

C++ Standard Library Algorithms

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Basic information

<https://en.cppreference.com/w/cpp/algorithm>

`<algorithm>`

Non-modifying sequence

(all_of, find_if, ...)

Modifying sequence

(copy, remove, ...)

Partitioning

Sorting

Permutation

Binary Search

lower/upper_bound, ...

Set/Heap operations

Min/max

Comparison

equal

lexographical_compare, ...

`<numeric>`

iota

accumulate

reduce

transform_reduce

inner_product

adjacent_difference

partial_sum

inclusive_scan

exclusive_scan

transform_inclusive_scan

transform_exclusive_scan

`<memory>`

uninitialized_copy, ...

destroy, ...

`<iterator>`

Adaptors

make_move_iterator,

make_reverse_iterator, ...

back_inserter, ...

Stream iterators

istream_iterator,

ostream_iterator, ...

Operations

begin, end, rbegin, ...

size, empty, data, ...

distance, next, prev, ...

Other links:

https://hackingcpp.com/cpp/cheat_sheets.html

Non-Modifying Sequence Operations

`min_element(@begin, @end) → @minimum`

7 9 3 5 3 2 6 1 8 0

`minmax_element(@begin, @end) → { @minimum, @maximum }`

7 9 3 5 3 2 6 1 8 0

`C++11`
`any_of (@begin, @end, f(○)→bool) →` true, if `f` yields true for any, all or none elements in the input range
`all_of (@begin, @end, f(○)→bool) →`
`none_of (@begin, @end, f(○)→bool) →` false otherwise

`C++11`
`find_if (@begin, @end, f(○)→bool) →` 1st match
`find (@begin, @end, value) →` @end if no match

5 2 9 1 3 8 5 2 0 0

`count_if (@begin, @end, f(○)→bool) →` number of occurrences
`count (@begin, @end, value) →`

5 2 9 1 3 8 5 2 0 0

`equal (@begin1, @end1, @begin2) → true` if all elements in both ranges are equal

0 1 2 3 4 5 6 7 8 9

`mismatch (@begin1, @end1, @begin2) → { @mismatch_in1, @mismatch_in2 }`

0 1 2 3 4 5 6 7 8 9

`search (@beg1, @end1, @beg2, @end2) →` 1st occurrence of sequence 2 in sorted sequence 1
@end1 otherwise

0 1 2 3 4 5 6 7 8 9

Binary Search On Sorted Sequences ⇒ $O(\log n)$

`lower_bound (@begin, @end, value) →` 1st element not < value
@end if no such element exists

0 1 2 3 4 5 6 7 8 9

`upper_bound (@begin, @end, value) →` 1st element > value
@end if no such element exists

0 1 2 3 4 5 6 7 8 9

`equal_range (@begin, @end, value) → { @1st item not < value or @end if none such found, @1st item > value or @end if none such found }`

1 1 2 3 4 5 5 6 6 7 8 9

Reordering Elements

`reverse (@begin, @end)`

0 1 2 3 4 5 6 7 8 → 8 7 6 5 4 3 2 1 0

`sort (@begin, @end, f(○,○)→bool)`

`sort (@begin, @end, std::less)`

8 9 3 1 2 5 4 7 6 → 8 9 1 2 3 4 5 7 6

`stable_sort (@begin, @end, compare(○,○)→bool)`
"stable" = preserves the relative order of equivalent elements

`nth_element (@begin, @nth, @end)`
element at `nth` position → element that would be in that position in a sorted sequence

`partition (@begin, @end, f(○)→bool) → @part2`
2 4 6 5 7 8 9, is_odd → 2 3 5 7 4 6 8 9

`rotate (@begin, @newfst, @end) → @old_begin`
0 1 2 3 4 5 6 7 8 → 0 3 4 5 6 7 1 2 8

`next_permutation (@begin, @end) → true` if new permutation is lexicographically greater
1 2 3 → 1 3 2

`shuffle (@begin, @end, random_engine)`

0 1 2 3 4 5 6 7 8 → 0 1 5 6 3 4 2 7 8

Manipulate Sorted Sequences ⇒ $O(n)$

`merge (@1beg, @1end, @2beg, @2end, @out)`

sorted input 0 2 4 6 7 9, 0 1 3 5 8 9 → sorted output 0 1 2 3 4 5 6 7 8 9

`set_union (@1beg, @1end, @2beg, @2end, @out)`

0 1 2 2 4 4 5, 1 1 3 4 5 → 0 1 1 2 2 3 4 4 5

Changing Values

`copy (@begin, @end, @out)`

1 2 3 4 5 6 7 8 9 0 → 0 4 5 6 7 8 9 0

`transform (@begin, @end, @out, f(○)→■)`

u v w x y z, f(u) f(x) f(y) →

`generate (@begin, @end, f(○)→■)`

0 0 0 0 0 0, ascending_step_2 → 0 2 4 6 8 0 0

`replace (@begin, @end, old, new)`

1 2 3 2 4 2 2 0, 2, 0 → 1 2 3 0 4 0 0 0

`replace_if (@begin, @end, f(○)→bool, new)`

3 2 5 4 6, is_even, 0 → 3 0 5 0 6

`remove (@begin, @end, value) → @end_of`

`remove_if (@begin, @end, f(○)→bool) → remaining`

0 1 4 3 5 8 2 7 8, is_even → 0 1 3 5 7 7 7 8

`unique (@begin, @end) → @end_of_remaining`

0 4 4 3 3 3 3 3 3 3 → 0 4 1 3 6 3 1 7 7 7 9

`erase (container, value) → erased_count`

1 7 3 5 7 7 7, 2 → 3

Numeric Algorithms

`reduce (@begin, @end, w = ○, @ = ○ + ○) → w + ○1 + ○2 + ... + ○n`
arbitrary evaluation order!

`transform_reduce (@begin, @end, @begin2, @end2, w, @ = ○ + ○, @ = ○ × ○) → R0`
`transform_reduce (@begin, @end, @begin2, @end2, w, @ = ○ + ○, @ = ○ × ○) → Rf`
arbitrary evaluation order!

`C++17`
 $R_f = w + f(○_0) + f(○_1) + \dots$
 $R_0 = w + (○_0 \times ○_1) + (○_1 \times ○_2) + \dots$

`inclusive_scan (@begin, @end, @out, @ = ○ + ○) → @end`
`inclusive_scan (@begin, @end, @out, @ = ○, @ = ○ × ○) → @end`

2 1 7 5 3, 2, 3, 10, 15, 18 →

Basic information – in-class algorithms

<https://en.cppreference.com/w/cpp/container>

Associative containers

$O(\log N)$

count
find
equal_range
lower_bound
upper_bound

Unordered associative containers

$O(1)$

count
find

Most containers

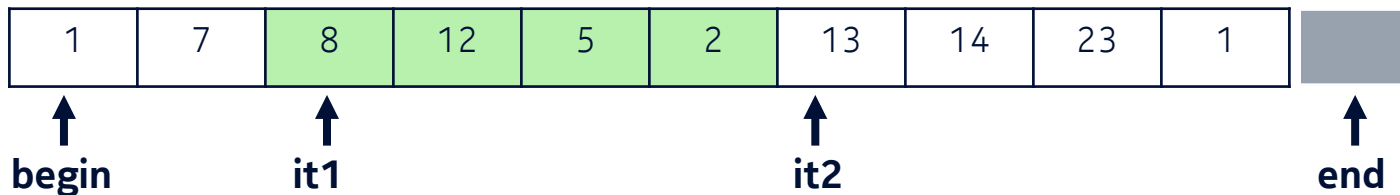
erase
swap

erase_if (C++20)

1. Provide better performance than standalone algorithms (like `std::find` ($O(N)$))
2. Can modify containers
 1. standalone algorithms can modify only elements
 2. compare behavior of `std::remove` and `std::vector<T>::erase`

Ranges in C++17

- Range defined by 2 iterators $[it1, it2)$ is the basic input to all algorithms
 - Range contains all element between $it1$ (inclusively) and $it2$ (exclusively!)

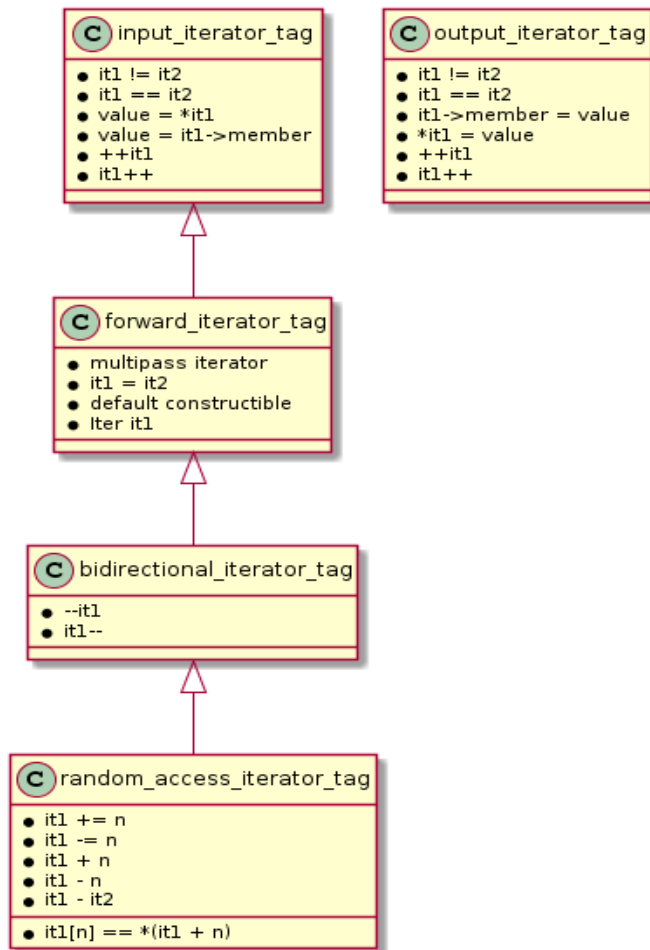


- Iterator can be anything that points to some element
 - “C” Pointer (**T***) is a valid iterator (when points to elements of an array **T[N]**)
 - All Standard Library containers have corresponding iterators (access via `begin/end` methods)
 - Full range for container (like **std::vector<int> a;**) is **(a.begin(), a.end())**
 - Full range for “C” array (like **char b[] = “ala ma kota”;**) is **(b, b + sizeof(b)/sizeof(b[0]))**
 - Since C++11 both containers and arrays ranges can be defined by functions `begin`, `end`: **(std::begin(x), std::end(x))**
 - Iterator can be also something not related to container nor array – like stream iterators
- An example – printing all elements of a **vector<int> v;** – by copying to **std::cout**:

```
std::copy(v.begin(), v.end(), std::ostream_iterator<int>(std::cout, ","));
```

About performance

- Algorithms are written with performance in mind
 - But compiler optimization must be on!
- Algorithms have various versions aligned to type of iterators (see on right →). This is to achieve the best performance for the given iterator/container type. Simple example of that is **std::distance**, **std::advance**



C++ idioms: erase/remove

1. `std::remove_if` works on iterators
2. We need to use container method (like `vector::erase`) to actually removes the elements
3. C++20 fixes that by adding `erase_if` to containers

```
std::vector<int> vv{1,2,3,4,5,6};  
print(vv);  
auto it = std::remove_if(begin(vv), end(vv), [](auto v) { return v & 1; });  
print(vv);  
print(begin(vv), it);  
vv.erase(it, end(vv));  
print(vv);
```

```
1 2 3 4 5 6  
2 4 6 4 5 6  
2 4 6  
2 4 6  
2 4 6
```

C++20 Introduced `std::erase/erase_if`

```
std::vector<int> vv{1,2,3,4,5,6};  
std::erase_if(vv, [](auto v) { return v & 1; });  
print(vv);
```

Exercise: implement erase/remove for `std::map` (and `std::set`)

1. Remove `erase_if` for associative containers – `associative_erase_if(container)`
2. Of course – for pre C++20 code
3. And note that `std::remove_if` is not working on such containers (cannot move elements)

Exercise: Implement C++20 equalUnordered

1. Shall work as `std::equal` – but:

1. It shall return true also for ranges that are equal after sorting.
2. It shall not sort input range – i.e. after execution of the algorithm – input shall be unchanged!

2. Examples:

```
const std::vector<int> a{1,12,23,34};  
const std::array<int, 4> b{1,12,23,34};  
const bool equal = equalUnordered(begin(a), end(a), begin(b));  
assert(equal);
```

```
const std::vector<int> a{21,1,34,23};  
const std::array<int, 4> b{1,21,23,34};  
const bool equal = equalUnordered(begin(a), end(a), begin(b));  
assert(equal);
```

```
const std::vector<int> a{1,2,4,3};  
const std::array<int, 4> b{1,2,3,3};  
const bool equal = equalUnordered(begin(a), end(a), begin(b));  
assert(!equal);
```

Exercise: Implement C++20 equalUnordered

1. Algorithm:

1. Copy iterator ranges (begin1, end1) and (begin2, ...) to local containers (vectors)
2. Sort these iterator ranges with comparing values pointed by iterators
3. Do std::equal on these local ranges, comparing values pointed by iterators (not iterators)

2. At first implement this signature:

```
template <typename Iter1, typename Iter2>  
bool equalUnordered(Iter1 begin1, Iter1 end1, Iter2 begin2);
```

Exercise: Implement C++20 equalUnordered

1. Algorithm:

1. **Copy iterator ranges (begin1, end1) and (begin2, ...) to local containers (vectors)**
2. Sort these iterator ranges with comparing values pointed by iterators
3. Do `std::equal` on these local ranges, comparing values pointed by iterators (not iterators)

```
template <typename Iter1, typename Iter2>
bool equalUnordered(Iter1 begin1, Iter1 end1, Iter2 begin2)
{
    const auto size = std::distance(begin1, end1);
    std::vector<Iter1> it1(size); std::vector<Iter2> it2(size);
    std::generate_n(it1.begin(), size, [begin1]() mutable { return begin1++; });
    std::generate_n(it2.begin(), size, [begin2]() mutable { return begin2++; });
    ...
}
```

Exercise: Implement C++20 equalUnordered

1. Algorithm:

1. Copy iterator ranges (begin1, end1) and (begin2, ...) to local containers (vectors)
- 2. Sort these iterator ranges with comparing values pointed by iterators**
3. Do std::equal on these local ranges, comparing values pointed by iterators (not iterators)

```
template <typename Iter1, typename Iter2>
bool equalUnordered(Iter1 begin1, Iter1 end1, Iter2 begin2)
{
    const auto size = std::distance(begin1, end1);
    std::vector<Iter1> it1(size); std::vector<Iter2> it2(size);
    std::generate_n(it1.begin(), size, [begin1]() mutable { return begin1++; });
    std::generate_n(it2.begin(), size, [begin2]() mutable { return begin2++; });
    std::sort(it1.begin(), it1.end(), [](Iter1 i1, Iter1 i2) { return *i1 < *i2; });
    std::sort(it2.begin(), it2.end(), [](Iter2 i1, Iter2 i2) { return *i1 < *i2; });
    ...
}
```

Exercise: Implement C++20 equalUnordered

1. Algorithm:

1. Copy iterator ranges (begin1, end1) and (begin2, ...) to local containers (vectors)
2. Sort these iterator ranges with comparing values pointed by iterators
- 3. Do std::equal on these local ranges, comparing values pointed by iterators (not iterators)**

```
template <typename Iter1, typename Iter2>
bool equalUnordered(Iter1 begin1, Iter1 end1, Iter2 begin2)
{
    const auto size = std::distance(begin1, end1);
    std::vector<Iter1> it1(size); std::vector<Iter2> it2(size);
    std::generate_n(it1.begin(), size, [begin1]() mutable { return begin1++; });
    std::generate_n(it2.begin(), size, [begin2]() mutable { return begin2++; });
    std::sort(it1.begin(), it1.end(), [](Iter1 i1, Iter1 i2) { return *i1 < *i2; });
    std::sort(it2.begin(), it2.end(), [](Iter2 i1, Iter2 i2) { return *i1 < *i2; });
    return std::equal(it1.begin(), it1.end(), it2.begin(), [](Iter1 i1, Iter2 i2) { return *i1 == *i2; });
}
```

Homework: Implement C++20 equalUnordered with custom comparator

1. What to do when there is no way to sort (no sorting comparator)?
 1. Prepare version when no std::sort is used
 2. Show in comments what is the algorithms computational complexity (big O notation)

```
template <typename Iter1, typename Iter2, typename Comparator>  
bool equalUnordered(Iter1 begin1, Iter1 end1, Iter2 begin2, Comparator comp);
```

```
template <typename Iter1, typename Iter2, typename Comparator, typename SortingComparator>  
bool equalUnordered(Iter1 begin1, Iter1 end1, Iter2 begin2, Comparator comp, SortingComparator sortComp);
```

About performance - multithreading

((from gcc9.1))

Some algorithms can be run in multithreads modes

- **namespace std::execution { sequenced_policy seq; }**
 - Default - operations are performed in sequence (like in default pre-C++17 mode)
- **namespace std::execution { parallel_policy par; }**
 - Operations might be performed in parallel (in different threads)
 - It requires from user to ensure no data races happen
- **namespace std::execution { parallel_unsequenced_policy par_unseq; }**
 - Operations might be performed in parallel, vectorized, migrated from thread to thread
 - It requires vectorization-safe code – e.g. no mutex allowed
 - But still no data races allowed – so it is really hard to use. But it is the most promising.

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