

// 9.5.7 Mergeable:
template <class I1, class I2, class Out, class R = less<>, class P1 = identity, class P2 = identity>
concept bool Mergeable() {
    return see below;
}

template <class I, class R = less<>, class P = identity>
concept bool Sortable() {
    return see below;
}

// 9.6, primitives:
// 9.6.1, traits:
template <class I1, class I2> struct is_indirectly_movable;
template <class I1, class I2 = I1> struct is_indirectly_swappable;
template <class I1, class I2> struct is_nothrow_indirectly_movable;
template <class I1, class I2 = I1> struct is_nothrow_indirectly_swappable;

template <class I1, class I2> constexpr bool is_indirectly_movable_v = is_indirectly_movable<I1, I2>::value;
template <class I1, class I2> constexpr bool is_indirectly_swappable_v = is_indirectly_swappable<I1, I2>::value;
template <class I1, class I2> constexpr bool is_nothrow_indirectly_movable_v = is_nothrow_indirectly_movable<I1, I2>::value;
template <class I1, class I2> constexpr bool is_nothrow_indirectly_swappable_v = is_nothrow_indirectly_swappable<I1, I2>::value;

template <class Iterator> using iterator_traits = see below;
template <Readable T> using iter_common_reference_t
    = common_reference_t<reference_t<T>, value_type_t<T>>;

// 9.6.3, iterator tags:
struct output_iterator_tag { };
struct input_iterator_tag { };
struct forward_iterator_tag : input_iterator_tag { };
struct bidirectional_iterator_tag : forward_iterator_tag { };
struct random_access_iterator_tag : bidirectional_iterator_tag { };

// 9.6.4, iterator operations:
template <Iterator I>
    void advance(I& i, difference_type_t<I> n);
template <Iterator I, Sentinel<I> S>
    void advance(I& i, S bound);
template <Iterator I, Sentinel<I> S>
    difference_type_t<I> advance(I& i, difference_type_t<I> n, S bound);
template <Iterator I, Sentinel<I> S>
    difference_type_t<I> distance(I first, S last);
template <Iterator I>
    I next(I x, difference_type_t<I> n = 1);
template <Iterator I, Sentinel<I> S>
    I next(I x, S bound);
template <Iterator I, Sentinel<I> S>
    I next(I x, difference_type_t<I> n, S bound);
template <BidirectionalIterator I>
    I prev(I x, difference_type_t<I> n = 1);
template <BidirectionalIterator I>
    I prev(I x, difference_type_t<I> n, I bound);

// 9.7, predefined iterators and sentinels:

// 9.7.1, reverse iterators:
template <class I1, class I2> class reverse_iterator;

    template <class I1, class I2>
        requires EqualityComparable<I1, I2>()
            bool operator==(const reverse_iterator<I1>& x, const reverse_iterator<I2>& y);
    template <class I1, class I2>
        requires EqualityComparable<I1, I2>()
            bool operator!=(const reverse_iterator<I1>& x, const reverse_iterator<I2>& y);
    template <class I1, class I2>
        requires Strict TotallyOrdered<I1, I2>()
            bool operator<(const reverse_iterator<I1>& x, const reverse_iterator<I2>& y);
    template <class I1, class I2>
        requires Strict TotallyOrdered<I1, I2>()
            bool operator>(const reverse_iterator<I1>& x,
const reverse_iterator<I2>& y);

template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator>=(
    const reverse_iterator<I1>& x,
    const reverse_iterator<I2>& y);

template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator<=(
    const reverse_iterator<I1>& x,
    const reverse_iterator<I2>& y);

template <class I1, class I2>
requires SizedSentinel<I1, I2>()
difference_type_t<I2> operator-(
    const reverse_iterator<I1>& x,
    const reverse_iterator<I2>& y);

template <RandomAccessIterator I>
reverse_iterator<I>
operator+(difference_type_t<I> n,
const reverse_iterator<I>& x);

template <BidirectionalIterator I>
reverse_iterator<I>
make_reverse_iterator(I i);

// 9.7.2, insert iterators:
template <class Container> class back_insert_iterator;
template <class Container>
back_insert_iterator<Container> back_inserter(Container& x);

template <class Container> class front_insert_iterator;
template <class Container>
front_insert_iterator<Container> front_inserter(Container& x);

template <class Container> class insert_iterator;
template <class Container>
insert_iterator<Container> inserter(Container& x, iterator_t<Container> i);

// 9.7.3, move iterators and sentinels:
template <InputIterator I> class move_iterator;
template <class I1, class I2>
requires EqualityComparable<I1, I2>()
bool operator==(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
requires EqualityComparable<I1, I2>()
bool operator!=(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator<(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
§ 9.2
bool operator<=(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
bool operator>
    (const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
bool operator>=
    (const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
    requires SizedSentinel<I1, I2>()
difference_type_t<I2> operator-(
    const move_iterator<I1>& x,
    const move_iterator<I2>& y);

// 9.7.4, common iterators:
template <Iterator I, Sentinel<I> S>
    requires !Same<I, S>()
class common_iterator;

template <Readable I, class S>
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struct value_type<common_iterator<I, S>>;

template <InputIterator I, class S>
struct iterator_category<common_iterator<I, S>>;

template <ForwardIterator I, class S>
struct iterator_category<common_iterator<I, S>>;

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
bool operator==( const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
requires EqualityComparable<I1, I2>()
bool operator==( const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
bool operator!=( const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

template <class I2, SizedSentinel<I2> I1, SizedSentinel<I2> S1, SizedSentinel<I1> S2>
difference_type_t<I2> operator-( const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

// 9.7.5, default sentinels:
class default_sentinel;

// 9.7.6, counted iterators:
template <Iterator I> class counted_iterator;

template <class I1, class I2>
requires Common<I1, I2>()
bool operator==( const counted_iterator<I1>& x, const counted_iterator<I2>& y);

requires Common<I1, I2>()
bool operator==( const counted_iterator<auto>& x, default_sentinel);

requires Common<I1, I2>()
bool operator==( default_sentinel, const counted_iterator<auto>& x);

requires Common<I1, I2>()
bool operator!( const counted_iterator<I1>& x, const counted_iterator<I2>& y);

requires Common<I1, I2>()
bool operator!( const counted_iterator<auto>& x, default_sentinel y);

requires Common<I1, I2>()
bool operator!( default_sentinel x, const counted_iterator<auto>& y);

requires Common<I1, I2>()
bool operator!( const counted_iterator<I1>& x, const counted_iterator<I2>& y);

requires Common<I1, I2>()
bool operator!( const counted_iterator<auto>& x, default_sentinel y);

requires Common<I1, I2>()
bool operator!( default_sentinel x, const counted_iterator<auto>& y);

§ 9.2
bool operator>(
    const counted_iterator<I1>& x, const counted_iterator<I2>& y);

template <class I1, class I2>
    requires Common<I1, I2>()
bool operator>=(
    const counted_iterator<I1>& x, const counted_iterator<I2>& y);

template <class I1, class I2>
    requires Common<I1, I2>()
difference_type_t<I2> operator-(
    const counted_iterator<I1>& x, const counted_iterator<I2>& y);

template <class I1, class I2>
    requires Common<I1, I2>()
difference_type_t<I1> operator-(
    const counted_iterator<I1>& x, default_sentinel y);

template <class I1, class I2>
    requires Common<I1, I2>()
difference_type_t<I1> operator-(
    default_sentinel x, const counted_iterator<I1>& y);

template <RandomAccessIterator I>
    counted_iterator<I>
    operator+(difference_type_t<I> n, const counted_iterator<I>& x);

template <Iterator I>
    counted_iterator<I> make_counted_iterator(I i, difference_type_t<I> n);

template <Iterator I>
    void advance(counted_iterator<I>& i, difference_type_t<I> n);

// 9.7.8, unreachable sentinels:
class unreachable;

template <Iterator I>
    constexpr bool operator==(const I&, unreachable) noexcept;
    constexpr bool operator==(unreachable, const I&) noexcept;

// 9.7.7, dangling wrapper:
template <class T> class dangling;

// 9.8, 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, class traits, class Distance>
    bool operator==(default_sentinel x,
        const istream_iterator<T, charT, traits, Distance>& y);

template <class T, class charT, class traits, class Distance>
    bool operator==(const istream_iterator<T, charT, traits, Distance>& x,
        default_sentinel y);

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, class traits, class Distance>
bool operator!=(default_sentinel x,
    const istream_iterator<T, charT, traits, Distance>& y);

template <class T, class charT, class traits, class Distance>
bool operator!=(const istream_iterator<T, charT, traits, Distance>& x,
    default_sentinel 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;

bool operator==(const istreambuf_iterator<charT, traits>& a,
    const istreambuf_iterator<charT, traits>& b);

bool operator==(default_sentinel a,
    const istreambuf_iterator<charT, traits>& b);

bool operator==(const istreambuf_iterator<charT, traits>& a,
    default_sentinel b);

bool operator!=(const istreambuf_iterator<charT, traits>& a,
    const istreambuf_iterator<charT, traits>& b);

bool operator!=(default_sentinel a,
    const istreambuf_iterator<charT, traits>& b);

bool operator!=(const istreambuf_iterator<charT, traits>& a,
    default_sentinel b);

template <class charT, class traits = char_traits<charT>>
class ostreambuf_iterator;

// 9.10, range access:
namespace {
    constexpr unspecified begin = unspecified ;
    constexpr unspecified end = unspecified ;
    constexpr unspecified cbegin = unspecified ;
    constexpr unspecified cend = unspecified ;
    constexpr unspecified rbegin = unspecified ;
    constexpr unspecified rend = unspecified ;
    constexpr unspecified crbegin = unspecified ;
    constexpr unspecified crend = unspecified ;
}

// 9.11, range primitives:
namespace {
    constexpr unspecified size = unspecified ;
    constexpr unspecified empty = unspecified ;
    constexpr unspecified data = unspecified ;
    constexpr unspecified cdata = unspecified ;
}

template <Range R>
difference_type_t<iterator_t<R>> distance(R& r);
template <SizedRange R>
difference_type_t<iterator_t<R>> distance(R&& r);
}}}

namespace std {
  // 9.6.2, iterator traits:
  template <experimental::ranges::Iterator Out>
  struct iterator_traits<Out>;
  template <experimental::ranges::InputIterator In>
  struct iterator_traits<In>;
  template <experimental::ranges::InputIterator In>
  requires experimental::ranges::Sentinel<In, In>()
  struct iterator_traits;
}

Any entities declared or defined in namespace std in header <iterator> that are not already defined in namespace std::experimental::ranges in header <experimental/ranges/iterator> are imported with using-declarations (ISO/IEC 14882:2014 §7.3.3).

9.3 Iterator requirements

9.3.1 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. All input iterators \( i \) support the expression \(*i\), resulting in a value of some object type \( T \), called the value type of the iterator. All output iterators support the expression \(*i = o\) where \( o \) is a value of some type that is in the set of types that are writable to the particular iterator type of \( i \). For every iterator type \( X \) there is a corresponding signed integer type 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 five categories of iterators, according to the operations defined on them: input iterators, output iterators, forward iterators, bidirectional iterators and random access iterators, as shown in Table 6.

<table>
<thead>
<tr>
<th>Random Access</th>
<th>Bidirectional</th>
<th>Forward</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
</table>

The five categories of iterators correspond to the iterator concepts InputIterator, OutputIterator, ForwardIterator, BidirectionalIterator, and RandomAccessIterator, respectively. The generic term iterator refers to any type that satisfies Iterator.

Forward iterators satisfy all the requirements of input iterators and can be used whenever an input iterator is specified; Bidirectional iterators also satisfy all the requirements of forward iterators and can be used whenever a forward iterator is specified; Random access iterators also satisfy all the requirements of bidirectional iterators and can be used whenever a bidirectional iterator is specified.

Iterators that further satisfy the requirements of output iterators are called mutable iterators. Nonmutable iterators are referred to as constant iterators.

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
These values are called *past-the-end* values. 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. [Example: After the declaration of an uninitialized pointer \( x \) (as with \( \text{int* } x; \)), \( x \) must always be assumed to have a singular value of a pointer. — end example] 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 using a value-initialized iterator as the source of a copy or move operation. [Note: This guarantee is not offered for default initialization, although the distinction only matters for types with trivial default constructors such as pointers or aggregates holding pointers. — end note] In these cases the singular value is overwritten the same way as any other value. Dereferenceable values are always non-singular.

Most of the library’s algorithmic templates that operate on data structures have interfaces that use ranges. A range is an iterator and a *sentinel* that designate the beginning and end of the computation. An iterator and a sentinel denoting a range are comparable. A sentinel denotes an element when it compares equal to an iterator \( i \), and \( i \) points to that element. The types of a sentinel and an iterator that denote a range must satisfy *Sentinel* (9.3.9).

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 pointed to by the first iterator \( j \) such that \( j == s \). A sentinel \( s \) is called *reachable* from an iterator \( i \) if and only if there is a finite sequence of applications of the expression \(++i\) that makes \( i == s \). If \( s \) is reachable from \( i \), they denote a range.

A range \([i,s)\) is valid if and only if \( s \) is reachable from \( i \). The result of the application of functions in the library to invalid ranges is undefined.

All the categories of iterators require only those functions that are realizable for a given category in constant time (amortized).

Destruction of an iterator may invalidate pointers and references previously obtained from that iterator.

An *invalid* iterator is an iterator that may be singular.\(^3\)

### 9.3.2 Customization points

The name *iter_move* denotes a *customization point object* (6.2.2.3). The effect of the expression `ranges::iter_move(E)` for some expression \( E \) is equivalent to the following:

\[(1.1)\] — \( \text{iter}_\text{move}(E) \), if that expression is well-formed when evaluated in a context that does not include `ranges::iter_move` but does include the lookup set produced by argument-dependent lookup (ISO/IEC 14882:2014 §3.4.2).

\[(1.2)\] — 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.

\(\text{If `ranges::iter_move(E)` does not equal } *E\text{, the program is ill-formed with no diagnostic required.}\)

3) This definition applies to pointers, since pointers are iterators. The effect of dereferencing an iterator that has been invalidated is undefined.
9.3.2.2 iter_swap

The name iter_swap denotes a customization point object (6.2.2.3). The effect of the expression ranges::iter_swap(E1, E2) for some expressions E1 and E2 is equivalent to the following:

1. (void)iter_swap(E1, E2), if that expression is well-formed when evaluated in a context that does not include ranges::iter_swap but does include the lookup set produced by argument-dependent lookup (ISO/IEC 14882:2014 §3.4.2) and the following declaration:

```cpp
void iter_swap(auto, auto) = delete;
```

2. Otherwise, if the types of E1 and E2 both satisfy Readable, and if the reference type of E1 is swappable with (7.3.11) the reference type of E2, then ranges::swap(*E1, *E2)

3. Otherwise, if the types T1 and T2 of E1 and E2 satisfy IndirectlyMovableStorable<T1, T2>() && IndirectlyMovableStorable<T2, T1>(), exchanges the values denoted by E1 and E2.

4. Otherwise, ranges::iter_swap(E1, E2) is ill-formed.

If ranges::iter_swap(E1, E2) does not swap the values denoted by the expressions E1 and E2, the program is ill-formed with no diagnostic required.

9.3.3 Iterator associated types

To implement algorithms only in terms of iterators, it is often necessary to determine the value and difference types that correspond to a particular iterator type. Accordingly, it is required that if WI is the name of a type that satisfies the WeaklyIncrementable concept (9.3.6), R is the name of a type that satisfies the Readable concept (9.3.4), and II is the name of a type that satisfies the InputIterator concept (9.3.11) concept, the types

```cpp
difference_type_t<WI>
value_type_t<R>
iterator_category_t<II>
```

be defined as the iterator’s difference type, value type and iterator category, respectively.

9.3.3.1 difference_type

difference_type_t<T> is implemented as if:

```cpp
template <class> struct difference_type { }

template <class T>
struct difference_type<T*> : enable_if<is_object<T>::value, ptrdiff_t> { }

template <class I>
struct difference_type<I const> : difference_type<decay_t<I>> { }

template <class T>
requires requires { typename T::difference_type; }
struct difference_type<T> { 
  using 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 difference_type<T>
```
Users may specialize `difference_type` on user-defined types.

9.3.3.2 `value_type`  
A Readable type has an associated value type that can be accessed with the `value_type_t` alias template.

```cpp
template <class> struct value_type { }; 
```

```cpp
template <class T> 
struct value_type<T*> : enable_if<is_object<T>::value, remove_cv_t<T>> { }; 
```

```cpp
template <class I> 
requires is_array<I>::value 
struct value_type<I> : value_type<decay_t<I>> { }; 
```

```cpp
template <class I> 
struct value_type<I const> : value_type<decay_t<I>> { }; 
```

```cpp
template <class T> 
requires requires { typename T::value_type; } 
struct value_type<T> : enable_if<is_object<typename T::value_type>::value, typename T::value_type> { }; 
```

```cpp
template <class T> 
requires requires { typename T::element_type; } 
struct value_type<T> : enable_if<is_object<typename T::element_type>::value, typename T::element_type> { }; 
```

```cpp
template <class T> using value_type_t = typename value_type<T>::type; 
```

2 If a type I has an associated value type, then `value_type<I>::type` shall name the value type. Otherwise, there shall be no nested type type.

3 The `value_type` class template may be specialized on user-defined types.

4 When instantiated with a type I such that `I::value_type` is valid and denotes a type, `value_type<I>::type` names that type, unless it is not an object type (ISO/IEC 14882:2014 §3.9) in which case `value_type<I>` shall have no nested type type. [Note: Some legacy output iterators define a nested type named `value_type` that is an alias for void. These types are not Readable and have no associated value types. —end note]

5 When instantiated with a type I such that `I::element_type` is valid and denotes a type, `value_type<I>::type` names that type, unless it is not an object type (ISO/IEC 14882:2014 §3.9) in which case `value_type<I>` shall have no nested type type. [Note: Smart pointers like `shared_ptr<int>` are Readable and have an associated value type. But a smart pointer like `shared_ptr<void>` is not Readable and has no associated value type. —end note]

9.3.3.3 `iterator_category`  
`iterator_category_t<T>` is implemented as if:

```cpp
template <class> struct iterator_category { }; 
```
template <class T>
struct iterator_category<T*>
  : enable_if<is_object<T>::value, random_access_iterator_tag> { }; 

template <class T>
struct iterator_category<T const> : iterator_category<T> { }; 

template <class T>
requires requires { typename T::iterator_category; }
struct iterator_category<T> {
  using type = see below; 
}; 

template <class T> using iterator_category_t = typename iterator_category<T>::type; 

2 Users may specialize iterator_category on user-defined types. 
3 If T::iterator_category is valid and denotes a type, then the type iterator_category<T>::type is computed as follows: 

(3.1) — If T::iterator_category is the same as or derives from std::random_access_iterator_tag, iterator_category<T>::type is ranges::random_access_iterator_tag. 

(3.2) — Otherwise, if T::iterator_category is the same as or derives from std::bidirectional_iterator_tag, iterator_category<T>::type is ranges::bidirectional_iterator_tag. 

(3.3) — Otherwise, if T::iterator_category is the same as or derives from std::forward_iterator_tag, iterator_category<T>::type is ranges::forward_iterator_tag. 

(3.4) — Otherwise, if T::iterator_category is the same as or derives from std::input_iterator_tag, iterator_category<T>::type is ranges::input_iterator_tag. 

(3.5) — Otherwise, if T::iterator_category is the same as or derives from std::output_iterator_tag, iterator_category<T> has no nested type. 

(3.6) — Otherwise, iterator_category<T>::type is T::iterator_category 

4 rvalue_reference_t<T> is implemented as if: 

template <dereferenceable T>
requires see below using rvalue_reference_t
  = decltype(ranges::iter_move(declval<T&>())); 

5 The expression in the requires clause is equivalent to: 

  requires(T& t) { { ranges::iter_move(t) } -> auto&&; } 

9.3.4 Concept Readable

1 The Readable concept is satisfied by types that are readable by applying operator* including pointers, smart pointers, and iterators. 

template <class In>
concept bool Readable() { 
  return Movable<In>() && DefaultConstructible<In>() &&
requires(const In& i) {
    typename value_type_t<In>;
    typename reference_t<In>;
    typename rvalue_reference_t<In>;
    { *i } -> Same<reference_t<In>>;
    { ranges::iter_move(i) } -> Same<rvalue_reference_t<In>>;
} &
CommonReference<reference_t<In>, value_type_t<In>&>() &
CommonReference<reference_t<In>, rvalue_reference_t<In>>() &
CommonReference<rvalue_reference_t<In>, const value_type_t<In>&>();

9.3.5 Concept Writable

The Writable concept specifies the requirements for writing a value into an iterator's referenced object.

template <class Out, class T>
concept bool Writable() {
    return Movable<Out>() && DefaultConstructible<Out>() &&
    requires(Out o, T&& t) {
        *o = std::forward<T>(t); // not required to be equality preserving
    };
}

Let E be an expression such that decltype((E)) is T, and let o be a dereferenceable object of type Out. Then Writable<Out, T>() is satisfied if and only if

— If Readable<Out>() && Same<value_type_t<Out>, decay_t<T>>() is satisfied, then *o after the assignment is equal to the value of E before the assignment.

— After evaluating the assignment expression, o is not required to be dereferenceable.

— If E is an xvalue (ISO/IEC 14882:2014 §3.10), the resulting state of the object it denotes is valid but unspecified (ISO/IEC 14882:2014 §17.6.5.15).

[Note: The only valid use of an operator* is on the left side of the assignment statement. Assignment through the same value of the writable type happens only once. —end note]

9.3.6 Concept WeaklyIncrementable

The WeaklyIncrementable 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 EqualityComparable.

template <class I>
concept bool WeaklyIncrementable() {
    return Semiregular<I>() &
    requires(I i) {
        typename difference_type_t<I>;
        requires SignedIntegral<difference_type_t<I>>();
        { ++i } -> Same<I&>; // not required to be equality preserving
        i++; // not required to be equality preserving
    };
}

Let i be an object of type I. When both pre- and post-increment are valid, i is said to be incrementable. Then WeaklyIncrementable<I>() is satisfied if and only if

— ++i is valid if and only if i++ is valid.

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If \( i \) is incrementable, then both \( ++i \) and \( i++ \) advance \( i \) to the next element.

If \( i \) is incrementable, then \&++\( i \) is equal to \&\( i \).

[Note: For \texttt{WeaklyIncrementable} types, \( a \) equals \( b \) does not imply that \( ++a \) equals \( ++b \). (Equality does not guarantee the substitution property or referential transparency.) Algorithms on weakly incrementable types should never attempt to pass through the same incrementable value twice. They should be single pass algorithms. These algorithms can be used with istreams as the source of the input data through the \texttt{istream\_iterator} class template. — end note]

9.3.7 Concept \texttt{Incrementable}

The \texttt{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 \texttt{EqualityComparable}. [Note: This requirement supersedes the annotations on the increment expressions in the definition of \texttt{WeaklyIncrementable}. — end note]

\begin{verbatim}
template <class I>
concept bool Incrementable() {
    return Regular\<I\>() &&
    WeaklyIncrementable\<I\>() &&
    requires(I i) {
        { i++ } -> Same\<I\>;
    };
}
\end{verbatim}

Let \( a \) and \( b \) be incrementable objects of type \( I \). Then \texttt{Incrementable\<I\>()} is satisfied if and only if

(2.1) — If \( \text{bool}(a == b) \) then \( \text{bool}(a++ == b) \).

(2.2) — If \( \text{bool}(a == b) \) then \( \text{bool}((a++, a) == ++b) \).

[Note: 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 satisfy \texttt{Incrementable}. — end note]

9.3.8 Concept \texttt{Iterator}

The \texttt{Iterator} concept forms the basis of the iterator concept taxonomy; every iterator satisfies the \texttt{Iterator} requirements. This concept specifies operations for dereferencing and incrementing an iterator. Most algorithms will require additional operations to compare iterators with sentinels (9.3.9), to read (9.3.11) or write (9.3.12) values, or to provide a richer set of iterator movements (9.3.13, 9.3.14, 9.3.15).

\begin{verbatim}
template <class I>
concept bool Iterator() {
    return WeaklyIncrementable\<I\>() &&
    requires(I i) {
        { *i } -> auto&&; // Requires: i is dereferenceable
    };
}
\end{verbatim}

[Note: The requirement that the result of dereferencing the iterator is deducible from \texttt{auto&&} means that it cannot be \texttt{void}. — end note]

9.3.9 Concept \texttt{Sentinel}

The \texttt{Sentinel} concept specifies the relationship between an \texttt{Iterator} type and a \texttt{Semiregular} type whose values denote a range.
template <class S, class I>
concept bool Sentinel() {
  return Semiregular<S>() &&
  Iterator<I>() &&
  WeaklyEqualityComparable<S, I>();
}

Let s and i be values of type S and I such that [i,s) denotes a range. Types S and I satisfy
Sentinel<S, I>() if and only if:

(2.1) — i == s is well-defined.
(2.2) — If bool(i != s) then i is dereferenceable and [++i,s) denotes a range.

The domain of == can change over time. Given an iterator i and sentinel s such that [i,s) denotes a range
and i != s, [i,s) is not required to continue to denote a range after incrementing any iterator equal to i.
Consequently, i == s is no longer required to be well-defined.

9.3.10 Concept SizedSentinel

The SizedSentinel concept specifies requirements on an Iterator and a Sentinel that allow the use of
the - operator to compute the distance between them in constant time.

template <class S, class I>
concept bool SizedSentinel() {
  return Sentinel<S, I>() &&
  !disable_sized_sentinel<remove_cv_t<S>, remove_cv_t<I>> &&
  requires(const I& i, const S& s) {
    { s - i } -> Same<difference_type_t<I>>;
    { i - s } -> Same<difference_type_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 bool(i == s) be true. SizedSentinel<S, I>() is satisfied if and only if:

(2.1) — If N is representable by difference_type_t<I>, then s - i is well-defined and equals N.
(2.2) — If -N is representable by difference_type_t<I>, then i - s is well-defined and equals -N.

[Note: disable_sized_sentinel provides a mechanism to enable use of sentinels and iterators with the
library that meet the syntactic requirements but do not in fact satisfy SizedSentinel. A program that
instantiates a library template that requires SizedSentinel with an iterator type I and sentinel type S that
meet the syntactic requirements of SizedSentinel<S, I>() but do not satisfy SizedSentinel is ill-formed
with no diagnostic required unless disable_sized_sentinel<S, I> evaluates to true (6.2.1.3). — end note]

[Note: The SizedSentinel concept is satisfied by pairs of RandomAccessIterators (9.3.15) and by counted
iterators and their sentinels (9.7.6.1). — end note]

9.3.11 Concept InputIterator

The InputIterator concept is a refinement of Iterator (9.3.8). It defines requirements for a type
whose referenced values can be read (from the requirement for Readable (9.3.4)) and which can be both
pre- and post-incremented. [Note: Unlike in ISO/IEC 14882, input iterators are not required to satisfy
EqualityComparable (7.4.3). — end note]

template <class I>
concept bool InputIterator() {
  return Iterator<I>() &&
Readable<I>() &&
requires(I i, const I ci) {
    typename iterator_category_t<I>;
    requires DerivedFrom<iterator_category_t<I>, input_iterator_tag>();
    { i++ } -> Readable; // not required to be equality preserving
    requires Same<value_type_t<I>, value_type_t<decltype(i++)>>();
    { *ci } -> const value_type_t<I>&;
};
}

9.3.12 Concept OutputIterator

The OutputIterator concept is a refinement of Iterator (9.3.8). It defines requirements for a type that can be used to write values (from the requirement for Writable (9.3.5)) and which can be both pre- and post-incremented. However, output iterators are not required to satisfy EqualityComparable.

```
template <class I, class T>
concept bool OutputIterator() {
    return Iterator<I>() && Writable<I, T>();
}
```

[Note: Algorithms on output iterators should never attempt to pass through the same iterator twice. They should be single pass algorithms. Algorithms that take output iterators can be used with ostreams as the destination for placing data through the ostream_iterator class as well as with insert iterators and insert pointers. —end note]

9.3.13 Concept ForwardIterator

The ForwardIterator concept refines InputIterator (9.3.11), adding equality comparison and the multi-pass guarantee, specified below.

```
template <class I>
concept bool ForwardIterator() {
    return InputIterator<I>() && DerivedFrom<iterator_category_t<I>, forward_iterator_tag>() && Incrementable<I>() && Sentinel<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: Value-initialized iterators behave as if they refer past the end of the same empty sequence. —end note]

Two dereferenceable iterators a and b of type X offer the multi-pass guarantee if:

1. a == b implies ++a == ++b and
2. The expression ([](X x){++x;}(a), *a) is equivalent to the expression *a.

[Note: The requirement that a == b implies ++a == ++b (which is not true for weaker iterators) 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]

9.3.14 Concept BidirectionalIterator

The BidirectionalIterator concept refines ForwardIterator (9.3.13), and adds the ability to move an iterator backward as well as forward.

§ 9.3.14
template <class I>
concept bool BidirectionalIterator() {
    return ForwardIterator<I>() &&
    DerivedFrom<iterator_category_t<I>, bidirectional_iterator_tag>() &&
    requires(I i) {
        { --i } -> Same<I&>;
        { i-- } -> Same<I>;
    };
}

A bidirectional iterator \( r \) is decrementable if and only if there exists some \( s \) such that \( ++s == r \). The expressions \( --r \) and \( r-- \) are only valid if \( r \) is decrementable.

Let \( a \) and \( b \) be decrementable objects of type \( I \). Then \( \text{BidirectionalIterator}<I>() \) is satisfied if and only if:

1. \( &--a == &a \).
2. If \( \text{bool}(a == b) \), then \( \text{bool}(a-- == b) \).
3. If \( \text{bool}(a == b) \), then after evaluating both \( a-- \) and \( --b \), \( \text{bool}(a == b) \) still holds.
4. If \( a \) is incrementable and \( \text{bool}(a == b) \), then \( \text{bool}(--(+a) == b) \).
5. If \( \text{bool}(a == b) \), then \( \text{bool}(++(--a) == b) \).

9.3.15 Concept RandomAccessIterator

The \( \text{RandomAccessIterator} \) concept refines \( \text{BidirectionalIterator} \) (9.3.14) and adds support for constant-time advancement with \( +=, +=, -=, \) and \( - \), and the computation of distance in constant time with \( - \). Random access iterators also support array notation via subscripting.

template <class I>
concept bool RandomAccessIterator() {
    return BidirectionalIterator<I>() &&
    DerivedFrom<iterator_category_t<I>, random_access_iterator_tag>() &&
    StrictTotallyOrdered<I>() &&
    SizedSentinel<I, I>() &&
    requires(I i, const I j, const difference_type_t<I> n) {
        { i += n } -> Same<I&>;
        { j + n } -> Same<I>;
        { n + j } -> Same<I>;
        { i -- n } -> Same<I&>;
        { j - n } -> Same<I>;
        { j[n] } -> Same<reference_t<I>>;
    };
}

Let \( a \) and \( b \) be valid iterators of type \( I \) such that \( b \) is reachable from \( a \). Let \( n \) be the smallest value of type \( \text{difference_type_t}<I> \) such that after \( n \) applications of \( ++a \), then \( \text{bool}(a == b) \). Then \( \text{RandomAccessIterator}<I>() \) is satisfied if and only if:

1. \( (a += n) \) is equal to \( b \).
2. \( &((a += n)) \) is equal to \( &a \).
3. \( (a + n) \) is equal to \( (a += n) \).
(2.4) — For any two positive integers \(x\) and \(y\), if \(a + (x + y)\) is valid, then \(a + (x + y)\) is equal to \((a + x) + y\).

(2.5) — \(a + 0\) is equal to \(a\).

(2.6) — If \((a + (n - 1))\) is valid, then \(a + n\) is equal to \(++(a + (n - 1))\).

(2.7) — \((b += -n)\) is equal to \(a\).

(2.8) — \((b -= n)\) is equal to \(a\).

(2.9) — \&(b -= n)\) is equal to \&\(b\).

(2.10) — \((b - n)\) is equal to \((b -= n)\).

(2.11) — If \(b\) is dereferenceable, then \(a[n]\) is valid and is equal to \(*b\).

9.4 Indirect callable requirements

9.4.1 In general

There are several concepts that group requirements of algorithms that take callable objects (ISO/IEC 14882:2014 §20.9.2) as arguments.

9.4.2 Indirect callables

The indirect callable concepts are used to constrain those algorithms that accept callable objects (ISO/IEC 14882:2014 §20.9.1) as arguments.

```cpp
template <class F>
concept bool IndirectInvocable() {
    return CopyConstructible<F>() &&
    Invocable<F&>();
}
template <class F, class I>
concept bool IndirectInvocable() {
    return Readable<I>() &&
    CopyConstructible<F>() &&
    Invocable<F&, value_type_t<I>&>() &&
    Invocable<F&, reference_t<I>&>() &&
    Invocable<F&, iter_common_reference_t<I>>();
}
template <class F, class I1, class I2>
concept bool IndirectInvocable() {
    return Readable<I1>() &&
    Readable<I2>() &&
    CopyConstructible<F>() &&
    Invocable<F&, value_type_t<I1>&, value_type_t<I2>&>() &&
    Invocable<F&, value_type_t<I1>&, reference_t<I2>&>() &&
    Invocable<F&, reference_t<I1>&, value_type_t<I2>&>() &&
    Invocable<F&, reference_t<I1>&, reference_t<I2>&>() &&
    Invocable<F&, iter_common_reference_t<I1>, iter_common_reference_t<I2>>();
}
template <class F>
concept bool IndirectRegularInvocable() {
    return CopyConstructible<F>() &&
    RegularInvocable<F&>();
}

§ 9.4.2
template <class F, class I>
concept bool IndirectRegularInvocable() {
    return Readable<I>() &&
    CopyConstructible<F>() &&
    RegularInvocable<F&, value_type_t<I>&>() &&
    RegularInvocable<F&, reference_t<I>>() &&
    RegularInvocable<F&, iter_common_reference_t<I>>();
}

template <class F, class I1, class I2>
concept bool IndirectRegularInvocable() {
    return Readable<I1>() && Readable<I2>() &&
    CopyConstructible<F>() &&
    RegularInvocable<F&, value_type_t<I1>&, value_type_t<I2>&>() &&
    RegularInvocable<F&, value_type_t<I1>&, reference_t<I2>>() &&
    RegularInvocable<F&, reference_t<I1>, value_type_t<I2>&>() &&
    RegularInvocable<F&, reference_t<I1>, reference_t<I2>>() &&
    RegularInvocable<F&, iter_common_reference_t<I1>, iter_common_reference_t<I2>>();
}

template <class F, class I>
concept bool IndirectPredicate() {
    return Readable<I>() &&
    CopyConstructible<F>() &&
    Predicate<F&, value_type_t<I>&>() &&
    Predicate<F&, reference_t<I>>() &&
    Predicate<F&, iter_common_reference_t<I>>();
}

template <class F, class I1, class I2>
concept bool IndirectPredicate() {
    return Readable<I1>() && Readable<I2>() &&
    CopyConstructible<F>() &&
    Predicate<F&, value_type_t<I1>&, value_type_t<I2>&>() &&
    Predicate<F&, value_type_t<I1>&, reference_t<I2>>() &&
    Predicate<F&, reference_t<I1>, value_type_t<I2>&>() &&
    Predicate<F&, reference_t<I1>, reference_t<I2>>() &&
    Predicate<F&, iter_common_reference_t<I1>, iter_common_reference_t<I2>>();
}

template <class F, class I1, class I2 = I1>
concept bool IndirectRelation() {
    return Readable<I1>() && Readable<I2>() &&
    CopyConstructible<F>() &&
    Relation<F&, value_type_t<I1>&, value_type_t<I2>&>() &&
    Relation<F&, value_type_t<I1>&, reference_t<I2>>() &&
    Relation<F&, reference_t<I1>, value_type_t<I2>&>() &&
    Relation<F&, reference_t<I1>, reference_t<I2>>() &&
    Relation<F&, iter_common_reference_t<I1>, iter_common_reference_t<I2>>();
}

template <class F, class I1, class I2 = I1>
concept bool IndirectStrictWeakOrder() {
    return Readable<I1>() && Readable<I2>() &&
    CopyConstructible<F>() &&
    StrictWeakOrder<F&, value_type_t<I1>&, value_type_t<I2>&>() &&
    StrictWeakOrder<F&, value_type_t<I1>&, reference_t<I2>>() &&

§ 9.4.2
StrictWeakOrder<F&, reference_t<I1>, value_type_t<I2>&>() &&
StrictWeakOrder<F&, reference_t<I1>, reference_t<I2>>() &&
StrictWeakOrder<F&, iter_common_reference_t<I1>, iter_common_reference_t<I2>>());
}

template <class> struct indirect_result_of { };

template <class F, class... Is>
requires IndirectInvocable<decay_t<F>, Is...>()
struct indirect_result_of<F(Is...)>
 :
 result_of<F(reference_t<Is>...)>
 { };

9.4.3 Class template projected

The projected class template is intended for use when specifying the constraints of algorithms that accept callable objects and projections (3.1). It bundles a Readable type I and a function Proj into a new Readable type whose reference type is the result of applying Proj to the reference of I.

template <Readable I, IndirectRegularInvocable<I> Proj>
struct projected
{
 using value_type = remove_cv_t<remove_reference_t<indirect_result_of_t<Proj& (I)>>>
 indirect_result_of_t<Proj& (I)> operator*() const;
};

template <WeaklyIncrementable I, class Proj>
struct difference_type<projected<I, Proj>>
{
 using type = difference_type_t<I>
};

[Note: projected is only used to ease constraints specification. Its member function need not be defined. — end note]

9.5 Common algorithm requirements

9.5.1 In 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 Readable and Writable types: IndirectlyMovable, IndirectlyCopyable, and IndirectlySwappable. There are three relational concepts for rearrangements: Permutable, Mergeable, and Sortable. There is one relational concept for comparing values from different sequences: IndirectlyComparable.

[Note: The equal_to<> and less<> (8.3.2) function types used in the concepts below impose additional constraints on their arguments beyond those that appear explicitly in the concepts' bodies. equal_to<> requires its arguments satisfy EqualityComparable (7.4.3), and less<> requires its arguments satisfy StrictTotallyOrdered (7.4.4). — end note]

9.5.2 Concept IndirectlyMovable

The IndirectlyMovable concept specifies the relationship between a Readable type and a Writable type between which values may be moved.

template <class In, class Out>
concept bool IndirectlyMovable()
{
 return Readable<In>() &&
 Writable<Out, rvalue_reference_t<In>>();
}
The `IndirectlyMovableStorable` concept augments `IndirectlyMovable` with additional requirements enabling the transfer to be performed through an intermediate object of the `Readable` type's value type.

```cpp
template <class In, class Out>
concept bool IndirectlyMovableStorable() {
  return IndirectlyMovable<In, Out>() &&
          Writable<Out, value_type_t<In>>() &&
          Movable<value_type_t<In>>() &&
          Constructible<value_type_t<In>, rvalue_reference_t<In>>() &&
          Assignable<value_type_t<In>&, rvalue_reference_t<In>>();
}
```

### 9.5.3 Concept `IndirectlyCopyable` [commonalgoreq.indirectlycopyable]

The `IndirectlyCopyable` concept specifies the relationship between a `Readable` type and a `Writable` type between which values may be copied.

```cpp
template <class In, class Out>
concept bool IndirectlyCopyable() {
  return Readable<In>() &&
          Writable<Out, reference_t<In>>();
}
```

The `IndirectlyCopyableStorable` concept augments `IndirectlyCopyable` with additional requirements enabling the transfer to be performed through an intermediate object of the `Readable` type's value type. It also requires the capability to make copies of values.

```cpp
template <class In, class Out>
concept bool IndirectlyCopyableStorable() {
  return IndirectlyCopyable<In, Out>() &&
          Writable<Out, const value_type_t<In>&>() &&
          Copyable<value_type_t<In>>() &&
          Constructible<value_type_t<In>, reference_t<In>>() &&
          Assignable<value_type_t<In>&, reference_t<In>>();
}
```

### 9.5.4 Concept `IndirectlySwappable` [commonalgoreq.indirectlyswappable]

The `IndirectlySwappable` concept specifies a swappable relationship between the values referenced by two `Readable` types.

```cpp
template <class I1, class I2 = I1>
concept bool IndirectlySwappable() {
  return Readable<I1>() &&
          Readable<I2>() &&
          requires(I1&& i1, I2&& i2) {
            ranges::iter_swap(i1, i2);
            ranges::iter_swap(std::forward<I1>(i1), std::forward<I2>(i2));
            ranges::iter_swap(std::forward<I2>(i1), std::forward<I1>(i2));
            ranges::iter_swap(std::forward<I1>(i1), std::forward<I2>(i1));
            ranges::iter_swap(std::forward<I2>(i1), std::forward<I1>(i1));
          }
}
```

Given an object `i1` of type `I1` and an object `i2` of type `I2`, `IndirectlySwappable<I1, I2>()` is satisfied if after `ranges::iter_swap(i1, i2)`, the value of `*i1` is equal to the value of `*i2` before the call, and vice versa.
9.5.5 Concept IndirectlyComparable

The `IndirectlyComparable` concept specifies the common requirements of algorithms that compare values from two different sequences.

```cpp
template <class I1, class I2, class R = equal_to<>, class P1 = identity, class P2 = identity>
concept bool IndirectlyComparable() {
    return IndirectRelation<R, projected<I1, P1>, projected<I2, P2>>();
}
```

9.5.6 Concept Permutable

The `Permutable` concept specifies the common requirements of algorithms that reorder elements in place by moving or swapping them.

```cpp
template <class I>
concept bool Permutable() {
    return ForwardIterator<I>() &&
    IndirectlyMovableStorable<I, I>() &&
    IndirectlySwappable<I, I>();
}
```

9.5.7 Concept Mergeable

The `Mergeable` concept specifies the requirements of algorithms that merge sorted sequences into an output sequence by copying elements.

```cpp
template <class I1, class I2, class Out, class R = less<>, class P1 = identity, class P2 = identity>
concept bool Mergeable() {
    return InputIterator<I1>() &&
    InputIterator<I2>() &&
    WeaklyIncrementable<Out>() &&
    IndirectlyCopyable<I1, Out>() &&
    IndirectlyCopyable<I2, Out>() &&
    IndirectStrictWeakOrder<R, projected<I1, P1>, projected<I2, P2>>();
}
```

9.5.8 Concept Sortable

The `Sortable` concept specifies the common requirements of algorithms that permute sequences into ordered sequences (e.g., `sort`).

```cpp
template <class I, class R = less<>, class P = identity>
concept bool Sortable() {
    return Permutable<I>() &&
    IndirectStrictWeakOrder<R, projected<I, P>>();
}
```

9.6 Iterator primitives

To simplify the task of defining iterators, the library provides several classes and functions:

9.6.1 Iterator traits

The class templates `is_indirectly_movable`, `is_nothrow_indirectly_movable`, `is_indirectly_swappable`, and `is_nothrow_indirectly_swappable` shall be defined as follows:
template <class In, class Out>
struct is_indirectly_movable : false_type { }
;

template <class In, class Out>
requires IndirectlyMovable<In, Out>()
struct is_indirectly_movable<In, Out> : true_type { }
;

template <class In, class Out>
struct is_nothrow_indirectly_movable : false_type { }
;

template <class In, class Out>
requires IndirectlyMovable<In, Out>()
struct is_nothrow_indirectly_movable<In, Out> : integral_constant<bool,
  is_nothrow_constructible<value_type_t<In>, rvalue_reference_t<In>>::value &&
  is_nothrow_assignable<value_type_t<In> &, rvalue_reference_t<In>>::value &&
  is_nothrow_assignable<reference_t<Out>, rvalue_reference_t<In>>::value &&
  is_nothrow_assignable<reference_t<Out>, value_type_t<In>>::value
{ }
;

template <class I1, class I2 = I1>
struct is_indirectly_swappable : false_type { }
;

template <class I1, class I2>
requires IndirectlySwappable<I1, I2>()
struct is_indirectly_swappable<I1, I2> : true_type { }
;

template <class I1, class I2 = I1>
struct is_nothrow_indirectly_swappable : false_type { }
;

template <class I1, class I2>
requires IndirectlySwappable<I1, I2>()
struct is_nothrow_indirectly_swappable<I1, I2> : integral_constant<bool,
  noexcept(ranges::iter_swap(declval<I1&>(), declval<I2&>())) &&
  noexcept(ranges::iter_swap(declval<I2&>(), declval<I1&>())) &&
  noexcept(ranges::iter_swap(declval<I1&>(), declval<I1&>())) &&
  noexcept(ranges::iter_swap(declval<I2&>(), declval<I2&>()))
{ }

2 For the sake of backwards compatibility, this document specifies the existence of an iterator_traits alias
that collects an iterator’s associated types. It is defined as if:

    template <InputIterator I> struct __pointer_type {       // exposition only
        using type = add_pointer_t<reference_t<I>>;
    };

    template <InputIterator I>
    requires requires(I i) { i.operator->() } -> auto&&;
    struct __pointer_type<I> {       // exposition only
        using type = decltype(declval<I>().operator->());
    };

    template <class> struct __iterator_traits { };           // exposition only
    template <Iterator I> struct __iterator_traits<I> {
        using difference_type = difference_type_t<I>;
        using value_type = void;
        using reference = void;
    };

§ 9.6.1
using pointer = void;
using iterator_category = output_iterator_tag;
};
template <InputIterator I> struct __iterator_traits<I> { // exposition only
    using difference_type = difference_type_t<I>;
    using value_type = value_type_t<I>;
    using reference = reference_t<I>;
    using pointer = typename __pointer_type<I>::type;
    using iterator_category = iterator_category_t<I>;
};
template <class I>
    using iterator_traits = __iterator_traits<I>;

3 [Note: iterator_traits is an alias template to prevent user code from specializing it. —end note]

4 [Example: To implement a generic reverse function, a C++ program can do the following:

    template <BidirectionalIterator I>
    void reverse(I first, I last) {
        difference_type_t<I> n = distance(first, last);
        --n;
        while(n > 0) {
            value_type_t<I> tmp = *first;
            *first++ = *--last;
            *last = tmp;
            n -= 2;
        }
    }

    —end example]

9.6.2 Standard iterator traits [iterator.stdtraits]

1 To facilitate interoperability between new code using iterators conforming to this document and older code using iterators that conform to the iterator requirements specified in ISO/IEC 14882, three specializations of std::iterator_traits are provided to map the newer iterator categories and associated types to the older ones.

namespace std {
    template <experimental::ranges::Iterator Out>
    struct iterator_traits<Out> {
        using difference_type = experimental::ranges::difference_type_t<Out>;
        using value_type = see below;
        using reference = see below;
        using pointer = see below;
        using iterator_category = std::output_iterator_tag;
    };

    2 The nested type value_type is computed as follows:

(2.1) — If Out::value_type is valid and denotes a type, then std::iterator_traits<Out>::value_type is Out::value_type.

(2.2) — Otherwise, std::iterator_traits<Out>::value_type is void.

3 The nested type reference is computed as follows:
(3.1) — If `Out::reference` is valid and denotes a type, then `std::iterator_traits<Out>::reference` is `Out::reference`.

(3.2) — Otherwise, `std::iterator_traits<Out>::reference` is `void`.

4 The nested type `pointer` is computed as follows:

(4.1) — If `Out::pointer` is valid and denotes a type, then `std::iterator_traits<Out>::pointer` is `Out::pointer`.

(4.2) — Otherwise, `std::iterator_traits<Out>::pointer` is `void`.

```cpp
template <experimental::ranges::InputIterator In>
struct iterator_traits<In> { };  

template <experimental::ranges::InputIterator In>
requires experimental::ranges::Sentinel<In, In>()
struct iterator_traits<In> {
  using difference_type = experimental::ranges::difference_type_t<In>;
  using value_type = experimental::ranges::value_type_t<In>;
  using reference = see below;
  using pointer = see below;
  using iterator_category = see below;
};
```

5 The nested type `reference` is computed as follows:

(5.1) — If `In::reference` is valid and denotes a type, then `std::iterator_traits<In>::reference` is `In::reference`.

(5.2) — Otherwise, `std::iterator_traits<In>::reference` is `experimental::ranges::reference_t<In>`.

6 The nested type `pointer` is computed as follows:

(6.1) — If `In::pointer` is valid and denotes a type, then `std::iterator_traits<In>::pointer` is `In::pointer`.

(6.2) — Otherwise, `std::iterator_traits<In>::pointer` is `experimental::ranges::iterator_traits<In>::pointer`.

7 Let type `C` be `experimental::ranges::iterator_category_t<In>`. The nested type `std::iterator_traits<In>::iterator_category` is computed as follows:

(7.1) — If `C` is the same as or inherits from `std::input_iterator_tag` or `std::output_iterator_tag`, `std::iterator_traits<In>::iterator_category` is `C`.

(7.2) — Otherwise, if `experimental::ranges::reference_t<In>` is not a reference type, `std::iterator_traits<In>::iterator_category` is `std::input_iterator_tag`.

(7.3) — Otherwise, if `C` is the same as or inherits from `experimental::ranges::random_access_iterator_tag`, `std::iterator_traits<In>::iterator_category` is `std::random_access_iterator_tag`.

(7.4) — Otherwise, if `C` is the same as or inherits from `experimental::ranges::bidirectional_iterator_tag`, `std::iterator_traits<In>::iterator_category` is `std::bidirectional_iterator_tag`.

§ 9.6.2
— Otherwise, if `C` is the same as or inherits from `experimental::ranges::forward_iterator_tag`,  
  `std::iterator_traits<In>::iterator_category` is `std::forward_iterator_tag`.

— Otherwise, `std::iterator_traits<In>::iterator_category` is `std::input_iterator_tag`.

8  [Note: Some implementations may find it necessary to add additional constraints to these partial specializations to prevent them from being considered for types that conform to the iterator requirements specified in ISO/IEC 14882. — end note]

9.6.3 Standard iterator tags  [std.iterator.tags]

It is often desirable for a function template specialization to find out what is the most specific category of its iterator argument, so that the function can select the most efficient algorithm at compile time. To facilitate this, the library introduces category tag classes which can be used as compile time tags for algorithm selection. [Note: The preferred way to dispatch to more specialized algorithm implementations is with concept-based overloading. — end note] The category tags are: `input_iterator_tag`, `output_iterator_tag`, `forward_iterator_tag`, `bidirectional_iterator_tag` and `random_access_iterator_tag`. For every input iterator of type `I`, `iterator_category_t<I>` shall be defined to be the most specific category tag that describes the iterator’s behavior.

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  struct output_iterator_tag { };  
  struct input_iterator_tag { };  
  struct forward_iterator_tag : input_iterator_tag { };  
  struct bidirectional_iterator_tag : forward_iterator_tag { };  
  struct random_access_iterator_tag : bidirectional_iterator_tag { };  
}}}}
```

2  [Note: The `output_iterator_tag` is provided for the sake of backward compatibility. — end note]

3  [Example: For a program-defined iterator `BinaryTreeIterator`, it could be included into the bidirectional iterator category by specializing the `difference_type`, `value_type`, and `iterator_category` templates:

```cpp
template <class T> struct difference_type<BinaryTreeIterator<T>> {
  using type = ptrdiff_t;
};
template <class T> struct value_type<BinaryTreeIterator<T>> {
  using type = T;
};
template <class T> struct iterator_category<BinaryTreeIterator<T>> {
  using type = bidirectional_iterator_tag;
};
```

— end example]

9.6.4 Iterator operations  [iterator.operations]

Since only types that satisfy `RandomAccessIterator` provide the `+` operator, and types that satisfy `SizedSentinel` provide the `-` operator, the library provides four function templates `advance`, `distance`, `next`, and `prev`. These function templates use `+` and `-` for random access iterators and ranges that satisfy `SizedSentinel`, respectively (and are, therefore, constant time for them); for output, input, forward and bidirectional iterators they use `++` to provide linear time implementations.

```cpp
template <Iterator I>
void advance(I& i, difference_type_t<I> n);
```
Requires: n shall be negative only for bidirectional iterators.

Effects: For random access iterators, equivalent to i += n. Otherwise, increments (or decrements for negative n) iterator i by n.

```cpp
template <Iterator I, Sentinel<I> S>
void advance(I& i, S bound);
```

Requires: If Assignable<I&, S>() is not satisfied, [i,bound) shall denote a range.

Effects:

(5.1) — If Assignable<I&, S>() is satisfied, equivalent to i = std::move(bound).
(5.2) — Otherwise, if SizedSentinel<S, I>() is satisfied, equivalent to advance(i, bound - i).
(5.3) — Otherwise, increments i until i == bound.

```cpp
template <Iterator I, Sentinel<I> S>
difference_type_t<I> advance(I& i, difference_type_t<I> n, S bound);
```

Requires: If n > 0, [i,bound) shall denote a range. If n == 0, [i,bound) or [bound,i) shall denote a range. If n < 0, [bound,i) shall denote a range and (BidirectionalIterator<I>() && Same<I, S>()) shall be satisfied.

Effects:

(7.1) — If SizedSentinel<S, I>() is satisfied:
(7.1.1) — If |n| > |bound - i|, equivalent to advance(i, bound).
(7.1.2) — Otherwise, equivalent to advance(i, n).
(7.2) — Otherwise, increments (or decrements for negative n) iterator i either n times or until i == bound, whichever comes first.

Returns: n - M, where M is the distance from the starting position of i to the ending position.

```cpp
template <Iterator I, Sentinel<I> S>
difference_type_t<I> distance(I first, S last);
```

Requires: [first,last) shall denote a range, or (Same<S, I>() && SizedSentinel<S, I>()) shall be satisfied and [last,first) shall denote a range.

Effects: If SizedSentinel<S, I>() is satisfied, returns (last - first); otherwise, returns the number of increments needed to get from first to last.

```cpp
template <Iterator I>
I next(I x, difference_type_t<I> n = 1);
```

Effects: Equivalent to: advance(x, n); return x;

```cpp
template <Iterator I, Sentinel<I> S>
I next(I x, S bound);
```

Effects: Equivalent to: advance(x, bound); return x;

```cpp
template <Iterator I, Sentinel<I> S>
I next(I x, difference_type_t<I> n, S bound);
```

Effects: Equivalent to: advance(x, n, bound); return x;

```cpp
template <BidirectionalIterator I>
I prev(I x, difference_type_t<I> n = 1);
```

§ 9.6.4
Effects: Equivalent to: \(\text{advance}(x, -n); \text{return } x;\)

```cpp
template <BidirectionalIterator I>
I prev(I x, difference_type_t<I> n, I bound);
```

Effects: Equivalent to: \(\text{advance}(x, -n, \text{bound}); \text{return } x;\)

### 9.7 Iterator adaptors

#### 9.7.1 Reverse iterators

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. The fundamental relation between a reverse iterator and its corresponding underlying iterator \(i\) is established by the identity: 

\[ *\text{make_reverse_iterator}(i) == *\text{prev}(i). \]

Class template `reverse_iterator`

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <BidirectionalIterator I>
    class reverse_iterator {
    public:
        using iterator_type = I;
        using difference_type = difference_type_t<I>;
        using value_type = value_type_t<I>;
        using iterator_category = iterator_category_t<I>;
        using reference = reference_t<I>;
        using pointer = I;
        reverse_iterator();
        explicit reverse_iterator(I x);
        reverse_iterator(const reverse_iterator<ConvertibleTo<I>>& i);
        reverse_iterator& operator=(const reverse_iterator<ConvertibleTo<I>>& i);
        I base() const;
        reference operator*() const;
        pointer operator->() const;
        reverse_iterator& operator++();
        reverse_iterator operator++(int);
        reverse_iterator& operator--();
        reverse_iterator operator--(int);
        reverse_iterator operator+ (difference_type n) const
            requires RandomAccessIterator<I>();
        reverse_iterator& operator+=(difference_type n)
            requires RandomAccessIterator<I>();
        reverse_iterator operator- (difference_type n) const
            requires RandomAccessIterator<I>();
        reverse_iterator& operator-=(difference_type n)
            requires RandomAccessIterator<I>();
        reference operator[] (difference_type n) const
            requires RandomAccessIterator<I>();
        private:
            I current; // exposition only
    };}
```
template <class I1, class I2>
    requires EqualityComparable<I1, I2>()
    bool operator==(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <class I1, class I2>
    requires EqualityComparable<I1, I2>()
    bool operator!=(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator<(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator>(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator>=(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator<=(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <class I1, class I2>
    requires SizedSentinel<I1, I2>()
    difference_type_t<I2> operator-(
        const reverse_iterator<I1>& x,
        const reverse_iterator<I2>& y);

template <RandomAccessIterator I>
    reverse_iterator<I> operator+(difference_type_t<I> n,
        const reverse_iterator<I>& x);

    template <BidirectionalIterator I>
        reverse_iterator<I> make_reverse_iterator(I i);
    }}}}

9.7.1.2 reverse_iterator operations [reverse.iter.ops]

9.7.1.2.1 reverse_iterator constructor [reverse.iter.cons]

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 I.

explicit reverse_iterator(I x);

§ 9.7.1.2.1
Effects: Initializes current with x.

reverse_iterator(const reverse_iterator<ConvertibleTo<I>>& i);

Effects: Initializes current with i.current.

9.7.1.2.2 reverse_iterator::operator=

reverse_iterator&
operator=(const reverse_iterator<ConvertibleTo<I>>& i);

Effects: Assigns i.current to current.

Returns: *this.

9.7.1.2.3 Conversion

I base() const;

Returns: current.

9.7.1.2.4 operator*

reference operator*() const;

Effects: Equivalent to: return *prev(current);

9.7.1.2.5 operator->

pointer operator->() const;

Effects: Equivalent to: return prev(current);

9.7.1.2.6 operator++

reverse_iterator& operator++();

Effects: --current;

Returns: *this.

reverse_iterator operator++(int);

Effects:

    reverse_iterator tmp = *this;
    --current;
    return tmp;

9.7.1.2.7 operator--

reverse_iterator& operator--();

Effects: ++current

Returns: *this.

reverse_iterator operator--(int);

Effects:

    reverse_iterator tmp = *this;
    ++current;
    return tmp;

§ 9.7.1.2.7
9.7.1.2.8 operator+  [reverse.iter.op+]

reverse_iterator
operator+(difference_type n) const
 requires RandomAccessIterator<I>();

1            Returns: reverse_iterator(current-n).

9.7.1.2.9 operator++  [reverse.iter.op++]

reverse_iterator&
operator+=(difference_type n)
 requires RandomAccessIterator<I>();

1            Effects: current -= n;
2            Returns: *this.

9.7.1.2.10 operator-  [reverse.iter.op-]

reverse_iterator
operator-(difference_type n) const
 requires RandomAccessIterator<I>();

1            Returns: reverse_iterator(current+n).

9.7.1.2.11 operator-=  [reverse.iter.op-]

reverse_iterator&
operator-=(difference_type n)
 requires RandomAccessIterator<I>();

1            Effects: current += n;
2            Returns: *this.

9.7.1.2.12 operator[]  [reverse.iter.opindex]

reference operator[](difference_type n) const
 requires RandomAccessIterator<I>();

1            Returns: current[-n-1].

9.7.1.2.13 operator==  [reverse.iter.op==]

template <class I1, class I2>
 requires EqualityComparable<I1, I2>()
 bool operator==(const reverse_iterator<I1>& x,
 const reverse_iterator<I2>& y);

1            Effects: Equivalent to: return x.current == y.current;

9.7.1.2.14 operator!=  [reverse.iter.op!=]

template <class I1, class I2>
 requires EqualityComparable<I1, I2>()
 bool operator!=(const reverse_iterator<I1>& x,
 const reverse_iterator<I2>& y);

1            Effects: Equivalent to: return x.current != y.current;
9.7.1.2.15  operator<

```cpp
template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator<(const reverse_iterator<I1>& x,
                  const reverse_iterator<I2>& y);
```

Effects: Equivalent to: return x.current > y.current;

9.7.1.2.16  operator>

```cpp
template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator>(const reverse_iterator<I1>& x,
                  const reverse_iterator<I2>& y);
```

Effects: Equivalent to: return x.current < y.current;

9.7.1.2.17  operator>=

```cpp
template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator>=(const reverse_iterator<I1>& x,
                   const reverse_iterator<I2>& y);
```

Effects: Equivalent to: return x.current <= y.current;

9.7.1.2.18  operator<=

```cpp
template <class I1, class I2>
    requires StrictTotallyOrdered<I1, I2>()
    bool operator<=(const reverse_iterator<I1>& x,
                   const reverse_iterator<I2>& y);
```

Effects: Equivalent to: return x.current >= y.current;

9.7.1.2.19  operator-

```cpp
template <class I1, class I2>
    requires SizedSentinel<I1, I2>()
    difference_type_t<I2> operator-(const reverse_iterator<I1>& x,
                                  const reverse_iterator<I2>& y);
```

Effects: Equivalent to: return y.current - x.current;

9.7.1.2.20  operator+

```cpp
template <RandomAccessIterator I>
    reverse_iterator<I>
    operator+(difference_type_t<I> n,
             const reverse_iterator<I>& x);
```

Effects: Equivalent to: return reverse_iterator<I>(x.current - n);
9.7.2.21 Non-member function make_reverse_iterator() [reverse.iter.make]

```cpp
template <BidirectionalIterator I>
reverse_iterator<I> make_reverse_iterator(I i);
```

Returns: reverse_iterator<I>(i).

9.7.2 Insert iterators [iterators.insert]

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,

```cpp
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 satisfy OutputIterator. 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.

9.7.2.1 Class template back_insert_iterator [back.insert.iterator]

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <class Container>
    class back_insert_iterator {
    public:
        using container_type = Container;
        using difference_type = ptrdiff_t;

        constexpr back_insert_iterator();
        explicit back_insert_iterator(Container& x);
        back_insert_iterator&
            operator=(const value_type_t<Container>& value);
        back_insert_iterator&
            operator=(value_type_t<Container>&& value);

        back_insert_iterator& operator*();
        back_insert_iterator& operator++();
        back_insert_iterator operator++(int);

        private:
        Container* container; // exposition only
    };

    template <class Container>
    back_insert_iterator<Container> back_inserter(Container& x);
}}}
```

9.7.2.2 back_insert_iterator operations [back.insert.iter.ops]

9.7.2.2.1 back_insert_iterator constructor [back.insert.iter.cons]

§ 9.7.2.2.1
constexpr back_insert_iterator();

Effects: Value-initializes container.

explicit back_insert_iterator(Container& x);

Effects: Initializes container with addressof(x).

9.7.2.2.2 back_insert_iterator::operator=

back_insert_iterator&
operator=(const value_type_t<Container>& value);

Effects: Equivalent to container->push_back(value).
Returns: *this.

back_insert_iterator&
operator=(value_type_t<Container>&& value);

Effects: Equivalent to container->push_back(std::move(value)).
Returns: *this.

9.7.2.2.3 back_insert_iterator::operator*

back_insert_iterator& operator*();
Returns: *this.

9.7.2.2.4 back_insert_iterator::operator++

back_insert_iterator& operator++();
back_insert_iterator operator++(int);
Returns: *this.

9.7.2.2.5 back_inserter

template <class Container>
back_insert_iterator<Container> back_inserter(Container& x);
Returns: back_insert_iterator<Container>(x).

9.7.2.3 Class template front_insert_iterator

namespace std { namespace experimental { namespace ranges { inline namespace v1 {

template <class Container>
class front_insert_iterator {
public:
using container_type = Container;
using difference_type = ptrdiff_t;

constexpr front_insert_iterator();
explicit front_insert_iterator(Container& x);
front_insert_iterator&
operator=(const value_type_t<Container>& value);
front_insert_iterator&
operator=(value_type_t<Container>&& value);

front_insert_iterator& operator*();
front_insert_iterator& operator++();

§ 9.7.2.3
front_insert_iterator operator++(int);

private:
  Container* container; // exposition only
);

template <class Container>
  front_insert_iterator<Container> front_inserter(Container& x);
})}

9.7.2.4  front_insert_iterator operations

9.7.2.4.1  front_insert_iterator constructor

constexpr front_insert_iterator();

Effects: Value-initializes container.

explicit front_insert_iterator(Container& x);

Effects: Initializes container with addressof(x).

front_insert_iterator::operator=

front_insert_iterator&
  operator=(const value_type_t<Container>& value);

Effects: Equivalent to container->push_front(value).

Returns: *this.

front_insert_iterator&
  operator=(value_type_t<Container>&& value);

Effects: Equivalent to container->push_front(std::move(value)).

Returns: *this.

front_insert_iterator::operator*

front_insert_iterator& operator*();

Returns: *this.

front_insert_iterator::operator++

front_insert_iterator& operator++();

front_insert_iterator operator++(int);

Returns: *this.

9.7.2.4.5  front_inserter

template <class Container>
  front_insert_iterator<Container> front_inserter(Container& x);

Returns: front_insert_iterator<Container>(x).

9.7.2.5  Class template insert_iterator

namespace std { namespace experimental { namespace ranges { inline namespace v1 {

template <class Container>
  class insert_iterator {

§ 9.7.2.5

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public:
    using container_type = Container;
    using difference_type = ptrdiff_t;

    insert_iterator();
    insert_iterator(Container& x, iterator_t<Container> i);

    insert_iterator&
    operator=(const value_type_t<Container>& value);
    insert_iterator&
    operator=(value_type_t<Container>&& value);

    insert_iterator& operator*();
    insert_iterator& operator++();
    insert_iterator operator++(int);

private:
    Container* container; // exposition only
    iterator_t<Container> iter; // exposition only
};

};

5.7.2.6 insert_iterator operations [insert.iter.ops]

5.7.2.6.1 insert_iterator constructor [insert.iter.cons]

insert_iterator();

Effects: Value-initializes container and iter.

insert_iterator(Container& x, iterator_t<Container> i);

Requires: i is an iterator into x.

Effects: Initializes container with addressof(x) and iter with i.

5.7.2.6.2 insert_iterator::operator= [insert.iter.op=]

insert_iterator&
    operator=(const value_type_t<Container>& value);

Effects: Equivalent to:
    iter = container->insert(iter, value);
    ++iter;

Returns: *this.

insert_iterator&
    operator=(value_type_t<Container>&& value);

Effects: Equivalent to:
    iter = container->insert(iter, std::move(value));
    ++iter;

Returns: *this.

§ 5.7.2.6.2
9.7.2.6.3  insert_iterator::operator*

insert_iterator& operator*();

Returns: *this.

9.7.2.6.4  insert_iterator::operator++

insert_iterator& operator++();
insert_iterator operator++(int);

Returns: *this.

9.7.2.6.5  inserter

template <class Container>
insert_iterator<Container> inserter(Container& x, iterator_t<Container> i);

Returns: insert_iterator<Container>(x, i).

9.7.3  Move iterators and sentinels

9.7.3.1  Class template move_iterator

Class template move_iterator is an iterator adaptor with the same behavior as the underlying iterator except that its indirection operator implicitly converts the value returned by the underlying iterator’s indirection operator to an rvalue of the value type. Some generic algorithms can be called with move iterators to replace copying with moving.

Example:

```cpp
list<string> s;
// populate the list s
vector<string> v1(s.begin(), s.end()); // copies strings into v1
vector<string> v2(make_move_iterator(s.begin()),
make_move_iterator(s.end())); // moves strings into v2
```

namespace std { namespace experimental { namespace ranges { inline namespace v1 {

class move_iterator {

public:
using iterator_type = I;
using difference_type = difference_type_t<I>;
using value_type = value_type_t<I>;
using iterator_category = input_iterator_tag;
using reference = rvalue_reference_t<I>;

move_iterator();
explicit move_iterator(I i);
move_iterator(const move_iterator<ConvertibleTo<I>>& i);
move_iterator& operator=(const move_iterator<ConvertibleTo<I>>& i);

I base() const;
reference operator*() const;

move_iterator& operator++();
move_iterator operator++(int);
move_iterator& operator--();
```
requires BidirectionalIterator<I>();
move_iterator operator--(int)
requires BidirectionalIterator<I>();

move_iterator operator+(difference_type n) const
requires RandomAccessIterator<I>();
move_iterator& operator+=(difference_type n)
requires RandomAccessIterator<I>();
move_iterator operator-(difference_type n) const
requires RandomAccessIterator<I>();
move_iterator& operator-=(difference_type n)
requires RandomAccessIterator<I>();

private:
I current; // exposition only
};

template <class I1, class I2>
requires EqualityComparable<I1, I2>()
bool operator==(const move_iterator<I1>& x, const move_iterator<I2>& y);
template <class I1, class I2>
requires EqualityComparable<I1, I2>()
bool operator!=(const move_iterator<I1>& x, const move_iterator<I2>& y);
template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator<(const move_iterator<I1>& x, const move_iterator<I2>& y);
template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator<=(const move_iterator<I1>& x, const move_iterator<I2>& y);
template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator>(const move_iterator<I1>& x, const move_iterator<I2>& y);
template <class I1, class I2>
requires StrictTotallyOrdered<I1, I2>()
bool operator>=(const move_iterator<I1>& x, const move_iterator<I2>& y);

template <class I1, class I2>
requires SizedSentinel<I1, I2>()
difference_type_t<I2> operator-((
    const move_iterator<I1>& x,
    const move_iterator<I2>& y);
template <RandomAccessIterator I>
move_iterator<I>
operator+(difference_type_t<I> n,
    const move_iterator<I>& x);
template <InputIterator I>
move_iterator<I> make_move_iterator(I i);
})}

3 [Note: move_iterator does not provide an operator-> because the class member access expression i->m may have different semantics than the expression (*i).m when the expression *i is an rvalue. — end note]

9.7.3.2 move_iterator operations
9.7.3.2.1 move_iterator constructors

move_iterator();
1 Effects: Constructs a move_iterator, value-initializing 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 I.

explicit move_iterator(I i);
2 Effects: Constructs a move_iterator, initializing current with i.

move_iterator(const move_iterator<ConvertibleTo<I>>& i); 3 Effects: Constructs a move_iterator, initializing current with i.current.

9.7.3.2.2 move_iterator::operator=

move_iterator& operator=(const move_iterator<ConvertibleTo<I>>& i);
1 Effects: Assigns i.current to current.

9.7.3.2.3 move_iterator conversion

I base() const;
1 Returns: current.

9.7.3.2.4 move_iterator::operator*

reference operator*() const;
1 Effects: Equivalent to: return iter_move(current);

9.7.3.2.5 move_iterator::operator++

move_iterator& operator++();
1 Effects: Equivalent to ++current.
2 Returns: *this.

move_iterator operator++(int);
3 Effects: Equivalent to:

move_iterator tmp = *this;
++current;
return tmp;

§ 9.7.3.2.5
9.7.3.2.6 move_iterator::operator--

move_iterator& operator--()
requires BidirectionalIterator<I>();

1 Effects: Equivalent to --current.
2 Returns: *this.

move_iterator operator--(int)
requires BidirectionalIterator<I>();

3 Effects: Equivalent to:
move_iterator tmp = *this;
--current;
return tmp;

9.7.3.2.7 move_iterator::operator+

move_iterator operator+(difference_type n) const
requires RandomAccessIterator<I>();

1 Effects: Equivalent to: return move_iterator(current + n);

9.7.3.2.8 move_iterator::operator++

move_iterator& operator+=(difference_type n)
requires RandomAccessIterator<I>();

1 Effects: Equivalent to current += n.
2 Returns: *this.

9.7.3.2.9 move_iterator::operator--

move_iterator operator-(difference_type n) const
requires RandomAccessIterator<I>();

1 Effects: Equivalent to: return move_iterator(current - n);

9.7.3.2.10 move_iterator::operator--=

move_iterator& operator=(difference_type n)
requires RandomAccessIterator<I>();

1 Effects: Equivalent to current -= n.
2 Returns: *this.

9.7.3.2.11 move_iterator::operator[]

reference operator[](difference_type n) const
requires RandomAccessIterator<I>();

1 Effects: Equivalent to: return iter_move(current + n);

9.7.3.2.12 move_iterator comparisons

template <class I1, class I2>
requires EqualityComparable<I1, I2>()
bool operator==(const move_iterator<I1>& x, const move_iterator<I2>& y);

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Effects: Equivalent to: \( \text{return } x\text{.current }== \text{y}\text{.current}; \)

template <class I1, class I2>
  requires EqualityComparable<I1, I2>()
  bool operator!=(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

Effects: Equivalent to: \( \text{return }!(x == y); \)

template <class I1, class I2>
  requires StrictTotallyOrdered<I1, I2>()
  bool operator<(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

Effects: Equivalent to: \( \text{return }x\text{.current }< \text{y}\text{.current}; \)

template <class I1, class I2>
  requires StrictTotallyOrdered<I1, I2>()
  bool operator<=(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

Effects: Equivalent to: \( \text{return }!(y < x); \)

template <class I1, class I2>
  requires StrictTotallyOrdered<I1, I2>()
  bool operator>(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

Effects: Equivalent to: \( \text{return }y < x; \)

template <class I1, class I2>
  requires StrictTotallyOrdered<I1, I2>()
  bool operator>=(
    const move_iterator<I1>& x, const move_iterator<I2>& y);

Effects: Equivalent to: \( \text{return }!(x < y);. \)

9.7.3.2.13 move_iterator non-member functions

[move.iter.nonmember]

template <class I1, class I2>
  requires SizedSentinel<I1, I2>()
  difference_type_t<I2> operator-(
    const move_iterator<I1>& x,
    const move_iterator<I2>& y);

Effects: Equivalent to: \( \text{return }x\text{.current }- \text{y}\text{.current}; \)

template <RandomAccessIterator I>
  move_iterator<I>
  operator+(difference_type_t<I> n,
    const move_iterator<I>& x);

Effects: Equivalent to: \( \text{return }x + n; \)

template <InputIterator I>
  move_iterator<I> make_move_iterator(I i);

Returns: move_iterator<I>(i).
9.7.3.3 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 satisfy Sentinel<S, I>(), Sentinel<move_sentinel<S>, move_iterator<I>>() is satisfied as well.

[Example: A move_if algorithm is easily implemented with copy_if using move_iterator and move_sentinel:

```cpp
template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O, IndirectPredicate<I> Pred>
    requires IndirectlyMovable<I, O>()
void move_if(I first, S last, O out, Pred pred)
{
    copy_if(move_iterator<I>{first}, move_sentinel<S>{last}, out, pred);
}
```

—end example]

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <Semiregular S>
    class move_sentinel {
    public:
        constexpr move_sentinel();
        explicit move_sentinel(S s);
        move_sentinel(const move_sentinel<ConvertibleTo<S>>& s);
        move_sentinel& operator=(const move_sentinel<ConvertibleTo<S>>& s);
        S base() const;
    private:
        S last; // exposition only
    };

    template <class I, Sentinel<I> S>
    bool operator==(const move_iterator<I>& i, const move_sentinel<S>& s);
    template <class I, Sentinel<I> S>
    bool operator==(const move_sentinel<S>& s, const move_iterator<I>& i);
    template <class I, Sentinel<I> S>
    bool operator!=(const move_iterator<I>& i, const move_sentinel<S>& s);
    template <class I, Sentinel<I> S>
    bool operator!=(const move_sentinel<S>& s, const move_iterator<I>& i);
    template <class I, SizedSentinel<I> S>
    difference_type_t<I> operator-(
        const move_sentinel<S>& s, const move_iterator<I>& i);
    template <class I, SizedSentinel<I> S>
    difference_type_t<I> operator-(
        const move_iterator<I>& i, const move_sentinel<S>& s);

    template <Semiregular S>
    move_sentinel<S> make_move_sentinel(S s);
}}}}
9.7.3.4 move_sentinel operations

9.7.3.4.1 move_sentinel constructors

constexpr move_sentinel();

Effects: Constructs a move_sentinel, value-initializing last. If is_trivially_default_constructible<S>::value is true, then this constructor is a constexpr constructor.

explicit move_sentinel(S s);

Effects: Constructs a move_sentinel, initializing last with s.

move_sentinel(const move_sentinel<ConvertibleTo<S>>& s);

Effects: Constructs a move_sentinel, initializing last with s.last.

9.7.3.4.2 move_sentinel::operator=

move_sentinel& operator=(const move_sentinel<ConvertibleTo<S>>& s);

Effects: Assigns s.last to last.

Returns: *this.

9.7.3.4.3 move_sentinel comparisons

template <class I, Sentinel<I> S>
bool operator==(const move_iterator<I>& i, const move_sentinel<S>& s);

template <class I, Sentinel<I> S>
bool operator==(const move_sentinel<S>& s, const move_iterator<I>& i);

Effects: Equivalent to: return i.current == s.last;

template <class I, Sentinel<I> S>
bool operator!=(const move_iterator<I>& i, const move_sentinel<S>& s);

template <class I, Sentinel<I> S>
bool operator!=(const move_sentinel<S>& s, const move_iterator<I>& i);

Effects: Equivalent to: return !(i == s);

9.7.3.4.4 move_sentinel non-member functions

template <class I, SizedSentinel<I> S>
difference_type_t<I> operator-(
    const move_sentinel<S>& s, const move_iterator<I>& i);

Effects: Equivalent to: return s.last - i.current;

template <class I, SizedSentinel<I> S>
difference_type_t<I> operator-(
    const move_iterator<I>& i, const move_sentinel<S>& s);

Effects: Equivalent to: return i.current - s.last;

template <Semiregular S>
move_sentinel<S> make_move_sentinel(S s);

Returns: move_sentinel<S>(s).
9.7.4 Common iterators

Class template common_iterator is an iterator/sentinel adaptor that is capable of representing a non-bounded range of elements (where the types of the iterator and sentinel differ) as a bounded 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: 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:

```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>;
// call fun on a range of 10 ints
fun(CI(make_counted_iterator(s.begin(), 10)), CI(default_sentinel()));
```

9.7.4.1 Class template common_iterator

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  template <Iterator I, Sentinel<I> S>
  requires !Same<I, S>()
  class common_iterator {
  public:
    using difference_type = difference_type_t<I>;

    common_iterator();
    common_iterator(I i);
    common_iterator(S s);
    common_iterator(const common_iterator<ConvertibleTo<I>, ConvertibleTo<S>>& u);
    common_iterator& operator=(const common_iterator<ConvertibleTo<I>, ConvertibleTo<S>>& u);

    ~common_iterator();

    see below operator*();
    see below operator*() const;
    see below operator->() const requires Readable<I>();

    common_iterator& operator++();
    common_iterator operator++(int);

    private:
      bool is_sentinel; // exposition only
      I iter;           // exposition only
      S sentinel;       // exposition only
  };

  template <Readable I, class S>
  struct value_type<common_iterator<I, S>> {
```
using type = value_type_t<I>;
};

template <InputIterator I, class S>
struct iterator_category<common_iterator<I, S>> {
    using type = input_iterator_tag;
};

template <ForwardIterator I, class S>
struct iterator_category<common_iterator<I, S>> {
    using type = forward_iterator_tag;
};

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
bool operator==(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
requires EqualityComparable<I1, I2>()
bool operator!=(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

difference_type_t<I2> operator-(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

1 [ Note: It is unspecified whether common_iterator’s members iter and sentinel have distinct addresses or not. — end note ]

9.7.4.2 common_iterator operations [common.iter.ops]

9.7.4.2.1 common_iterator constructors [common.iter.op.const]

common_iterator();

1 Effects: Constructs a common_iterator, value-initializing is_sentinel and iter. 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 I.

Remarks: It is unspecified whether any initialization is performed for sentinel.

common_iterator(I i);

3 Effects: Constructs a common_iterator, initializing is_sentinel with false and iter with i.

Remarks: It is unspecified whether any initialization is performed for sentinel.

common_iterator(S s);

5 Effects: Constructs a common_iterator, initializing is_sentinel with true and sentinel with s.

Remarks: It is unspecified whether any initialization is performed for iter.

common_iterator(const common_iterator<ConvertibleTo<I>, ConvertibleTo<S>>& u);

7 Effects: Constructs a common_iterator, initializing is_sentinel with u.is_sentinel.

(7.1) — If u.is_sentinel is true, sentinel is initialized with u.sentinel.
(7.2) If \texttt{u.is\_sentinel} is \texttt{false}, \texttt{iter} is initialized with \texttt{u.iter}.

(8.1) If \texttt{u.is\_sentinel} is \texttt{true}, it is unspecified whether any initialization is performed for \texttt{iter}.

(8.2) If \texttt{u.is\_sentinel} is \texttt{false}, it is unspecified whether any initialization is performed for \texttt{sentinel}.

9.7.4.2.2 \texttt{common\_iterator::operator=} \hspace{1cm} [common.iter.op=]

\begin{verbatim}
common\_iterator& operator=(const common\_iterator\<ConvertibleTo\<I>, ConvertibleTo\<S\>\>& u);
\end{verbatim}

1 \textbf{Effects:} Assigns \texttt{u.is\_sentinel} to \texttt{is\_sentinel}.

(1.1) If \texttt{u.is\_sentinel} is \texttt{true}, assigns \texttt{u.sentinel} to \texttt{sentinel}.

(1.2) If \texttt{u.is\_sentinel} is \texttt{false}, assigns \texttt{u.iter} to \texttt{iter}.

\textbf{Remarks:}

(1.3) If \texttt{u.is\_sentinel} is \texttt{true}, it is unspecified whether any operation is performed on \texttt{iter}.

(1.4) If \texttt{u.is\_sentinel} is \texttt{false}, it is unspecified whether any operation is performed on \texttt{sentinel}.

2 \textbf{Returns:} \texttt{*this}

\texttt{~common\_iterator();}

3 \textbf{Effects:} Destroys all members that are currently initialized.

9.7.4.2.3 \texttt{common\_iterator::operator*} \hspace{1cm} [common.iter.op.star]

\begin{verbatim}
dectype(auto) operator*();
dectype(auto) operator*() const;
\end{verbatim}

1 \textbf{Requires:} \texttt{!is\_sentinel}

2 \textbf{Effects:} Equivalent to: return \texttt{*iter};

9.7.4.2.4 \texttt{common\_iterator::operator->} \hspace{1cm} [common.iter.op.ref]

\texttt{see below operator->() const requires Readable\<I\>();}

1 \textbf{Requires:} \texttt{!is\_sentinel}

2 \textbf{Effects:} Given an object \texttt{i} of type \texttt{I}

(2.1) if \texttt{I} is a pointer type or if the expression \texttt{i.operator->()} is well-formed, this function returns \texttt{iter}.

(2.2) Otherwise, if the expression \texttt{*iter} is a glvalue, this function is equivalent to \texttt{return addressof(*iter);}

(2.3) Otherwise, this function returns a proxy object of an unspecified type equivalent to the following:

\begin{verbatim}
class proxy {
  // exposition only
  value\_type\_<I> keep\_;
  proxy(reference\_t\_<I>&& x)
    : keep_(std::move(x)) {} 
  public:
    const value\_type\_<I>* operator->() const {
      return addressof(keep\_);
    }
};
\end{verbatim}

that is initialized with \texttt{*iter}.
9.7.4.2.5 common_iterator::operator++

common_iterator& operator++();

1 Requires: !is_sentinel
2 Effects: ++iter.
3 Returns: *this.

common_iterator operator++(int);

4 Requires: !is_sentinel
5 Effects: Equivalent to:
   common_iterator tmp = *this;
   ++iter;
   return tmp;

9.7.4.2.6 common_iterator comparisons

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
bool operator==(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

1 Effects: Equivalent to:
   return x.is_sentinel ?
   (y.is_sentinel || y.iter == x.sentinel) :
   (!y.is_sentinel || x.iter == y.sentinel);

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
requires EqualityComparable<I1, I2>()
bool operator==(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

2 Effects: Equivalent to:
   return x.is_sentinel ?
   (y.is_sentinel || y.iter == x.sentinel) :
   (y.is_sentinel ?
   x.iter == y.sentinel :
   x.iter == y.iter);

template <class I1, class I2, Sentinel<I2> S1, Sentinel<I1> S2>
bool operator!=(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

3 Effects: Equivalent to: return !(x == y);

template <class I2, SizedSentinel<I2> I1, SizedSentinel<I2> S1, SizedSentinel<I1> S2>
difference_type_t<I2> operator-(const common_iterator<I1, S1>& x, const common_iterator<I2, S2>& y);

4 Effects: Equivalent to:
   return x.is_sentinel ?
   (y.is_sentinel ? 0 : x.sentinel - y.iter) :
   (y.is_sentinel ?
   x.iter - y.sentinel :
   x.iter - y.iter);

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9.7.5 Default sentinels

9.7.5.1 Class default_sentinel

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    class default_sentinel {;
}}}}}

1 Class default_sentinel is an empty type used to denote the end of a range. It is intended to be used together with iterator types that know the bound of their range (e.g., counted_iterator (9.7.6.1)).

9.7.6 Counted iterators

9.7.6.1 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 its distance from its starting position. It can be used together with class default_sentinel in calls to generic algorithms to operate on a range of $N$ elements starting at a given position without needing to know the end position a priori.

[Example:

```cpp
list<string> s;
// populate the list s with at least 10 strings
vector<string> v(make_counted_iterator(s.begin(), 10),
    default_sentinel()); // copies 10 strings into v
```
— end example]

2 Two values $i_1$ and $i_2$ of (possibly differing) types counted_iterator$I_1$ and counted_iterator$I_2$ refer to elements of the same sequence if and only if next$\left(i_1.base(), i_1.count()\right)$ and next$\left(i_2.base(), i_2.count()\right)$ refer to the same (possibly past-the-end) element.

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <Iterator I>
    class counted_iterator {
        public:
            using iterator_type = I;
            using difference_type = difference_type_t<I>;

            counted_iterator();
            counted_iterator(I x, difference_type_t<I> n);
            counted_iterator(const counted_iterator<ConvertibleTo<I>>& i);
            counted_iterator& operator=(const counted_iterator<ConvertibleTo<I>>& i);

            I base() const;
            difference_type_t<I> count() const;
            see below operator*();
            see below operator*() const;

            counted_iterator& operator++();
            counted_iterator operator++(int);
            counted_iterator& operator--()
                requires BidirectionalIterator<I>();
            counted_iterator operator--(int)
                requires BidirectionalIterator<I>();

            counted_iterator operator+(difference_type n) const
                requires RandomAccessIterator<I>();
            counted_iterator& operator+=(difference_type n)
```

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requires RandomAccessIterator<I>();
counted_iterator operator- (difference_type n) const
    requires RandomAccessIterator<I>();
counted_iterator& operator-=(difference_type n)
    requires RandomAccessIterator<I>();
see below operator[](difference_type n) const
    requires RandomAccessIterator<I>();
private:
    I current; // exposition only
difference_type_t<I> cnt; // exposition only
};

#include <type_traits>

template <Readable I>
struct value_type<counted_iterator<I>> {
    using type = value_type_t<I>;
};

template <InputIterator I>
struct iterator_category<counted_iterator<I>> {
    using type = iterator_category_t<I>;
};

template <class I1, class I2>
requires Common<I1, I2>()
bool operator==(const counted_iterator<I1>& x, const counted_iterator<I2>& y);
bool operator==(const counted_iterator<auto>& x, default_sentinel);
bool operator==(default_sentinel x, const counted_iterator<auto>& y);

template <class I1, class I2>
requires Common<I1, I2>()
bool operator!=(const counted_iterator<I1>& x, const counted_iterator<I2>& y);
bool operator!=(const counted_iterator<auto>& x, default_sentinel y);
bool operator!=(default_sentinel x, const counted_iterator<auto>& y);

template <class I1, class I2>
requires Common<I1, I2>()
bool operator<(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

template <class I1, class I2>
requires Common<I1, I2>()
bool operator<=(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

template <class I1, class I2>
requires Common<I1, I2>()
bool operator>(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

template <class I1, class I2>
requires Common<I1, I2>()
bool operator>=(const counted_iterator<I1>& x, const counted_iterator<I2>& y);
const counted_iterator<I1>& x, const counted_iterator<I2>& y);

```cpp
template <class I1, class I2>
require Common<I1, I2>()
difference_type_t<I2> operator-(
    const counted_iterator<I1>& x, const counted_iterator<I2>& y);
```

```cpp
template <class I>
difference_type_t<I> operator-(
    const counted_iterator<I>& x, default_sentinel y);
```

```cpp
template <class I>
difference_type_t<I> operator-(
    default_sentinel x, const counted_iterator<I>& y);
```

```cpp
template <RandomAccessIterator I>
counted_iterator<I>
    operator+(difference_type_t<I> n, const counted_iterator<I>& x);
```

```cpp
template <Iterator I>
counted_iterator<I> make_counted_iterator(I i, difference_type_t<I> n);
```

```cpp
template <Iterator I>
void advance(counted_iterator<I>& i, difference_type_t<I> n);
```
9.7.6.2.5 counted_iterator::operator*

decltype(auto) operator*();
decltype(auto) operator*() const;

1   Effects: Equivalent to: return *current;

9.7.6.2.6 counted_iterator::operator++

counted_iterator& operator++();

1   Requires: cnt > 0
2   Effects: Equivalent to:
          ++current;
          --cnt;

3   Returns: *this.

counted_iterator operator++(int);

4   Requires: cnt > 0
5   Effects: Equivalent to:
          counted_iterator tmp = *this;
          ++current;
          --cnt;
          return tmp;

9.7.6.2.7 counted_iterator::operator--

counted_iterator& operator--();

1   Requires BidirectionalIterator<I>();
2   Effects: Equivalent to:
          --current;
          ++cnt;

2   Returns: *this.

counted_iterator operator--(int)

3   Requires BidirectionalIterator<I>();
    Effects: Equivalent to:
           counted_iterator tmp = *this;
           --current;
           ++cnt;
           return tmp;

9.7.6.2.8 counted_iterator::operator+

counted_iterator operator+(difference_type n) const

1   Requires: n <= cnt
2   Effects: Equivalent to: return counted_iterator(current + n, cnt - n);
9.7.6.2.9 counted_iterator::operator+=

counted_iterator& operator+=(difference_type n)
requires RandomAccessIterator<I>();

1 Requires: n <= cnt
2 Effects:
   current += n;
   cnt -= n;
3 Returns: *this.

9.7.6.2.10 counted_iterator::operator-=

counted_iterator operator-=(difference_type n)
requires RandomAccessIterator<I>();

1 Requires: -n <= cnt
2 Effects: Equivalent to: return counted_iterator(current - n, cnt + n);

9.7.6.2.11 counted_iterator::operator[]

dcltype(auto) operator[](difference_type n) const
requires RandomAccessIterator<I>();

1 Requires: n <= cnt
2 Effects: Equivalent to: return current[n];

9.7.6.2.12 counted_iterator comparisons

template <class I1, class I2>
requires Common<I1, I2>()
bool operator==(
   const counted_iterator<I1>& x, const counted_iterator<I2>& y);

1 Requires: x and y shall refer to elements of the same sequence (9.7.6).
2 Effects: Equivalent to: return x.cnt == y.cnt;

bool operator==(
   const counted_iterator<auto>& x, default_sentinel);
bool operator==(
   default_sentinel, const counted_iterator<auto>& x);

3 Effects: Equivalent to: return x.cnt == 0;
template <class I1, class I2>
  requires Common<I1, I2>()
bool operator!=(
    const counted_iterator<I1>& x, const counted_iterator<I2>& y);
bool operator!=(
    const counted_iterator<auto>& x, default_sentinel);
bool operator!=(
    default_sentinel, const counted_iterator<auto>& x);

  Requires: For the first overload, \(x\) and \(y\) shall refer to elements of the same sequence (9.7.6).
  Effects: Equivalent to: return \(!(x == y)\);

template <class I1, class I2>
  requires Common<I1, I2>()
bool operator<(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

  Requires: \(x\) and \(y\) shall refer to elements of the same sequence (9.7.6).
  Effects: Equivalent to: return \(y\).cnt < \(x\).cnt;

  Note: The argument order in the Effects element is reversed because cnt counts down, not up. — end note

template <class I1, class I2>
  requires Common<I1, I2>()
bool operator<=(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

  Requires: \(x\) and \(y\) shall refer to elements of the same sequence (9.7.6).
  Effects: Equivalent to: return \(!(y < x)\);

template <class I1, class I2>
  requires Common<I1, I2>()
bool operator>(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

  Requires: \(x\) and \(y\) shall refer to elements of the same sequence (9.7.6).
  Effects: Equivalent to: return \(y < x\);

template <class I1, class I2>
  requires Common<I1, I2>()
bool operator>=(const counted_iterator<I1>& x, const counted_iterator<I2>& y);

  Requires: \(x\) and \(y\) shall refer to elements of the same sequence (9.7.6).
  Effects: Equivalent to: return \(!(x < y)\);

9.7.6.2.14  counted_iterator non-member functions

template <class I1, class I2>
  requires Common<I1, I2>()
difference_type_t<I2> operator-(
    const counted_iterator<I1>& x, const counted_iterator<I2>& y);

  Requires: \(x\) and \(y\) shall refer to elements of the same sequence (9.7.6).
  Effects: Equivalent to: return \(y\).cnt - \(x\).cnt;
template <class I>
  difference_type_t<I> operator-(
    const counted_iterator<I>& x, default_sentinel y);

  Effects: Equivalent to: return -x.cnt;

template <class I>
  difference_type_t<I> operator-(
    default_sentinel x, const counted_iterator<I>& y);

  Effects: Equivalent to: return y.cnt;

template <RandomAccessIterator I>
  counted_iterator<I>
    operator+(difference_type_t<I> n, const counted_iterator<I>& x);

  Requires: n <= x.cnt.
  Effects: Equivalent to: return x + n;

template <Iterator I>
  counted_iterator<I>
    make_counted_iterator(I i, difference_type_t<I> n);

  Requires: n >= 0.
  Returns: counted_iterator<I>(i, n).

template <Iterator I>
  void advance(counted_iterator<I>& i, difference_type_t<I> n);

  Requires: n <= i.cnt.
  Effects:
    i = make_counted_iterator(next(i.current, n), i.cnt - n);

### 9.7.7 Dangling wrapper

#### 9.7.7.1 Class template dangling

Class template `dangling` is a wrapper for an object that refers to another object whose lifetime may have ended. It is used by algorithms that accept rvalue ranges and return iterators.

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  template <CopyConstructible T> 
  class dangling {
  public:
    dangling() requires DefaultConstructible<T>();
    dangling(T t);
    T get_unsafe() const;
  private:
    T value; // exposition only
  };

  template <Range R>
  using safe_iterator_t = 
    conditional_t<is_lvalue_reference<R>::value, iterator_t<R>, 
                 dangling<iterator_t<R>>::>;
}}}
```

§ 9.7.7.1
9.7.7.2 dangling operations

9.7.7.2.1 dangling constructors

dangling() requires DefaultConstructible<T>();

1

Effects: Constructs a dangling, value-initializing value.

dangling(T t);

2

Effects: Constructs a dangling, initializing value with t.

9.7.7.2.2 dangling::get_unsafe

T get_unsafe() const;

1

Returns: value.

9.7.8 Unreachable sentinel

9.7.8.1 Class unreachable

Class unreachable is a sentinel type that can be used with any Iterator to denote an infinite range. Comparing an iterator for equality with an object of type unreachable always returns false.

[Example:

```cpp
char* p;
// set p to point to a character buffer containing newlines
char* nl = find(p, unreachable(), 'n');
```

Provided a newline character really exists in the buffer, the use of unreachable 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 { namespace experimental { namespace ranges { inline namespace v1 {

class unreachable { 

template <Iterator I>
    constexpr bool operator==(const I&, unreachable) noexcept;

template <Iterator I>
    constexpr bool operator==(unreachable, const I&) noexcept;

template <Iterator I>
    constexpr bool operator!=(const I&, unreachable) noexcept;

template <Iterator I>
    constexpr bool operator!=(unreachable, const I&) noexcept;

}}}

9.7.8.2 unreachable operations

9.7.8.2.1 operator==

template <Iterator I>
    constexpr bool operator==(const I&, unreachable) noexcept;

template <Iterator I>
    constexpr bool operator==(unreachable, const I&) noexcept;

1

Returns: false.
9.7.8.2.2  \texttt{operator\!\!=} \quad [\texttt{unreachable.sentinel.op\!\!=}]

template <\texttt{Iterator I}>
const\texttt{expr bool} \texttt{operator\!\!=}(const I& x, unreachable y) noexcept;

template <\texttt{Iterator I}>
const\texttt{expr bool} \texttt{operator\!\!=}(unreachable x, const I& y) noexcept;

1  \textit{Returns:} true.

9.8  \textbf{Stream iterators} \quad [\texttt{iterators.stream}]

1  To make it possible for algorithmic templates to work directly with input/output streams, appropriate iterator-like class templates are provided.

[\textit{Example:}]

\begin{verbatim}
partial_sum(istream_iterator<double, char>(cin),
        istream_iterator<double, char>(),
        ostream_iterator<double, char>(cout, "\n"));
\end{verbatim}

reads a file containing floating point numbers from \texttt{cin}, and prints the partial sums onto \texttt{cout}. — end example]

9.8.1  \textbf{Class template istream_iterator} \quad [\texttt{istream.iterator}]

1  The class template \texttt{istream_iterator} is an input iterator (9.3.11) that reads (using \texttt{operator\textgreater\textgreater}) successive elements from the input stream for which it was constructed. After it is constructed, and every time ++ is used, the iterator reads and stores a value of \(T\). If the iterator fails to read and store a value of \(T\) (\texttt{fail()} on the stream returns \texttt{true}), the iterator becomes equal to the end-of-stream iterator value. The constructor with no arguments \texttt{istream_iterator()} always constructs an end-of-stream input iterator object, which is the only legitimate iterator to be used for the end condition. The result of \texttt{operator*} on an end-of-stream iterator is not defined. For any other iterator value a \texttt{const T\&} is returned. The result of \texttt{operator->} on an end-of-stream iterator is not defined. For any other iterator value a \texttt{const T\*} is returned. The behavior of a program that applies \texttt{operator++()} to an end-of-stream iterator is undefined. It is impossible to store things into istream iterators.

2  Two end-of-stream iterators are always equal. An end-of-stream iterator is not equal to a non-end-of-stream iterator. Two non-end-of-stream iterators are equal when they are constructed from the same stream.

namespace std { namespace experimental { namespace ranges { inline namespace v1 { 
    template <\texttt{class T, class charT = char, class traits = char_traits<charT>, class Distance = ptrdiff_t}>
    class istream_iterator {
    public:
        typedef input_iterator_tag iterator_category;
        typedef Distance difference_type;
        typedef T value_type;
        typedef const T\& reference;
        typedef const T\* pointer;
        typedef charT char_type;
        typedef traits traits_type;
        typedef basic_istream<charT, traits> istream_type;
        see below istream_iterator();
        see below istream_iterator(default_sentinel);
        istream_iterator(istream_type& s);
        istream_iterator(const istream_iterator& x) = default;
        "-istream_iterator() = default;

§ 9.8.1  103
const T& operator*() const;
const T* operator->() const;
istream_iterator& operator++();
istream_iterator operator++(int);
private:
    basic_istream<charT, traits>* in_stream;  // exposition only
    T value;  // exposition only
};

};

}}}}

9.8.1.1 istream_iterator constructors and destructor

see below istream_iterator();
see below istream_iterator(default_sentinel);

1 Effects: Constructs the end-of-stream iterator. If T is a literal type, then these constructors shall be constexpr constructors.

2 Postcondition: in_stream == nullptr.

istream_iterator(istream_type& s);

3 Effects: Initializes in_stream with &s. value may be initialized during construction or the first time it is referenced.

4 Postcondition: in_stream == &s.

istream_iterator(const istream_iterator& x) = default;

5 Effects: Constructs a copy of x. If T is a literal type, then this constructor shall be a trivial copy constructor.

6 Postcondition: in_stream == x.in_stream.

~istream_iterator() = default;

7 Effects: The iterator is destroyed. If T is a literal type, then this destructor shall be a trivial destructor.
9.8.1.2 istream_iterator operations

const T& operator*() const;

Returns: value.

const T* operator->() const;

Effects: Equivalent to: return addressof(operator*()).

istream_iterator& operator++();

Requires: in_stream != nullptr.

Effects: *in_stream >> value.

Returns: *this.

istream_iterator operator++(int);

Requires: in_stream != nullptr.

Effects:

    istream_iterator tmp = *this;
    *in_stream >> value;
    return tmp;

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.

template <class T, class charT, class traits, class Distance>
bool operator==(default_sentinel x,
                const istream_iterator<T, charT, traits, Distance> &y);

Returns: nullptr == y.in_stream.

template <class T, class charT, class traits, class Distance>
bool operator==(const istream_iterator<T, charT, traits, Distance> &x,
                default_sentinel y);

Returns: x.in_stream == nullptr.

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, class traits, class Distance>
bool operator!=(default_sentinel x,
                const istream_iterator<T, charT, traits, Distance>& y);

template <class T, class charT, class traits, class Distance>
bool operator!=(const istream_iterator<T, charT, traits, Distance>& x,
                default_sentinel y);

Returns: !(x == y)
9.8.2 Class template ostream_iterator

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. It is not possible to get a value out of the output iterator. Its only use is as an output iterator in situations like

```cpp
while (first != last)
    *result++ = *first++;
```

ostream_iterator is defined as:

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <class T, class charT = char, class traits = char_traits<charT>>
    class ostream_iterator {
        public:
            typedef ptrdiff_t difference_type;
            typedef charT char_type;
            typedef traits traits_type;
            typedef basic_ostream<charT, traits> ostream_type;
            constexpr ostream_iterator() noexcept;
            ostream_iterator(ostream_type& s) noexcept;
            ostream_iterator(ostream_type& s, const charT* delimiter) noexcept;
            ostream_iterator(const ostream_iterator& x) noexcept;
            ~ostream_iterator();
            ostream_iterator& operator=(const T& value);
            ostream_iterator& operator*();
            ostream_iterator& operator++();
            ostream_iterator operator++(int);
        private:
            basic_ostream<charT, traits>* out_stream; // exposition only
            const charT* delim; // exposition only
        };
    }}}
}}
```

9.8.2.1 ostream_iterator constructors and destructor

```cpp
constexpr ostream_iterator() noexcept;
    Effects: Initializes out_stream and delim with nullptr.

ostream_iterator(ostream_type& s) noexcept;
    Effects: Initializes out_stream with &s and delim with nullptr.

ostream_iterator(ostream_type& s, const charT* delimiter) noexcept;
    Effects: Initializes out_stream with &s and delim with delimiter.

ostream_iterator(const ostream_iterator& x) noexcept;
    Effects: Constructs a copy of x.

~ostream_iterator();
    Effects: The iterator is destroyed.
```
9.8.2.2 ostream_iterator operations

ostream_iterator& operator=(const T& value);

Effects: Equivalent to:

*out_stream << value;
if(delim != nullptr)
    *out_stream << delim;
return *this;

ostream_iterator& operator*();

Returns: *this.

ostream_iterator& operator++();
ostream_iterator operator++(int);

Returns: *this.

9.8.3 Class template istreambuf_iterator

The class template istreambuf_iterator defines an input iterator (9.3.11) that reads successive characters from the streambuf for which it was constructed. operator* provides access to the current input character, if any. [Note: operator-> may return a proxy. —end note] Each time operator++ is evaluated, the iterator advances to the next input character. If the end of stream is reached (streambuf_type::sgetc() returns traits::eof()), the iterator becomes equal to the end-of-stream iterator value. The default constructor istreambuf_iterator() and the constructor istreambuf_iterator(nullptr) both construct an end-of-stream iterator object suitable for use as an end-of-range. All specializations of istreambuf_iterator shall have a trivial copy constructor, a constexpr default constructor, and a trivial destructor.

The result of operator*() on an end-of-stream iterator is undefined. For any other iterator value a char_-type value is returned. It is impossible to assign a character via an input iterator.

namespace std { namespace experimental { namespace ranges { inline namespace v1 {

template <class charT, class traits = char_traits<charT>>
class istreambuf_iterator {
public:
    typedef input_iterator_tag iterator_category;
    typedef charT value_type;
    typedef typename traits::off_type difference_type;
    typedef charT reference;
    typedef unspecified pointer;
    typedef charT char_type;
    typedef traits traits_type;
    typedef typename traits::int_type int_type;
    typedef basic_streambuf<charT, traits> streambuf_type;
    typedef basic_istream<charT, traits> istream_type;

class proxy;  // exposition only

    constexpr istreambuf_iterator() noexcept;
    constexpr istreambuf_iterator(default_sentinel) noexcept;
    istreambuf_iterator(const istreambuf_iterator&) noexcept = default;
    ~istreambuf_iterator() = default;
    istreambuf_iterator(istream_type& s) noexcept;
    istreambuf_iterator(istream_type* s) noexcept;
    istreambuf_iterator(const proxy& p) noexcept;

}}}

§ 9.8.3
charT operator*() const;
pointer operator->() const;
istreambuf_iterator& operator++();
proxy operator++(int);
bool equal(const istreambuf_iterator& b) const;
private:
  streambuf_type* sbuf_;     // exposition only
};

template <class charT, class traits>
bool operator==(const istreambuf_iterator<charT, traits>& a,
              const istreambuf_iterator<charT, traits>& b);

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
  template <class charT, class traits = char_traits<charT>>
  class istreambuf_iterator<charT, traits>::proxy {
    // exposition only
    charT keep_;           // exposition only
    basic_streambuf<charT, traits>* sbuf_; // exposition only
    proxy(charT c, basic_streambuf<charT, traits>* sbuff)
      : keep_(c), sbuff_(sbuff) { }
  public:
    charT operator*() { return keep_; }
  };
}}}

1 Class istreambuf_iterator::proxy is for exposition only. An implementation is permitted to provide equivalent functionality without providing a class with this name. Class istreambuf_iterator::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.

9.8.3.2 istreambuf_iterator constructors

constexpr istreambuf_iterator() noexcept;
constexpr istreambuf_iterator(default_sentinel) noexcept;

1 Effects: Constructs the end-of-stream iterator.

istreambuf_iterator(basic_istream<charT, traits>& s) noexcept;

§ 9.8.3.2
istreambuf_iterator(basic_streambuf<charT, traits>* s) noexcept;

Effects: Constructs an istreambuf_iterator<> that uses the basic_streambuf<> object *(s.rdbuf()), or *s, respectively. Constructs an end-of-stream iterator if s.rdbuf() is null.

istreambuf_iterator(const proxy& p) noexcept;

Effects: Constructs a istreambuf_iterator<> that uses the basic_streambuf<> object pointed to by the proxy object’s constructor argument p.

9.8.3.3 istreambuf_iterator::operator*

charT operator*() const

Returns: The character obtained via the streambuf member sbuf_->sgetc().

9.8.3.4 istreambuf_iterator::operator++

istreambuf_iterator&

istreambuf_iterator<charT, traits>::operator++();

Effects: Equivalent to sbuf_->sbumpc().

Returns: *this.

proxy istreambuf_iterator<charT, traits>::operator++(int);

Effects: Equivalent to: return proxy(sbuf_->sbumpc(), sbuf_);

9.8.3.5 istreambuf_iterator::equal

bool equal(const istreambuf_iterator& b) const;

Returns: true if and only if both iterators are at end-of-stream, or neither is at end-of-stream, regardless of what streambuf object they use.

9.8.3.6 operator==

template <class charT, class traits>

bool operator==(const istreambuf_iterator<charT, traits>& a,
        const istreambuf_iterator<charT, traits>& b);

Effects: Equivalent to: return a.equal(b);

template <class charT, class traits>

bool operator==(default_sentinel a,
        const istreambuf_iterator<charT, traits>& b);

Effects: Equivalent to: return istreambuf_iterator<charT, traits>{}.equal(b);

template <class charT, class traits>

bool operator==(const istreambuf_iterator<charT, traits>& a,
        default_sentinel b);

Effects: Equivalent to: return a.equal(istreambuf_iterator<charT, traits>{});
9.8.3.7 operator!=

```cpp
template <class charT, class traits>
bool operator!=<const istreambuf_iterator<charT, traits>& a,
const istreambuf_iterator<charT, traits>& b>;

template <class charT, class traits>
bool operator!=(default_sentinel a,
const istreambuf_iterator<charT, traits>& b);

template <class charT, class traits>
bool operator!=(const istreambuf_iterator<charT, traits>& a,
default_sentinel b);
```

1 Effects: Equivalent to: return !(a == b);

9.8.4 Class template ostreambuf_iterator

```cpp
namespace std { namespace experimental { namespace ranges { inline namespace v1 {

class ostreambuf_iterator {
public:
    typedef ptrdiff_t difference_type;
    typedef charT char_type;
    typedef traits traits_type;
    typedef basic_streambuf<charT, traits> streambuf_type;
    typedef basic_ostream<charT, traits> ostream_type;

    constexpr ostreambuf_iterator() noexcept;
    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
    };
}}}
```

1 The class template `ostreambuf_iterator` writes successive characters onto the output stream from which it was constructed. It is not possible to get a character value out of the output iterator.

9.8.4.1 ostreambuf_iterator constructors

```cpp
constexpr ostreambuf_iterator() noexcept;
```

1 Effects: Initializes sbuf_ with nullptr.

```cpp
ostreambuf_iterator(ostream_type& s) noexcept;
```

2 Requires: s.rdbuf() != nullptr.

3 Effects: Initializes sbuf_ with s.rdbuf().

```cpp
ostreambuf_iterator(streambuf_type* s) noexcept;
```

4 Requires: s != nullptr.

5 Effects: Initializes sbuf_ with s.
9.8.4.2 ostreambuf_iterator operations

ostreambuf_iterator&
operator=(charT c);

1 Requires: sbuf_ != nullptr.
2 Effects: If failed() yields false, calls sbuf_-&gt;sputc(c); otherwise has no effect.
3 Returns: *this.

ostreambuf_iterator& operator*();
4 Returns: *this.

ostreambuf_iterator& operator++();
ostreambuf_iterator operator++(int);
5 Returns: *this.

bool failed() const noexcept;
6 Requires: sbuf_ != nullptr.
7 Returns: true if in any prior use of member operator=, the call to sbuf_-&gt;sputc() returned traits::eof(); or false otherwise.

9.9 Range concepts

9.9.1 General

1 This subclause describes components for dealing with ranges of elements.
2 The following subclauses describe range and view requirements, and components for range primitives, pre-defined ranges, and stream ranges, as summarized in Table 7.

Table 7 — Ranges library summary

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9.9.2 Range requirements

9.9.2.1 In general

1 Ranges are an abstraction of containers that allow a C++ program to operate on elements of data structures uniformly. It their simplest form, a range object is one on which one can call begin and end to get an iterator (9.3.8) and a sentinel (9.3.9). To be able to construct template algorithms and range adaptors that work correctly and efficiently on different types of sequences, the library formalizes not just the interfaces but also the semantics and complexity assumptions of ranges.
2 This document defines three fundamental categories of ranges based on the syntax and semantics supported by each: range, sized range and view, as shown in Table 8.
3 The Range concept requires only that begin and end return an iterator and a sentinel. The SizedRange concept refines Range with the requirement that the number of elements in the range can be determined in constant time using the size function. The View concept specifies requirements on an Range type with constant-time copy and assign operations.
In addition to the three fundamental range categories, this document defines a number of convenience refinements of `Range` that group together requirements that appear often in the concepts, algorithms, and range adaptors. `Bounded ranges` are ranges for which `begin` and `end` return objects of the same type. `Random access ranges` are ranges for which `begin` returns a type that satisfies `RandomAccessIterator` (9.3.15). The range categories `bidirectional ranges`, `forward ranges`, `input ranges`, and `output ranges` are defined similarly.

### 9.9.2.2 Ranges

The `Range` concept defines the requirements of a type that allows iteration over its elements by providing a `begin` iterator and an `end` sentinel. [Note: Most algorithms requiring this concept simply forward to an `Iterator`-based algorithm by calling `begin` and `end`. —end note]

```
template <class T>
using iterator_t = decltype(ranges::begin(declval<T&>()));

template <class T>
using sentinel_t = decltype(ranges::end(declval<T&>()));

template <class T>
concept bool Range() {
    return requires(T&& t) {
        ranges::end(t);
    };
}
```

2  Given an lvalue `t` of type `remove_reference_t<T>`, `Range<T>()` is satisfied if and only if

- Both `begin(t)` and `end(t)` are amortized constant time and non-modifying. [Note: `begin(t)` and `end(t)` do not require implicit expression variants. —end note]

- If `iterator_t<T>` satisfies `ForwardIterator`, `begin(t)` is equality preserving.

3  [Note: Equality preservation of both `begin` and `end` enables passing a `Range` whose iterator type satisfies `ForwardIterator` to multiple algorithms and making multiple passes over the range by repeated calls to `begin` and `end`. Since `begin` is not required to be equality preserving when the return type does not satisfy `ForwardIterator`, repeated calls might not return equal values or might not be well-defined; `begin` should be called at most once for such a range. —end note]

### 9.9.2.3 Sized ranges

The `SizedRange` concept specifies the requirements of a `Range` type that knows its size in constant time with the `size` function.

```
template <class T>
constexpr bool disable_sized_range = false;

template <class T>
concept bool SizedRange() {
```
Given an lvalue \( t \) of type `remove_reference_t<T>`, `SizedRange<T>()` is satisfied if and only if:

1. \( \text{size}(t) \) returns the number of elements in \( t \).
2. If \( \text{iterator}_t<T> \) satisfies `ForwardIterator`, \( \text{size}(t) \) is well-defined regardless of the evaluation of \( \text{begin}(t) \). [Note: \( \text{size}(t) \) is otherwise not required be well-defined after evaluating \( \text{begin}(t) \). For a `SizedRange` whose iterator type does not model `ForwardIterator`, for example, \( \text{size}(t) \) might only be well-defined if evaluated before the first call to \( \text{begin}(t) \). —end note]

[Note: The `disable_sized_range` predicate provides a mechanism to enable use of range types with the library that meet the syntactic requirements but do not in fact satisfy `SizedRange`. A program that instantiates a library template that requires a `Range` with such a range type \( R \) is ill-formed with no diagnostic required unless `disable_sized_range<remove_cv_t<remove_reference_t<R>>>` evaluates to `true` (6.2.1.3). —end note]

### 9.9.2.4 Views

The `View` concept specifies the requirements of a `Range` type that has constant time copy, move and assignment operators; that is, the cost of these operations is not proportional to the number of elements in the `View`.

[Example: Examples of `Views` are:

1. A `Range` type that wraps a pair of iterators.
2. A `Range` type that holds its elements by `shared_ptr` and shares ownership with all its copies.
3. A `Range` type that generates its elements on demand.

A container (ISO/IEC 14882:2014 §23) is not a `View` since copying the container copies the elements, which cannot be done in constant time. —end example]

```cpp
template <class T>
struct enable_view { };

struct view_base { };  // exposition only

template <class T>
constexpr bool __view_predicate = see below;

template <class T>
concept bool View() {
    return Range<T>() &&
    Semiregular<T>() &&
    __view_predicate<T>;
}
```

Since the difference between `Range` and `View` is largely semantic, the two are differentiated with the help of the `enable_view` trait. Users may specialize `enable_view` to derive from `true_type` or `false_type`.

For a type \( T \), the value of `__view_predicate<T>` shall be:

1. If `enable_view<T>` has a member type `type`, `enable_view<T>::type::value;`
— Otherwise, if $T$ is derived from `view_base`, `true`;


— Otherwise, if both $T$ and `const T` satisfy `Range` and `reference_t<iterator_t<T>>` is not the same type as `reference_t<iterator_t<const T>>`, `false`; [Note: Deep `const`-ness implies element ownership, whereas shallow `const`-ness implies reference semantics. — end note]

— Otherwise, `true`.

9.9.2.5 Bounded ranges

The `BoundedRange` concept specifies requirements of a `Range` type for which `begin` and `end` return objects of the same type. [Note: The standard containers (ISO/IEC 14882:2014 §23) satisfy `BoundedRange`. — end note]

```cpp
template <class T>
cancept bool BoundedRange() {
  return Range<T>() && Same<iterator_t<T>, sentinel_t<T>>();
}
```

9.9.2.6 Input ranges

The `InputRange` concept specifies requirements of an `Range` type for which `begin` returns a type that satisfies `InputIterator` (9.3.11).

```cpp
template <class T>
cancept bool InputRange() {
  return Range<T>() && InputIterator<iterator_t<T>>();
}
```

9.9.2.7 Output ranges

The `OutputRange` concept specifies requirements of an `Range` type for which `begin` returns a type that satisfies `OutputIterator` (9.3.12).

```cpp
template <class R, class T>
cancept bool OutputRange() {
  return Range<R>() && OutputIterator<iterator_t<R>, T>();
}
```

9.9.2.8 Forward ranges

The `ForwardRange` concept specifies requirements of an `InputRange` type for which `begin` returns a type that satisfies `ForwardIterator` (9.3.13).

```cpp
template <class T>
cancept bool ForwardRange() {
  return InputRange<T>() && ForwardIterator<iterator_t<T>>();
}
```

9.9.2.9 Bidirectional ranges

The `BidirectionalRange` concept specifies requirements of a `ForwardRange` type for which `begin` returns a type that satisfies `BidirectionalIterator` (9.3.14).
template <class T>
concept bool BidirectionalRange() {
    return ForwardRange<T>() && BidirectionalIterator<iterator_t<T>>();
}

9.9.2.10 Random access ranges
[ranges.random.access]

The RandomAccessRange concept specifies requirements of a BidirectionalRange type for which begin returns a type that satisfies RandomAccessIterator (9.3.15).

template <class T>
concept bool RandomAccessRange() {
    return BidirectionalRange<T>() && RandomAccessIterator<iterator_t<T>>();
}

9.10 Range access
[iterator.range]

9.10.1 begin
[iterator.range.begin]

The name begin denotes a customization point object (6.2.2.3). The effect of the expression ranges::begin(E) for some expression E is equivalent to:

1) ranges::begin(static_cast<const T&>(E)) if E is an rvalue of type T. This usage is deprecated. 
   [Note: This deprecated usage exists so that ranges::begin(E) behaves similarly to std::begin(E) as defined in ISO/IEC 14882 when E is an rvalue. — end note]

2) Otherwise, (E) + 0 if E has array type (ISO/IEC 14882:2014 §3.9.2).

3) Otherwise, DECAY_COPY((E).begin()) if it is a valid expression and its type I meets the syntactic requirements of Iterator<I>(). If Iterator is not satisfied, the program is ill-formed with no diagnostic required.

4) Otherwise, DECAY_COPY(begin(E)) if it is a valid expression and its type I meets the syntactic requirements of Iterator<I>(). With overload resolution performed in a context that includes the declaration
   void begin(auto&) = delete; and does not include a declaration of ranges::begin. If Iterator is not satisfied, the program is ill-formed with no diagnostic required.

5) Otherwise, ranges::begin(E) is ill-formed.

[Note: Whenever ranges::begin(E) is a valid expression, its type satisfies Iterator. — end note]

9.10.2 end
[iterator.range.end]

The name end denotes a customization point object (6.2.2.3). The effect of the expression ranges::end(E) for some expression E is equivalent to:

1) ranges::end(static_cast<const T&>(E)) if E is an rvalue of type T. This usage is deprecated. 
   [Note: This deprecated usage exists so that ranges::end(E) behaves similarly to std::end(E) as defined in ISO/IEC 14882 when E is an rvalue. — end note]

2) Otherwise, (E) + extent<T>::value if E has array type (ISO/IEC 14882:2014 §3.9.2) T.

3) Otherwise, DECAY_COPY((E).end()) if it is a valid expression and its type S meets the syntactic requirements of Sentinel<S, decltype(ranges::begin(E))>(). If Sentinel is not satisfied, the program is ill-formed with no diagnostic required.
Otherwise, DECAY_COPY(end(E)) if it is a valid expression and its type S meets the syntactic requirements of Sentinel<S, declype(ranges::begin(E))>() with overload resolution performed in a context that includes the declaration void end(auto&) = delete; and does not include a declaration of ranges::end. If Sentinel is not satisfied, the program is ill-formed with no diagnostic required.

Otherwise, ranges::end(E) is ill-formed.

2 [Note: Whenever ranges::end(E) is a valid expression, the types of ranges::end(E) and ranges::begin(E) satisfy Sentinel. —end note]

9.10.3 cbegin

The name cbegin denotes a customization point object (6.2.2.3). The effect of the expression ranges::cbegin(E) for some expression E of type T is equivalent to ranges::begin(static_const<const T&>(E)).

Use of ranges::cbegin(E) with rvalue E is deprecated. [Note: This deprecated usage exists so that ranges::cbegin(E) behaves similarly to std::cbegin(E) as defined in ISO/IEC 14882 when E is an rvalue. —end note]

3 [Note: Whenever ranges::cbegin(E) is a valid expression, its type satisfies Iterator. —end note]

9.10.4 cend

The name cend denotes a customization point object (6.2.2.3). The effect of the expression ranges::cend(E) for some expression E of type T is equivalent to:

— (1.1) ranges::cend(static_cast<const T&>(E)) if E is an rvalue of type T. This usage is deprecated.

[Note: This deprecated usage exists so that ranges::cend(E) behaves similarly to std::cend(E) as defined in ISO/IEC 14882 when E is an rvalue. —end note]

— (1.2) Otherwise, DECAY_COPY((E).rbegin()) if it is a valid expression and its type I meets the syntactic requirements of Iterator<I>(). If Iterator is not satisfied, the program is ill-formed with no diagnostic required.

— (1.3) Otherwise, make_reverse_iterator(ranges::end(E)) if both ranges::begin(E) and ranges::end(E) are valid expressions of the same type I which meets the syntactic requirements of BidirectionalIterator<I>() (9.3.14).

— (1.4) Otherwise, ranges::rbegin(E) is ill-formed.

2 [Note: Whenever ranges::rbegin(E) is a valid expression, its type satisfies Iterator. —end note]

9.10.5 rbegin

The name rbegin denotes a customization point object (6.2.2.3). The effect of the expression ranges::rbegin(E) for some expression E is equivalent to:

— (1.1) ranges::rbegin(static_cast<const T&>(E)) if E is an rvalue of type T. This usage is deprecated.

[Note: This deprecated usage exists so that ranges::rbegin(E) behaves similarly to std::rbegin(E) as defined in ISO/IEC 14882 when E is an rvalue. —end note]

— (1.2) Otherwise, DECAY_COPY((E).begin()) if it is a valid expression and its type I meets the syntactic requirements of Iterator<I>(). If Iterator is not satisfied, the program is ill-formed with no diagnostic required.

— (1.3) Otherwise, ranges::rbegin(E) if both ranges::begin(E) and ranges::end(E) are valid expressions of the same type I which meets the syntactic requirements of BidirectionalIterator<I>() (9.3.14).

— (1.4) Otherwise, ranges::rbegin(E) is ill-formed.

2 [Note: Whenever ranges::rbegin(E) is a valid expression, its type satisfies Iterator. —end note]

9.10.6 rend

The name rend denotes a customization point object (6.2.2.3). The effect of the expression ranges::rend(E) for some expression E is equivalent to:

— (1.1) ranges::rend(static_cast<const T&>(E)) if E is an rvalue of type T. This usage is deprecated.

[Note: This deprecated usage exists so that ranges::rend(E) behaves similarly to std::rend(E) as defined in ISO/IEC 14882 when E is an rvalue. —end note]
(1.2) — Otherwise, \( \text{DECAY\_COPY}((E).\text{rend}()) \) if it is a valid expression and its type \( S \) meets the syntactic requirements of \( \text{Sentinel}<S, \text{decltype(ranges::rbegin(E))}>() \). If \( \text{Sentinel} \) is not satisfied, the program is ill-formed with no diagnostic required.

(1.3) — Otherwise, \( \text{make\_reverse\_iterator}(\text{ranges::begin(E)}) \) if both \( \text{ranges::begin(E)} \) and \( \text{ranges::end(E)} \) are valid expressions of the same type \( I \) which meets the syntactic requirements of \( \text{BidirectionalIterator}<I>() \) (9.3.14).

(1.4) — Otherwise, \( \text{ranges::rend(E)} \) is ill-formed.

2 [Note: Whenever \( \text{ranges::rend(E)} \) is a valid expression, the types of \( \text{ranges::rend(E)} \) and \( \text{ranges::rbegin(E)} \) satisfy \( \text{Sentinel} \). — end note]

9.10.7 crbegin
[iterator.range.crbegin]

1 The name \( \text{crbegin} \) denotes a customization point object (6.2.2.3). The effect of the expression \( \text{ranges::crbegin(E)} \) for some expression \( E \) of type \( T \) is equivalent to \( \text{ranges::rbegin(stat\text{static\_cast\<\text{const T}\&\>(E)})} \).

2 Use of \( \text{ranges::crbegin(E)} \) with \text{rvalue} \( E \) is deprecated. [Note: This deprecated usage exists so that \( \text{ranges::crbegin(E)} \) behaves similarly to \( \text{std::crbegin(E)} \) as defined in ISO/IEC 14882 when \( E \) is an \text{rvalue}. — end note]

3 [Note: Whenever \( \text{ranges::crbegin(E)} \) is a valid expression, its type satisfies \( \text{Iterator} \). — end note]

9.10.8 crend
[iterator.range.crend]

1 The name \( \text{crend} \) denotes a customization point object (6.2.2.3). The effect of the expression \( \text{ranges::crend(E)} \) for some expression \( E \) of type \( T \) is equivalent to \( \text{ranges::rend(stat\text{static\_cast\<\text{const T}\&\>(E)})} \).

2 Use of \( \text{ranges::crend(E)} \) with \text{rvalue} \( E \) is deprecated. [Note: This deprecated usage exists so that \( \text{ranges::crend(E)} \) behaves similarly to \( \text{std::crend(E)} \) as defined in ISO/IEC 14882 when \( E \) is an \text{rvalue}. — end note]

3 [Note: Whenever \( \text{ranges::crend(E)} \) is a valid expression, the types of \( \text{ranges::crend(E)} \) and \( \text{ranges::crbegin(E)} \) satisfy \( \text{Sentinel} \). — end note]

9.11 Range primitives
[range.primitives]

\[
\text{template <Range R>} \\
\text{difference\_type\_t<iterator\_t<R>> distance(R&& r);} \\
1 \quad \text{Effects: Equivalent to: return ranges::distance(ranges::begin(r), ranges::end(r));} \\
\text{template <SizedRange R>} \\
\text{difference\_type\_t<iterator\_t<R>> distance(R&& r);} \\
2 \quad \text{Effects: Equivalent to: return ranges::size(r);} \\
\]

9.11.1 size
[range.primitives.size]

1 The name \( \text{size} \) denotes a customization point object (6.2.2.3). The effect of the expression \( \text{ranges::size(E)} \) for some expression \( E \) with type \( T \) is equivalent to:

1.1 — extent\( <T>::\text{value} \) if \( T \) is an array type (ISO/IEC 14882:2014 §3.9.2).

1.2 — Otherwise, \( \text{DECAY\_COPY(stat\text{static\_cast\<\text{const T}\&\>(E)}.\text{size}())} \) if it is a valid expression and its type \( I \) satisfies \( \text{Integral}<I>() \) and \( \text{disable\_sized\_range<T>}(9.9.2.3) \) is false.

1.3 — Otherwise, \( \text{DECAY\_COPY(size(stat\text{static\_cast\<\text{const T}\&\>(E)))}) \) if it is a valid expression and its type \( I \) satisfies \( \text{Integral}<I>() \) with overload resolution performed in a context that includes the declaration void \( \text{size(const auto&)} = \text{delete}; \) and does not include a declaration of \( \text{ranges::size}, \) and \( \text{disable\_sized\_range<T> is false.} \)
(1.4) Otherwise, \( \text{DECAY\_COPY}(\text{ranges}::\text{cend}(E) - \text{ranges}::\text{cbegin}(E)) \), except that \( E \) is only evaluated once, if it is a valid expression and the types \( I \) and \( S \) of \( \text{ranges}::\text{cbegin}(E) \) and \( \text{ranges}::\text{cend}(E) \) meet the syntactic requirements of \( \text{SizedSentinel}<S, I>() \) (9.3.10) and \( \text{ForwardIterator}<I>() \). If \( \text{SizedSentinel} \) and \( \text{ForwardIterator} \) are not satisfied, the program is ill-formed with no diagnostic required.

(1.5) Otherwise, \( \text{ranges}::\text{size}(E) \) is ill-formed.

[Note: Whenever \( \text{ranges}::\text{size}(E) \) is a valid expression, its type satisfies \text{Integral}. — end note]

9.11.2 empty

The name \text{empty} denotes a customization point object (6.2.2.3). The effect of the expression \( \text{ranges}::\text{empty}(E) \) for some expression \( E \) is equivalent to:

(1.1) \( \text{bool}((E).\text{empty}()) \) if it is a valid expression.

(1.2) Otherwise, \( \text{ranges}::\text{size}(E) == 0 \) if it is a valid expression.

(1.3) Otherwise, \( \text{bool}(\text{ranges}::\text{begin}(E) == \text{ranges}::\text{end}(E)) \), except that \( E \) is only evaluated once, if it is a valid expression and the type of \( \text{ranges}::\text{begin}(E) \) satisfies \text{ForwardIterator}.

(1.4) Otherwise, \( \text{ranges}::\text{empty}(E) \) is ill-formed.

[Note: Whenever \( \text{ranges}::\text{empty}(E) \) is a valid expression, it has type \text{bool}. — end note]

9.11.3 data

The name \text{data} denotes a customization point object (6.2.2.3). The effect of the expression \( \text{ranges}::\text{data}(E) \) for some expression \( E \) is equivalent to:

(1.1) \( \text{ranges}::\text{data}(\text{static\_cast}<\text{const } T&>(E)) \) if \( E \) is an rvalue of type \( T \). This usage is deprecated. [Note: This deprecated usage exists so that \( \text{ranges}::\text{data}(E) \) behaves similarly to \( \text{std}::\text{data}(E) \) as defined in the C++ Working Paper when \( E \) is an rvalue. — end note]

(1.2) Otherwise, \( \text{DECAY\_COPY}((E).\text{data}()) \) if it is a valid expression of pointer to object type.

(1.3) Otherwise, \( \text{ranges}::\text{begin}(E) \) if it is a valid expression of pointer to object type.

(1.4) Otherwise, \( \text{ranges}::\text{data}(E) \) is ill-formed.

[Note: Whenever \( \text{ranges}::\text{data}(E) \) is a valid expression, it has pointer to object type. — end note]

9.11.4 cdata

The name \text{cdata} denotes a customization point object (6.2.2.3). The effect of the expression \( \text{ranges}::\text{cdata}(E) \) for some expression \( E \) of type \( T \) is equivalent to \( \text{ranges}::\text{data}(\text{static\_cast}<\text{const } T&>(E)) \).

2 Use of \( \text{ranges}::\text{cdata}(E) \) with rvalue \( E \) is deprecated. [Note: This deprecated usage exists so that \( \text{ranges}::\text{cdata}(E) \) has behavior consistent with \( \text{ranges}::\text{data}(E) \) when \( E \) is an rvalue. — end note]

3 [Note: Whenever \( \text{ranges}::\text{cdata}(E) \) is a valid expression, it has pointer to object type. — end note]
10 Algorithms library

10.1 General

1 This Clause describes components that C++ programs may use to perform algorithmic operations on containers (Clause ISO/IEC 14882:2014 §23) and other sequences.

2 The following subclauses describe components for non-modifying sequence operations, modifying sequence operations, and sorting and related operations, as summarized in Table 9.

Table 9 — Algorithms library summary

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Header <experimental/ranges/algorithm> synopsis

```cpp
#include <initializer_list>

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    namespace tag {
        // 10.2, tag specifiers (See 8.5.2):
        struct in;
        struct in1;
        struct in2;
        struct out;
        struct out1;
        struct out2;
        struct fun;
        struct min;
        struct max;
        struct begin;
        struct end;
    }
    // 10.3, non-modifying sequence operations:
    template <InputIterator I, Sentinel<I> S, class Proj = identity,
               IndirectPredicate<projected<I, Proj>>, Pred>
    bool all_of(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
           IndirectPredicate<iterator_t<Rng> proj,Rng, Proj>>, Pred>
    bool all_of(Rng&& rng, Pred pred, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
           IndirectPredicate<projected<I, Proj>>, Pred>
    bool any_of(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
           IndirectPredicate<iterator_t<Rng>>, Pred>
    bool any_of(Rng&& rng, Pred pred, Proj proj = Proj{});

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bool any_of(Rng&& rng, Pred pred, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
IndirectPredicate<projected<I, Proj>> Pred>
bool none_of(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
bool none_of(Rng&& rng, Pred pred, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
IndirectInvocable<projected<I, Proj>> Fun>
tagged_pair<tag::in(I), tag::fun(Fun)>
for_each(I first, S last, Fun f, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
IndirectInvocable<projected<iterator_t<Rng>, Proj>> Fun>
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::fun(Fun)>
for_each(Rng&& rng, Fun f, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class T, class Proj = identity>
requires IndirectRelation<equal_to<>, projected<I, Proj>, const T*>()
I find(I first, S last, const T& value, Proj proj = Proj{});

template <InputRange Rng, class T, class Proj = identity>
requires IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T*>()
safe_iterator_t<Rng>
find(Rng&& rng, const T& value, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
I find_if(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
safe_iterator_t<Rng>
find_if(Rng&& rng, Pred pred, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
I find_if_not(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
safe_iterator_t<Rng>
find_if_not(Rng&& rng, Pred pred, Proj proj = Proj{});

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2,
Sentinel<I2> S2, class Proj = identity,
IndirectRelation<I2, projected<I1, Proj>> Pred = equal_to<>>
I1
find_end(I1 first1, S1 last1, I2 first2, S2 last2,
Pred pred = Pred{}, Proj proj = Proj{});

template <ForwardRange Rng1, ForwardRange Rng2, class Proj = identity,
IndirectRelation<iterator_t<Rng2>,
    projected<iterator_t<Rng>, Proj>> Pred = equal_to<> >
safe_iterator_t<Rng1>
    find_end(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{}, Proj proj = Proj{});

template <InputIterator I1, Sentinel<I1> S1, ForwardIterator I2, Sentinel<I2> S2,
    class Proj1 = identity, class Proj2 = identity,
    IndirectPredicate<projected<I1, Proj1>, projected<I2, Proj2>> Pred = equal_to<> >
    I1
    find_first_of(I1 first1, S1 last1, I2 first2, S2 last2,
        Pred pred = Pred{},
        Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, ForwardRange Rng2, class Proj1 = identity,
    class Proj2 = identity,
    IndirectPredicate<projected<iterator_t<Rng1>, Proj1>,
    projected<iterator_t<Rng2>, Proj2>> Pred = equal_to<> >
    safe_iterator_t<Rng1>
    find_first_of(Rng1&& rng1, Rng2&& rng2,
        Pred pred = Pred{},
        Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
    IndirectRelation<projected<I, Proj>> Pred = equal_to<> >
    I
    adjacent_find(I first, S last, Pred pred = Pred{},
        Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
    IndirectRelation<projected<iterator_t<Rng>, Proj>> Pred = equal_to<> >
    safe_iterator_t<Rng>
    adjacent_find(Rng&& rng, Pred pred = Pred{}, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class T, class Proj = identity>
    requires IndirectRelation<equal_to<>, projected<I, Proj>, const T*>(>)
    difference_type_t<I>
    count(I first, S last, const T& value, Proj proj = Proj{});

template <InputRange Rng, class T, class Proj = identity>
    requires IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T*>(>)
    difference_type_t<iterator_t<Rng>>
    count(Rng&& rng, const T& value, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
    IndirectPredicate<projected<I, Proj>> Pred>
    difference_type_t<I>
    count_if(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
    IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
    difference_type_t<iterator_t<Rng>>
    count_if(Rng&& rng, Pred pred, Proj proj = Proj{});
IndirectPredicate<projected<I1, Proj1>, projected<I2, Proj2>> Pred = equal_to<>>
tagged_pair<tag::in1(I1), tag::in2(I2)>
mismatch(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = Pred{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2,
class Proj1 = identity, class Proj2 = identity,
IndirectPredicate<projected<iterator_t<Rng1>>, Proj1>,
projected<iterator_t<Rng2>>, Proj2>> Pred = equal_to<>>
tagged_pair<tag::in1(safe_iterator_t<Rng1>),
tag::in2(safe_iterator_t<Rng2)>
mismatch(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, class Pred = equal_to<>,
class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<iterator_t<Rng1>, iterator_t<Rng2>, Pred, Proj1, Proj2>()
bool equal(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardRange Rng1, ForwardRange Rng2, class Pred = equal_to<>,
class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<iterator_t<Rng1>, iterator_t<Rng2>, Pred, Proj1, Proj2>()
bool is_permutation(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

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search(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardIterator I, Sentinel<I> S, class T, class Pred = equal_to<>, class Proj = identity>
requires IndirectlyComparable<I, const T*, Pred, Proj>()
I
 search_n(I first, S last, difference_type_t<I> count, const T& value, Pred pred = Pred{}, Proj proj = Proj{});

template <ForwardRange Rng, class T, class Pred = equal_to<>, class Proj = identity>
requires IndirectlyComparable<iterator_t<Rng>, const T*, Pred, Proj>()
safe_iterator_t<Rng>
 search_n(Rng&& rng, difference_type_t<iterator_t<Rng>> count, const T& value, Pred pred = Pred{}, Proj proj = Proj{});

// 10.4, modifying sequence operations:
// 10.4.1, copy:

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O>
requires IndirectlyCopyable<I, O>()
tagged_pair<tag::in(I), tag::out(O)>
copy(I first, S last, O result);

template <InputRange Rng, WeaklyIncrementable O>
requires IndirectlyCopyable<iterator_t<Rng>, O>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
copy(Rng&& rng, O result);

template <InputIterator I, WeaklyIncrementable O>
requires IndirectlyCopyable<I, O>()
tagged_pair<tag::in(I), tag::out(O)>
copy_n(I first, difference_type_t<I> n, O result);

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O, class Proj = identity, IndirectPredicate<ProjectedIterator_t<I, Proj>> Pred>
requires IndirectlyCopyable<I, O>()
tagged_pair<tag::in(I), tag::out(O)>
copy_if(I first, S last, O result, Pred pred, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class Proj = identity, IndirectPredicate<ProjectedIterator_t<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
copy_if(Rng&& rng, O result, Pred pred, Proj proj = Proj{});

template <BidirectionalIterator I1, Sentinel<I1> S1, BidirectionalIterator I2>
requires IndirectlyCopyable<I1, I2>()
tagged_pair<tag::in(I1), tag::out(I2)>
copy_backward(I1 first, S1 last, I2 result);

template <BidirectionalRange Rng, BidirectionalIterator I>
requires IndirectlyCopyable<iterator_t<Rng>, I>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(I)>
// 10.4.2, move:
template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O>
  requires IndirectlyMoveable<I, O>()
  tagged_pair<tag::in(I), tag::out(O)>
  move(I first, S last, O result);

template <InputRange Rng, WeaklyIncrementable O>
  requires IndirectlyMoveable<iterator_t<Rng>, O>()
  tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
  move(Rng&& rng, O result);

template <BidirectionalIterator I1, Sentinel<I1> S1, BidirectionalIterator I2>
  requires IndirectlyMoveable<I1, I2>()
  tagged_pair<tag::in(I1), tag::out(I2)>
  move_backward(I1 first, S1 last, I2 result);

template <BidirectionalRange Rng, BidirectionalIterator I>
  requires IndirectlyMoveable<iterator_t<Rng>, I>()
  tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(I)>
  move_backward(Rng&& rng, I result);

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2, Sentinel<I2> S2>
  requires IndirectlySwappable<I1, I2>()
  tagged_pair<tag::in1(I1), tag::in2(I2)>
  swap_ranges(I1 first1, S1 last1, I2 first2, S2 last2);
template < Iterable<iterator_t<Rng1>, Proj1>, iterable<iterator_t<Rng2>, Proj2> >> { }

tagged_tuple<
tag::in1(safe_iterator_t<Rng1>),
tag::in2(safe_iterator_t<Rng2>),
tag::out(O)>
transform(Rng1&& rng1, Rng2&& rng2, O result,
F binary_op, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template < ForwardIterator I, Sentinel<I> S, class T1, class T2, class Proj = identity >
requires Writable<I, const T2&>() &&
IndirectRelation<equal_to<>, projected<I, Proj>, const T1*>() 
I
replace(I first, S last, const T1& old_value, const T2& new_value, Proj proj = Proj{});

template < ForwardRange Rng, class T1, class T2, class Proj = identity >
requires Writable<iterator_t<Rng>, const T2&>() &&
IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T1*>() 
safe_iterator_t<Rng>
replace(Rng&& rng, const T1& old_value, const T2& new_value, Proj proj = Proj{});

template < ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
IndirectPredicate<projected<I, Proj>>, Pred >
requires Writable<I, const T&>()
I
replace_if(I first, S last, Pred pred, const T& new_value, Proj proj = Proj{});

template < ForwardRange Rng, class T, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>>, Pred >
safe_iterator_t<Rng>
replace_if(Rng&& rng, Pred pred, const T& new_value, Proj proj = Proj{});

template < InputIterator I, Sentinel<I> S, class T1, class T2, OutputIterator<const T2&> O, 
class Proj = identity >
requires IndirectlyCopyable<I, O>() &&
IndirectRelation<equal_to<>, projected<I, Proj>, const T1*>() 
tagged_pair<tag::in(I), tag::out(O)>
replace_copy(I first, S last, O result, const T1& old_value, const T2& new_value, 
Proj proj = Proj{});

template < InputRange Rng, class T1, class T2, OutputIterator<const T2&> O, 
class Proj = identity >
requires IndirectlyCopyable<iterator_t<Rng>, O>() &&
IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T1*>() 
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
replace_copy(Rng&& rng, O result, const T1& old_value, const T2& new_value, 
Proj proj = Proj{});

template < InputIterator I, Sentinel<I> S, class T, OutputIterator<const T&> O, 
class Proj = identity, IndirectPredicate<projected<I, Proj>>, Pred >
requires IndirectlyCopyable<I, O>() 
tagged_pair<tag::in(I), tag::out(O)>
replace_copy_if(I first, S last, O result, Pred pred, const T& new_value, 
Proj proj = Proj{});

template < InputRange Rng, class T, OutputIterator<const T&> O, class Proj = identity, § 10.1 125
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
replace_copy_if(Rng&& rng, O result, Pred pred, const T& new_value,
    Proj proj = Proj{});
tagged_pair<tag::in(I), tag::out(O)>
    remove_copy(I first, S last, O result, const T& value, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class T, class Proj = identity>
    requires IndirectlyCopyable<iterator_t<Rng>, O>()
    IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T*>::()
    tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
    remove_copy(Rng&& rng, O result, const T& value, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class T, class Proj = identity>
    requires IndirectlyCopyable<iterator_t<Rng>, O>()
    IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T*>::()
    tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
    remove_copy_if(Rng&& rng, O result, Pred pred, Proj proj = Proj{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
    IndirectRelation<projected<I, Proj>> R = equal_to<>()
    requires Permutable<I>()
    I unique(I first, S last, R comp = R{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
    IndirectRelation<projected<iterator_t<Rng>, Proj>> R = equal_to<>()
    requires Permutable<iterator_t<Rng>>()
    safe_iterator_t<Rng>
    unique(Rng&& rng, R comp = R{}, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O,
    class Proj = identity, IndirectRelation<projected<I, Proj>> R = equal_to<>()
    requires IndirectlyCopyable<iterator_t<Rng>, O>() &&
    (ForwardIterator<I>() || ForwardIterator<O>() || IndirectlyCopyableStorable<I, O>())
    tagged_pair<tag::in(I), tag::out(O)>
    unique_copy(I first, S last, O result, R comp = R{}, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class Proj = identity,
    IndirectRelation<projected<iterator_t<Rng>, Proj>> R = equal_to<>()
    requires IndirectlyCopyable<iterator_t<Rng>, O>() &&
    (ForwardIterator<iterator_t<Rng>>() || ForwardIterator<O>() || IndirectlyCopyableStorable<iterator_t<Rng>, O>())
    tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
    unique_copy(Rng&& rng, O result, R comp = R{}, Proj proj = Proj{});

template <BidirectionalIterator I, Sentinel<I> S>
    requires Permutable<I>()
    I reverse(I first, S last);

template <BidirectionalRange Rng>
    requires Permutable<iterator_t<Rng>>()
    safe_iterator_t<Rng>
    reverse(Rng&& rng);
template <BidirectionalIterator I, Sentinel<I> S, WeaklyIncrementable O>
   requires IndirectlyCopyable<I, O>()
   tagged_pair<tag::in(I), tag::out(O)> reverse_copy(I first, S last, O result);

template <BidirectionalRange Rng, WeaklyIncrementable O>
   requires IndirectlyCopyable<iterator_t<Rng>, O>()
   tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
   reverse_copy(Rng&& rng, O result);

template <ForwardIterator I, Sentinel<I> S>
   requires Permutable<I>()
   tagged_pair<tag::begin(I), tag::end(I)>
   rotate(I first, I middle, S last);

template <ForwardRange Rng>
   requires Permutable<iterator_t<Rng>>()
   tagged_pair<tag::begin(safe_iterator_t<Rng>), tag::end(safe_iterator_t<Rng>)>
   rotate(Rng&& rng, iterator_t<Rng> middle);

template <ForwardIterator I, Sentinel<I> S, WeaklyIncrementable O>
   requires IndirectlyCopyable<I, O>()
   tagged_pair<tag::in(I), tag::out(O)>
   rotate_copy(I first, I middle, S last, O result);

template <ForwardRange Rng, WeaklyIncrementable O>
   requires IndirectlyCopyable<iterator_t<Rng>, O>()
   tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
   rotate_copy(Rng&& rng, iterator_t<Rng> middle, O result);

// 10.4.12, shuffle:
template <RandomAccessIterator I, Sentinel<I> S, class Gen>
   requires Permutable<I>() &&
   UniformRandomNumberGenerator<remove_reference_t<Gen>>() &&
   ConvertibleTo<result_of_t<Gen&()>, difference_type_t<I>>()
   I shuffle(I first, S last, Gen& g);

template <RandomAccessRange Rng, class Gen>
   requires Permutable<I>() &&
   UniformRandomNumberGenerator<remove_reference_t<Gen>>() &&
   ConvertibleTo<result_of_t<Gen&()>, difference_type_t<I>>()
   safe_iterator_t<Rng>
   shuffle(Rng&& rng, Gen& g);

// 10.4.13, partitions:
template <InputIterator I, Sentinel<I> S, class Proj = identity,
   IndirectPredicate<projected<I, Proj>> Pred>
   bool is_partitioned(I first, S last, Pred pred, Proj proj = Proj());

template <InputRange Rng, class Proj = identity,
   IndirectPredicate<projected<iterator_t<Rng>*, Proj>> Pred>
   bool
   is_partitioned(Rng&& rng, Pred pred, Proj proj = Proj());
template <ForwardIterator I, Sentinel<I> S, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires Permutable<I>()
I partition(I first, S last, Pred pred, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity, IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires Permutable<iterator_t<Rng>>()
safe_iterator_t<Rng>
partition(Rng&& rng, Pred pred, Proj proj = Proj{});

template <BidirectionalIterator I, Sentinel<I> S, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires Permutable<I>()
I stable_partition(I first, S last, Pred pred, Proj proj = Proj{});

template <BidirectionalRange Rng, class Proj = identity, IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires Permutable<iterator_t<Rng>>()
safe_iterator_t<Rng>
stable_partition(Rng&& rng, Pred pred, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O1, WeaklyIncrementable O2, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires IndirectlyCopyable<I, O1>() && IndirectlyCopyable<I, O2>()
tagged_tuple<tag::in(I), tag::out1(O1), tag::out2(O2)>
partition_copy(I first, S last, O1 out_true, O2 out_false, Pred pred, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O1, WeaklyIncrementable O2, class Proj = identity, IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O1>() && IndirectlyCopyable<iterator_t<Rng>, O2>()
tagged_tuple<tag::in(safe_iterator_t<Rng>), tag::out1(O1), tag::out2(O2)>
partition_copy(Rng&& rng, O1 out_true, O2 out_false, Pred pred, Proj proj = Proj{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
I partition_point(I first, S last, Pred pred, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity, IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
safe_iterator_t<Rng>
partition_point(Rng&& rng, Pred pred, Proj proj = Proj{});

// 10.5, sorting and related operations:
// 10.5.1, sorting:
template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>, class Proj = identity>
requires Sortable<I, Comp, Proj>()
I sort(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng>
sort(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
class Proj = identity>
requires Sortable<I, Comp, Proj>()
I stable_sort(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng>
stable_sort(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
class Proj = identity>
requires Sortable<I, Comp, Proj>()
I partial_sort(I first, I middle, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng>
partial_sort(Rng&& rng, iterator_t<Rng> middle, Comp comp = Comp{},
Proj proj = Proj{});

template <InputIterator I1, Sentinel<I1> S1, RandomAccessIterator I2, Sentinel<I2> S2,
class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires IndirectlyCopyable<I1, I2>() && Sortable<I2, Comp, Proj2>() &&
IndirectStrictWeakOrder<Comp, projected<I1, Proj1>, projected<I2, Proj2>>()
I2
partial_sort_copy(I1 first, S1 last, I2 result_first, S2 result_last,
Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, RandomAccessRange Rng2, class Comp = less<>,
class Proj1 = identity, class Proj2 = identity>
requires IndirectlyCopyable<iterator_t<Rng1>, iterator_t<Rng2>>() &&
Sortable<iterator_t<Rng1>, iterator_t<Rng2>>() &&
IndirectStrictWeakOrder<Comp, projected<iterator_t<Rng1>, Proj1>,
projected<iterator_t<Rng2>, Proj2>>()
safe_iterator_t<Rng2>
partial_sort_copy(Rng1&& rng, Rng2&& result_rng, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
bool is_sorted(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
bool
is_sorted(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

return is_sorted_until(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
template <ForwardRange Rng, class Proj = identity,
    IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
safe_iterator_t<Rng>
    is_sorted_until(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
    class Proj = identity>
    requires Sortable<I, Comp, Proj>()
    I nth_element(I first, I nth, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>,
    class Proj = identity>
    requires Sortable<iterator_t<Rng>, Comp, Proj>()
    safe_iterator_t<Rng>
    nth_element(Rng&& rng, iterator_t<Rng> nth, Comp comp = Comp{}, Proj proj = Proj{});

// 10.5.3. binary search:

    template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
        I
        lower_bound(I first, S last, const T& value, Comp comp = Comp{},
                Proj proj = Proj{});

    template <ForwardRange Rng, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
        safe_iterator_t<Rng>
        lower_bound(Rng&& rng, const T& value, Comp comp = Comp{}, Proj proj = Proj{});

    template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
        I
        upper_bound(I first, S last, const T& value, Comp comp = Comp{}, Proj proj = Proj{});

    template <ForwardRange Rng, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
        safe_iterator_t<Rng>
        upper_bound(Rng&& rng, const T& value, Comp comp = Comp{}, Proj proj = Proj{});

    template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
        tagged_pair<tag::begin(I), tag::end(I)>
        equal_range(I first, S last, const T& value, Comp comp = Comp{}, Proj proj = Proj{});

    template <ForwardRange Rng, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
        tagged_pair<tag::begin(safe_iterator_t<Rng>),
                        tag::end(safe_iterator_t<Rng>)>
        equal_range(Rng&& rng, const T& value, Comp comp = Comp{}, Proj proj = Proj{});

    template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
        bool
        binary_search(I first, S last, const T& value, Comp comp = Comp{},
                        Proj proj = Proj{});

    template <ForwardRange Rng, class T, class Proj = identity,
        IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
        safe_iterator_t<Rng>
        is_sorted_until(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});
IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>
bool
binary_search(Rng&& rng, const T& value, Comp comp = Comp{},
    Proj proj = Proj{});

// 10.5.4, merge:
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    WeaklyIncrementable 0, class Comp = less<>, class Proj1 = identity,
    class Proj2 = identity>
requires Mergeable<I1, I2, 0, Comp, Proj1, Proj2>()
tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(O)>
merge(I1 first1, S1 last1, I2 first2, S2 last2, 0 result,
    Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable 0, class Comp = less<>,
    class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>, 0, Comp, Proj1, Proj2>()
tagged_tuple<tag::in1(safe_iterator_t<Rng1>),
    tag::in2(safe_iterator_t<Rng2>),
    tag::out(O)>
merge(Rng1&& rng1, Rng2&& rng2, 0 result,
    Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

// 10.5.5, set operations:
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    class Proj1 = identity, class Proj2 = identity,
    IndirectStrictWeakOrder<projected<I1, Proj1>, projected<I2, Proj2>> Comp = less<>
bool
includes(I1 first1, S1 last1, I2 first2, S2 last2, Comp comp = Comp{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
template <InputRange Rng1, InputRange Rng2, class Proj1 = identity,
    class Proj2 = identity,
    IndirectStrictWeakOrder<projected<iterator_t<Rng1>, Proj1>,
    projected<iterator_t<Rng2>, Proj2>> Comp = less<>
bool
includes(Rng1&& rng1, Rng2&& rng2, Comp comp = Comp{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    WeaklyIncrementable 0, class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<I1, I2, 0, Comp, Proj1, Proj2>()
tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(O)>

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set_union(I1 first1, S1 last1, I2 first2, S2 last2, O result, Comp comp = Comp{},
                Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O,
          class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>>, O, Comp, Proj1, Proj2>()
tagged_tuple<tag::init(safe_iterator_t<Rng1>),
                tag::in2(safe_iterator_t<Rng2>),
                tag::out(O)>
set_union(Rng1&& rng1, Rng2&& rng2, O result, Comp comp = Comp{},
                Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
          WeaklyIncrementable O, class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<I1, I2, O, Comp, Proj1, Proj2>()
O
set_intersection(I1 first1, S1 last1, I2 first2, S2 last2, O result,
                 Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O,
          class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>>, O, Comp, Proj1, Proj2>()
tagged_pair<tag::init(I1), tag::out(O)>
set_intersection(Rng1&& rng1, Rng2&& rng2, O result,
                 Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
          WeaklyIncrementable O, class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<I1, I2, O, Comp, Proj1, Proj2>()
tagged_tuple<tag::init(I1), tag::init2(I2), tag::out(O)>
set_difference(I1 first1, S1 last1, I2 first2, S2 last2, O result,
               Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O,
          class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>>, O, Comp, Proj1, Proj2>()
tagged_pair<tag::init(safe_iterator_t<Rng1>), tag::out(O)>
set_difference(Rng1&& rng1, Rng2&& rng2, O result,
               Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
          WeaklyIncrementable O, class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<I1, I2, O, Comp, Proj1, Proj2>()
tagged_tuple<tag::init(I1), tag::init2(I2), tag::out(O)>
set_symmetric_difference(I1 first1, S1 last1, I2 first2, S2 last2, O result,
                         Comp comp = Comp{}, Proj1 proj1 = Proj1{},
                         Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O,
          class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>>, O, Comp, Proj1, Proj2>()
tagged_pair<tag::init(safe_iterator_t<Rng1>),
                tag::in2(safe_iterator_t<Rng2>),
                tag::out(O)>
set_symmetric_difference(Rng1&& rng1, Rng2&& rng2, O result, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{};

// 10.5.6, heap operations:

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
           class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  I push_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>,
           class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    push_heap(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
           class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  I pop_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>,
           class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    pop_heap(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
           class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  I make_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>,
           class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    make_heap(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
           class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  I sort_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>,
           class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    sort_heap(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Proj = identity,
           IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
  bool is_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Proj = identity,
           IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
  bool is_heap(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessIterator I, Sentinel<I> S, class Proj = identity,
           IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
  I is_heap_until(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

§ 10.1
template <RandomAccessRange Rng, class Proj = identity, 
IndirectStrictWeakOrder<Projected<iterator_t<Rng>, Proj>> Comp = less<>>
safe_iterator_t<Rng>
is_heap_until(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

// 10.5.7, minimum and maximum:
template <class T, class Proj = identity, 
IndirectStrictWeakOrder<Projected<const T*, Proj>> Comp = less<>>
constexpr const T& min(const T& a, const T& b, Comp comp = Comp{}, Proj proj = Proj{});

template <Copyable T, class Proj = identity, 
IndirectStrictWeakOrder<Projected<const T*, Proj>> Comp = less<>>
constexpr T min(initializer_list<T> t, Comp comp = Comp{}, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity, 
IndirectStrictWeakOrder<Projected<iterator_t<Rng>, Proj>> Comp = less<>>
requires Copyable<value_type_t<iterator_t<Rng>>>() 
value_type_t<iterator_t<Rng>>
min(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <class T, class Proj = identity, 
IndirectStrictWeakOrder<Projected<const T*, Proj>> Comp = less<>>
constexpr T max(const T& a, const T& b, Comp comp = Comp{}, Proj proj = Proj{});

template <Copyable T, class Proj = identity, 
IndirectStrictWeakOrder<Projected<const T*, Proj>> Comp = less<>>
constexpr T max(initializer_list<T> t, Comp comp = Comp{}, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity, 
IndirectStrictWeakOrder<Projected<iterator_t<Rng>, Proj>> Comp = less<>>
requires Copyable<value_type_t<iterator_t<Rng>>>() 
value_type_t<iterator_t<Rng>>
max(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <class T, class Proj = identity, 
IndirectStrictWeakOrder<Projected<const T*, Proj>> Comp = less<>>
constexpr tagged_pair<tag::min(const T&), tag::max(const T&)> 
minmax(const T& a, const T& b, Comp comp = Comp{}, Proj proj = Proj{});

template <Copyable T, class Proj = identity, 
IndirectStrictWeakOrder<Projected<const T*, Proj>> Comp = less<>>
constexpr tagged_pair<tag::min(T), tag::max(T)> 
minmax(initializer_list<T> t, Comp comp = Comp{}, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity, 
IndirectStrictWeakOrder<Projected<iterator_t<Rng>, Proj>> Comp = less<>>
requires Copyable<value_type_t<iterator_t<Rng>>>() 
value_type_t<iterator_t<Rng>>
minmax(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
IndirectStrictWeakOrder<Projected<I, Proj>> Comp = less<>>
I min_element(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
template <ForwardRange Rng, class Proj = identity,
IndirectStrictWeakOrder<projected<iterator_t<Rng>>, Proj>> Comp = less<>>
safe_iterator_t<Rng>
  min_element(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
IndirectStrictWeakOrder<projected<I>, Proj>> Comp = less<>>
I max_element(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
IndirectStrictWeakOrder<projected<iterator_t<Rng>>, Proj>> Comp = less<>>
safe_iterator_t<Rng>
  max_element(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
IndirectStrictWeakOrder<projected<I>, Proj>> Comp = less<>>
tagged_pair<tag::min(I), tag::max(I)>
  minmax_element(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
IndirectStrictWeakOrder<projected<iterator_t<Rng>>, Proj>> Comp = less<>>
tagged_pair<tag::min(safe_iterator_t<Rng>),
  tag::max(safe_iterator_t<Rng>)>
  minmax_element(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
class Proj1 = identity, class Proj2 = identity,
IndirectStrictWeakOrder<projected<I1, Proj1>, projected<I2, Proj2>> Comp = less<>>
bool
  lexicographical_compare(I1 first1, S1 last1, I2 first2, S2 last2,
  Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, class Proj1 = identity,
class Proj2 = identity,
IndirectStrictWeakOrder<projected<iterator_t<Rng1>, Proj1>,
  projected<iterator_t<Rng2>, Proj2>> Comp = less<>>
bool
  lexicographical_compare(Rng1&& rng1, Rng2&& rng2, Comp comp = Comp{},
  Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

// 10.5.9, permutations:

template <BidirectionalIterator I, Sentinel<I> S, class Comp = less<>,
class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  bool next_permutation(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <BidirectionalRange Rng, class Comp = less<>,
class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  bool
    next_permutation(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

template <BidirectionalIterator I, Sentinel<I> S, class Comp = less<>,
class Proj = identity>
requires Sortable<I, Comp, Proj>()
bool prev_permutation(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <BidirectionalRange Rng, class Comp = less<>,
class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
bool
prev_permutation(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});
}}}}

3 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.

4 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.

5 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).

6 [Note: Unless otherwise specified, algorithms that take function objects as arguments are permitted to copy those function objects freely. Programmers for whom object identity is important should consider using a wrapper class that points to a noncopied implementation object such as reference_wrapper<T> (ISO/IEC 14882:2014 §20.9.3), or some equivalent solution. —end note]

7 In the description of the algorithms operators + and - are used for some of the iterator categories for which they do not have to be defined. In these cases the semantics of a+n is the same as that of

\[ X \text{ tmp } = a; \]
\[ \text{advance(}\text{tmp, n}); \]
\[ \text{return tmp; } \]

and that of b-a is the same as of

\[ \text{return distance(a, b); } \]

8 In the description of algorithm return values, sentinel values are sometimes returned where an iterator is expected. In these cases, the semantics are as if the sentinel is converted into an iterator as follows:

\[ I \text{ tmp } = \text{first}; \]
\[ \text{while(}\text{tmp != last}) \]
\[ \text{++tmp; } \]
\[ \text{return tmp; } \]

9 Overloads of algorithms that take Range arguments (9.9.2.2) behave as if they are implemented by calling begin and end on the Range and dispatching to the overload that takes separate iterator and sentinel arguments.

10 Some algorithms declare both an overload that takes a Range and an Iterator, and an overload that takes two Range parameters. Since an array type (ISO/IEC 14882:2014 §3.9.2) both satisfies Range and decays to a pointer (ISO/IEC 14882:2014 §4.2) which satisfies Iterator, such overloads are ambiguous when an array is passed as the second argument. Implementations provide a mechanism to resolve this ambiguity in favor of the overload that takes two ranges.

4) 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 might as well do copy followed by sort.
The number and order of template parameters for algorithm declarations is unspecified, except where explicitly stated otherwise.

Despite that the algorithm declarations nominally accept parameters by value, it is unspecified when and if the argument expressions are used to initialize the actual parameters except that any such initialization shall be sequenced before (ISO/IEC 14882:2014 §1.9) the algorithm returns. [ Note: The behavior of a program that modifies the values of the actual argument expressions is consequently undefined unless the algorithm return happens before (ISO/IEC 14882:2014 §1.10) any such modifications. —end note ]

## 10.2 Tag specifiers

```cpp
namespace tag {
    struct in { /* implementation-defined */ };  // 1
    struct in1 { /* implementation-defined */ };  // 1
    struct in2 { /* implementation-defined */ };  // 1
    struct out { /* implementation-defined */ };  // 1
    struct out1 { /* implementation-defined */ };  // 1
    struct out2 { /* implementation-defined */ };  // 1
    struct fun { /* implementation-defined */ };  // 1
    struct min { /* implementation-defined */ };  // 1
    struct max { /* implementation-defined */ };  // 1
    struct begin { /* implementation-defined */ };  // 1
    struct end { /* implementation-defined */ };  // 1
}
```

In the following description, let $X$ be the name of a type in the `tag` namespace above.

tag::*$X$* is a tag specifier (8.5.2) such that `TAGGET(D, tag::*$X$, N)` names a tagged getter (8.5.2) with DerivedCharacteristic $D$, ElementIndex $N$, and ElementName $X$.

[Example: `tag::in` is a type such that `TAGGET(D, tag::in, N)` names a type with the following interface:
```cpp
struct __input_getter {
    constexpr decltype(auto) in() & { return get<N>(static_cast<typename char_traits::constant_reference<
    D>&>(*this)); }  // 3
    constexpr decltype(auto) in() && { return get<N>(static_cast<typename char_traits::std::move<
    D>&>(*this)); }  // 3
    constexpr decltype(auto) in() const & { return get<N>(static_cast<const char_traits::constant_reference<
    D>&>(*this)); }  // 3
}  // 3
```
—end example]

## 10.3 Non-modifying sequence operations

### 10.3.1 All of

```
template <InputIterator I, Sentinel<I> S, class Proj = identity,
    IndirectPredicate<projected<I, Proj>> Pred>
bool all_of(I first, S last, Pred pred, Proj proj = Proj{});
```

```
template <InputRange Rng, class Proj = identity,
    IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
bool all_of(Rng& rng, Pred pred, Proj proj = Proj{});
```

1. **Returns:** true if `[first,last)` is empty or if `invoke(pred, invoke(proj, *i))` is true for every iterator $i$ in the range `[first,last)` and false otherwise.

2. **Complexity:** At most `last - first` applications of the predicate and `last - first` applications of the projection.
10.3.2 Any of [alg.any_of]

```cpp
template <InputIterator I, Sentinel<I> S, class Proj = identity,
    IndirectPredicate<projected<I, Proj>> Pred>
bool any_of(I first, S last, Pred pred, Proj proj = Proj{});
```

```cpp
template <InputRange Rng, class Proj = identity,
    IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
bool any_of(Rng&& rng, Pred pred, Proj proj = Proj{});
```

1 Returns: false if [first, last) is empty or if there is no iterator \(i\) in the range [first, last) such that \(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, *i))\) is true, and true otherwise.

2 Complexity: At most \(\text{last} - \text{first}\) applications of the predicate and \(\text{last} - \text{first}\) applications of the projection.

10.3.3 None of [alg.none_of]

```cpp
template <InputIterator I, Sentinel<I> S, class Proj = identity,
    IndirectPredicate<projected<I, Proj>> Pred>
bool none_of(I first, S last, Pred pred, Proj proj = Proj{});
```

```cpp
template <InputRange Rng, class Proj = identity,
    IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
bool none_of(Rng&& rng, Pred pred, Proj proj = Proj{});
```

1 Returns: true if [first, last) is empty or if \(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, *i))\) is false for every iterator \(i\) in the range [first, last), and false otherwise.

2 Complexity: At most \(\text{last} - \text{first}\) applications of the predicate and \(\text{last} - \text{first}\) applications of the projection.

10.3.4 For each [alg.foreach]

```cpp
template <InputIterator I, Sentinel<I> S, class Proj = identity,
    IndirectInvocable<projected<I, Proj>> Fun>
tagged_pair<tag::in(I), tag::fun(Fun)> for_each(I first, S last, Fun f, Proj proj = Proj{});
```

```cpp
template <InputRange Rng, class Proj = identity,
    IndirectInvocable<projected<iterator_t<Rng>, Proj>> Fun>
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::fun(Fun)> for_each(Rng&& rng, Fun f, Proj proj = Proj{});
```

1 Effects: Calls \(\text{invoke}(f, \text{invoke}(\text{proj}, *i))\) for every iterator \(i\) in the range [first, last), starting from first and proceeding to last - 1. [ Note: If the result of \(\text{invoke}(\text{proj}, *i)\) is a mutable reference, \(f\) may apply nonconstant functions. — end note ]

2 Returns: \{last, std::move(f)\}.

3 Complexity: Applies \(f\) and \(\text{proj}\) exactly \(\text{last} - \text{first}\) times.

4 Remarks: If \(f\) returns a result, the result is ignored.

5 [ Note: The requirements of this algorithm are more strict than those specified in ISO/IEC 14882:2014 §25.2.4. This algorithm requires \(\text{Fun}\) to satisfy CopyConstructible, whereas the algorithm in the C++ Standard requires only MoveConstructible. — end note ]

10.3.5 Find [alg.find]

§ 10.3.5
template <InputIterator I, Sentinel<I> S, class T, class Proj = identity>
  requires IndirectRelation<equal_to<>, projected<I, Proj>, const T*>()
  I find(I first, S last, const T& value, Proj proj = Proj{});

template <InputRange Rng, class T, class Proj = identity>
  requires IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T*>()
  safe_iterator_t<Rng>
  find(Rng&& rng, const T& value, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
  IndirectPredicate<projected<I, Proj>> Pred>
  I find_if(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
  IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
  safe_iterator_t<Rng>
  find_if(Rng&& rng, Pred pred, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class Proj = identity,
  IndirectPredicate<projected<I, Proj>> Pred>
  I find_if_not(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
  IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
  safe_iterator_t<Rng>
  find_if_not(Rng&& rng, Pred pred, Proj proj = Proj{});

1 Returns: The first iterator i in the range [first,last) for which the following corresponding conditions hold:
  invoke(proj, *i) == value, invoke(pred, invoke(proj, *i)) != false.
  Returns last if no such iterator is found.

2 Complexity: At most last - first applications of the corresponding predicate and projection.

10.3.6 Find end [alg.find.end]

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2,
  Sentinel<I2> S2, class Proj = identity,
  IndirectRelation<I2, projected<I1, Proj>> Pred = equal_to<>>
  I1 find_end(I1 first1, S1 last1, I2 first2, S2 last2,
    Pred pred = Pred{}, Proj proj = Proj{});

template <ForwardRange Rng1, ForwardRange Rng2,
  class Proj = identity,
  IndirectRelation<iterator_t<Rng2>,
    projected<iterator_t<Rng1>, Proj>> Pred = equal_to<>>
  safe_iterator_t<Rng1>
  find_end(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{}, Proj proj = Proj{});

1 Effects: Finds a subsequence of equal values in a sequence.

2 Returns: The last iterator i in the range [first1,last1 - (last2 - first2)) such that for every non-negative integer n < (last2 - first2), the following condition holds: invoke(pred, invoke(proj, *(i + n)), *(first2 + n)) != false. Returns last1 if [first2,last2) is empty or if no such iterator is found.

3 Complexity: At most (last2 - first2) * (last1 - first1 - (last2 - first2) + 1) applications of the corresponding predicate and projection.
10.3.7 Find first of

```
template <InputIterator I1, Sentinel<I1> S1, ForwardIterator I2, Sentinel<I2> S2,
         class Proj1 = identity, class Proj2 = identity,
         IndirectPredicate<projected<I1, Proj1>, projected<I2, Proj2>> Pred = equal_to<>>
I1
    find_first_of(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = Pred{},
                  Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

```
template <InputRange Rng1, ForwardRange Rng2, class Proj1 = identity,
          class Proj2 = identity,
          IndirectPredicate<iterator_t<Rng1>, Proj1>,
          projected<iterator_t<Rng2>, Proj2>> Pred = equal_to<>>
safe_iterator_t<Rng1>
    find_first_of(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{},
                  Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

1 Effects: Finds an element that matches one of a set of values.
2 Returns: The first iterator \( i \) in the range \([first1, last1)\) such that for some iterator \( j \) in the range \([first2, last2)\) the following condition holds: \( \text{invoke}(\text{pred}, \text{invoke}(\text{proj1}, *i), \text{invoke}(\text{proj2}, *j)) \neq \text{false} \). Returns \( last1 \) if \([first2, last2)\) is empty or if no such iterator is found.
3 Complexity: At most \((last1-first1) \times (last2-first2)\) applications of the corresponding predicate and the two projections.

10.3.8 Adjacent find

```
template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
          IndirectRelation<projected<I, Proj>> Pred = equal_to<>>
I
    adjacent_find(I first, S last, Pred pred = Pred{},
                 Proj proj = Proj{});
```

```
template <ForwardRange Rng, class Proj = identity,
          IndirectRelation<iterator_t<Rng>, Proj>> Pred = equal_to<>>
safe_iterator_t<Rng>
    adjacent_find(Rng&& rng, Pred pred = Pred{}, Proj proj = Proj{});
```

1 Returns: The first iterator \( i \) such that both \( i \) and \( i + 1 \) are in the range \([first, last)\) for which the following corresponding condition holds: \( \text{invoke}(\text{pred}, \text{invoke}(\text{proj}, *i), \text{invoke}(\text{proj}, *(i + 1))) \neq \text{false} \). Returns \( last \) if no such iterator is found.
2 Complexity: For a nonempty range, exactly \( \min((i - first) + 1, (last - first) - 1) \) applications of the corresponding predicate, where \( i \) is \text{adjacent_find}'s return value, and no more than twice as many applications of the projection.

10.3.9 Count

```
template <InputIterator I, Sentinel<I> S, class T, class Proj = identity>
    requires IndirectRelation<equal_to<>, projected<I, Proj>, const T*>()
    difference_type_t<I>
        count(I first, S last, const T& value, Proj proj = Proj{});
```

```
template <InputRange Rng, class T, class Proj = identity>
    requires IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T*>()
    difference_type_t<iterator_t<Rng>>
        count(Rng&& rng, const T& value, Proj proj = Proj{});
```

§ 10.3.9
template <InputIterator I, Sentinel<I> S, class Proj = identity,
    IndirectPredicate<projected<I, Proj>> Pred>
    difference_type_t<I>
count_if(I first, S last, Pred pred, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity,
    IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
    difference_type_t<iterator_t<Rng>>
count_if(Rng&& rng, Pred pred, Proj proj = Proj{});

**Effects:** Returns the number of iterators \( i \) in the range \([first, last)\) for which the following corresponding conditions hold: \( \text{invoke}(\text{proj}, *i) == \text{value} \), \( \text{invoke}(\text{pred}, \text{invoke}(\text{proj}, *i)) != \text{false} \).

**Complexity:** Exactly \( last - first \) applications of the corresponding predicate and projection.

### 10.3.10 Mismatch

```
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    class Proj1 = identity, class Proj2 = identity,
    IndirectPredicate<projected<I1, Proj1>, projected<I2, Proj2>> Pred = equal_to<>>
tagged_pair<tag::in1(I1), tag::in2(I2)>
mismatch(I1 first1, S1 last1, I2 first2, S2 last2, Pred pred = Pred{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

**Returns:** A pair of iterators \( i \) and \( j \) such that \( j == \text{first2} + (i - \text{first1}) \) and \( i \) is the first iterator in the range \([first1, last1)\) for which the following corresponding conditions hold:

1. \( j \) is in the range \([first2, last2)\).
2. \( !(*i == *(first2 + (i - first1))) \)
3. \( \text{invoke}(\text{pred}, \text{invoke}(\text{proj1}, *i), \text{invoke}(\text{proj2}, *(first2 + (i - first1)))) == \text{false} \)

Returns the pair \( \text{first1} + \min(last1 - first1, last2 - first2) \) and \( \text{first2} + \min(last1 - first1, last2 - first2) \) if such an iterator \( i \) is not found.

**Complexity:** At most \( last1 - first1 \) applications of the corresponding predicate and both projections.

### 10.3.11 Equal

```
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    class Pred = equal_to<>., class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<I1, I2, Pred, Proj1, Proj2>()
bool equal(I1 first1, S1 last1, I2 first2, S2 last2,
    Pred pred = Pred{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

```
template <InputRange Rng1, InputRange Rng2, class Pred = equal_to<>,
    class Proj1 = identity, class Proj2 = identity>
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```
requires IndirectlyComparable<iterator_t<Rng1>, iterator_t<Rng2>, Pred, Proj1, Proj2>()

bool equal(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{},
            Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

1 Returns: If last1 - first1 != last2 - first2, return false. Otherwise return true if for every iterator i in the range [first1, last1) the following condition holds: invoke(pred, invoke(proj1, *i), invoke(proj2, *(first2 + (i - first1)))) != false. Otherwise, returns false.

2 Complexity: No applications of the corresponding predicate and projections if SizedSentinel<S1, I1>() is satisfied, and SizedSentinel<S2, I2>() is satisfied, and last1 - first1 != last2 - first2. Otherwise, at most min(last1 - first1, last2 - first2) applications of the corresponding predicate and projections.

10.3.12 Is permutation

[alg.is_permutation]

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2,
          Sentinel<I2> S2, class Pred = equal_to<>, class Proj1 = identity,
          class Proj2 = identity>
requires IndirectlyComparable<I1, I2, Pred, Proj1, Proj2>()

bool is_permutation(I1 first1, S1 last1, I2 first2, S2 last2,
                    Pred pred = Pred{},
                    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardRange Rng1, ForwardRange Rng2, class Pred = equal_to<>,
          class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<iterator_t<Rng1>, iterator_t<Rng2>, Pred, Proj1, Proj2>()

bool is_permutation(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{},
                    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

1 Returns: If last1 - first1 != last2 - first2, return false. Otherwise return true if there exists a permutation of the elements in the range [first2, first2 + (last1 - first1)), beginning with I2 begin, such that equal(first1, last1, begin, pred, proj1, proj2) returns true; otherwise, returns false.

2 Complexity: No applications of the corresponding predicate and projections if SizedSentinel<S1, I1>() is satisfied, and SizedSentinel<S2, I2>() is satisfied, and last1 - first1 != last2 - first2. Otherwise, exactly last1 - first1 applications of the corresponding predicate and projections if equal(first1, last1, first2, last2, pred, proj1, proj2) would return true; otherwise, at worst \(O(N^2)\), where \(N\) has the value last1 - first1.

10.3.13 Search

[alg.search]

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2,
          Sentinel<I2> S2, class Pred = equal_to<>,
          class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<I1, I2, Pred, Proj1, Proj2>()

I1

search(I1 first1, S1 last1, I2 first2, S2 last2,
       Pred pred = Pred{},
       Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardRange Rng1, ForwardRange Rng2, class Pred = equal_to<>,
          class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<iterator_t<Rng1>, iterator_t<Rng2>, Pred, Proj1, Proj2>()

safe_iterator_t<Rng1>

search(Rng1&& rng1, Rng2&& rng2, Pred pred = Pred{},
       Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
### Effects
Finds a subsequence of equal values in a sequence.

### Returns
The first iterator \( i \) in the range \([\text{first1}, \text{last1} - (\text{last2} - \text{first2}))\) such that for every non-negative integer \( n \) less than \( \text{last2} - \text{first2} \) the following condition holds: \( \text{invoke} (\text{pred}, \text{invoke} (\text{proj1}, *(i + n)), \text{invoke} (\text{proj2}, *(\text{first2} + n))) \neq \text{false} \). Returns \( \text{first1} \) if \([\text{first2}, \text{last2})\) is empty, otherwise returns \( \text{last1} \) if no such iterator is found.

### Complexity
At most \((\text{last1} - \text{first1}) \times (\text{last2} - \text{first2})\) applications of the corresponding predicate and projections.

```
template <ForwardIterator I, Sentinel<I> S, class T, 
        class Pred = equal_to<>, class Proj = identity> 
    requires IndirectlyComparable<I, const T*, Pred, Proj>() 
    I  
    search_n(I first, S last, difference_type_t<I> count, 
            const T& value, Pred pred = Pred{}, 
            Proj proj = Proj{});
```

### Effects
Finds a subsequence of equal values in a sequence.

### Returns
The first iterator \( i \) in the range \([\text{first}, \text{last} - \text{count})\) such that for every non-negative integer \( n < \text{count} \) the following condition holds: \( \text{invoke} (\text{pred}, \text{invoke} (\text{proj}, *(i + n)), \text{value}) \neq \text{false} \). Returns \( \text{last} \) if no such iterator is found.

### Complexity
At most \(\text{last} - \text{first}\) applications of the corresponding predicate and projection.

10.4 Mutating sequence operations

10.4.1 Copy

```
template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O> 
    requires IndirectlyCopyable<I, O>() 
    tagged_pair<tag::in(I), tag::out(O)> 
    copy(I first, S last, O result); 
```

```
template <InputRange Rng, WeaklyIncrementable O> 
    requires IndirectlyCopyable<iterator_t<Rng>, O>() 
    tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)> 
    copy(Rng&& rng, O result); 
```

### Effects
Copies elements in the range \([\text{first}, \text{last})\) into the range \([\text{result}, \text{result} + (\text{last} - \text{first}))\) starting from \( \text{first} \) and proceeding to \( \text{last} \). For each non-negative integer \( n < (\text{last} - \text{first}) \), performs \( *(\text{result} + n) = *(\text{first} + n) \).

### Returns
\( \{\text{last}, \text{result} + (\text{last} - \text{first})\} \).

### Requires
\( \text{result} \) shall not be in the range \([\text{first}, \text{last})\).

### Complexity
Exactly \(\text{last} - \text{first}\) assignments.
Effects: For each non-negative integer \( i < n \), performs \( *(result + i) = *(first + i) \).

Returns: \( \{first + n, result + n\} \).

Complexity: Exactly \( n \) assignments.

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires IndirectlyCopyable<I, O>()
tagged_pair<tag::in(I), tag::out(O)>
copy_if(I first, S last, O result, Pred pred, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class Proj = identity, IndirectPredicate<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
copy_if(Rng&& rng, O result, Pred pred, Proj proj = Proj{});

Requires: The ranges \([first, last)\) and \([result, result + (last - first))\) shall not overlap.

Effects: Copies all of the elements referred to by the iterator \( i \) in the range \([first, last)\) for which \( invoke(pred, invoke(proj, *i)) \) is true.

Returns: \( \{last, result + (last - first)\} \).

Complexity: Exactly last - first applications of the corresponding predicate and projection.

Remarks: Stable (ISO/IEC 14882:2014 §17.6.5.7).

template <BidirectionalIterator I1, Sentinel<I1> S1, BidirectionalIterator I2>
requires IndirectlyCopyable<I1, I2>()
tagged_pair<tag::in(I1), tag::out(I2)>
copy_backward(I1 first, S1 last, I2 result);

template <BidirectionalRange Rng, BidirectionalIterator I>
requires IndirectlyCopyable<iterator_t<Rng>, I>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(I)>
copy_backward(Rng&& rng, I result);

Effects: Copies elements in the range \([first, last)\) into the range \([result - (last-first), result)\) starting from \( last - 1 \) and proceeding to \( first \). For each positive integer \( n < (last - first) \), performs \( *(result - n) = *(last - n) \).

Requires: result shall not be in the range \([first,last)\).

Returns: \( \{last, result - (last - first)\} \).

Complexity: Exactly last - first assignments.

10.4.2 Move

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O>
requires IndirectlyMovable<I, O>()
tagged_pair<tag::in(I), tag::out(O)>
move(I first, S last, O result);

template <InputRange Rng, WeaklyIncrementable O>
requires IndirectlyMovable<iterator_t<Rng>, O>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
move(Rng&& rng, O result);

5) \( \text{copy_backward} \) should be used instead of \( \text{copy} \) when \( \text{last} \) is in the range \([result - (last - first), result)\).
Effects: Moves elements in the range \([\text{first}, \text{last})\) into the range \([\text{result}, \text{result} + (\text{last} - \text{first}))\) starting from first and proceeding to last. For each non-negative integer \(n < (\text{last} - \text{first})\), performs \(*(\text{result} + n) = \text{std::move}(*(\text{first} + n))\).

Returns: \{\text{last}, \text{result} + (\text{last} - \text{first})\}.

Requires: result shall not be in the range \([\text{first}, \text{last})\).

Complexity: Exactly \(\text{last} - \text{first}\) move assignments.

\[\text{move_backward}(\text{I1} \text{ first}, \text{S1} \text{ last}, \text{I2} \text{ result});\]

\[\text{move_backward}(\text{Rng} \text{ first}, \text{I} \text{ result});\]

Effects: Moves elements in the range \([\text{first}, \text{last})\) into the range \([\text{result} - (\text{last} - \text{first}), \text{result})\) starting from \(\text{last} - 1\) and proceeding to first. For each positive integer \(n \leq (\text{last} - \text{first})\), performs \(*(\text{result} - n) = \text{std::move}(*(\text{last} - n))\).

Requires: result shall not be in the range \([\text{first}, \text{last})\).

Returns: \{\text{last}, \text{result} - (\text{last} - \text{first})\}.

Complexity: Exactly \(\text{last} - \text{first}\) assignments.

\[\text{swap_ranges}(\text{I1} \text{ first1}, \text{S1} \text{ last1}, \text{I2} \text{ first2}, \text{S2} \text{ last2});\]

Effects: For each non-negative integer \(n < \min(\text{last1} - \text{first1}, \text{last2} - \text{first2})\) performs: \(\text{swap}(*(\text{first1} + n), *(\text{first2} + n))\).

Requires: The two ranges \([\text{first1}, \text{last1})\) and \([\text{first2}, \text{last2})\) shall not overlap. \(*(\text{first1} + n)\) shall be swappable with \((7.3.11) * (\text{first2} + n)\).

Returns: \{\text{first1} + n, \text{first2} + n\}, where \(n\) is \(\min(\text{last1} - \text{first1}, \text{last2} - \text{first2})\).

Complexity: Exactly \(\min(\text{last1} - \text{first1}, \text{last2} - \text{first2})\) swaps.

\[\text{transform}(\text{I} \text{ first}, \text{S} \text{ last}, \text{O} \text{ result}, \text{F} \text{ op}, \text{Proj} \text{ proj = Proj{}{}});\]
template <InputRange Rng, WeaklyIncrementable O, class F, class Proj = identity>
  requires Writable<O, indirect_result_of_t<F&(
      projected<iterator_t<Rng>, Proj>)>>()
  tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
  transform(Rng&& rng, 0 result, F op, Proj proj = Proj{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
  WeaklyIncrementable O, class F, class Proj1 = identity, class Proj2 = identity>
  requires Writable<O, indirect_result_of_t<F&(projected<I1, Proj1>,
    projected<I2, Proj2>)>>()
  tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(O)>
  transform(I1 first1, S1 last1, I2 first2, S2 last2, O result,
    F binary_op, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O, class F,
  class Proj1 = identity, class Proj2 = identity>
  requires Writable<O, indirect_result_of_t<F&(
      projected<iterator_t<Rng1>, Proj1>, projected<iterator_t<Rng2>, Proj2>)>>()
  tagged_tuple<tag::in1(safe_iterator_t<Rng1>),
    tag::in2(safe_iterator_t<Rng2>),
    tag::out(O)>
  transform(Rng1&& rng1, Rng2&& rng2, O result,
    F binary_op, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

1 Let \( N \) be \((last1 - first1)\) for unary transforms, or \(\min(last1 - first1, last2 - first2)\) for binary transforms.

2 Effects: Assigns through every iterator \( i \) in the range \([result, result + N)\) a new corresponding value equal to
\(\text{invoke}(op, \text{invoke}(proj, *(first1 + (i - result))))\) or
\(\text{invoke}(binary\_op, \text{invoke}(proj1, *(first1 + (i - result))), \text{invoke}(proj2, *(first2 + (i - result))))\).

3 Requires: \(op\) and \(binary\_op\) shall not invalidate iterators or subranges, or modify elements in the
ranges \([first1, first1 + N]\), \([first2, first2 + N]\), and \([result, result + N]\).

4 Returns: \((first1 + N, result + N)\) or \(\text{make\_tagged\_tuple}\tag::in1, tag::in2, tag::out>(first1 + N, first2 + N, result + N)\).

5 Complexity: Exactly \(N\) applications of \(op\) or \(binary\_op\).

6 Remarks: \(result\) may be equal to \(first1\) in case of unary transform, or to \(first1\) or \(first2\) in case of
binary transform.

### 10.4.5 Replace

[alg.replace]

```
template <ForwardIterator I, Sentinel<I> S, class T1, class T2, class Proj = identity>
  requires Writable<I, const T2&>() &&
  IndirectRelation<equal_to<>, projected<I, Proj>, const T1*>()>>()
  I
  replace(I first, S last, const T1& old_value, const T2& new_value, Proj proj = Proj{});
```

```
template <ForwardRange Rng, class T1, class T2, class Proj = identity>
  requires Writable<iterator_t<Rng>, const T2&>() &&
  IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T1*>()>>()
  safe_iterator_t<Rng>
  replace(Rng&& rng, const T1& old_value, const T2& new_value, Proj proj = Proj{});
```

7) The use of fully closed ranges is intentional.
template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity, 
    IndirectPredicate<projected<I, Proj>> Pred>
requires Writable<I, const T&>()
I
    replace_if(I first, S last, Pred pred, const T& new_value, Proj proj = Proj{});

template <ForwardRange Rng, class T, class Proj = identity, 
    IndirectPredicate<iterator_t<Rng>, Proj>> Pred>
requires Writable<iterator_t<Rng>, const T&>()
safe_iterator_t<Rng>
    replace_if(Rng& rng, Pred pred, const T& new_value, Proj proj = Proj{});

1 Effects: Substitutes elements referred by the iterator i in the range [first, last) with new_value, 
when the following corresponding conditions hold: invoke(proj, *i) == old_value, invoke(pred, 
invoke(proj, *i)) != false.
2 Returns: last.
3 Complexity: Exactly last - first applications of the corresponding predicate and projection.

template <InputIterator I, Sentinel<I> S, class T1, class T2, OutputIterator<const T2&> O, 
    class Proj = identity>
requires IndirectlyCopyable<I, O>() && 
IndirectRelation<equal_to<>, projected<I, Proj>, const T1*>() 
tagged_pair<tag::in(I), tag::out(O)>
    replace_copy(I first, S last, O result, const T1& old_value, const T2& new_value, 
    Proj proj = Proj{});

template <InputRange Rng, class T1, class T2, OutputIterator<const T2&> O, 
    class Proj = identity>
requires IndirectlyCopyable<iterator_t<Rng>, O>() && 
IndirectRelation<equal_to<>, projected<iterator_t<Rng>, Proj>, const T1*>() 
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
    replace_copy(Rng& rng, O result, const T1& old_value, const T2& new_value, 
    Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, class T, OutputIterator<const T&> O, 
    class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires IndirectlyCopyable<I, O>() 
tagged_pair<tag::in(I), tag::out(O)>
    replace_copy_if(I first, S last, O result, Pred pred, const T& new_value, 
    Proj proj = Proj{});

template <InputRange Rng, class T, OutputIterator<const T&> O, class Proj = identity, 
    IndirectPredicate<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O>() 
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
    replace_copy_if(Rng& rng, O result, Pred pred, const T& new_value, 
    Proj proj = Proj{});

4 Requires: The ranges [first, last) and [result, result + (last - first)) shall not overlap.
5 Effects: Assigns to every iterator i in the range [result, result + (last - first)) either new_value 
or *(first + (i - result)) depending on whether the following corresponding conditions hold:
   invoke(proj, *(first + (i - result))) == old_value 
   invoke(pred, invoke(proj, *(first + (i - result)))) != false
6 \quad \textit{Returns:} \{\text{last}, \text{result} + (\text{last} - \text{first})\}.

7 \quad \textit{Complexity:} \text{Exactly last} - \text{first} \text{ applications of the corresponding predicate and projection.}

10.4.6 Fill

\[\text{template } <\text{class } T, \text{OutputIterator<const } T\&> \text{ O, Sentinel<} O\text{> S}>\]
\[0 \text{ fill}(O \text{ first}, S \text{ last}, \text{const } T\& \text{ value});\]

\[\text{template } <\text{class } T, \text{OutputRange<const } T\&> \text{ Rng}>\]
\[\text{safe_iterator_t}<\text{Rng}>\]
\[\text{fill}(\text{Rng}\&\& \text{ rng}, \text{const } T\& \text{ value});\]

\[\text{template } <\text{class } T, \text{OutputIterator<const } T\&> \text{ O}>\]
\[O \text{ fill}_n(O \text{ first}, \text{difference_type_t<} O\text{> n}, \text{const } T\& \text{ value});\]

1 \quad \textit{Effects:} \text{fill assigns value through all the iterators in the range } \text{[first, last)}. \text{ fill}_n \text{ assigns value through all the iterators in the range } \text{[first, first + n)} \text{ if n is positive, otherwise it does nothing.}

2 \quad \textit{Returns:} \text{fill returns last. fill}_n \text{ returns first} + \text{n for non-negative values of } \text{n and first} \text{ for negative values.}

3 \quad \textit{Complexity:} \text{Exactly last} - \text{first, n, or 0 assignments, respectively.}

10.4.7 Generate

\[\text{template } <\text{Iterator } O, \text{Sentinel<} O\text{> S, CopyConstructible } F\text{> requires Callable<} F\&()\text{>>}}\]
\[0 \text{ generate}(0 \text{ first}, S \text{ last, } F \text{ gen});\]

\[\text{template } <\text{class } Rng, \text{CopyConstructible } F\text{> requires Callable<} F\&()\text{>>}}\]
\[\text{safe_iterator_t}<\text{Rng}>\]
\[\text{generate}(\text{Rng}\&\& \text{ rng}, F \text{ gen});\]

\[\text{template } <\text{Iterator } O, \text{CopyConstructible } F\text{> requires Callable<} F\&()\text{>>}}\]
\[0 \text{ generate}_n(0 \text{ first}, \text{difference_type_t<} O\text{> n}, F \text{ gen});\]

1 \quad \textit{Effects:} \text{Assigns the value of } \text{invoke(gen)} \text{ through successive iterators in the range } \text{[first, last), where last is first} + \text{max(n, 0)} \text{ for generate}_n.

2 \quad \textit{Returns:} \text{last.}

3 \quad \textit{Complexity:} \text{Exactly last} - \text{first evaluations of } \text{invoke(gen)} \text{ and assignments.}

10.4.8 Remove

\[\text{template } <\text{ForwardIterator } I, \text{Sentinel<} I\text{> S, class } T, \text{class } Proj = \text{identity}>\]
\[\text{requires Permutable<} I\text{>() \&\& IndirectRelation<equal_to<>, projected<} I\text{, Proj}, \text{const } T\star()\text{>}}\]
\[I \text{ remove}(I \text{ first}, S \text{ last, } \text{const } T\& \text{ value, Proj proj} = \text{Proj}());\]

\[\text{template } <\text{ForwardRange } Rng, \text{class } T, \text{class } Proj = \text{identity}>\]
\[\text{requires Permutable<} \text{iterator_t<} Rng\text{>() \&\& IndirectRelation<equal_to<>, projected<} \text{iterator_t<} Rng\text{, Proj}, \text{const } T\star()\text{>}}\]
\[\text{safe_iterator_t}<\text{Rng}>\]
\[\text{remove}(\text{Rng}\&\& \text{ rng}, \text{const } T\& \text{ value, Proj proj} = \text{Proj}());\]

\[\text{template } <\text{ForwardIterator } I, \text{Sentinel<} I\text{> S, class } Proj = \text{identity},\]

\[\S \ 10.4.8 \quad 149\]
IndirectPredicate<projected<I, Proj>> Pred>
requires Permutable<I>()
I remove_if(I first, S last, Pred pred, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires Permutable<iterator_t<Rng>>()
safe_iterator_t<Rng>
remove_if(Rng&& rng, Pred pred, Proj proj = Proj{});

Effects: Eliminates all the elements referred to by iterator i in the range [first, last) for which the following corresponding conditions hold: invoke(proj, *i) == value, invoke(pred, invoke(proj, *i)) != false.

Returns: The end of the resulting range.
Remarks: Stable (ISO/IEC 14882:2014 §17.6.5.7).
Note: each element in the range [ret, last), where ret is the returned value, has a valid but unspecified state, because the algorithms can eliminate elements by moving from elements that were originally in that range.

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O, class T,
class Proj = identity>
requires IndirectlyCopyable<I, O>() &&
IndirectRelation<equal_to<>>, projected<I, Proj>, const T*>()
tagged_pair<in(I), out(O)>
remove_copy(I first, S last, O result, const T& value, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class T, class Proj = identity>
requires IndirectlyCopyable<iterator_t<Rng>, O>() &&
IndirectRelation<equal_to<>>, projected<iterator_t<Rng>, Proj>, const T*>()
tagged_pair<in(safe_iterator_t<Rng>), out(O)>
remove_copy(Rng&& rng, O result, const T& value, Proj proj = Proj{});

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O,
class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires IndirectlyCopyable<I, O>()
tagged_pair<in(I), out(O)>
remove_copy_if(I first, S last, O result, Pred pred, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O, class Proj = identity,
IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O>()
tagged_pair<in(safe_iterator_t<Rng>), out(O)>
remove_copy_if(Rng&& rng, O result, Pred pred, Proj proj = Proj{});

Requires: The ranges [first, last) and [result, result + (last - first)) shall not overlap.
Effects: Copies all the elements referred to by the iterator i in the range [first, last) for which the following corresponding conditions do not hold: invoke(proj, *i) == value, invoke(pred, invoke(proj, *i)) != false.

Returns: A pair consisting of last and the end of the resulting range.
Complexity: Exactly last - first applications of the corresponding predicate and projection.
Remarks: Stable (ISO/IEC 14882:2014 §17.6.5.7).
10.4.9 Unique

```
template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
          IndirectRelation<Projected<I, Proj>> R = equal_to<>>
requires Permutable(I())
I unique(I first, S last, R comp = R{}, Proj proj = Proj{});
```

```
template <ForwardRange Rng, class Proj = identity, 
          IndirectRelation<Projected<iterator_t<Rng>, Proj>> R = equal_to<>>
requires Permutable(iterator_t<Rng>())
safe_iterator_t<Rng>
unique(Rng&& rng, R comp = R{}, Proj proj = Proj{});
```

1 Effects: For a nonempty range, eliminates all but the first element from every consecutive group of equivalent elements referred to by the iterator i in the range [first + 1, last) for which the following conditions hold: `invoke(proj, *(i - 1)) == invoke(proj, *i)` or `invoke(pred, invoke(proj, *(i - 1)), invoke(proj, *i)) != false`.

2 Returns: The end of the resulting range.

3 Complexity: For nonempty ranges, exactly \((last - first) - 1\) applications of the corresponding predicate and no more than twice as many applications of the projection.

```
template <InputIterator I, Sentinel<I>, WeaklyIncrementable O, 
          class Proj = identity, IndirectRelation<Projected<I, Proj>> R = equal_to<>>
requires IndirectlyCopyable<I, O>() && (ForwardIterator<I>() || ForwardIterator<O>() || IndirectlyCopyableStorable<I, O>())
tagged_pair<tag::in(I), tag::out(O)>
unique_copy(I first, S last, O result, R comp = R{}, Proj proj = Proj{});
```

```
template <InputRange Rng, WeaklyIncrementable O, class Proj = identity, 
          IndirectRelation<Projected<iterator_t<Rng>, Proj>> R = equal_to<>>
requires IndirectlyCopyable<iterator_t<Rng>, O>() || IndirectlyCopyableStorable<iterator_t<Rng>, O>()
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)>
unique_copy(Rng&& rng, O result, R comp = R{}, Proj proj = Proj{});
```

4 Requires: The ranges [first, last) and [result, result+(last-first)) shall not overlap.

5 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 the following corresponding conditions hold: `invoke(proj, *i) == invoke(proj, *(i - 1))` or `invoke(pred, invoke(proj, *i), invoke(proj, *(i - 1))) != false`.

6 Returns: A pair consisting of last and the end of the resulting range.

7 Complexity: For nonempty ranges, exactly last - first - 1 applications of the corresponding predicate and no more than twice as many applications of the projection.

10.4.10 Reverse

```
template <BidirectionalIterator I, Sentinel<I> S>
requires Permutable(I())
I reverse(I first, S last);
```

```
template <BidirectionalRange Rng>
requires Permutable(iterator_t<Rng>())
safe_iterator_t<Rng>
```

§ 10.4.10
reverse(Rng&& rng);

Effects: For each non-negative integer \( i < (\text{last} - \text{first})/2 \), applies \text{iter_swap} to all pairs of iterators \( \text{first} + i, (\text{last} - i) - 1 \).

Returns: last.

Complexity: Exactly \((\text{last} - \text{first})/2\) swaps.

template <BidirectionalIterator I, Sentinel<I> S, WeaklyIncrementable O>
requires IndirectlyCopyable<I, O>()  
tagged_pair<tag::in(I), tag::out(O)> reverse_copy(I first, S last, O result);

template <BidirectionalRange Rng, WeaklyIncrementable O>
requires IndirectlyCopyable<iterator_t<Rng>, O>()  
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)> reverse_copy(Rng&& rng, O result);

Effects: Copies the range \([\text{first}, \text{last})\) to the range \([\text{result}, \text{result}+(\text{last}-\text{first}))\) such that for every non-negative integer \( i < (\text{last} - \text{first}) \) the following assignment takes place: \( *\text{result} + (\text{last} - \text{first}) - 1 - i = *\text{first} + i \).

Requires: The ranges \([\text{first}, \text{last})\) and \([\text{result}, \text{result}+(\text{last}-\text{first}))\) shall not overlap.

Returns: \( \{\text{last}, \text{result} + (\text{last} - \text{first})\} \).

Complexity: Exactly \( \text{last} - \text{first} \) assignments.

10.4.11 Rotate

[alg.rotate]

template <ForwardIterator I, Sentinel<I> S>
requires Permutable<I>()  
tagged_pair<tag::begin(I), tag::end(I)> rotate(I first, I middle, S last);

template <ForwardRange Rng>
requires Permutable<iterator_t<Rng>>()  
tagged_pair<tag::begin(safe_iterator_t<Rng>), tag::end(safe_iterator_t<Rng>)> rotate(Rng&& rng, iterator_t<Rng> middle);

Effects: For each non-negative integer \( i < (\text{last} - \text{first}) \), places the element from the position \( \text{first} + i \) into position \( \text{first} + (i + (\text{last} - \text{middle})) \% (\text{last} - \text{first}) \).

Returns: \( \{\text{first} + (\text{last} - \text{middle}), \text{last}\} \).

Remarks: This is a left rotate.

Requires: \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\) shall be valid ranges.

Complexity: At most \( \text{last} - \text{first} \) swaps.

template <ForwardIterator I, Sentinel<I> S, WeaklyIncrementable O>
requires IndirectlyCopyable<I, O>()  
tagged_pair<tag::in(I), tag::out(O)> rotate_copy(I first, I middle, S last, O result);

template <ForwardRange Rng, WeaklyIncrementable O>
requires IndirectlyCopyable<iterator_t<Rng>, O>()  
tagged_pair<tag::in(safe_iterator_t<Rng>), tag::out(O)> rotate_copy(Rng&& rng, iterator_t<Rng> middle, O result);
Effects: Copies the range \([\text{first}, \text{last})\) to the range \([\text{result}, \text{result} + (\text{last} - \text{first}))\) such that for each non-negative integer \(i < (\text{last} - \text{first})\) the following assignment takes place: \(*(\text{result} + i) = *(\text{first} + (i + (\text{middle} - \text{first})) \% (\text{last} - \text{first}))\).

Returns: \{last, result + (last - first)}.

Requires: The ranges \([\text{first}, \text{last})\) and \([\text{result}, \text{result} + (\text{last} - \text{first}))\) shall not overlap.

Complexity: Exactly \(\text{last} - \text{first}\) assignments.

### 10.4.12 Shuffle

\[\text{shuffle}(\text{I first, S last, Gen& g);}\]

Effects: Permutes the elements in the range \([\text{first}, \text{last})\) such that each possible permutation of those elements has equal probability of appearance.

Complexity: Exactly \((\text{last} - \text{first}) - 1\) swaps.

Returns: \text{last}

Remarks: To the extent that the implementation of this function makes use of random numbers, the object \(g\) shall serve as the implementation’s source of randomness.

### 10.4.13 Partitions

\[\text{is_partitioned}(\text{I first, S last, Pred pred, Proj proj = Proj{});}\]

Returns: true if \([\text{first}, \text{last})\) is empty or if \([\text{first}, \text{last})\) is partitioned by \(\text{pred}\) and \(\text{proj}\), i.e. if all iterators \(i\) for which \(\text{invoke}(\text{pred}, \text{invoke}(\text{proj}, \ast i)) \neq \text{false}\) come before those that do not, for every \(i\) in \([\text{first}, \text{last})\).

Complexity: Linear. At most \(\text{last} - \text{first}\) applications of \(\text{pred}\) and \(\text{proj}\).
safe_iterator_t<Rng>
partition(Rng&& rng, Pred pred, Proj proj = Proj{});

3 Effects: Permutes the elements in the range \([first, last)\) such that there exists an iterator \(i\) such that for every iterator \(j\) in the range \([first, i)\) \(\text{invoke}(pred, \text{invoke}(proj, \ast j)) \neq false\), and for every iterator \(k\) in the range \([i, last)\), \(\text{invoke}(pred, \text{invoke}(proj, \ast k)) = false\).

4 Returns: An iterator \(i\) such that for every iterator \(j\) in the range \([first, i)\) \(\text{invoke}(pred, \text{invoke}(proj, \ast j)) \neq false\), and for every iterator \(k\) in the range \([i, last)\), \(\text{invoke}(pred, \text{invoke}(proj, \ast k)) = false\).

5 Complexity: If \(I\) meets the requirements for a BidirectionalIterator, at most \((last - first) / 2\) swaps; otherwise at most \(last - first\) swaps. Exactly \(last - first\) applications of the predicate and projection.

template <BidirectionalIterator I, Sentinel<I> S, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires Permutable<I>()
I stable_partition(I first, S last, Pred pred, Proj proj = Proj{});

template <BidirectionalRange Rng, class Proj = identity, IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires Permutable<iterator_t<Rng>>()
safe_iterator_t<Rng>
stable_partition(Rng&& rng, Pred pred, Proj proj = Proj{});

6 Effects: Permutes the elements in the range \([first, last)\) such that there exists an iterator \(i\) such that for every iterator \(j\) in the range \([first, i)\) \(\text{invoke}(pred, \text{invoke}(proj, \ast j)) \neq false\), and for every iterator \(k\) in the range \([i, last)\), \(\text{invoke}(pred, \text{invoke}(proj, \ast k)) = false\).

7 Returns: An iterator \(i\) such that for every iterator \(j\) in the range \([first, i)\), \(\text{invoke}(pred, \text{invoke}(proj, \ast j)) \neq false\), and for every iterator \(k\) in the range \([i, last)\), \(\text{invoke}(pred, \text{invoke}(proj, \ast k)) = false\). The relative order of the elements in both groups is preserved.

8 Complexity: At most \((last - first) \ast \log(last - first)\) swaps, but only linear number of swaps if there is enough extra memory. Exactly \(last - first\) applications of the predicate and projection.

template <InputIterator I, Sentinel<I> S, WeaklyIncrementable O1, WeaklyIncrementable O2, class Proj = identity, IndirectPredicate<projected<I, Proj>> Pred>
requires IndirectlyCopyable<I, O1>() && IndirectlyCopyable<I, O2>()
tagged_tuple<tag::in(I), tag::out1(O1), tag::out2(O2)>
partition_copy(I first, S last, O1 out_true, O2 out_false, Pred pred, Proj proj = Proj{});

template <InputRange Rng, WeaklyIncrementable O1, WeaklyIncrementable O2, class Proj = identity, IndirectPredicate<projected<iterator_t<Rng>, Proj>> Pred>
requires IndirectlyCopyable<iterator_t<Rng>, O1>() && IndirectlyCopyable<iterator_t<Rng>, O2>()
tagged_tuple<tag::in(safe_iterator_t<Rng>), tag::out1(O1), tag::out2(O2)>
partition_copy(Rng&& rng, O1 out_true, O2 out_false, Pred pred, Proj proj = Proj{});

9 Requires: The input range shall not overlap with either of the output ranges.

10 Effects: For each iterator \(i\) in \([first, last)\), copies \(\ast i\) to the output range beginning with \(out\_true\) if \(\text{invoke}(pred, \text{invoke}(proj, \ast i))\) is true, or to the output range beginning with \(out\_false\) otherwise.
Returns: A tuple \( p \) such that \( \text{get}<0>(p) \) is \( \text{last} \), \( \text{get}<1>(p) \) is the end of the output range beginning at \( \text{out\_true} \), and \( \text{get}<2>(p) \) is the end of the output range beginning at \( \text{out\_false} \).

Complexity: Exactly \( \text{last} - \text{first} \) applications of \( \text{pred} \) and \( \text{proj} \).

```
template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
    IndirectPredicate<Projected<I, Proj>> Pred>
I partition_point(I first, S last, Pred pred, Proj proj = Proj{});
```

```
template <ForwardRange Rng, class Proj = identity, 
    IndirectPredicate<Projected<iterator_t<Rng>, Proj>> Pred>
safe_iterator_t<Rng> 
partition_point(Rng&& rng, Pred pred, Proj proj = Proj{});
```

Requires: \([\text{first}, \text{last})\) shall be partitioned by \( \text{pred} \) and \( \text{proj} \), i.e. there shall be an iterator \( \text{mid} \) such that all_of(\( \text{first} \), \( \text{mid} \), \( \text{pred} \), \( \text{proj} \)) and none_of(\( \text{mid} \), \( \text{last} \), \( \text{pred} \), \( \text{proj} \)) are both true.

Returns: An iterator \( \text{mid} \) such that all_of(\( \text{first} \), \( \text{mid} \), \( \text{pred} \), \( \text{proj} \)) and none_of(\( \text{mid} \), \( \text{last} \), \( \text{pred} \), \( \text{proj} \)) are both true.

Complexity: \( \Theta(\log(\text{last} - \text{first})) \) applications of \( \text{pred} \) and \( \text{proj} \).

### 10.5 Sorting and related operations

All the operations in 10.5 take an optional binary callable predicate of type \( \text{Comp} \) that defaults to \( \text{less<>} \).

\( \text{Comp} \) is a callable object (ISO/IEC 14882:2014 §20.9.2). The return value of the \( \text{invoke} \) operation applied to an object of type \( \text{Comp} \), when contextually converted to \( \text{bool} \) (Clause ISO/IEC 14882:2014 §4), yields \text{true} if the first argument of the call is less than the second, and \text{false} otherwise. \( \text{Comp} \) \( \text{comp} \) is used throughout for algorithms assuming an ordering relation. It is assumed that \( \text{comp} \) will not apply any non-constant function through the dereferenced iterator.

A sequence is \textit{sorted with respect to a comparator and projection} \( \text{comp} \) and \( \text{proj} \) if for every iterator \( \text{i} \) pointing to the sequence and every non-negative integer \( \text{n} \) such that \( \text{i} + \text{n} \) is a valid iterator pointing to an element of the sequence, \( \text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \text{*}(\text{i} + \text{n})), \text{invoke}(\text{proj}, \text{*i})) == \text{false} \).

A sequence \([\text{start}, \text{finish})\) is \textit{partitioned with respect to an expression} \( f(e) \) if there exists an integer \( \text{n} \) such that for all \( 0 <= \text{i} < \text{distance}(\text{start}, \text{finish}) \), \( f(\text{*}(\text{start} + \text{i})) \) is true if and only if \( \text{i} < \text{n} \).

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 \( \text{a} \) and \( \text{b} \) are considered equivalent if and only if \((\text{a} < \text{b}) \ \&\& \ \!(\text{b} < \text{a})\).

### 10.5.1 Sorting

#### 10.5.1.1 sort

```
template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>, 
    class Proj = identity>
requires Sortable<I, Comp, Proj>()
I sort(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
```

```
template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng> 
sort(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});
```

Effects: Sorts the elements in the range \([\text{first}, \text{last})\).

Complexity: \( \Theta(N \log(N)) \) (where \( N = \text{last} - \text{first} \)) comparisons.

§ 10.5.1.1
10.5.1.2 stable_sort

```cpp
template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
         class Proj = identity>
    requires Sortable<I, Comp, Proj>()
    I stable_sort(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
```

```cpp
template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
    requires Sortable<iterator_t<Rng>, Comp, Proj>()
    safe_iterator_t<Rng>
    stable_sort(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});
```

1 Effects: Sorts the elements in the range \([\text{first},\text{last})\).

2 Complexity: It does at most \(N \log^2(N)\) (where \(N = \text{last} - \text{first}\)) comparisons; if enough extra
   memory is available, it is \(N \log(N)\).

3 Remarks: Stable (ISO/IEC 14882:2014 §17.6.5.7).

10.5.1.3 partial_sort

```cpp
template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
         class Proj = identity>
    requires Sortable<I, Comp, Proj>()
    I partial_sort(I first, I middle, S last, Comp comp = Comp{}, Proj proj = Proj{});
```

```cpp
template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
    requires Sortable<iterator_t<Rng>, Comp, Proj>()
    safe_iterator_t<Rng>
    partial_sort(Rng&& rng, iterator_t<Rng> middle, Comp comp = Comp{},
                 Proj proj = Proj{});
```

1 Effects: Places the first \(\text{middle} - \text{first}\) sorted elements from the range \([\text{first},\text{last})\)
   into the range \([\text{first},\text{middle})\). The rest of the elements in the range \([\text{middle},\text{last})\)
   are placed in an unspecified order.

2 Complexity: It takes approximately \((\text{last} - \text{first}) \times \log(\text{middle} - \text{first})\) comparisons.

10.5.1.4 partial_sort_copy

```cpp
template <InputIterator I1, Sentinel<I1> S1, RandomAccessIterator I2, Sentinel<I2> S2,
         class Comp = less<>, class Proj1 = identity, class Proj2 = identity>
    requires IndirectlyCopyable<I1, I2>() && Sortable<I2, Comp, Proj2>() &&
            IndirectStrictWeakOrder<Comp, projected<I1, Proj1>, projected<I2, Proj2>>()
    I2
    partial_sort_copy(I1 first, S1 last, I2 result_first, S2 result_last,
                      Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

```cpp
template <InputRange Rng1, RandomAccessRange Rng2, class Comp = less<>,
         class Proj1 = identity, class Proj2 = identity>
    requires IndirectlyCopyable<iterator_t<Rng1>, iterator_t<Rng2>>() &&
            Sortable<iterator_t<Rng2>, Comp, Proj2>() &&
            IndirectStrictWeakOrder<Comp, projected<iterator_t<Rng1>, Proj1>,
                                  projected<iterator_t<Rng2>, Proj2>>()
    safe_iterator_t<Rng2>
    partial_sort_copy(Rng1&& rng, Rng2&& result_rng, Comp comp = Comp{},
                      Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

1 Effects: Places the first \(\min(\text{last} - \text{first}, \text{result_last} - \text{result_first})\) sorted elements into the
   range \([\text{result_first},\text{result_first} + \min(\text{last} - \text{first}, \text{result_last} - \text{result_first})\]).
Returns: The smaller of: \( \text{result\_last} \) or \( \text{result\_first} + (\text{last} - \text{first}) \).

Complexity: Approximately \( (\text{last} - \text{first}) \times \log(\min(\text{last} - \text{first}, \text{result\_last} - \text{result\_first})) \) comparisons.

10.5.1.5 \text{is\_sorted} \quad [\text{is\_sorted}]

\begin{verbatim}
template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
IndirectStrictWeakOrder<projected<I, Proj>> Comp = less>>
bool is_sorted(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity, 
IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less>>
bool
is_sorted(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

Returns: \( \text{is\_sorted\_until} \) \( \text{first}, \text{last}, \text{comp}, \text{proj} \) == \( \text{last} \)

template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
IndirectStrictWeakOrder<projected<I, Proj>> Comp = less>>
I is_sorted_until(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity, 
IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less>>
safe_iterator_t<Rng>
is_sorted_until(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

Returns: If \( \text{distance} \) \( \text{first}, \text{last} < 2 \), returns \( \text{last} \). Otherwise, returns the last iterator \( i \) in \( \text{[first, last]} \) for which the range \( \text{[first, i)} \) is sorted.

Complexity: Linear.

10.5.2 \text{Nth element} \quad [\text{alg.nth.element}]

\begin{verbatim}
template <RandomAccessIterator I, Sentinel<I> S, class Comp = less>, 
class Proj = identity>
requires Sortable<I, Comp, Proj>()
I nth_element(I first, I nth, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng>
nth_element(Rng&& rng, iterator_t<Rng> nth, Comp comp = Comp{}, Proj proj = Proj{});

After \text{nth\_element} the element in the position pointed to by \text{nth} is the element that would be in that position if the whole range were sorted, unless \text{nth} == \text{last}. Also for every iterator \( i \) in the range \( \text{[first, nth]} \) and every iterator \( j \) in the range \( \text{[nth, last]} \) it holds that: \text{invoke}(\text{comp}, \text{invoke}(\text{proj}, \star j), \text{invoke}(\text{proj}, \star i)) == \text{false}.

Complexity: Linear on average.

10.5.3 \text{Binary search} \quad [\text{alg.binary.search}]

All of the algorithms in this section 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 and projection. 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.

§ 10.5.3
10.5.3.1 lower_bound

```cpp
template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
          IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
I
  lower_bound(I first, S last, const T& value, Comp comp = Comp{},
              Proj proj = Proj{});
```

```cpp
template <ForwardRange Rng, class T, class Proj = identity,
          IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
  safe_iterator_t<Rng>
  lower_bound(Rng&& rng, const T& value, Comp comp = Comp{}, Proj proj = Proj{});
```

1. Requires: The elements e of [first,last) shall be partitioned with respect to the expression 
   `invoke(comp, invoke(proj, e), value)`.
2. Returns: The furthermost iterator i in the range [first, last) such that for every iterator 
   j in the range [first, i) the following corresponding condition holds: 
   `invoke(comp, invoke(proj, *j), value) != false`.
3. Complexity: At most \( \log_2(\text{last} - \text{first}) + O(1) \) applications of the comparison function and projection.

10.5.3.2 upper_bound

```cpp
template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
          IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
I
  upper_bound(I first, S last, const T& value, Comp comp = Comp{}, Proj proj = Proj{});
```

```cpp
template <ForwardRange Rng, class T, class Proj = identity,
          IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
  safe_iterator_t<Rng>
  upper_bound(Rng&& rng, const T& value, Comp comp = Comp{}, Proj proj = Proj{});
```

1. Requires: The elements e of [first, last) shall be partitioned with respect to the expression 
   `!invoke(comp, value, invoke(proj, e))`.
2. Returns: The furthermost iterator i in the range [first, last) such that for every iterator 
   j in the range [first, i) the following corresponding condition holds: 
   `invoke(comp, value, invoke(proj, *j)) == false`.
3. Complexity: At most \( \log_2(\text{last} - \text{first}) + O(1) \) applications of the comparison function and projection.

10.5.3.3 equal_range

```cpp
template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
          IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
  tagged_pair<tag::begin(I), tag::end(I)>
  equal_range(I first, S last, const T& value, Comp comp = Comp{}, Proj proj = Proj{});
```

```cpp
template <ForwardRange Rng, class T, class Proj = identity,
          IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
  tagged_pair<tag::begin(safe_iterator_t<Rng>),
              tag::end(safe_iterator_t<Rng>)>
  equal_range(Rng&& rng, const T& value, Comp comp = Comp{}, Proj proj = Proj{});
```

1. Requires: The elements e of [first, last) shall be partitioned with respect to the expressions 
   `invoke(comp, invoke(proj, e), value)` and `!invoke(comp, value, invoke(proj, e))`. Also,
for all elements \( e \) of \([\text{first}, \text{last})\), \( \text{invoke}(\text{comp}, \text{invoke}(\text{proj}, e), \text{value}) \) shall imply \( \neg \text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, e)) \).

2. Returns:

\[
\{\text{lower_bound}(\text{first}, \text{last}, \text{value}, \text{comp}, \text{proj}),
\text{upper_bound}(\text{first}, \text{last}, \text{value}, \text{comp}, \text{proj})\}
\]

3. Complexity: At most \( 2 \times \log_2(\text{last} - \text{first}) + \Theta(1) \) applications of the comparison function and projection.

### 10.5.3.4 binary_search

[binary.search]

```cpp
template <ForwardIterator I, Sentinel<I> S, class T, class Proj = identity,
         IndirectStrictWeakOrder<const T*, projected<I, Proj>> Comp = less<>>
bool
binary_search(I first, S last, const T& value, Comp comp = Comp{},
              Proj proj = Proj{});
```

```cpp
template <ForwardRange Rng, class T, class Proj = identity,
         IndirectStrictWeakOrder<const T*, projected<iterator_t<Rng>, Proj>> Comp = less<>>
bool
binary_search(Rng&& rng, const T& value, Comp comp = Comp{},
              Proj proj = Proj{});
```

1. Requires: The elements \( e \) of \([\text{first}, \text{last})\) are partitioned with respect to the expressions \( \text{invoke}(\text{comp}, \text{invoke}(\text{proj}, e), \text{value}) \) and \( \neg \text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, e)) \). Also, for all elements \( e \) of \([\text{first}, \text{last})\), \( \text{invoke}(\text{comp}, \text{invoke}(\text{proj}, e), \text{value}) \) shall imply \( \neg \text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, e)) \).

2. Returns: \( \text{true} \) if there is an iterator \( i \) in the range \([\text{first}, \text{last})\) that satisfies the corresponding conditions: \( \text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *i), \text{value}) == \text{false} \&\& \text{invoke}(\text{comp}, \text{value}, \text{invoke}(\text{proj}, *i)) == \text{false} \).

3. Complexity: At most \( \log_2(\text{last} - \text{first}) + \Theta(1) \) applications of the comparison function and projection.

### 10.5.4 Merge

[alg.merge]

```cpp
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
          WeaklyIncrementable O, class Comp = less<>,
          class Proj1 = identity,
          class Proj2 = identity>
requires Mergeable<I1, I2, O, Comp, Proj1, Proj2>()
tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(O)>
merge(I1 first1, S1 last1, I2 first2, S2 last2, O result,
      Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

```cpp
template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O, class Comp = less<>,
          class Proj1 = identity,
          class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>, O, Comp, Proj1, Proj2>()
tagged_tuple<tag::in1(safe_iterator_t<Rng1>),
              tag::in2(safe_iterator_t<Rng2>),
              tag::out(O)>
merge(Rng1&& rng1, Rng2&& rng2, O result,
      Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

1. Effects: Copies all the elements of the two ranges \([\text{first1}, \text{last1})\) and \([\text{first2}, \text{last2})\) into the range \([\text{result}, \text{result_last})\), where \( \text{result_last} \) is \( \text{result} + (\text{last1} - \text{first1}) + (\text{last2} - \text{first2}) \).
If an element \(a\) precedes \(b\) in an input range, \(a\) is copied into the output range before \(b\). If \(e_1\) is an element of \([\text{first}_1, \text{last}_1)\) and \(e_2\) of \([\text{first}_2, \text{last}_2)\), \(e_2\) is copied into the output range before \(e_1\) if and only if \(\text{bool}(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}_2, e_2), \text{invoke}(\text{proj}_1, e_1)))\) is true.

**Requires:** The ranges \([\text{first}_1, \text{last}_1)\) and \([\text{first}_2, \text{last}_2)\) shall be sorted with respect to \(\text{comp}\), \(\text{proj}_1\), and \(\text{proj}_2\). The resulting range shall not overlap with either of the original ranges.

**Returns:** \(\text{make\_tagged\_tuple}::<\text{in}_1, \text{tag}\_\text{in}_2, \text{tag}\_\text{out}>(\text{last}_1, \text{last}_2, \text{result}_\text{last})\).

**Complexity:** At most \((\text{last}_1 - \text{first}_1) + (\text{last}_2 - \text{first}_2) - 1\) applications of the comparison function and each projection.

**Remarks:** Stable (ISO/IEC 14882:2014 §17.6.5.7).

```
template <BidirectionalIterator I, Sentinel<I> S, class Comp = less<>,
           class Proj = identity>
requires Sortable<I, Comp, Proj>()
I
  inplace_merge(I first, I middle, S last, Comp comp = Comp{}, Proj proj = Proj{});
```

```
template <BidirectionalRange Rng, class Comp = less<>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng>
  inplace_merge(Rng&& rng, iterator_t<Rng> middle, Comp comp = Comp{},
               Proj proj = Proj{});
```

**Effects:** Merges two sorted consecutive ranges \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\), putting the result of the merge into the range \([\text{first}, \text{last})\). The resulting range will be in non-decreasing order; that is, for every iterator \(i\) in \([\text{first}, \text{last})\) other than \(\text{first}\), the condition \(\text{invoke}(\text{comp}, \text{invoke}(\text{proj}, *i), \text{invoke}(\text{proj}, *(i - 1)))\) will be false.

**Requires:** The ranges \([\text{first}, \text{middle})\) and \([\text{middle}, \text{last})\) shall be sorted with respect to \(\text{comp}\) and \(\text{proj}\).

**Returns:** \(\text{last}\)

**Complexity:** When enough additional memory is available, \((\text{last} - \text{first}) - 1\) applications of the comparison function and projection. If no additional memory is available, an algorithm with complexity \(N \log(N)\) (where \(N\) is equal to \(\text{last} - \text{first}\)) may be used.

**Remarks:** Stable (ISO/IEC 14882:2014 §17.6.5.7).

### 10.5.5 Set operations on sorted structures

This section defines all the basic set operations on sorted structures. They also work with **multisets** (ISO/IEC 14882:2014 §23.4.7) containing multiple copies of equivalent elements. The semantics of the set operations are generalized to multisets in a standard way by defining \(\text{set\_union()}\) to contain the maximum number of occurrences of every element, \(\text{set\_intersection()}\) to contain the minimum, and so on.

**10.5.5.1 includes**

```
#include <algorithm>
```

```
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
           class Proj1 = identity, class Proj2 = identity,
           IndirectStrictWeakOrder<projected<I1, Proj1>, projected<I2, Proj2>> Comp = less<>>
bool
  includes(I1 first1, S1 last1, I2 first2, S2 last2, Comp comp = Comp{},
            Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});
```

```
template <InputRange Rng1, InputRange Rng2, class Proj1 = identity,
           class Proj2 = identity
```
IndirectStrictWeakOrder<projected<iterator_t<Rng1>>, Proj1>,
projected<iterator_t<Rng2>>, Proj2>> Comp = less<>>

bool
includes(Rng1&& rng1, Rng2&& rng2, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

1 Returns: true if [first2,last2) is empty or if every element in the range [first2,last2) is con-
tained in the range [first1,last1). Returns false otherwise.

2 Complexity: At most 2 * ((last1 - first1) + (last2 - first2)) - 1 applications of the com-
parison function and projections.

10.5.5.2 set_union

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
WeaklyIncrementable 0, class Comp = less<>>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<I1, I2, 0, Comp, Proj1, Proj2>()
tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(0)>
set_union(I1 first1, S1 last1, I2 first2, S2 last2, 0 result, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable 0,
class Comp = less<>>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>, 0, Comp, Proj1, Proj2>()
tagged_tuple>tag::in1(safe_iterator_t<Rng1>),
tag::in2(safe_iterator_t<Rng2>),
tag::out(0)>
set_union(Rng1&& rng1, Rng2&& rng2, 0 result, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

1 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.

2 Requires: The resulting range shall not overlap with either of the original ranges.

3 Returns: make_tagged_tuple<Tag::in1, Tag::in2, Tag::out>(last1, last2, result + n), where
n is the number of elements in the constructed range.

4 Complexity: At most 2 * ((last1 - first1) + (last2 - first2)) - 1 applications of the com-
parison function and projections.

5 Remarks: If [first1,last1) contains m elements that are equivalent to each other and [first2,
last2) contains n elements that are equivalent to them, then all m elements from the first range shall
be copied to the output range, in order, and then max(n − m, 0) elements from the second range shall
be copied to the output range, in order.

10.5.5.3 set_intersection

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
WeaklyIncrementable 0, class Comp = less<>>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<I1, I2, 0, Comp, Proj1, Proj2>()
0
set_intersection(I1 first1, S1 last1, I2 first2, S2 last2, 0 result,
Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable 0,
class Comp = less<>>, class Proj1 = identity, class Proj2 = identity>
requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>, 0, Comp, Proj1, Proj2>()
0

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set_intersection(Rng1&& rng1, Rng2&& rng2, 0 result,
    Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

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.

Requires: The resulting range shall not overlap with either of the original ranges.

Returns: The end of the constructed range.

Complexity: At most $2 \times ((\text{last1} - \text{first1}) + (\text{last2} - \text{first2})) - 1$ applications of the com-
parison function and projections.

Remarks: If $[\text{first1}, \text{last1})$ contains $m$ elements that are equivalent to each other and $[\text{first2}, 
\text{last2})$ contains $n$ elements that are equivalent to them, the first $\min(m,n)$ elements shall be copied
from the first range to the output range, in order.

10.5.5.4 set_difference
    [set.difference]

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    WeaklyIncrementable O, class Comp = less<> class Proj1 = identity, class Proj2 = identity>
    requires Mergeable<I1, I2, 0, Comp, Proj1, Proj2>()
    tagged_pair<tag::in1(I1), tag::out(O)>
    set_difference(I1 first1, S1 last1, I2 first2, S2 last2, 0 result,
        Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O,
    class Comp = less<> class Proj1 = identity, class Proj2 = identity>
    requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>, 0, Comp, Proj1, Proj2>()
    tagged_pair<tag::in1(safe_iterator_t<Rng1>), tag::out(O)>
    set_difference(Rng1&& rng1, Rng2&& rng2, 0 result,
        Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

Effects: Copies the elements of the range $[\text{first1}, \text{last1})$ which are not present in the range $[\text{first2}, 
\text{last2})$ to the range beginning at result. The elements in the constructed range are sorted.

Requires: The resulting range shall not overlap with either of the original ranges.

Returns: $\{\text{last1}, \text{result} + n\}$, where $n$ is the number of elements in the constructed range.

Complexity: At most $2 \times ((\text{last1} - \text{first1}) + (\text{last2} - \text{first2})) - 1$ applications of the com-
parison function and projections.

Remarks: If $[\text{first1}, \text{last1})$ contains $m$ elements that are equivalent to each other and $[\text{first2}, 
\text{last2})$ contains $n$ elements that are equivalent to them, the last $\max(m-n,0)$ elements from $[\text{first1}, 
\text{last1})$ shall be copied to the output range.

10.5.5.5 set_symmetric_difference
    [set.symmetric.difference]

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
    WeaklyIncrementable O, class Comp = less<> class Proj1 = identity, class Proj2 = identity>
    requires Mergeable<I1, I2, 0, Comp, Proj1, Proj2>()
    tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(O)>
    set_symmetric_difference(I1 first1, S1 last1, I2 first2, S2 last2, 0 result,
        Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, WeaklyIncrementable O,
    class Comp = less<> class Proj1 = identity, class Proj2 = identity>
    requires Mergeable<iterator_t<Rng1>, iterator_t<Rng2>, 0, Comp, Proj1, Proj2>()
    tagged_tuple<tag::in1(safe_iterator_t<Rng1>),

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tag::in2(safe_iterator_t<Rng2>),
tag::out(O)>
set_symmetric_difference(Rng1&& rng1, Rng2&& rng2, O result, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

Effects: Copies the elements of the range [first1, last1) that are not present in the range [first2,
last2), and the elements of the range [first2, last2) that are not present in the range [first1,
last1) to the range beginning at result. The elements in the constructed range are sorted.

Requires: The resulting range shall not overlap with either of the original ranges.

Returns: make_tagged_tuple<tag::in1, tag::in2, tag::out>(last1, last2, result +
n), where
n is the number of elements in the constructed range.

Complexity: At most \(2 \times ((last1 - first1) + (last2 - first2)) - 1\) applications of the comp-
parison function and projections.

Remarks: If [first1, last1) contains \(m\) elements that are equivalent to each other and [first2,
last2) contains \(n\) elements that are equivalent to them, then \(|m - n|\) of those elements shall be cop-
ted to the output range: the last \(m - n\) of these elements from [first1, last1) if \(m > n\), and the last
\(n - m\) of these elements from [first2, last2) if \(m < n\).

10.5.6 Heap operations [alg.heap.operations]

A heap is a particular organization of elements in a range between two random access iterators [a,b). Its
two key properties are:

(1) There is no element greater than \(a\) in the range and

(2) \(a\) may be removed by pop_heap(), or a new element added by push_heap(), in \(O(\log(N))\) time.

These properties make heaps useful as priority queues.

make_heap() converts a range into a heap and sort_heap() turns a heap into a sorted sequence.

10.5.6.1 push_heap [push.heap]

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
class Proj = identity>
requires Sortable<I, Comp, Proj>()
I push_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
safe_iterator_t<Rng> push_heap(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

Effects: Places the value in the location last - 1 into the resulting heap [first, last).

Requires: The range [first, last - 1) shall be a valid heap.

Returns: last

Complexity: At most \(\log(last - first)\) applications of the comparison function and projection.

10.5.6.2 pop_heap [pop.heap]

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
class Proj = identity>
requires Sortable<I, Comp, Proj>()
I pop_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    pop_heap(Rng& rng, Comp comp = Comp{}, Proj proj = Proj{});

  Requires: The range [first,last) shall be a valid non-empty heap.
  Effects: Swaps the value in the location first with the value in the location last - 1 and makes
            [first,last - 1) into a heap.
  Returns: last
  Complexity: At most 2 * log(last - first) applications of the comparison function and projection.

10.5.6.3 make_heap

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
          class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  I make_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    make_heap(Rng& rng, Comp comp = Comp{}, Proj proj = Proj{});

  Effects: Constructs a heap out of the range [first,last).
  Returns: last
  Complexity: At most 3 * (last - first) applications of the comparison function and projection.

10.5.6.4 sort_heap

template <RandomAccessIterator I, Sentinel<I> S, class Comp = less<>,
          class Proj = identity>
  requires Sortable<I, Comp, Proj>()
  I sort_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Comp = less<>, class Proj = identity>
  requires Sortable<iterator_t<Rng>, Comp, Proj>()
  safe_iterator_t<Rng>
    sort_heap(Rng& rng, Comp comp = Comp{}, Proj proj = Proj{});

  Effects: Sorts elements in the heap [first,last).
  Requires: The range [first,last) shall be a valid heap.
  Returns: last
  Complexity: At most N log(N) comparisons (where N == last - first).

10.5.6.5 is_heap

template <RandomAccessIterator I, Sentinel<I> S, class Proj = identity,
          IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
  bool is_heap(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Proj = identity,
          IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
  bool
    is_heap(Rng& rng, Comp comp = Comp{}, Proj proj = Proj{});
template <RandomAccessIterator I, Sentinel<I> S, class Proj = identity, 
          IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
I is_heap_until(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <RandomAccessRange Rng, class Proj = identity, 
          IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
safe_iterator_t<Rng>
is_heap_until(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

Returns: If distance(first, last) < 2, returns last. Otherwise, returns the last iterator \(i\) in 
[first,last] for which the range [first,i) is a heap.

Complexity: Linear.

10.5.7 Minimum and maximum

template <class T, class Proj = identity, 
          IndirectStrictWeakOrder<projected<const T*, Proj>> Comp = less<>>
constexpr const T& min(const T& a, const T& b, Comp comp = Comp{}, Proj proj = Proj{});

Returns: The smaller value.

Remarks: Returns the first argument when the arguments are equivalent.

template <Copyable T, class Proj = identity, 
          IndirectStrictWeakOrder<projected<const T*, Proj>> Comp = less<>>
constexpr T min(initializer_list<T> rng, Comp comp = Comp{}, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity, 
          IndirectStrictWeakOrder<projected<iterator_t<Rng>>, Proj>> Comp = less<>>
requires Copyable<value_type_t<iterator_t<Rng>>>()
value_type_t<iterator_t<Rng>>
min(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

Requires: distance(rng) > 0.

Returns: The smallest value in the initializer_list or range.

Remarks: Returns a copy of the leftmost argument when several arguments are equivalent to the
smallest.

template <class T, class Proj = identity, 
          IndirectStrictWeakOrder<projected<const T*, Proj>> Comp = less<>>
constexpr const T& max(const T& a, const T& b, Comp comp = Comp{}, Proj proj = Proj{});

Returns: The larger value.

Remarks: Returns the first argument when the arguments are equivalent.

template <Copyable T, class Proj = identity, 
          IndirectStrictWeakOrder<projected<const T*, Proj>> Comp = less<>>
constexpr T max(initializer_list<T> rng, Comp comp = Comp{}, Proj proj = Proj{});

template <InputRange Rng, class Proj = identity, 
          IndirectStrictWeakOrder<projected<iterator_t<Rng>>, Proj>> Comp = less<>>
requires Copyable<value_type_t<iterator_t<Rng>>>()
value_type_t<iterator_t<Rng>>
max(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});
Requires: \( \text{distance(rng)} > 0 \).
Returns: The largest value in the initializer_list or range.
Remarks: Returns a copy of the leftmost argument when several arguments are equivalent to the largest.

```cpp
template <class T, class Proj = identity, 
IndirectStrictWeakOrder<projected<const T*, Proj>> Comp = less<>>
constexpr tagged_pair<tag::min(const T&), tag::max(const T&)> 
minmax(const T& a, const T& b, Comp comp = Comp{}, Proj proj = Proj{});
```

Returns: \{b, a\} if b is smaller than a, and \{a, b\} otherwise.
Remarks: Returns \{a, b\} when the arguments are equivalent.

Complexity: Exactly one comparison and exactly two applications of the projection.

```cpp
template <Copyable T, class Proj = identity, 
IndirectStrictWeakOrder<projected<const T*, Proj>> Comp = less<>>
constexpr tagged_pair<tag::min(T), tag::max(T)> 
minmax(initializer_list<T> rng, Comp comp = Comp{}, Proj proj = Proj{});
```

Returns: \{x, y\}, where x has the smallest and y has the largest value in the initializer_list or range.
Remarks: x is a copy of the leftmost argument when several arguments are equivalent to the smallest.
y is a copy of the rightmost argument when several arguments are equivalent to the largest.
Complexity: At most \((3/2) \times \text{distance(rng)}\) applications of the corresponding predicate, and at most twice as many applications of the projection.

```cpp
template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
I min_element(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
```

Returns: The first iterator i in the range \([\text{first}, \text{last})\) such that for every iterator j in the range \([\text{first}, \text{last})\) the following corresponding condition holds: \(\text{invoke(comp, invoke(proj, *j)), invoke(proj, *i)) == false}\). Returns last if \(\text{first} == \text{last}\).
Complexity: Exactly \(\text{max((last - first) - 1, 0)}\) applications of the comparison function and exactly twice as many applications of the projection.

```cpp
template <ForwardIterator I, Sentinel<I> S, class Proj = identity, 
IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
I max_element(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});
```
template <ForwardRange Rng, class Proj = identity,
        IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
safe_iterator_t<Rng>
max_element(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj{});

Returns: The first iterator in the range \([\text{first}, \text{last})\) such that for every iterator \(j\) in the range \([\text{first}, \text{last})\) the following corresponding condition holds: \(\text{invoke(comp, invoke(proj, *i), invoke(proj, *j))} = \text{false}\). Returns \(\text{last}\) if \(\text{first} == \text{last}\).

Complexity: Exactly \(\text{max}((\text{last} - \text{first}) - 1, 0)\) applications of the comparison function and exactly twice as many applications of the projection.

template <ForwardIterator I, Sentinel<I> S, class Proj = identity,
          IndirectStrictWeakOrder<projected<I, Proj>> Comp = less<>>
tagged_pair<tag::min(I), tag::max(I)>
minmax_element(I first, S last, Comp comp = Comp{}, Proj proj = Proj{});

template <ForwardRange Rng, class Proj = identity,
          IndirectStrictWeakOrder<projected<iterator_t<Rng>, Proj>> Comp = less<>>
tagged_pair<tag::min(safe_iterator_t<Rng>),
          tag::max(safe_iterator_t<Rng>)>
minmax_element(Rng&& rng, Comp comp = Comp{}, Proj 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 \([\text{first}, \text{last})\) such that no iterator in the range refers to a larger element.

Complexity: At most \(\text{max}\left(\left\lfloor \frac{3}{2}(N - 1)\right\rfloor, 0\right)\) applications of the comparison function and at most twice as many applications of the projection, where \(N\) is \(\text{distance(first, last)}\).

10.5.8 Lexicographical comparison
[alg.lex.comparison]

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, Sentinel<I2> S2,
          class Proj1 = identity, class Proj2 = identity,
          IndirectStrictWeakOrder<projected<I1, Proj1>, projected<I2, Proj2>> Comp = less<>>
bool
lexicographical_compare(I1 first1, S1 last1, I2 first2, S2 last2,
Comp comp = Comp{}, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputRange Rng2, class Proj1 = identity,
          class Proj2 = identity,
          IndirectStrictWeakOrder<projected<iterator_t<Rng1>, Proj1>, projected<iterator_t<Rng2>, Proj2>> Comp = less<>>
bool
lexicographical_compare(Rng1&& rng1, Rng2&& rng2, Comp comp = Comp{},
Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

Returns: true if the sequence of elements defined by the range \([\text{first1}, \text{last1})\) is lexicographically less than the sequence of elements defined by the range \([\text{first2}, \text{last2})\) and false otherwise.

Complexity: At most \(2\times\text{min}((\text{last1} - \text{first1}), (\text{last2} - \text{first2}))\) applications of the corresponding comparison and projections.

Remarks: If two sequences have the same number of elements and their corresponding elements are equivalent, then neither sequence is lexicographically less than the other. If one sequence is a 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.
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;

Remarks: An empty sequence is lexicographically less than any non-empty sequence, but not less than any empty sequence.

10.5.9 Permutation generators

```cpp
template <BidirectionalIterator I, Sentinel<I> S, class Comp = less<>,
          class Proj = identity>
requires Sortable<I, Comp, Proj>()
bool next_permutation(I first, S last, Comp comp = Comp{}, Proj proj = Proj());
```

```cpp
template <BidirectionalRange Rng, class Comp = less<>,
          class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
bool next_permutation(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj());
```

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 such a permutation exists, it returns `true`. Otherwise, it transforms the sequence into the smallest permutation, that is, the ascendingly sorted one, and returns `false`.

Complexity: At most `(last - first)/2` swaps.

```cpp
template <BidirectionalIterator I, Sentinel<I> S, class Comp = less<>,
          class Proj = identity>
requires Sortable<I, Comp, Proj>()
bool prev_permutation(I first, S last, Comp comp = Comp{}, Proj proj = Proj());
```

```cpp
template <BidirectionalRange Rng, class Comp = less<>,
          class Proj = identity>
requires Sortable<iterator_t<Rng>, Comp, Proj>()
bool prev_permutation(Rng&& rng, Comp comp = Comp{}, Proj proj = Proj());
```

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`.

Returns: `true` if such a permutation exists. Otherwise, it transforms the sequence into the largest permutation, that is, the descendingly sorted one, and returns `false`.

Complexity: At most `(last - first)/2` swaps.
11 Numerics library [numerics]

Header <experimental/ranges/random> synopsis

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <class G>
    concept bool UniformRandomNumberGenerator() { return see below; }
}}}}

11.1 Uniform random number generator requirements [rand.req.urng]

// defined in <experimental/ranges/random>

namespace std { namespace experimental { namespace ranges { inline namespace v1 {
    template <class G>
    concept bool UniformRandomNumberGenerator() {
        return requires(G g) {
            { g() } -> UnsignedIntegral; // not required to be equality preserving
            { G::min() } -> Same<result_of_t<G&()>>;
            { G::max() } -> Same<result_of_t<G&()>>;
        };
    }
}}}}

A uniform random number 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: The degree to which g’s results approximate the ideal is often determined statistically. — end note]

Let g be any object of type G. Then UniformRandomNumberGenerator<G>() is satisfied if and only if

1. Both G::min() and G::max() are constant expressions (ISO/IEC 14882:2014 §5.19).
2. G::min() < G::max().
3. G::min() <= g().
4. g() <= G::max().
5. g() has amortized constant complexity.
Annex A  (normative)
Compatibility features  [depr]

1 This Clause describes features of this document that are specified for compatibility with existing implementations.

2 These are deprecated features, where deprecated is defined as: Normative for the current edition of the Ranges TS, but having been identified as a candidate for removal from future revisions. An implementation may declare library names and entities described in this section with the deprecated attribute (ISO/IEC 14882:2014 §7.6.5).

A.1 Rvalue range access  [depr.rvalue.ranges]

1 Use of the range access customization point objects begin, end, cbegin, cend, rbegin, rend, crbegin, crend, data, and cdata with rvalue arguments is deprecated. In a future revision of this document, such usage could become ill-formed.

A.2 Range-and-a-half algorithms  [depr.algo.range-and-a-half]

1 The following algorithm signatures are deemed unsafe and are deprecated in this document.

```cpp
template <InputIterator I1, Sentinel<I1> S1, InputIterator I2,
    class Proj1 = identity, class Proj2 = identity,
    IndirectPredicate<Projected<I1, Proj1>, Projected<I2, Proj2>> Pred = equal_to<>>
tagged_pair<tag::in1(I1), tag::in2(I2)>
mismatch(I1 first1, S1 last1, I2 first2, Pred pred = Pred{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputIterator I2,
    class Proj1 = identity, class Proj2 = identity,
    IndirectPredicate<Projected<iterator_t<Rng1>, Proj1>,
        projected<I2, Proj2>> Pred = equal_to<>>
tagged_pair<tag::in1(safe_iterator_t<Rng1>), tag::in2(I2)>
mismatch(Rng1& rng1, I2 first2, Pred pred = Pred{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2,
    class Pred = equal_to<>, class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<I1, I2, Pred, Proj1, Proj2>()
bool equal(I1 first1, S1 last1,
    I2 first2, Pred pred = Pred{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng1, InputIterator I2, class Pred = equal_to<>,
    class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<iterator_t<Rng1>, I2, Pred, Proj1, Proj2>()
bool equal(Rng1& rng1, I2 first2, Pred pred = Pred{},
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2,
    class Pred = equal_to<>, class Proj1 = identity, class Proj2 = identity>
requires IndirectlyComparable<I1, I2, Pred, Proj1, Proj2>()
```
bool is_permutation(I1 first1, S1 last1, I2 first2, 
    Pred pred = Pred{}, 
    Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardRange Rng1, ForwardIterator I2, class Pred = equal_to<>, 
    class Proj1 = identity, class Proj2 = identity> 
    requires IndirectlyComparable<iterator_t<Rng1>, I2, Pred, Proj1, Proj2>() 
    bool is_permutation(Rng1&& rng1, I2 first2, Pred pred = Pred{}, 
        Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <ForwardIterator I1, Sentinel<I1> S1, ForwardIterator I2> 
    requires IndirectlySwappable<I1, I2>() 
    tagged_pair<tag::in1(I1), tag::in2(I2)> 
        swap_ranges(I1 first1, S1 last1, I2 first2);

template <ForwardRange Rng, ForwardIterator I> 
    requires IndirectlySwappable<iterator_t<Rng>, I>() 
    tagged_pair<tag::in1(safe_iterator_t<Rng>), tag::in2(I)> 
        swap_ranges(Rng&& rng1, I first2);

template <InputIterator I1, Sentinel<I1> S1, InputIterator I2, WeaklyIncrementable O, 
    class F, class Proj1 = identity, class Proj2 = identity> 
    requires Writable<O, indirect_result_of_t<F&(projected<I1, Proj1>, projected<I2, Proj2>)>>() 
    tagged_tuple<tag::in1(I1), tag::in2(I2), tag::out(O)> 
        transform(I1 first1, S1 last1, I2 first2, O result, 
            F binary_op, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

template <InputRange Rng, InputIterator I, WeaklyIncrementable O, class F, 
    class Proj1 = identity, class Proj2 = identity> 
    requires Writable<O, indirect_result_of_t<F&( 
        projected<iterator_t<Rng>, Proj1>, projected<I, Proj2>)>>() 
    tagged_tuple<tag::in1(safe_iterator_t<Rng>), tag::in2(I), tag::out(O)> 
        transform(Rng&& rng1, I first2, O result, 
            F binary_op, Proj1 proj1 = Proj1{}, Proj2 proj2 = Proj2{});

Remark: These signatures behave as described in Clause 10 with the name last2 defined as first2 + (last1 - first1).
Annex B  (informative)

Acknowledgements  [acknowledgements]

The design of this specification is based, in part, on a concept specification of the algorithms part of the C++ standard library, known as “The Palo Alto” report (2), which was developed by a large group of experts as a test of the expressive power of the idea of concepts.

The authors would like to thank Andrew Sutton for his work on the Concepts TS (2), for his help formalizing the ideas of the range-v3 library [2] on which this work is based, and for his review of this document.

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Annex C  (informative)
Compatibility

C.1  C++ and Ranges

1 This section details the known breaking changes likely to effect user code when being ported to the version of the Standard Library described in this document.

C.1.1  Algorithm Return Types

1 The algorithms described in this document permit the type of the end sentinel to differ from the type of the begin iterator. This is so that the algorithms can operate on ranges for which the physical end position is not yet known.

2 The physical end position of the input range is determined during the execution of many of the algorithms. Rather than lose that potentially useful information, the design presented here has such algorithms return the iterator position of the end of the range. In many cases, this is a breaking change. Some algorithms that return iterators in today’s STL are changed to return pairs, and algorithms that return pairs today are changed to return tuples. This is likely to be the most noticeable breaking change.

3 Alternate designs that were less impactful were considered and dismissed. See Section 3.3.6 in N4128 (2) for a discussion of the issues.

C.1.2  Stronger Constraints

1 In this proposal, many algorithms and utilities get stricter type checking. For example, algorithms constrained with `LessThanComparable` today are constrained by `StrictTotallyOrdered` in this document. This concept requires types to provide all the relational operators, not just `operator<`.

2 The use of coarser-grained, higher-level concepts in algorithm constraints is to make the type checks more semantic in nature and less syntactic. It also has the benefit of being less verbose while giving algorithm implementors greater implementation freedom. This approach is in contrast to the previous effort to add concepts to the Standard Library in the C++0x timeframe, which saw a proliferation of small, purely syntactic concepts and algorithm constraints that merely restated the algorithms’ implementation details more verbosely in the algorithms’ function signatures.

3 The potential for breakage must be carefully weighed against the integrity and complexity of the constraints system. The coarseness of the concepts may need to change in response to real-world usage.

C.1.3  Constrained Functional Objects

1 The algorithm design described in this document assumes that the function objects `std::equal_to` and `std::less` get constraints added to their function call operators. (The former is constrained with `Equality-Comparable` and the latter with `StrictTotallyOrdered`). Similar constraints are added to the other function objects in `<functional>`. As with the coarsely-grained algorithm constraints, these function object constraints are likely to cause user code to break.

2 Real-world experience is needed to assess the seriousness of the breakage. From a correctness point of view, the constraints are logical and valuable, but it’s possible that for the sake of compatibility we provide both constrained and unconstrained functional objects.
C.1.4 Iterators and Default-Constructibility

In today’s STL, iterators need not be default-constructible. The `Iterator` concept described in this document requires default-constructibility. This could potentially cause breakage in users’ code. Also, it makes the implementation of some types of iterators more complicated. Any iterator that has members that are not default constructible (e.g., an iterator that contains a lambda that has captured by reference) must take special steps to provide default-constructibility (e.g., by wrapping non-default-constructible types in something like `std::optional`, as specified in the C++ 17 Working Draft N4618 §20.6). This can weaken class invariants.

The guarantee of default-constructibility simplifies the implementation of much iterator- and range-based code that would otherwise need to wrap iterators in `std::optional`. But the needs of backward-compatibility, the extra complexity to iterator implementors, and the weakened invariants may prove to be too great a burden.

We may in fact go even farther and remove the requirement of default-constructibility from the `Semiregular` concept. Time and experience will give us guidance here.

C.1.5 `iterator_traits` cannot be specialized

In this STL design, `iterator_traits` changes from being a class template to being an alias template. This is to intentionally break any code that tries to specialize it. In its place are the three class templates `difference_type`, `value_type`, and `iterator_category`. The need for this traits balkanization is because the associated types belong to separate concepts: `difference_type` belongs to `WeaklyIncrementable`; `value_type` belongs to `Readable`; and `iterator_category` belongs to `InputIterator`.

This breakage is intentional and inherent in the decomposition of the iterator concepts established by The Palo Alto report (2).

C.2 Ranges and the Palo Alto TR (N3351)

The Palo Alto report (2) presents a comprehensive design for the Standard Template Library constrained with concepts. It served both as a basis for the Concepts Lite language feature and for this document. However, this document diverges from the Palo Alto report in small ways. The differences are in the interests of backwards compatibility, to avoid confusing a large installed base of programmers already familiar with the STL, and to keep the scope of this document as small as possible. This section describes the ways in which the two suggested designs differ.

C.2.1 Sentinels

In the design presented in this document, the type of a range’s end delimiter may differ from the iterator representing the range’s start position. The reasons for this change are described in N4128 (2). This causes a number of differences from the Palo Alto report:

(1.1) — The algorithms get an additional constraint for the sentinel.
(1.2) — The return types of the algorithms are changed as described above (C.1.1).
(1.3) — Some algorithms have operational semantics that require them to know the physical end position (e.g., `reverse`). Those algorithms must make an $O(N)$ probe for the end position before proceeding. This does not change the operational semantics of any code that is valid today (the probe is unnecessary when the types of the begin and end are the same), and even when the probe is needed, in no cases does this change the complexity guarantee of any algorithm.

C.2.2 Invocables and Projections

Adobe’s Source Libraries [1] pioneered the use of `callable` and `projection` in the standard algorithms. Invocables let users pass member pointers where the algorithms expect callables, saving users the trouble...
of using a binder or a lambda. Projections are extra optional arguments that give users a way to trivially transform input data on the fly during the execution of the algorithms. Neither significantly changes the operational semantics of the algorithms, but they do change the form of the algorithm constraints. To deal with the extra complexity of the constraints, the design presented here adds higher-level composite concepts for concisely expressing the necessary relationships between callables, iterators, and projections.

C.2.3 No Distinct DistanceType Associated Type [diff.n3351.distance__type]

In the Palo Alto report, the WeaklyIncrementable concept has an associated type called DistanceType, and the RandomAccessIterator concepts adds another associated type called DifferenceType. The latter is required to be convertible to the former, but they are not required to be the same type. (DifferenceType is required to be a signed integral type, but DistanceType need not be signed.) Although sensible from a soundness point of view, the author of this document feels this is potentially a rich source of confusion. This document hews closer to the current standard by having only one associated type, DifferenceType, and requiring it to be signed.

C.2.4 Distance Primitive is O(1) for Random Access Iterators [diff.n3351.distance__algo]

In the Palo Alto report, the distance iterator primitive for computing the distance from one iterator position to another is not implemented in terms of operator- for random access iterators. distance, according to the report, should always be \( O(N) \). It reads:

The standard mandates a different definition for random access iterators: distance(i, j) == j - i. We see this as a specification error; the guarantees of the distance operation have been weakened for an iterator specialization.

In our design, we consider the two operations to be distinct.

The design presented in this document keeps the specialization for random access iterators. To do otherwise would be to silently break complexity guarantees in an unknown amount of working code.

To address the concern about weakened guarantees of the distance primitive, the design presented here requires that random access iterators model SizedSentinel (9.3.10). The SizedSentinel concept requires that \( b - a \) return the number of times \( a \) would have to be incremented to make it compare equal to \( b \). Any type purporting to be a random access iterator that fails to meet that requirement is by definition not a valid random access iterator.

C.2.5 Output Iterators [diff.n3351.output__iters]

The Palo Alto report does not define concepts for output iterators, making do with WeaklyIncrementable, Writable, and (where needed) EqualityComparable. The author of this document sees little downside to grouping these into the familiar OutputIterator concept. Even if not strictly needed, its absence would be surprising.

C.2.6 No Algorithm Reformulations [diff.n3351.no__eop__algos]

Between the standardization of the Standard Library and the Palo Alto report, much new research was done to further generalize the standard algorithms (see “Element of Programming”, Stepanov, McJones [3]). The algorithms presented in The Palo Alto report reflect the results of that research in the algorithm constraints, some of which (e.g., sort, inplace_merge) take iterators with weaker categories than they do in the current standard. The design presented in this document does not reflect those changes. Although those changes are desirable, generalizing the algorithms as described in The Palo Alto report feels like it would be best done in a separate proposal.
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