C++ now

2025

Parallel Range Algorithms

The Evolution of Parallelism in C++

Ruslan Arutyunyan

About myself

- Working for Intel

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- oneAPI Data Parallel C++ (oneDPL) lead developer

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- SG1: Concurrency and Parallelism co-chair in the C++ committee

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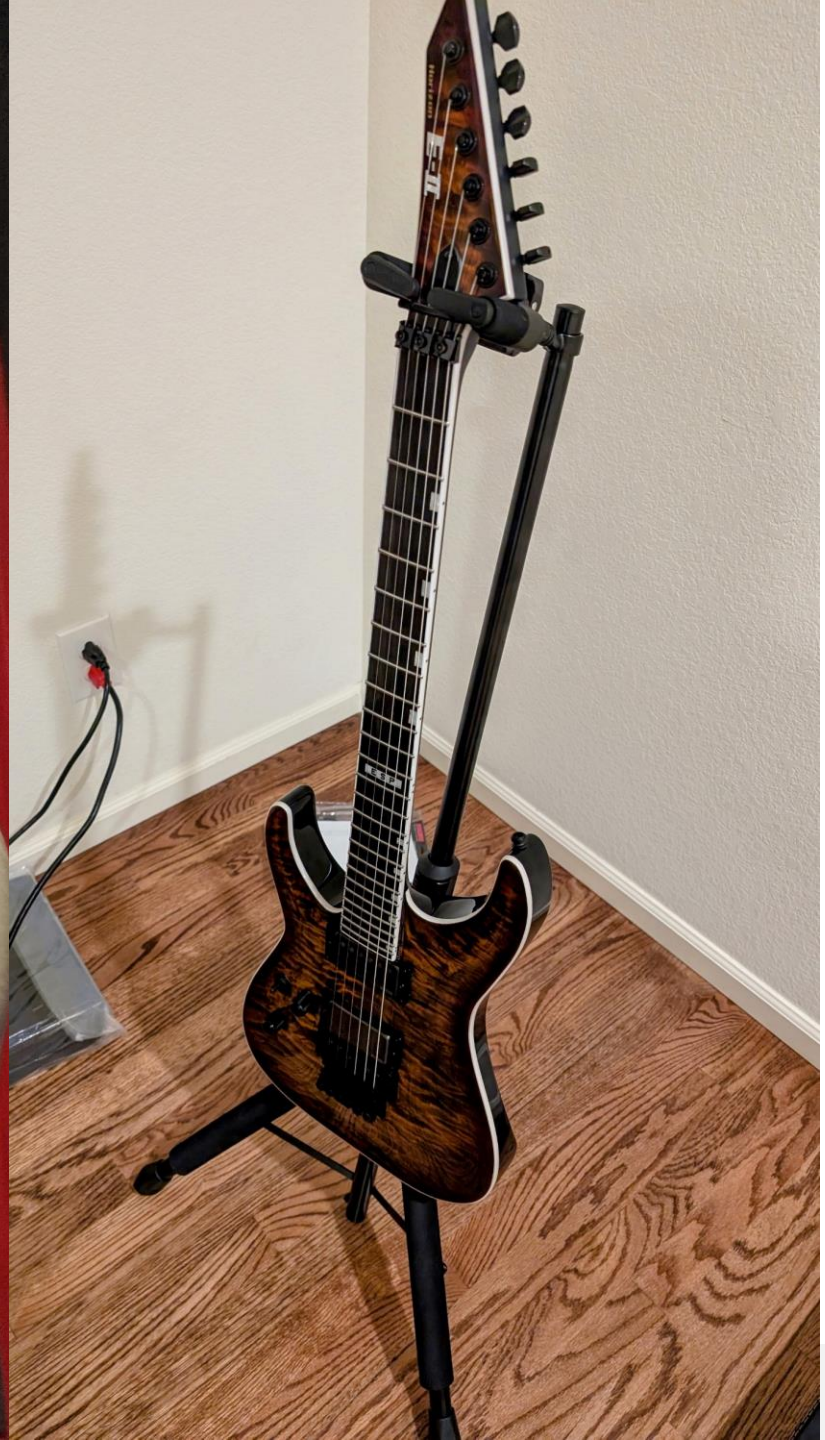

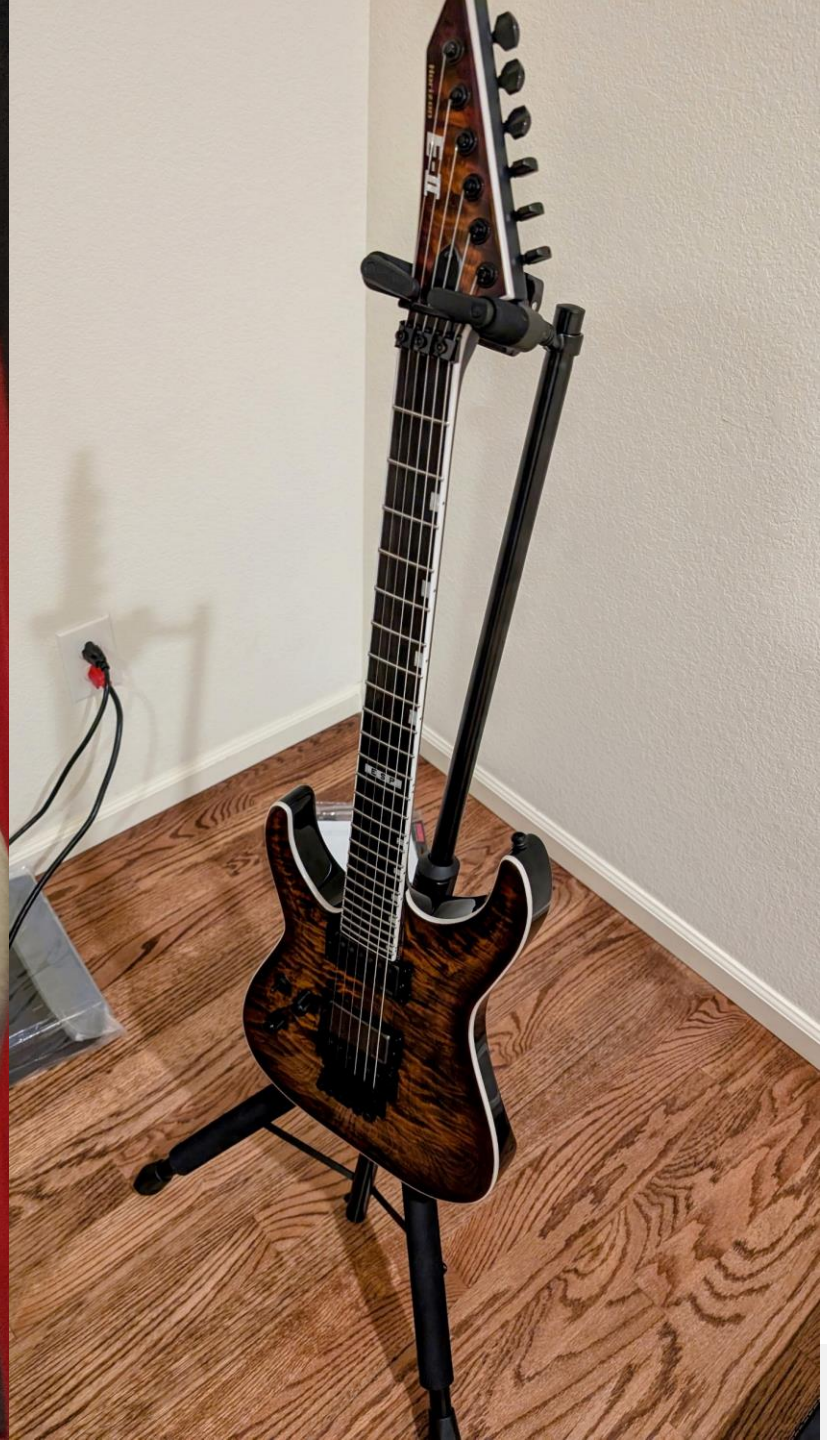




Parallel Range Algorithms

Parallel Algorithms (C++17)

Algorithms:

- With the first `ExecutionPolicy` template parameter
- In `std` namespace
- Taking iterators

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Algorithms:

- With the first **`ExecutionPolicy`** template parameter
- In **`std`** namespace
- Taking iterators

```
// serial
auto res = std::find_if(std::begin(input), std::end(input), pred);

// parallel
auto res = std::find_if(std::execution::par, std::begin(input), std::end(input), pred);
```

Parallel Range algorithms (P3179 proposal)

Algorithms:

- With the first template parameter constrained by the *`execution-policy`* concept
- In `ranges` namespace
- Taking
  - ranges
  - iterators and sentinels

Parallel Range algorithms (P3179 proposal)

Algorithms:

- With the first template parameter constrained by the *`execution-policy`* concept
- In `ranges` namespace
- Taking
  - ranges
  - iterators and sentinels

```
// serial
auto res = std::ranges::find_if(input, pred);

// parallel with P3179
auto res = std::ranges::find_if(std::execution::par, input, pred);
```

Motivation

Combining the powerful ranges API with parallelism:

- Opportunity to fuse several parallel algorithm invocations into one
- Better expressiveness and productivity for parallel code
- Ease of use

Example with C++17 Parallel Algorithms

```
std::transform(policy, std::begin(data), std::end(data), std::begin(result),
               [](auto i){ return i + 1; });
std::reverse(policy, std::begin(result), std::end(result));
auto res = std::find_if(policy, std::begin(result), std::end(result), pred);
```

Example with C++17 Parallel Algorithms

```
std::transform(policy, std::begin(data), std::end(data), std::begin(result),
               [](auto i){ return i + 1; });
std::reverse(policy, std::begin(result), std::end(result));
auto res = std::find_if(policy, std::begin(result), std::end(result), pred);
```

- Three algorithm invocations, each invocation adds its own overhead
- The unnecessary work might be skipped only for the third algorithm call

Example with fancy iterators and Parallel Algorithms

```
auto res = std::find_if(policy,
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::end(data), [](auto i){ return i + 1; })),
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::begin(data), [](auto i){ return i + 1; })),
             pred);
```

Example with fancy iterators and Parallel Algorithms

```
auto res = std::find_if(policy,
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::end(data), [](auto i){ return i + 1; })),
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::begin(data), [](auto i){ return i + 1; })),
             pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

Example with fancy iterators and Parallel Algorithms

```
auto res = std::find_if(policy,
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::end(data), [](auto i){ return i + 1; })),
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::begin(data), [](auto i){ return i + 1; })),
             pred);
```

- One algorithm invocation, less overhead for parallelism
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But:

- A lot of verbosity
- `end(data)` is a `reverse_iterator` begin

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             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::begin(data), [](auto i){ return i + 1; })),
             pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

But:

- A lot of verbosity
- **`end(data)`** is a **`reverse_iterator`** begin
- The code does not compile as is

Example with fancy iterators and Parallel Algorithms

```
template<class ExecutionPolicy, class ForwardIt, class UnaryPred>
ForwardIt find_if(ExecutionPolicy&& policy, ForwardIt first, ForwardIt last, UnaryPred p);
```

Example with fancy iterators and Parallel Algorithms

```
template<class ExecutionPolicy, class ForwardIt, class UnaryPred>
ForwardIt find_if(ExecutionPolicy&& policy, ForwardIt first, ForwardIt last, UnaryPred p);

template<class It, class Func>
class dpl::transform_iterator;
```

Example with fancy iterators and Parallel Algorithms

```
template<class ExecutionPolicy, class ForwardIt, class UnaryPred>
ForwardIt find_if(ExecutionPolicy&& policy, ForwardIt first, ForwardIt last, UnaryPred p);

template<class It, class Func>
class dpl::transform_iterator;

auto begin = dpl::make_transform_iterator(std::begin(data), [](auto x) { return x + 1; });
auto end = dpl::make_transform_iterator(std::end(data), [](auto x) { return x + 1; });
```

Example with fancy iterators and Parallel Algorithms

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template<class ExecutionPolicy, class ForwardIt, class UnaryPred>
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auto begin = dpl::make_transform_iterator(std::begin(data), [](auto x) { return x + 1; });
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```

```
std::find_if(policy, begin, end, pred);     // compile-time error
```

Example with fancy iterators and Parallel Algorithms

```
template<class ExecutionPolicy, class ForwardIt, class UnaryPred>
ForwardIt find_if(ExecutionPolicy&& policy, ForwardIt first, ForwardIt last, UnaryPred p);

template<class It, class Func>
class dpl::transform_iterator;

auto begin = dpl::make_transform_iterator(std::begin(data), [](auto x) { return x + 1; });
auto end = dpl::make_transform_iterator(std::end(data), [](auto x) { return x + 1; });

// begin type: dpl::transform_iterator<base, lambda1>
// end type: dpl::transform_iterator<base, lambda2>


std::find_if(policy, begin, end, pred);     // compile-time error
```

Example with fancy iterators and Parallel Algorithms

```
auto res = std::find_if(policy,
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::end(data), [](auto i){ return i + 1; })),
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::begin(data), [](auto i){ return i + 1; })),
             pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

But:

- A lot of verbosity
- **`end(data)`** is a **`reverse_iterator`** begin
- The code does not compile as is

Example with fancy iterators and Parallel Algorithms

```
auto add_one = [](auto i){ return i + 1; };
auto res = std::find_if(policy,
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::end(data), add_one)),
             std::make_reverse_iterator(
                    dpl::make_transform_iterator(std::begin(data), add_one)),
             pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

But:

- A lot of verbosity
- `end(data)` is a `reverse_iterator` begin

Example with C++17 parallel algorithms and ranges

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::find_if(policy, std::ranges::begin(pipeline), std::ranges::end(pipeline),
                        pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

Example with C++17 parallel algorithms and ranges

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::find_if(policy, std::ranges::begin(pipeline), std::ranges::end(pipeline),
                        pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

But:

- Still unnecessary verbosity

Example with P3179

```
auto res = std::ranges::find_if(policy,
                data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse,
                pred);
```

Example with P3179

```
auto res = std::ranges::find_if(policy,
                data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse,
                pred);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

Example with P3179

```
auto res = std::ranges::find_if(policy,
                data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse,
                pred);



*res;   // compile-time error
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped

But:

- `res` is unusable since `transform_view` is not a `borrowed_range`

Example with P3179

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::ranges::find_if(policy, pipeline, pred);
```

Example with P3179

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```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped
- Concise

Example with P3179

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::ranges::find_if(policy, pipeline, pred, proj);
```

- One algorithm invocation, less overhead for parallelism
- The unnecessary work might be skipped
- Concise
- Ability to use projections

Key differences to existing algorithms

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Comparing to the existing algorithms, we propose the following modifications:

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c) Parallel algorithms require sized ranges

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Comparing to the existing algorithms, we propose the following modifications:

a) The execution policy parameter is added

b) Parallel algorithms require `random_access_{iterator,range}`

c) Parallel algorithms require sized ranges

d) Parallel range algorithms take a range, not an iterator, as the output for the overloads with ranges, and additionally take an output sentinel for the "iterator and sentinel" overloads

Starting from the serial signature

```
template<std::input_iterator I, std::sentinel_for<I> S, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(I first1, S last1, O result, F op, Proj proj = {});
```

```
template<ranges::input_range R, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O,
    std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
unary_transform_result<ranges::borrowed_iterator_t<R>, O>
  transform(R&& r, O result, F op, Proj proj = {});
```

a) Adding an execution policy parameter

```
template<execution-policy Ep, std::input_iterator I, std::sentinel_for<I> S,
         std::weakly_incrementable O, std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(Ep&& exec, I first1, S last1, O result, F op, Proj proj = {});
```

```
template<execution-policy Ep, ranges::input_range R, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O,
    std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
unary_transform_result<ranges::borrowed_iterator_t<R>, O>
  transform(Ep&& exec, R&& r, O result, F op, Proj proj = {});
```

```
template<class Ep>
concept execution-policy = // exposition only
  std::is_execution_policy_v<std::remove_cvref_t<Ep>>;
```

b) Requiring random access

```
template<execution-policy Ep, std::random_access_iterator I, std::sentinel_for<I> S,
         std::random_access_iterator O, std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(Ep&& exec, I first1, S last1, O result, F op, Proj proj = {});
```

```
template<execution-policy Ep, ranges::random_access_range R, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O,
    std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
unary_transform_result<ranges::borrowed_iterator_t<R>, O>
  transform(Ep&& exec, R&& r, O result, F op, Proj proj = {});
```

c) Requiring sized range

```
template<execution-policy Ep, std::random_access_iterator I, std::sized_sentinel_for<I> S,
         std::random_access_iterator O, std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(Ep&& exec, I first1, S last1, O result, F op, Proj proj = {});
```

```
template<execution-policy Ep, sized-random-access-range R, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O,
    std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
unary_transform_result<ranges::borrowed_iterator_t<R>, O>
  transform(Ep&& exec, R&& r, O result, F op, Proj proj = {});
```

```
template<class R>
concept sized-random-access-range = // exposition only
    ranges::random_access_range<R> && ranges::sized_range<R>;
```

d) Using a range for the output

```
template<execution-policy Ep, std::random_access_iterator I, std::sized_sentinel_for<I> S,
         std::random_access_iterator O, std::sized_sentinel_for<O> OutS,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(Ep&& exec, I first1, S last1, O result, OutS result_last, F op, Proj proj = {});
```

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<ranges::iterator_t<OutR>,
    std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
unary_transform_result<ranges::borrowed_iterator_t<R>, ranges::borrowed_iterator_t<OutR>>
  transform(Ep&& exec, R&& r, OutR&& result_r, F op, Proj proj = {});
```

Comparing side-by-side (Iterator and Sentinel overload)

```
// serial
template<std::input_iterator I, std::sentinel_for<I> S, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(I first1, S last1, O result, F op, Proj proj = {});


// parallel
template<execution-policy Ep, std::random_access_iterator I, std::sized_sentinel_for<I> S,
         std::random_access_iterator O, std::sized_sentinel_for<O> OutS,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O, std::indirect_result_t<F&, std::projected<I, Proj>>>
unary_transform_result<I, O>
  transform(Ep&& exec, I first1, S last1, O result, OutS result_last, F op, Proj proj = {});
```

Comparing side-by-side (range overload)

```
// serial
template<ranges::input_range R, std::weakly_incrementable O,
         std::copy_constructible F, class Proj = std::identity>
  requires std::indirectly_writable<O,
      std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
ranges::unary_transform_result<ranges::borrowed_iterator_t<R>, O>
  ranges::transform(R&& r, O result, F op, Proj proj = {});
```

```
// parallel
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR,
         std::copy_constructible F, class Proj = std::identity>
  requires indirectly_writable<ranges::iterator_t<OutR>,
      std::indirect_result_t<F&, std::projected<ranges::iterator_t<R>, Proj>>>
ranges::unary_transform_result<ranges::borrowed_iterator_t<R>, ranges::borrowed_iterator_t<OutR>>
  ranges::transform(Ep&& exec, R&& r, OutR&& result_r, F op, Proj proj = {});
```

More about design

sized-random-access-range

- C++17 parallel algorithms require *Cpp17ForwardIterator*
  - Intel oneDPL, Nvidia Thrust, GNU libstdc++ implementations are based on random access
  - Only Microsoft STL supports forward iterators*

sized-random-access-range

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  - Only Microsoft STL supports forward iterators*
- Random access is the best abstraction in the standard (for now)
  - Some potentially useful views are not supported (e.g., `filter_view`)
  - Might be relaxed in the future

sized-random-access-range

- C++17 parallel algorithms require *Cpp17ForwardIterator*
  - Intel oneDPL, Nvidia Thrust, GNU libstdc++ implementations are based on random access
  - Only Microsoft STL supports forward iterators*
- Random access is the best abstraction in the standard (for now)
  - Some potentially useful views are not supported (e.g., `filter_view`)
  - Might be relaxed in the future
- Size is necessary to know in advance for parallelization
  - memory safety: everything is bounded, including the output
  - performance: no need to do unnecessary work

Range-as-the-output

Category – algorithms with output

Range-as-the-output

- Pros:
  - Ease of use
  - Better memory safety
  - Potentially better performance
  - Ability to detect an error

Range-as-the-output

- Pros:
  - Ease of use
  - Better memory safety
  - Potentially better performance
  - Ability to detect an error
- The objection was:
  - More complicated switch between serial and parallel algorithms
  - Inconsistency with serial range algorithms
  - Unclear semantics

Input evolution example

```
template<class InputIterator1, class InputIterator2,
         class OutputIterator, class BinaryOperation>
  constexpr OutputIterator
    transform(InputIterator1 first1, InputIterator1 last1,
              InputIterator2 first2, OutputIterator result,
              BinaryOperation binary_op);
```

Input evolution example

```
template<class InputIterator1, class InputIterator2,
         class OutputIterator, class BinaryOperation>
  constexpr OutputIterator
    transform(InputIterator1 first1, InputIterator1 last1,
              InputIterator2 first2, OutputIterator result,
              BinaryOperation binary_op);

template<input_iterator I1, sentinel_for<I1> S1, input_iterator I2, sentinel_for<I2> S2,
         weakly_incrementable O, copy_constructible F, class Proj1 = identity,
         class Proj2 = identity>
  requires indirectly_writable<O, indirect_result_t<F&, projected<I1, Proj1>, projected<I2, Proj2>>>
constexpr ranges::binary_transform_result<I1, I2, O>
  ranges::transform(I1 first1, S1 last1, I2 first2, S2 last2, O result,
                    F binary_op, Proj1 proj1 = {}, Proj2 proj2 = {});

template<input_range R1, input_range R2, weakly_incrementable O,
         copy_constructible F, class Proj1 = identity, class Proj2 = identity>
  requires indirectly_writable<O, indirect_result_t<F&, projected<iterator_t<R1>, Proj1>,
                               projected<iterator_t<R2>, Proj2>>>
constexpr ranges::binary_transform_result<borrowed_iterator_t<R1>, borrowed_iterator_t<R2>, O>
  ranges::transform(R1&& r1, R2&& r2, O result, F binary_op, Proj1 proj1 = {}, Proj2 proj2 = {});
```

Output inconsistency

```
template<input_iterator I, sentinel_for<I> S, weakly_incrementable O>
  requires indirectly_copyable<I, O>
constexpr ranges::copy_result<I, O> ranges::copy(I first, S last, O result);

template<input_range R, weakly_incrementable O>
  requires indirectly_copyable<iterator_t<R>, O>
constexpr ranges::copy_result<borrowed_iterator_t<R>, O> ranges::copy(R&& r, O result);
```

Output inconsistency

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template<input_iterator I, sentinel_for<I> S, weakly_incrementable O>
  requires indirectly_copyable<I, O>
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template<input_range R, weakly_incrementable O>
  requires indirectly_copyable<iterator_t<R>, O>
constexpr ranges::copy_result<borrowed_iterator_t<R>, O> ranges::copy(R&& r, O result);


template<input_iterator I, sentinel_for<I> S1, nothrow-forward-iterator O, nothrow-sentinel-for<O> S2>
  requires constructible_from<iter_value_t<O>, iter_reference_t<I>>
constexpr uninitialized_copy_result<I, O>
  uninitialized_copy(I ifirst, S1 ilast, O ofirst, S2 olast);

template<input_range IR, nothrow-forward-range OR>
  requires constructible_from<range_value_t<OR>, range_reference_t<IR>>
constexpr uninitialized_copy_result<borrowed_iterator_t<IR>, borrowed_iterator_t<OR>>
  uninitialized_copy(IR&& in_range, OR&& out_range);
```

Unclear semantics

```
std::vector<int> v1{1,2,3,4,5};
std::vector<int> v2(3);
std::ranges::copy(v1, v2); // might appear that copy allocates for v2
```

Addressing unclear semantics

```
std::vector<int> v1{1,2,3,4,5};
std::vector<int> v2(3);
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Our proposal: Execute an algorithm until any of the ranges ends

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std::vector<int> v1{1,2,3,4,5};
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Our proposal: Execute an algorithm until any of the ranges ends

Algorithm with the same semantics:

- uninitialize_copy

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std::vector<int> v1{1,2,3,4,5};
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std::ranges::copy(v1, v2); // might appear that copy allocates for v2
```

Our proposal: Execute an algorithm until any of the ranges ends

Algorithms with the same semantics:

- uninitialize_copy
- uninitialize_move
- partial_sort_copy

Range-as-the-output

- Pros:
  - Ease of use
  - Better memory safety
  - Potentially better performance
  - Ability to detect an error
- The objection was:
  - More complicated switch between serial and parallel algorithms
  - Inconsistency with serial range algorithms
  - Unclear semantics

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  - ~~Unclear semantics~~

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  - Ability to detect an error
- The objection was:
  - More complicated switch between serial and parallel algorithms
  - ~~Inconsistency with serial range algorithms~~
  - ~~Unclear semantics~~

P3490 proposal has more detail about range-as-the-output design aspect

`reverse_copy` and `rotate_copy`

Category – special algorithms

reverse_copy

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR>
  requires indirectly_copyable<iterator_t<R>, iterator_t<OutR>>
ranges::reverse_copy_result<borrowed_iterator_t<R>, borrowed_iterator_t<OutR>>
  reverse_copy(Ep&& exec, R&& r, OutR&& result_r);
```

reverse_copy

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR>
  requires indirectly_copyable<iterator_t<R>, iterator_t<OutR>>
ranges::reverse_copy_result<borrowed_iterator_t<R>, borrowed_iterator_t<OutR>>
  reverse_copy(Ep&& exec, R&& r, OutR&& result_r);
```

```
std::vector input{1,2,3,4};
std::vector<int> output(2);

// Takes 2 elements from input
auto res = std::ranges::reverse_copy(policy, input, output);
```

reverse_copy

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR>
  requires indirectly_copyable<iterator_t<R>, iterator_t<OutR>>
ranges::reverse_copy_result<borrowed_iterator_t<R>, borrowed_iterator_t<OutR>>
  reverse_copy(Ep&& exec, R&& r, OutR&& result_r);
```

```
std::vector input{1,2,3,4};
std::vector<int> output(2);

// Takes 2 elements from input
auto res = std::ranges::reverse_copy(policy, input, output);
// After the algorithm execution:
// - output is {4,3}
// - res.in == (input.end() - 2) is true, res.in points to the element equal to 3
// - [ input.begin(), res.in ) gives uncopied range
```

reverse_copy

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR>
  requires indirectly_copyable<iterator_t<R>, iterator_t<OutR>>
ranges::reverse_copy_result<borrowed_iterator_t<R>, borrowed_iterator_t<OutR>>
  reverse_copy(Ep&& exec, R&& r, OutR&& result_r);
```

```
std::vector input{1,2,3,4};
std::vector<int> output(4);

// Takes 2 elements from input
auto res = std::ranges::reverse_copy(policy, input, output);
// After the algorithm execution:
// - output is {4,3,2,1}
// - res.in == (input.end() - 4) is true, res.in points to the element equal to 1
// - [ input.begin(), res.in ) is an empty range
```

`reverse_copy` emulation

```cpp
std::vector input{1,2,3,4};
std::vector<int> output(10);

// Emulates reverse_copy
auto res = std::ranges::copy(input | std::views::reverse | std::views::take(2), output.begin());
// After the algorithm execution:
// - output is {4,3}
// - res.in points to the element equal to 2, however it is a reverse_iterator,
//     thus is not comparable with input.end()
// - res.in.base() has the same type as input.end(), and res.in.base() == input.end() - 2 is true
```

`reverse_copy` emulation for output

```cpp
std::vector input{1,2,3,4};
std::unique_ptr mem = std::make_unique_for_overwrite<int[]>(10);
std::ranges::subrange<int*, int*> mem_range{mem.get(), mem.get() + 10};

auto res = std::ranges::uninitialized_copy(input | std::views::reverse, mem_range | std::views::take(2));
// After the algorithm execution:
// - output is {4,3}
// - res.in points to the element equal to 2, however it is a reverse_iterator,
//     thus is not comparable with input.end()
// - res.in.base() has the same type as input.end(), and res.in.base() == input.end() - 2 is true
```

rotate_copy

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR>
  requires indirectly_copyable<iterator_t<R>, iterator_t<OutR>>
ranges::rotate_copy_result<borrowed_iterator_t<R>, borrowed_iterator_t<OutR>>
  ranges::rotate_copy(Ep&& exec, R&& r, iterator_t<R> middle, OutR&& result_r);
```

rotate_copy

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR>
  requires indirectly_copyable<iterator_t<R>, iterator_t<OutR>>
ranges::rotate_copy_result<borrowed_iterator_t<R>, borrowed_iterator_t<OutR>>
  ranges::rotate_copy(Ep&& exec, R&& r, iterator_t<R> middle, OutR&& result_r);
```

Scenarios:

1. `result_r` has space for some elements
2. `result_r` has space for all elements
3. `result_r` has space equal to “tail”
4. `result_r` is empty

rotate_copy (case 1a)

```
std::vector input{1,2,3,4,5,6};
std::vector<int> output(2);

auto res = std::ranges::rotate_copy(policy, input, input.begin() + 3, output);
// After the algorithm execution:
// - output is {4,5}
// - res.in points to the element equal to 6, past the last element written to the output
```

rotate_copy (case 1b)

```
std::vector input{1,2,3,4,5,6};
std::vector<int> output(5);

auto res = std::ranges::rotate_copy(policy, input, input.begin() + 3, output);
// After the algorithm execution:
// - output is {4,5,6,1,2}
// - res.in points to the element equal to 3, past the last element written to the output
```

rotate_copy (case 2)

```
std::vector input{1,2,3,4,5,6};
std::vector<int> output(6);

auto res = std::ranges::rotate_copy(policy, input, input.begin() + 3, output);
// After the algorithm execution:
// - output is {4,5,6,1,2,3}
// - res.in points to the element equal to 4, past the last element written to the output
```

rotate_copy (case 3)

```
std::vector input{1,2,3,4,5,6};
std::vector<int> output(3);

auto res = std::ranges::rotate_copy(policy, input, input.begin() + 3, output);
// After the algorithm execution:
// - output is {4,5,6}
// - res.in points to the element equal to 1, past the last element written to the output
```

rotate_copy (case 4)

```
std::vector input{1,2,3,4,5,6};
std::vector<int> output;

auto res = std::ranges::rotate_copy(policy, input, input.begin() + 3, output);
// After the algorithm execution:
// - output is {}
// - res.in points to the element equal to 4, middle, because no elements were written
// - res.out == output.begin() is true
```

`rotate_copy` emulation

```cpp
std::vector input{1,2,3,4,5,6};
std::vector<int> output(6);

// rotate_view emulation
auto middle_to_last = input | std::views::drop(3);
auto first_to_middle = input | std::views::take(3);
auto rotate_view = ::ranges::views::concat(middle_to_last, first_to_middle); // from range-v3
```

`rotate_copy` emulation

```cpp
std::vector input{1,2,3,4,5,6};
std::vector<int> output(6);

// rotate_view emulation
auto middle_to_last = input | std::views::drop(3);
auto first_to_middle = input | std::views::take(3);
auto rotate_view = ::ranges::views::concat(middle_to_last, first_to_middle); // from range-v3

auto res = std::ranges::copy(rotate_view, output.begin());
// After the algorithm execution:
// - output is {4,5,6,1,2,3}
// - res.in points to the element equal to 4, middle, which is past the last element written to the output
```

`rotate_copy` emulation

```cpp
std::vector input{1,2,3,4,5,6};
std::vector<int> output(6);

// rotate_view emulation
auto middle_to_last = input | std::views::drop(3);
auto first_to_middle = input | std::views::take(3);
auto rotate_view = ::ranges::views::concat(middle_to_last, first_to_middle); // from range-v3

auto res = std::ranges::copy(rotate_view | std::views::take(3), output.begin());
// After the algorithm execution:
// - output is {4,5,6}
// - res.in points to the element equal to 1, past the last element written to the output
```

`copy_if`

Category – algorithms with output and gaps

`copy_if` parallel signature

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR,
         class Proj = std::identity,
         std::indirect_unary_predicate<std::projected<std::ranges::iterator_t<R>, Proj>> Pred>
  requires std::indirectly_copyable<std::ranges::iterator_t<R>, std::ranges::iterator_t<OutR>>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {})
{









}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR,
         class Proj = std::identity,
         std::indirect_unary_predicate<std::projected<std::ranges::iterator_t<R>, Proj>> Pred>
  requires std::indirectly_copyable<std::ranges::iterator_t<R>, std::ranges::iterator_t<OutR>>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {})
{
    std::size_t size = std::ranges::size(r);

    std::ranges::for_each(exec, std::views::iota(std::size_t(0), size), [=, &r, &result_r](auto i) {
        if (std::invoke(pred, std::invoke(proj, r[i])))
            result_r[i] = r[i];
    });

    return {std::ranges::begin(r) + size, std::ranges::begin(result_r) + size};
}
```

`copy_if` parallel implementation (wrong)

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR,
         class Proj = std::identity,
         std::indirect_unary_predicate<std::projected<std::ranges::iterator_t<R>, Proj>> Pred>
  requires std::indirectly_copyable<std::ranges::iterator_t<R>, std::ranges::iterator_t<OutR>>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {})
{
    std::size_t size = std::ranges::size(r);

    std::ranges::for_each(exec, std::views::iota(std::size_t(0), size), [=, &r, &result_r](auto i) {
        if (std::invoke(pred, std::invoke(proj, r[i])))
            result_r[i] = r[i];
    });

    return {std::ranges::begin(r) + size, std::ranges::begin(result_r) + size};
}

// Input:  {1,7,4,4,4,6,5,2,3,7,9}, pred: [](auto x) { return (x & 0x01) == 1; }
// Output: {0,0,0,0,0,0,0,0,0,0,0}
// Result: {1,7,0,0,0,0,5,0,3,7,9}
```

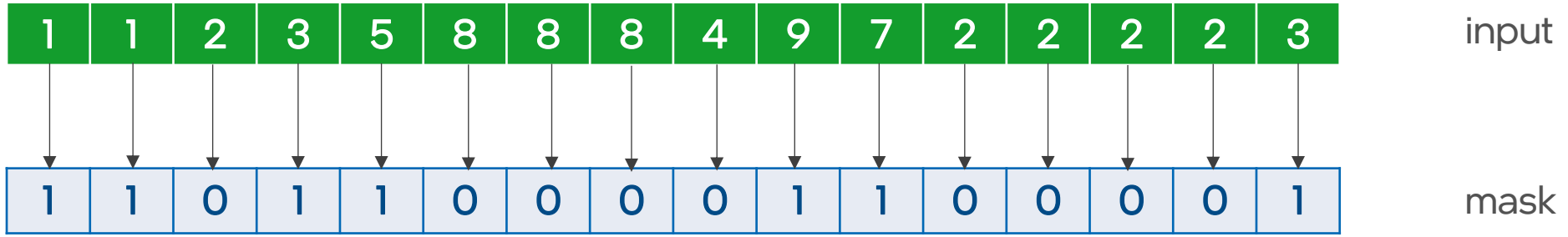

For demonstration purposes only

`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(data.size());

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```

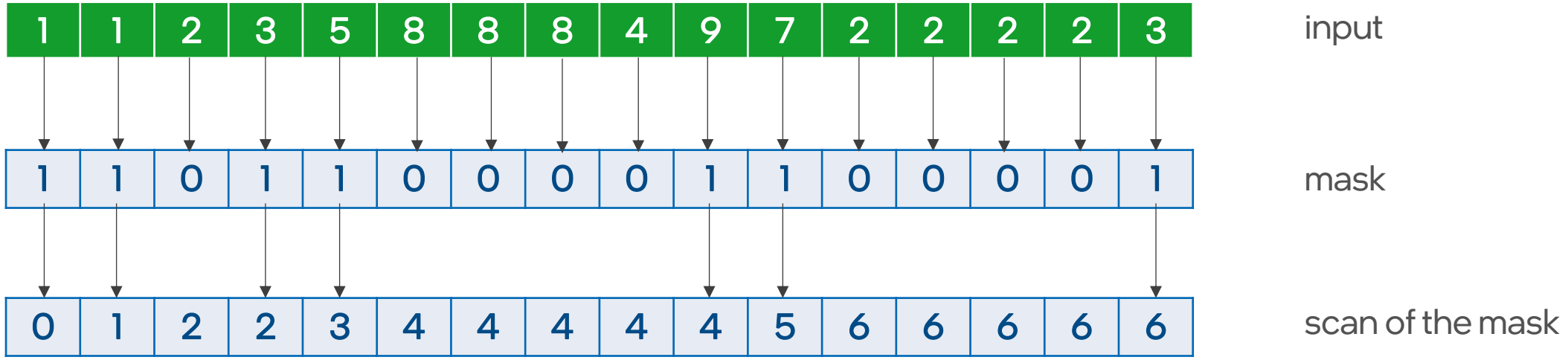
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(data.size());

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



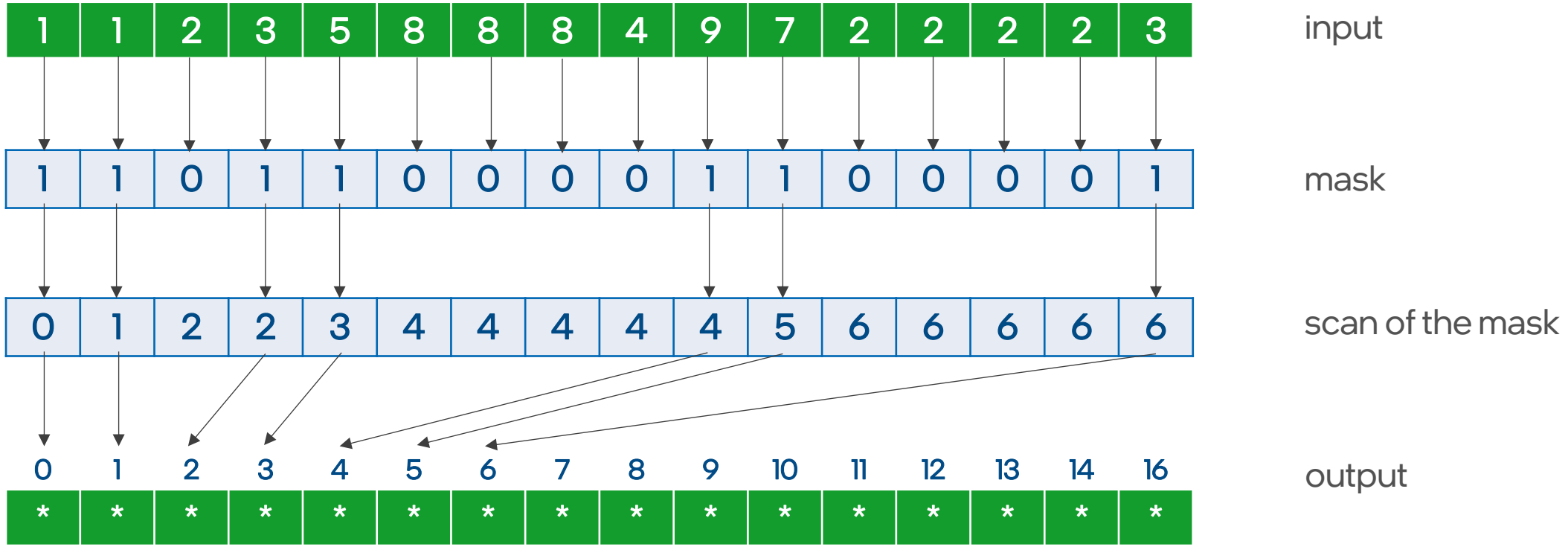
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(data.size());

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



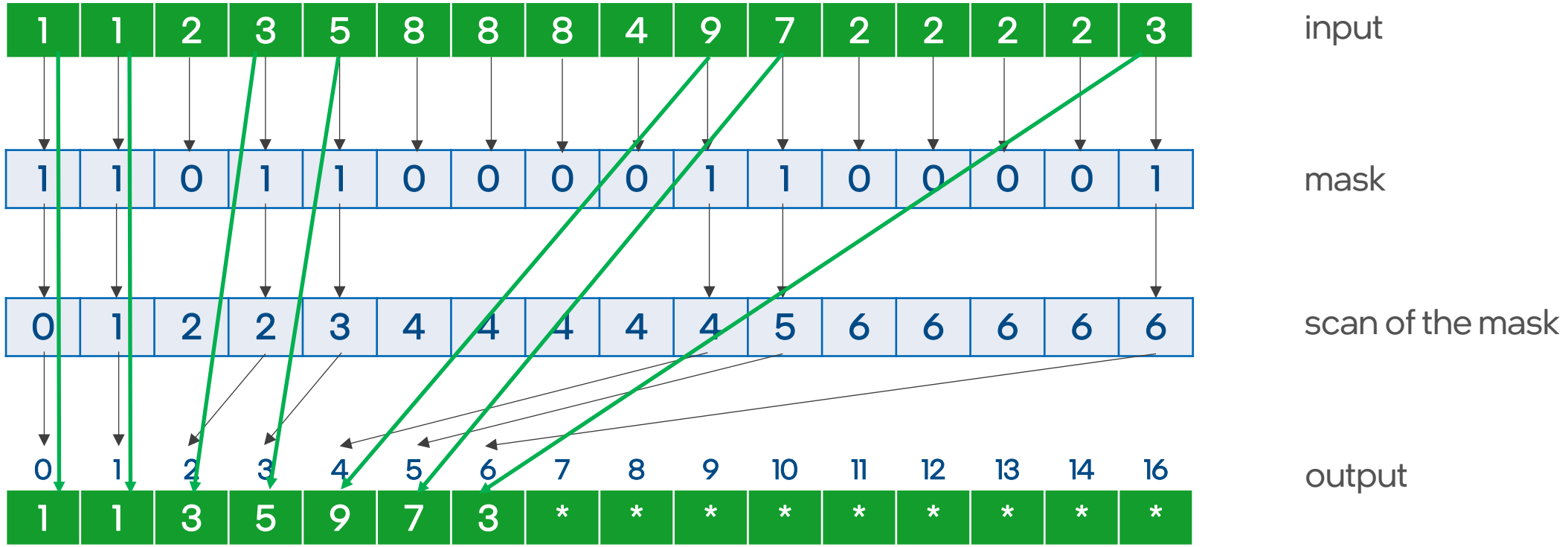
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(data.size());

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(data.size());

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {









}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));


    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });









}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });

    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);









}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });

    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);




    auto zip = std::views::zip(r, mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });


}
```

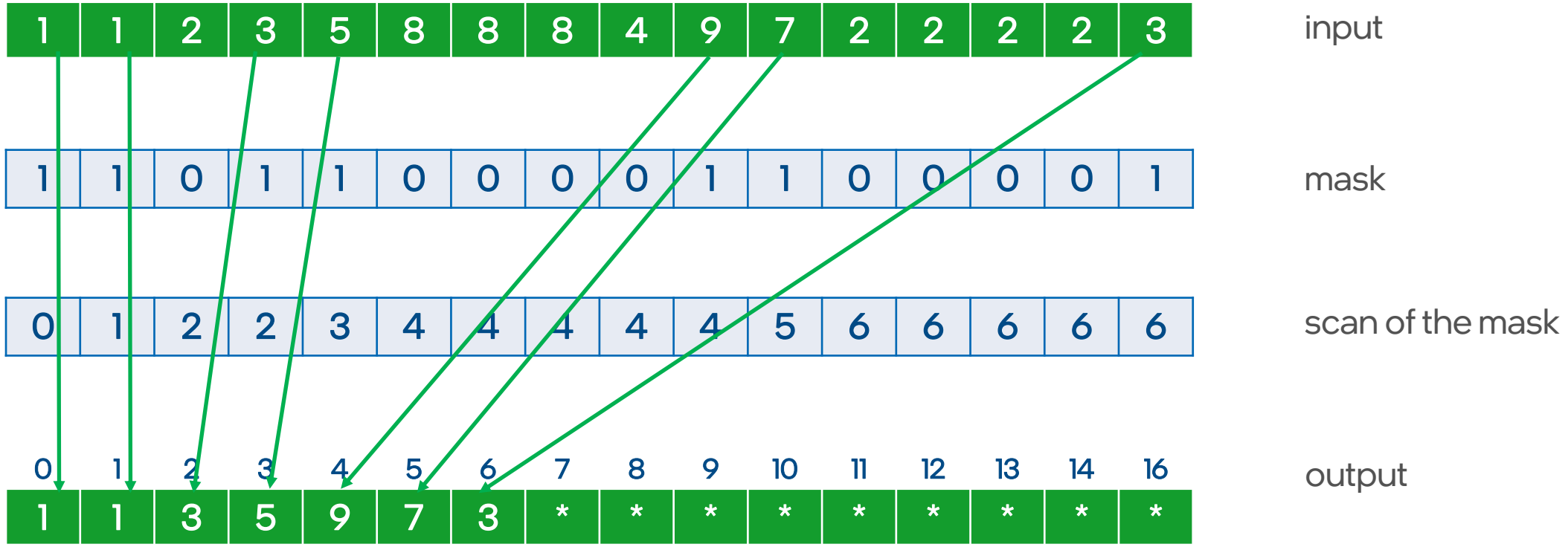

For demonstration purposes only

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });

    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);




    auto zip = std::views::zip(r, mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result.back() + mask.back();
    return {std::ranges::begin(r) + std::ranges::size(r), std::ranges::begin(result_r) + copied_elements};
}
```

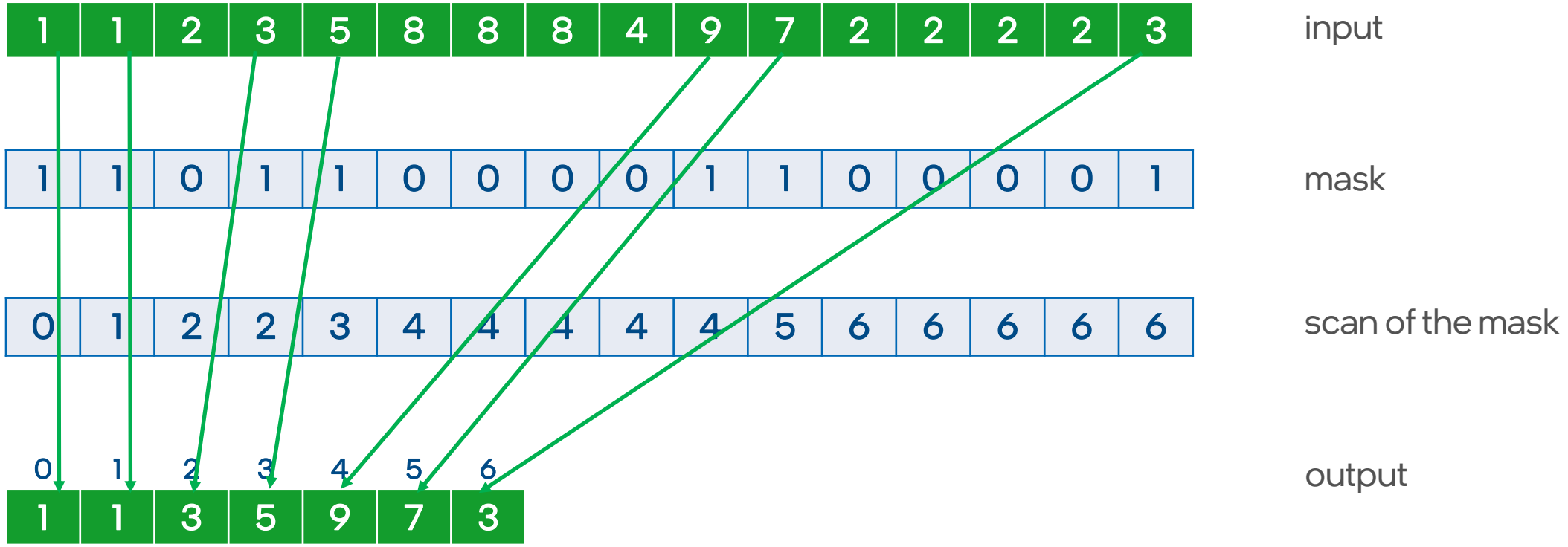
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(data.size());

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



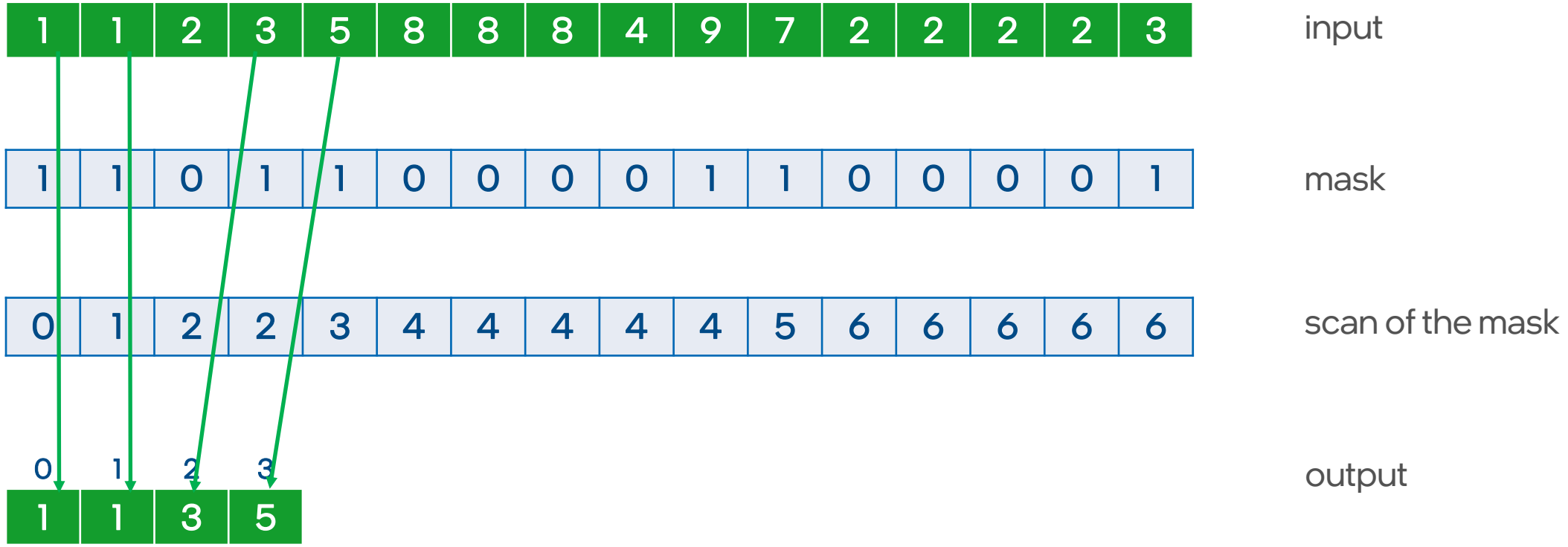
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(7);

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



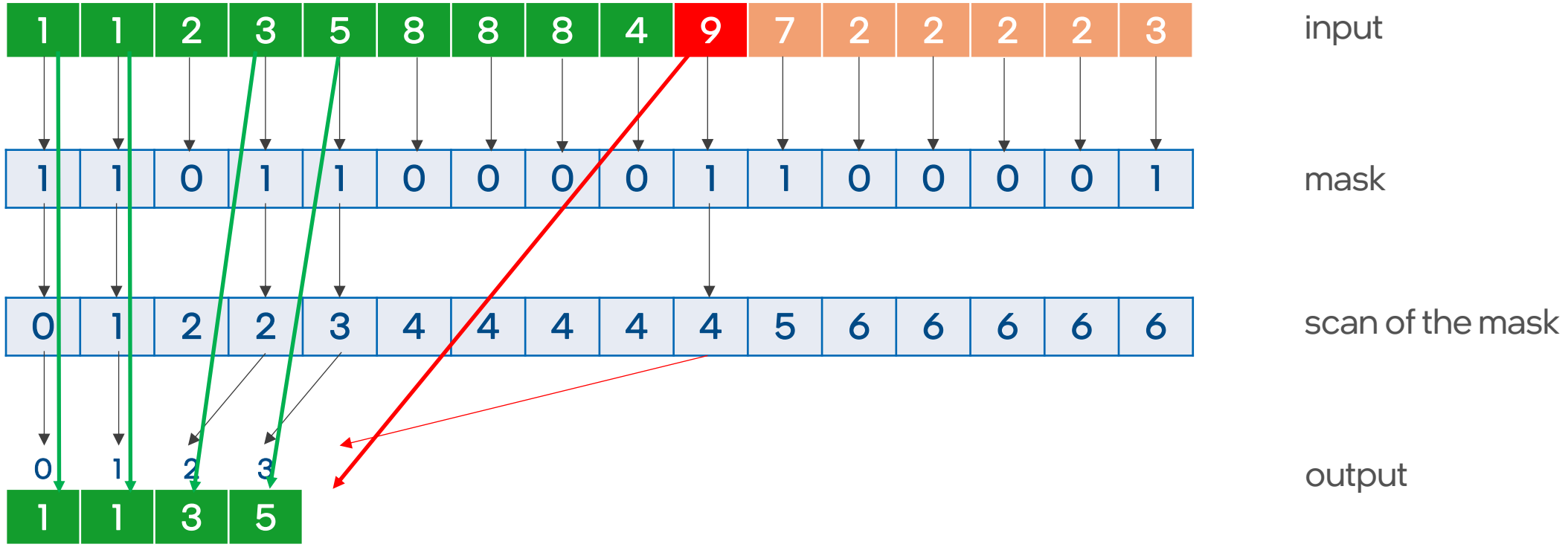
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(4);

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



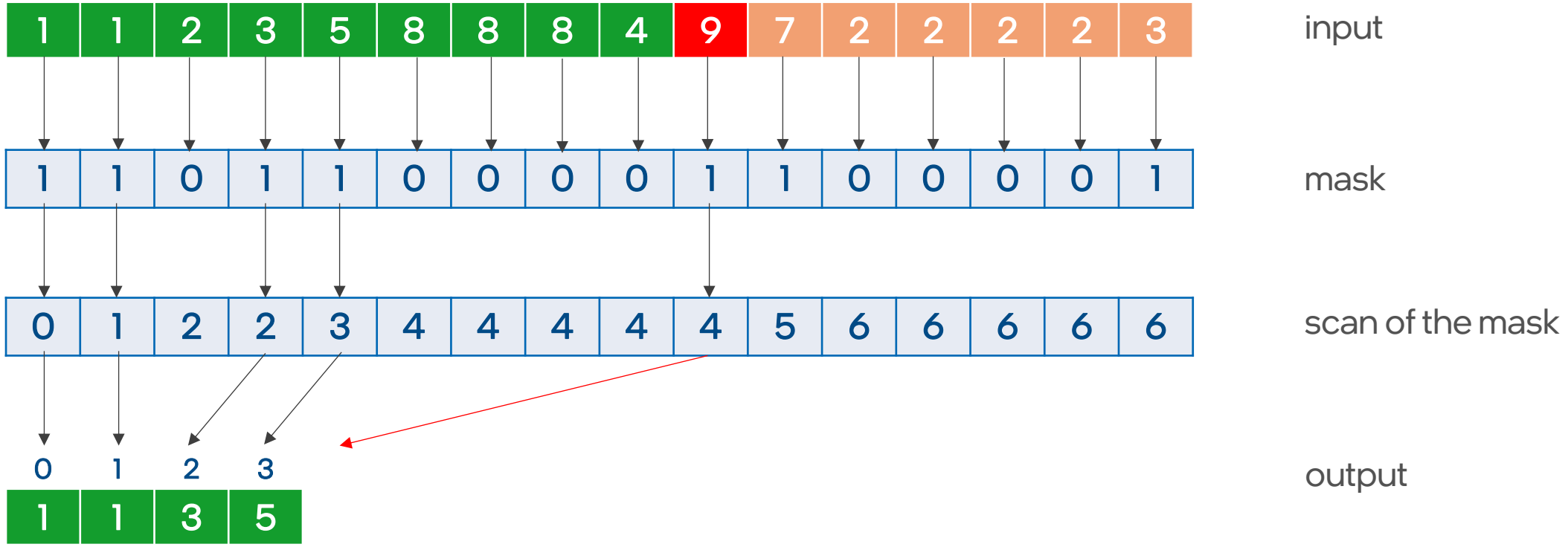
`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(4);

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2,3};
std::vector<int> out(4);

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });
    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);

    auto zip = std::views::zip(r, mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result.back() + mask.back();
    return {std::ranges::begin(r) + std::ranges::size(r), std::ranges::begin(result_r) + copied_elements};
}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });
    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);

    auto last_iterator = std::ranges::upper_bound(scan_result, std::ranges::size(result_r)) - 1;




    auto zip = std::views::zip(r, mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result.back() + mask.back();
    return {std::ranges::begin(r) + std::ranges::size(r), std::ranges::begin(result_r) + copied_elements};
}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });
    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);

    auto last_iterator = std::ranges::upper_bound(scan_result, std::ranges::size(result_r)) - 1;
    bool enough_space = std::ranges::size(result_r) > scan_result.back();



    auto zip = std::views::zip(r, mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result.back() + mask.back();
    return {std::ranges::begin(r) + std::ranges::size(r), std::ranges::begin(result_r) + copied_elements};
}
```


For demonstration purposes only

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });
    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);

    auto last_iterator = std::ranges::upper_bound(scan_result, std::ranges::size(result_r)) - 1;
    bool enough_space = std::ranges::size(result_r) > scan_result.back();
    last_iterator += std::size_t(enough_space || (*last_iterator == scan_result.back() && mask.back() == 0));


    auto zip = std::views::zip(r, mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result.back() + mask.back();
    return {std::ranges::begin(r) + std::ranges::size(r), std::ranges::begin(result_r) + copied_elements};
}
```

`copy_if` parallel implementation

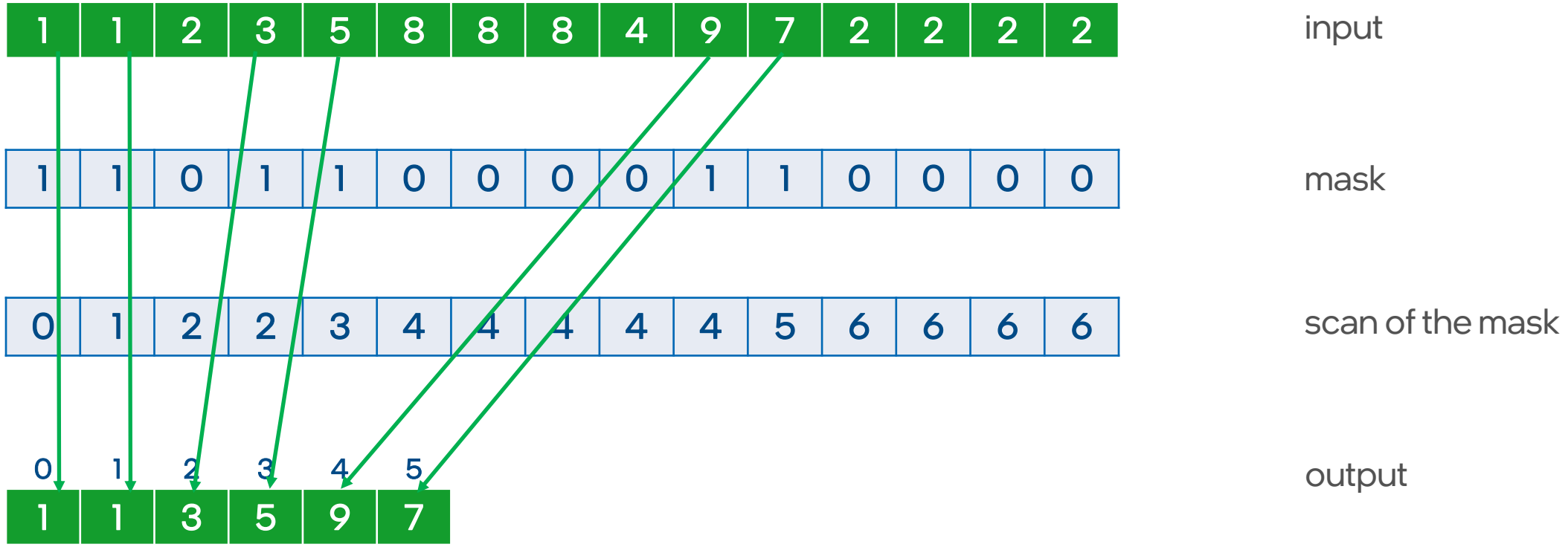
```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });
    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);

    auto last_iterator = std::ranges::upper_bound(scan_result, std::ranges::size(result_r)) - 1;
    bool enough_space = std::ranges::size(result_r) > scan_result.back();
    last_iterator += std::size_t(enough_space || (*last_iterator == scan_result.back() && mask.back() == 0));
    std::size_t distance = std::ranges::distance(scan_result.begin(), last_iterator);

    auto zip = std::views::zip(r | std::views::take(distance), mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result.back() + mask.back();
    return {std::ranges::begin(r) + std::ranges::size(r), std::ranges::begin(result_r) + copied_elements};
}
```

`copy_if` parallel implementation

```
template<execution-policy Ep, sized-random-access-range R, sized-random-access-range OutR, //, Pred, Proj>
std::ranges::copy_if_result<std::ranges::borrowed_iterator_t<R>, std::ranges::borrowed_iterator_t<OutR>>
  copy_if(Ep&& exec, R&& r, OutR&& result_r, Pred pred, Proj proj = {}) {
    std::vector<std::size_t> mask(std::ranges::size(r));
    std::vector<std::size_t> scan_result(std::ranges::size(r));

    std::ranges::transform(exec, r, mask, [pred = std::move(pred), proj = std::move(proj)](auto x) {
        return std::size_t(std::invoke(pred, std::invoke(proj, x))); });
    std::exclusive_scan(exec, mask.begin(), mask.end(), scan_result.begin(), 0);

    auto last_iterator = std::ranges::upper_bound(scan_result, std::ranges::size(result_r)) - 1;
    bool enough_space = std::ranges::size(result_r) > scan_result.back();
    last_iterator += std::size_t(enough_space || (*last_iterator == scan_result.back() && mask.back() == 0));
    std::size_t distance = std::ranges::distance(scan_result.begin(), last_iterator);

    auto zip = std::views::zip(r | std::views::take(distance), mask, scan_result);
    std::ranges::for_each(exec, zip, [&result_r](auto tuple) {
        auto [in, mask, scan_result] = tuple;
        if (mask == 1) result_r[scan_result] = in;
    });
    auto copied_elements = scan_result[distance - 1] + mask[distance - 1];
    return {std::ranges::begin(r) + distance, std::ranges::begin(result_r) + copied_elements};
}
```

`copy_if` example

```
std::vector data{1,1,2,3,5,8,8,8,4,9,7,2,2,2,2};
std::vector<int> out(6);

auto res = std::ranges::copy_if(std::execution::par, data, out, [](auto x) { return (x & 0x01) == 1; });
```



for_each (Category - return type)

API	Return type
`std::for_each`	`Function`
Parallel `std::for_each`	`void`
`std::for_each_n`	`Iterator`
Parallel `std::for_each_n`	`Iterator`
`std::ranges::for_each`	`for_each_result<ranges::borrowed_iterator_t<Range>, Function>`
`std::ranges::for_each`, I + S overload	`for_each_result<Iterator, Function>`
`std::ranges::for_each_n`	`for_each_n_result<Iterator, Function>`

for_each

API	Return type
Parallel `std::ranges::for_each`	`ranges::borrowed_iterator_t<Range>`
Parallel `std::ranges::for_each`, I + S overload	`Iterator`
Parallel `std::ranges::for_each_n`	`Iterator`

Heterogeneity with oneDPL

oneAPI DPC++ library (oneDPL):

- Implementation of standard Parallel Algorithms made by Intel
- Evolution of former Parallel STL
  - Donated to LLVM, used as GNU libstc++ parallel algorithms implementation
- Supports heterogeneous execution via SYCL
- Currently a part of UXL Foundation: both specification and source code
- ~40 parallel range algorithms available as experimental (hetero only)
- ~20 parallel range algorithms available as a product quality

Heterogeneous example

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::find_if(std::execution::par, pipeline, pred);
```

Heterogeneous example

```
// Has an associated device
sycl::queue q;
```

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::find_if(std::execution::par, pipeline, pred);
```

Heterogeneous example

```
// Has an associated device
sycl::queue q;

// Accessible memory on both the host and the device
using alloc_type = sycl::usm_allocator<std::size_t, sycl::usm::alloc::shared>;

// Creating an allocator object
alloc_type alloc(q);
```

```
auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::find_if(std::execution::par, pipeline, pred);
```

Heterogeneous example

```
// Has an associated device
sycl::queue q;

// Accessible memory on both the host and the device
using alloc_type = sycl::usm_allocator<std::size_t, sycl::usm::alloc::shared>;

// Creating an allocator object
alloc_type alloc(q);

// Creating data
std::vector<std::size_t, alloc_type> v(size, alloc);
std::ranges::subrange data{v.begin(), v.end()};

auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = std::find_if(std::execution::par, pipeline, pred);
```

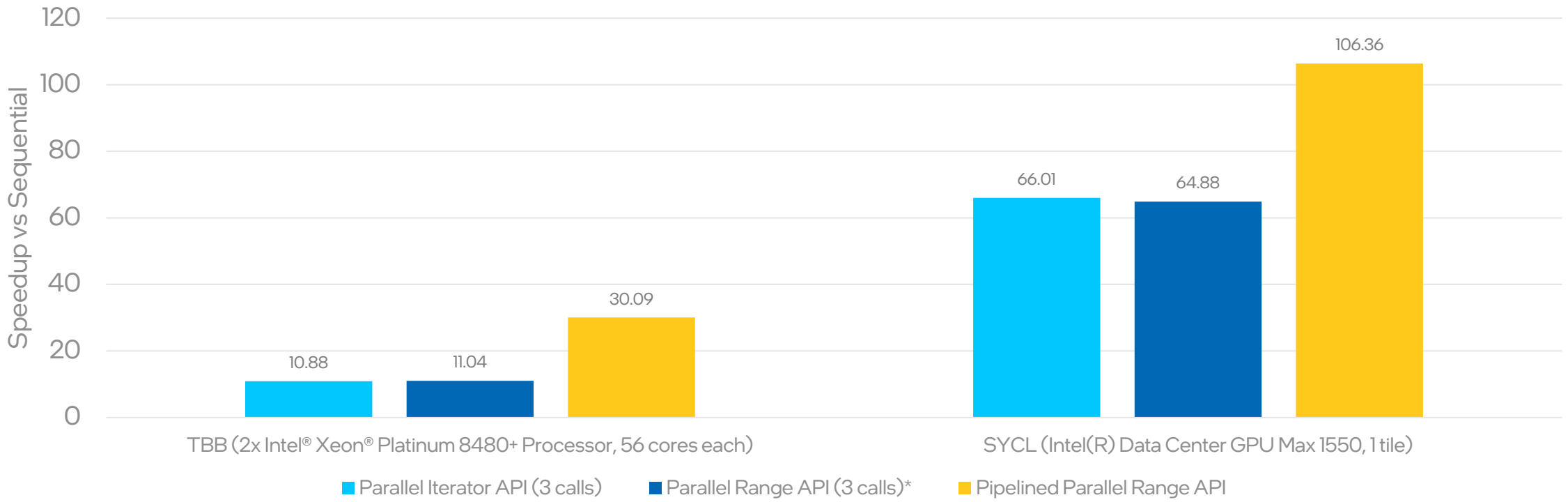
Heterogeneous example

```
// Has an associated device
sycl::queue q;

// Accessible memory on both the host and the device
using alloc_type = sycl::usm_allocator<std::size_t, sycl::usm::alloc::shared>;

// Creating an allocator object
alloc_type alloc(q);

// Creating data
std::vector<std::size_t, alloc_type> v(size, alloc);
std::ranges::subrange data{v.begin(), v.end()};

auto pipeline = data | std::views::transform([](auto i){ return i + 1; }) | std::views::reverse;
auto res = dpl::find_if(dpl::make_device_policy(q), pipeline, pred);
```

Performance

Speedup Over Sequential (higher is better)

16M Elements, Target Element in Center of Range
100 Iterations, Median, icpx 2025.1.0



Scope and status

79 algorithms in namespace std already with policies

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

10 algorithms only in namespace `std::ranges`

std::ranges algorithms to add policies	std algorithms used as the guidance
contains	*find*
contains_subrange	*search*
find_last	*find*
find_last_if	*find_if*
find_last_if_not	*find_if_not*
starts_with	*mismatch*
ends_with	*equal*
min	*min_element*
max	*max_element*
minmax	*minmax_element*

Out of scope algorithms

- All algorithms that do not have an `ExecutionPolicy` in their C++17 counterpart
- Algorithms from `<numeric>`
- Algorithms only in namespace `std::ranges` other than mentioned before:
  - `fold` algorithm family
  - `generate_random`

“Algorithms with output” category

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

“Special algorithms” category

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

“Algorithms with output and gaps” category

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

“Return type” category

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

oneDPL: implemented

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

oneDPL: implemented + coming

all_of	search[_n]	remove_copy	is_sorted	is_heap
any_of	copy[_n]	remove_copy_if	is_sorted_until	is_heap_until
none_of	copy_if	unique	nth_element	min_element
for_each[_n]	move	unique_copy	is_partitioned	max_element
find	swap_ranges	reverse	partition	minmax_element
find_if	transform	reverse_copy	stable_partition	lexicographical_compare
find_if_not	replace	rotate	partition_copy	uninitialized_default_construct[_n]
find_end	replace_if	rotate_copy	merge	uninitialized_value_construct[_n]
find_first_of	replace_copy	shift_left	inplace_merge	uninitialized_copy[_n]
adjacent_find	replace_copy_if	shift_right	includes	uninitialized_move[_n]
count	fill[_n]	sort	set_union	uninitialized_fill[_n]
count_if	generate[_n]	stable_sort	set_intersection	destroy[_n]
mismatch	remove	partial_sort	set_difference	
equal	remove_if	partial_sort_copy	set_symmetric_difference	

oneDPL: coming

std::ranges algorithms to add policies	std algorithms used as the guidance
contains	*find*
contains_subrange	*search*
find_last	*find*
find_last_if	*find_if*
find_last_if_not	*find_if_not*
starts_with	*mismatch*
ends_with	*equal*
min	*min_element*
max	*max_element*
minmax	*minmax_element*

P3179 proposal status

- Design approved
  - Successfully passed SG1: Concurrency and Parallelism, SG9: Ranges, and Library Evolution Working Group (LEWG)
- Is actively reviewed in Library Working Group (LWG)
- Has an opportunity to be included in C++26

Further work

- Numeric range algorithms
- Synchronous parallel algorithms and Senders/Receivers (P2500)
- Asynchronous parallel algorithms (P3300)
- Stretch goal: Range-as-the-output for serial range algorithms

Useful links

- Parallel Range Algorithms proposal:
  https://wg21.link/P3179
- Range-as-the-output paper:
  https://wg21.link/P3490
- oneDPL source code:
  https://github.com/uxlfoundation/oneDPL
- oneDPL specification:
  https://oneapi-spec.uxlfoundation.org/specifications/oneapi/latest/elements/onedpl/source/
- SYCL specification:
  https://registry.khronos.org/SYCL/specs/sycl-2020/html/sycl-2020.html

Special thanks

- Alexey Kukanov

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- Jonathan Muller

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- Zach Laine and Jonathan Muller for reviewing the abstract

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- Alexey Kukanov
- Jonathan Muller
- Inbal Levi
- Jeff Garland and Jonathan Wakely
- Zach Laine and Jonathan Muller for reviewing the abstract
  - Feedback: “The abstract looks good as is” ☺

Bonus

Count words example with C++ 17 parallel algorithms

```
int word_count(const std::string& text) {

    // check for empty string
    if (text.empty()) return 0;

    // compute the number characters that start a new word
    int wc = std::transform_reduce(std::execution::par,
        text.begin(), text.end() - 1,            // sequence of left characters
        text.begin() + 1,                        // sequence of right characters
        0,                                       // initial value
        [](int s1, int s2) { return s1 + s2; },  // sum values together
        [](char s1, char s2) {
            return int(!std::isalpha(s1)
                       && std::isalpha(s2));     // check if the right character starts the word
    });

    // if the first character is alphabetical, then it also begins a word
    if (std::isalpha(*text.begin())) ++wc;

    return wc;
}
```

Count words example with parallel range algorithms

```
int word_count(const std::string& text) {
    using namespace std;
    // check for empty string
    if (text.empty()) return 0;

    // compute the number characters that start a new word
    int wc = ranges::count_if(std::execution::par,
        views::zip(text | views::take(text.size() - 1), text | views::drop(1)),
        [](auto v) {
            auto [s1, s2] = v;
            return !std::isalpha(s1)
                   && std::isalpha(s2);
        }
    );


    // if the first character is alphabetical, then it also begins a word
    if (std::isalpha(*text.begin())) wc++;

    return wc;
}
```


intel