

Modern C++ Programming

17. CONTAINERS, ITERATORS, RANGES, AND ALGORITHMS

Federico Busato

2024-03-11

1 Containers and Iterators

- Semantic

2 Sequence Containers

- `std::array`
- `std::vector`
- `std::deque`
- `std::list`
- `std::forward_list`

3 Associative Containers

- `std::set`
- `std::map`
- `std::multiset`

4 Container Adaptors

- `std::stack`, `std::queue`, `std::priority_queue`

5 View

- `std::span`

6 Implement a Custom Iterator

- Implement a Simple Iterator

7 Iterator Utility Methods

- `std::advance`, `std::next`
- `std::prev`, `std::distance`
- Container Access Methods
- Iterator Traits

8 Algorithms Library

- `std::find_if`, `std::sort`
- `std::accumulate`, `std::generate`, `std::remove_if`

9 C++20 Ranges

- Key Concepts
- Range View
- Range Adaptor
- Range Factory
- Range Algorithms
- Range Actions

Containers and Iterators

Containers and Iterators

Container

A **container** is a class, a data structure, or an abstract data type, whose instances are collections of other objects

- *Containers* store objects following specific access rules

Iterator

An **iterator** is an object allowing to traverse a container

- *Iterators* are a generalization of pointers
- A pointer is the simplest *iterator*, and it supports all its operations

C++ Standard Template Library (STL) is strongly based on *containers* and *iterators*

Reasons to use Standard Containers

- STL containers eliminate redundancy, and save time avoiding writing your own code (productivity)
- STL containers are implemented correctly, and they do not need to spend time to debug (reliability)
- STL containers are well-implemented and fast
- STL containers do not require external libraries
- STL containers share common interfaces, making it simple to utilize different containers without looking up member function definitions
- STL containers are well-documented and easily understood by other developers, improving the understandability and maintainability
- STL containers are thread safe. Sharing objects across threads preserve the consistency of the container

Container Properties

C++ Standard Template Library (STL) Containers have the following properties:

- Default constructor
- Destructor
- Copy constructor and assignment (deep copy)
- Iterator methods `begin()` , `end()`
- Support `std::swap`
- Content-based and order equality (`==` , `!=`)
- Lexicographic order comparison (`>` , `>=` , `<` , `<=`)
- `size()` *, `empty()` , and `max_size()` methods

* except for `std::forward_list`

Iterator Concept

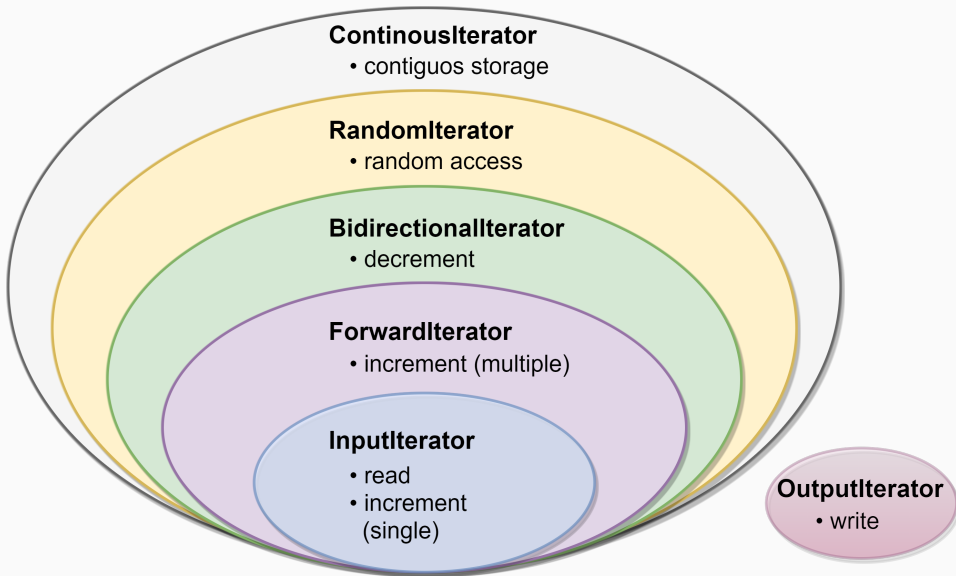
STL containers provide the following methods to get iterator objects:

- `begin()` returns an iterator pointing to the first element
- `end()` returns an iterator pointing to the end of the container (i.e. the element after the last element)

There are different categories of **iterators** and each of them supports a subset of the following operations:

Operation	Example
Read	<code>*it</code>
Write	<code>*it =</code>
Increment	<code>it++</code>
Decrement	<code>it--</code>
Comparison	<code>it1 < it2</code>
Random access	<code>it + 4, it[2]</code>

Iterator Categories/Tags



Iterator

- Copy Constructible `It(const It&)`
- Copy Assignable `It operator=(const It&)`
- Destructible `~X()`
- Dereferenceable `It_value& operator*()`
- Pre-incrementable `It& operator++()`

Input/Output Iterator

- Satisfy Iterator
- Equality `bool operator==(const It&)`
- Inequality `bool operator!=(const It&)`
- Post-incrementable `It operator++(int)`

Forward Iterator

- Satisfy Input/Output Iterator
- Default constructible `It()`

Bidirectional Iterator

- Satisfy Forward Iterator
- Pre/post-decrementable `It& operator--(), It operator--(int)`

Random Access Iterator

- Satisfy Bidirectional Iterator
- Addition/Subtraction
`void operator+(const It& it), void operator+=(const It& it),`
`void operator-(const It& it), void operator-=(const It& it)`
- Comparison
`bool operator<(const It& it), bool operator>(const It& it),`
`bool operator<=(const It& it), bool operator>=(const It& it)`
- Subscripting `It& operator[](int index)`

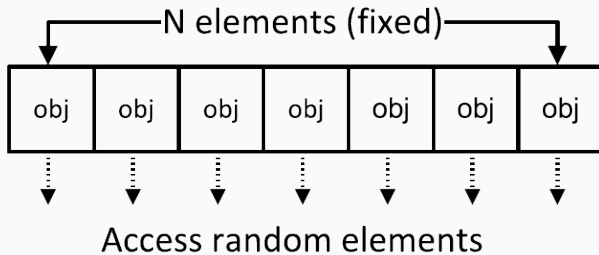
Sequence Containers

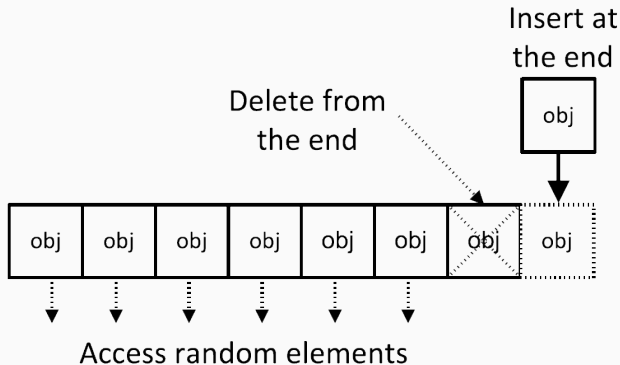
Sequence containers are data structures storing objects of the same data type in a linear manner

The *STL Sequence Container* types are:

- `std::array` provides a *fixed-size* contiguous array (on stack)
- `std::vector` provides a *dynamic* contiguous array (`constexpr` in C++20)
- `std::list` provides a *double-linked list*
- `std::deque` provides a *double-ended queue* (implemented as array-of-array)
- `std::forward_list` provides a *single-linked list*

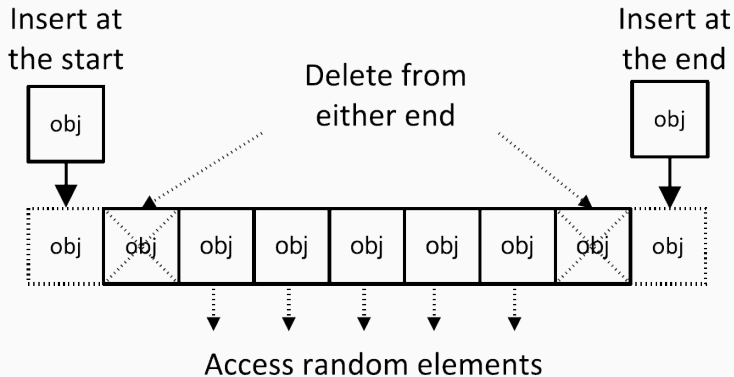
While `std::string` is not included in most container lists, it actually meets the requirements of a Sequence Container





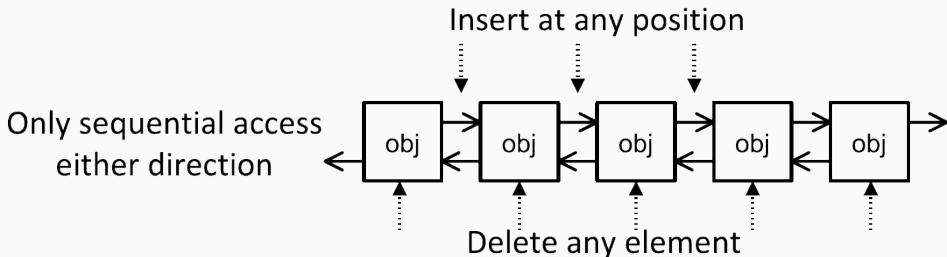
Other methods:

- `resize()` resizes the allocated elements of the container
- `capacity()` number of allocated elements
- `reserve()` resizes the allocated memory of the container (not size)
- `shrink_to_fit()` reallocate to remove unused capacity
- `clear()` removes all elements from the container (no reallocation)



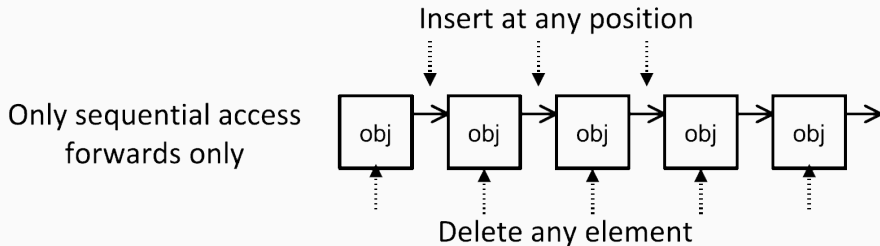
Other methods:

- `resize()` resizes the allocated elements of the container
- `shrink_to_fit()` reallocate to remove unused capacity
- `clear()` removes all elements from the container (no reallocation)



Other methods:

- `resize()` resizes the allocated elements of the container
- `shrink_to_fit()` reallocate to remove unused capacity
- `clear()` removes all elements from the container (no reallocation)
- `remove()` removes all elements satisfying specific criteria
- `reverse()` reverses the order of the elements
- `unique()` removes all consecutive duplicate elements
- `sort()` sorts the container elements



Other methods:

- `resize()` resizes the allocated elements of the container
- `shrink_to_fit()` reallocate to remove unused capacity
- `clear()` removes all elements from the container (no reallocation)
- `remove()` removes all elements satisfying specific criteria
- `reverse()` reverses the order of the elements
- `unique()` removes all consecutive duplicate elements
- `sort()` sorts the container elements

Supported Operations and Complexity

CONTAINERS	operator[]/at	front	back
std::array	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
std::vector	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
std::list		$\mathcal{O}(1)$	$\mathcal{O}(1)$
std::deque	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
std::forward_list		$\mathcal{O}(1)$	

CONTAINERS	push_front	pop_front	push_back	pop_back	insert ^(it)	erase ^(it)
std::array						
std::vector			$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	$\mathcal{O}(n)$	$\mathcal{O}(n)$
std::list	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
std::deque	$\mathcal{O}(1)^*$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)^*/\mathcal{O}(n)^\dagger$	$\mathcal{O}(1)$
std::forward_list	$\mathcal{O}(1)$	$\mathcal{O}(1)$			$\mathcal{O}(1)$	$\mathcal{O}(1)$

* Amortized time [†] Worst case (middle insertion)

std::array example

```
#include <algorithm> // std::sort
#include <array>
// std::array supports initialization only throw initialization list
std::array<int, 3> arr1 = { 5, 2, 3 };
std::array<int, 4> arr2 = { 1, 2 };           // [3]: 0, [4]: 0
// std::array<int, 3> arr3 = { 1, 2, 3, 4 }; // compiler error
std::array<int, 3> arr4(arr1);               // copy constructor
std::array<int, 3> arr5 = arr1;              // assign operator

arr5.fill(3);                               // equal to { 3, 3, 3 }
std::sort(arr1.begin(), arr1.end()); // arr1: 2, 3, 5
cout << (arr1 >= arr5);                  // true

cout << sizeof(arr1);                     // 12
cout << arr1.size();                       // 3
for (const auto& it : arr1)
    cout << it << ", ";                  // 2, 3, 5
cout << arr1[0];                          // 2
cout << arr1.at(0);                        // 2, throw if the index is not within the range
cout << arr1.data()[0];                    // 2 (raw array)
```

std::vector example

```
#include <vector>

std::vector<int>          vec1  { 2, 3, 4 };
std::vector<std::string> vec2 = { "abc", "efg" };
std::vector<int>          vec3(2);      // [0, 0]
std::vector<int>          vec4{2};      // [2]
std::vector<int>          vec5(5, -1);  // [-1, -1, -1, -1, -1]

fill(vec5.begin(), vec5.end(), 3);      // equal to { 3, 3, 3 }
cout << sizeof(vec1);                  // 24
cout << vec1.size();                   // 3
for (const auto& it : vec1)
    std::cout << it << ", ";          // 2, 3, 4

cout << vec1[0];                       // 2
cout << vec1.at(0);                    // 2 (bound check)
cout << vec1.data()[0];                // 2 (raw array)
vec1.push_back(5);                     // [2, 3, 4, 5]
```

std::list example

```
#include <list>

std::list<int>      list1  { 2, 3, 2 };
std::list<std::string> list2 = { "abc", "efg" };
std::list<int>      list3(2);           // [0, 0]
std::list<int>      list4{2};           // [2]
std::list<int>      list5(2, -1);       // [-1, -1]
std::fill(list5.begin(), list5.end(), 3); // [3, 3]

list1.push_back(5);                     // [2, 3, 2, 5]
list1.sort();                           // [2, 2, 3, 5]
list1.merge(list5);                     // [-1, -1, 2, 2, 3, 5] merge two sorted lists
list1.remove(2);                        // [-1, -1, 3, 5]
list1.unique();                         // [-1, 3, 5]
list1.reverse();                       // [5, 3, -1]
```


std::deque example

```
#include <deque>

std::deque<int>      queue1  { 2, 3, 2 };
std::deque<std::string> queue2 = { "abc", "efg" };
std::deque<int>      queue3(2);          // [0, 0]
std::deque<int>      queue4{2};          // [2]
std::deque<int>      queue5(2, -1);      // [-1, -1]
std::fill(queue5.begin(), queue5.end(), 3); // [3, 3]

queue1.push_front(5);                    // [5, 2, 3, 2]
queue1[0];                               // returns 5
```

std::forward_list example

```
#include <forward_list>

std::forward_list<int>      flist1  { 2, 3, 2 };
std::forward_list<std::string> flist2 = { "abc", "efg" };
std::forward_list<int>      flist3(2);      // [0, 0]
std::forward_list<int>      flist4{2};      // [2]
std::forward_list<int>      flist5(2, -1);  // [-1, -1]
std::fill(flist5.begin(), flist5.end(), 4); // [4, 4]

flist1.push_front(5);           // [5, 2, 3, 2]
flist1.insert_after(flist1.begin(), 0); // [5, 0, 2, 3, 2]
flist1.erase_after(flist1.begin());    // [5, 2, 3, 2]
flist1.remove(2);                 // [5, 3, 3]
flist1.unique();                  // [5, 3]
flist1.reverse();                // [3, 5]
flist1.sort();                   // [3, 5]
flist1.merge(flist5);            // [3, 4, 4, 5] merge two sorted lists
```

Associative Containers

Overview

An **associative container** is a collection of elements not necessarily indexed with sequential integers and that supports efficient retrieval of the stored elements through keys

Keys are unique

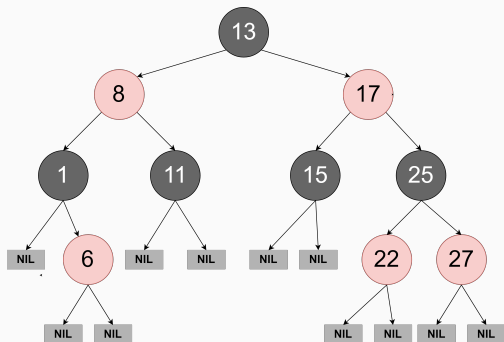
- `std::set` is a collection of sorted unique elements (`operator<`)
- `std::unordered_set` is a collection of unsorted unique keys
- `std::map` is a collection of unique `<key, value>` pairs, sorted by keys
- `std::unordered_map` is a collection of unique `<key, value>` pairs, unsorted

Multiple entries for the same key are permitted

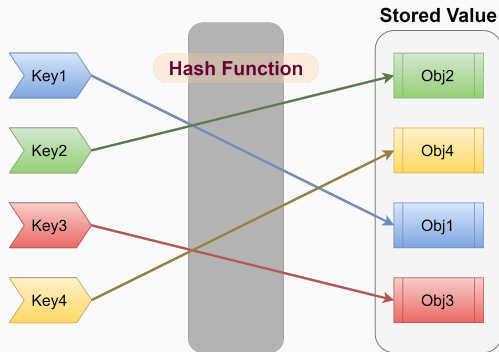
- `std::multiset` is a collection of sorted elements (`operator<`)
- `std::unordered_multiset` is a collection of unsorted elements
- `std::multimap` is a collection of `<key, value>` pairs, sorted by keys

Internal Representation

Sorted associative containers are typically implemented using *red-black trees*, while unordered associative containers (C++11) are implemented using *hash tables*



Red-Black Tree



Hash Table

Hash Table

Supported Operations and Complexity

CONTAINERS	<i>insert</i>	<i>erase</i>	<i>count</i>	<i>find</i>	<i>lower_bound</i> <i>upper_bound</i>
Ordered Containers	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$
Unordered Containers	$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	

* $\mathcal{O}(n)$ worst case

- `count()` returns the number of elements with **key** equal to a specified argument
- `find()` returns the element with **key** equal to a specified argument
- `lower_bound()` returns an iterator pointing to the first element that is *not less* than **key**
- `upper_bound()` returns an iterator pointing to the first element that is *greater* than **key**

Other Methods

Ordered/Unordered containers:

- `equal_range()` returns a range containing all elements with the given `key`

`std::map`, `std::unordered_map`

- `operator[]/at()` returns a reference to the element having the specified key in the container. A new element is generated in the set unless the key is found

Unordered containers:

- `bucket_count()` returns the number of buckets in the container
- `reserve()` sets the number of buckets to the number needed to accommodate at least `count` elements without exceeding maximum load factor and rehashes the container

std::set example

```
#include <set>

std::set<int>          set1  { 5, 2, 3, 2, 7 };
std::set<int>          set2 = { 2, 3, 2 };
std::set<std::string> set3 = { "abc", "efg" };
std::set<int>          set4;           // empty set

set2.erase(2);                        // [ 3 ]
set3.insert("hij");                   // [ "abc", "efg", "hij" ]
for (const auto& it : set1)
    cout << it << " ";              // 2, 3, 5, 7 (sorted)

auto search = set1.find(2);            // iterator
cout << search != set1.end();         // true
auto it     = set1.lower_bound(4);
cout << *it;                          // 5
set1.count(2);                         // 1, note: it can only be 0 or 1
auto it_pair = set1.equal_range(2);   // iterator between [2, 3)
```


std::map example

```
#include <map>

std::map<std::string, int> map1 { {"bb", 5}, {"aa", 3} };
std::map<double, int> map2;           // empty map

cout << map1["aa"];                  // prints 3
map1["dd"] = 3;                      // insert <"dd", 3>
map1["dd"] = 7;                      // change <"dd", 7>
cout << map1["cc"];                  // insert <"cc", 0>
for (const auto& it : map1)
    cout << it.second << " ";      // 3, 5, 0, 7

map1.insert( {"jj", 1} );            // insert pair
auto search = set1.find("jj");       // iterator
cout << search != set1.end();        // true
auto it      = set1.lower_bound("bb");
cout << *it.second;                  // 5
```

std::multiset example

```
#include <set> // std::multiset

std::multiset<int>    mset1 {1, 2, 5, 2, 2}; // 1, 2, 2, 5, 5
std::multiset<double> mset2;    // empty set

mset1.insert(5);
for (const auto& it : mset1)
    cout << it << " ";           // 1, 2, 2, 2, 5, 5
cout << mset1.count(2);           // 3

auto it = mset1.find(3);          // iterator
cout << *it;                     // 5, 5

it      = mset1.lower_bound(4);
cout << *it;                     // position 5
```

Container Adaptors

Container adaptors are interfaces for reducing the number of functionalities normally available in a container

The underlying container of a container adaptors can be optionally specified in the declaration

The *STL Container Adaptors* are:

- `std::stack` LIFO data structure
default underlying container: `std::deque`
- `std::queue` FIFO data structure
default underlying container: `std::deque`
- `std::priority_queue` (max) priority queue
default underlying container: `std::vector`

Container Adaptors Methods

`std::stack` interface for a FILO (first-in, last-out) data structure

- `top()` accesses the top element
- `push()` inserts element at the top
- `pop()` removes the top element

`std::queue` interface for a FIFO (first-in, first-out) data structure

- `front()` access the first element
- `back()` access the last element
- `push()` inserts element at the end
- `pop()` removes the first element

`std::priority_queue` interface for a priority queue data structure (lookup to the largest element by default)

- `top()` accesses the top element
- `push()` inserts element at the end
- `pop()` removes the first element

Container Adaptor Examples

```
#include <stack>           // <--
#include <queue>            // <--
#include <priority_queue>  // <--

std::stack<int> stack1;
stack1.push(1); stack1.push(4);  // [1, 4]
stack1.top();    // 4
stack1.pop();    // [1]

std::queue<int> queue1;
queue1.push(1); queue1.push(4);  // [1, 4]
queue1.front();  // 1
queue1.pop();    // [4]

std::priority_queue<int> pqueue1;
pqueue1.push(1); pqueue1.push(5); pqueue1.push(4);  // [5, 4, 1]
pqueue1.top();    // 5
pqueue1.pop();    // [4, 1]
```

View



C++20 introduces `std::span` which is a non-owning view of an underlying sequence or array

A `std::span` can either have a static extent, in which case the number of elements in the sequence is known at compile-time, or a dynamic extent

```
template<
    class T,
    std::size_t Extent = std::dynamic_extent
> class span;
```



```
#include <span>

int array1[] = {1, 2, 3};
std::span s1{array1}; // static extent

std::array2<int, 3> array2 = {1, 2, 3};
std::span s2{array2}; // static extent

auto array3 = new int[3];
std::span s3{array3}; // dynamic extent

std::vector<int> v{1, 2, 3};
std::span s4{v.data(), v.size()}; // dynamic extent
```

```
void f(std::span<int> span) {  
    for (auto x : span) // range-based loop (safe)  
        cout << x;  
    std::fill(span.begin(), span.end(), 3); // std algorithms  
}  
  
int array1[] = {1, 2, 3};  
f(array1);  
  
auto array2 = new int[3];  
f({array2, 3});
```

Implement a Custom Iterator

Goal: implement a simple iterator to iterate over a `List` of elements:

```
#include <iostream>

// !! List implementation here

int main() {
    List list;
    list.push_back(2);
    list.push_back(4);
    list.push_back(7);
    std::cout << *std::find(list.begin(), list.end(), 4); // print 4

    for (const auto& it : list) // range-based loop
        std::cout << it << " "; // 2, 4, 7
}
```

Range-based loops require: `begin()`, `end()`, pre-increment `++it`, not equal comparison `it != end()`, dereferencing `*it`

```
using value_t = int;

struct List {
    struct Node {           // Internal Node Structure
        value_t _value;     // Node value
        Node* _next;       // Pointer to next node
    };
    Node* _head { nullptr }; // head of the list
    Node* _tail { nullptr }; // tail of the list

    void push_back(const value_t& value); // insert a value at the end

    // !! here we have to define the List iterator "It"

    It begin() { return It{head}; } // begin of the list
    It end()   { return It{nullptr}; } // end of the list
};
```

```
void List::push_back(const value_t& value) {  
    auto new_node = new Node{value, nullptr};  
    if (head == nullptr) { // empty list  
        head = new_node;    // head is updated  
        tail = head;  
        return;  
    }  
    assert(tail != nullptr);  
    tail->_next = new_node; // add new node at the end  
    tail       = new_node; // tail is updated  
}
```

```
struct It {  
    Node* _ptr;           // internal pointer  
  
    It(Node* ptr);        // Constructor  
  
    value_t& operator*(); // Deferencing  
  
    // Not equal -> stop traversing  
    friend bool operator!=(const It& itA, const It& itA);  
  
    It& operator++();      // Pre-increment  
  
    It operator++(int);     // Post-increment  
  
    // !! Type traits here  
};
```

```
void It::It(Node* ptr) :_ptr(ptr) {}

value_t& It::operator*() { return _ptr->_data; }

bool operator!=(const It& itA, const It& itB) {
    return itA._ptr != itB._ptr;
}

It& It::operator++() {
    _ptr = _ptr->_next;
    return *this;
}

It It::operator++(int) {
    auto tmp = *this;
    ++(*this);
    return tmp;
}
```


The *type traits* of an iterator describe its properties, e.g. the type of the value held, and they are widely used in the `std` algorithms

`std::iterator` class template defines the type traits for an iterator. It has been deprecated in C++17, so users need to provide the type traits explicitly

```
#include <iterator>

// !! Type traits
using iterator_category = std::forward_iterator_tag;
using difference_type   = std::ptrdiff_t;
using value_type        = value_t;
using pointer           = value_t*;
using reference         = value_t&;
```

Iterator Utility Methods

- `std::advance`(InputIt& it, Distance n)

Increments a given iterator it by n elements

- InputIt must support input iterator requirements
- Modifies the iterator
- Returns void
- More general than adding a value `it + 4`
- No performance loss if it satisfies random access iterator requirements

- `std::next`(ForwardIt it, Distance n) C++11

Returns the n-th successor of the iterator

- ForwardIt must support forward iterator requirements
- Does not modify the iterator
- More general than adding a value `it + 4`
- The compiler should optimize the computation if it satisfies random access iterator requirements
- Supports negative values if it satisfies bidirectional iterator requirements

- `std::prev`(BidirectionalIt it, Distance n) C++11

Returns the n-th predecessor of the iterator

- `InputIt` must support bidirectional iterator requirements
- Does not modify the iterator
- More general than adding a value `it + 4`
- The compiler should optimize the computation if `it` satisfies random access iterator requirements

- `std::distance`(InputIt start, InputIt end)

Returns the number of elements from start to last

- `InputIt` must support input iterator requirements
- Does not modify the iterator
- More general than adding iterator difference `it2 - it1`
- The compiler should optimize the computation if `it` satisfies random access iterator requirements
- C++11 Supports negative values if `it` satisfies random iterator requirements

Examples

```
#include <iterator>
#include <iostream>
#include <vector>
#include <forward_list>
int main() {
    std::vector<int> vector { 1, 2, 3 }; // random access iterator

    auto it1 = std::next(vector.begin(), 2);
    auto it2 = std::prev(vector.end(), 2);
    std::cout << *it1;    // 3
    std::cout << *it2;    // 2
    std::cout << std::distance(it2, it1); // 1

    std::advance(it2, 1);
    std::cout << *it2;    // 3

    //-----
    std::forward_list<int> list { 1, 2, 3 }; // forward iterator
    // std::prev(list.end(), 1);          // compile error
}
```

Container Access Methods

C++11 provides a generic interface for containers, plain arrays, and std::initializer_list to access to the corresponding iterator.

Standard method `.begin()` , `.end()` etc., are not supported by plain array and initializer list

- `std::begin` begin iterator
- `std::cbegin` begin const iterator
- `std::rbegin` begin reverse iterator
- `std::crbegin` begin const reverse iterator
- `std::end` end iterator
- `std::cend` end const iterator
- `std::rend` end reverse iterator
- `std::crend` end const reverse iterator

```
#include <iterator>
#include <iostream>

int main() {
    int array[] = { 1, 2, 3 };

    for (auto it = std::crbegin(array); it != std::crend(array); it++)
        std::cout << *it << ", ";    // 3, 2, 1
}
```

`std::iterator_traits` allows retrieving iterator properties

- `difference_type` a type that can be used to identify distance between iterators
- `value_type` the type of the values that can be obtained by dereferencing the iterator. This type is void for output iterators
- `pointer` defines a pointer to the type iterated over `value_type`
- `reference` defines a reference to the type iterated over `value_type`
- `iterator_category` the category of the iterator. Must be one of iterator category tags

```
#include <iterator>

template<typename T>
void f(const T& list) {
    using D = std::iterator_traits<T>::difference_type;    // D is std::ptrdiff_t
                                                           // (pointer difference)
                                                           // (signed size_t)

    using V = std::iterator_traits<T>::value_type;         // V is double
    using P = std::iterator_traits<T>::pointer;            // P is double*
    using R = std::iterator_traits<T>::reference;          // R is double&

    // C is BidirectionalIterator
    using C = std::iterator_traits<T>::iterator_category;
}

int main() {
    std::list<double> list;
    f(list);
}
```


Algorithms Library

C++ STL Algorithms library

The algorithm library provides functions for a variety of purposes (e.g. searching, sorting, counting, manipulating) that operate on ranges of elements

- STL Algorithm library allow great flexibility which makes included functions suitable for solving real-world problem
- The user can adapt and customize the STL through the use of function objects
- Library functions work independently on containers and plain array
- Many of them support `constexpr` in C++20

```
#include <algorithm>
#include <vector>

struct Unary {
    bool operator()(int value) {
        return value <= 6 && value >= 3;
    }
};

struct Descending {
    bool operator()(int a, int b) {
        return a > b;
    }
};

int main() {
    std::vector<int> vector { 7, 2, 9, 4 };
    // returns an iterator pointing to the first element in the range[3, 6]
    std::find_if(vector.begin(), vector.end(), Unary());
    // sort in descending order : { 9, 7, 4, 2 };
    std::sort(vector.begin(), vector.end(), Descending());
}
```

```
#include <algorithm> // it includes also std::multiplies
#include <vector>
#include <cstdlib> // std::rand
struct Unary {
    bool operator()(int value) {
        return value > 100;
    }
};

int main() {
    std::vector<int> vector { 7, 2, 9, 4 };

    int product = std::accumulate(vector.begin(), vector.end(), // product = 504
                                   1, std::multiplies<int>());

    std::srand(0);
    std::generate(vector.begin(), vector.end(), std::rand);
    // now vector has 4 random values

    std::remove_if(vector.begin(), vector.end(), Unary());
    // remove all values > 100
}
```

STL Algorithms Library (Possible Implementations)

`std::find`

```
template<class InputIt, class T>
InputIt find(InputIt first, InputIt last, const T& value) {
    for (; first != last; ++first) {
        if (*first == value)
            return first;
    }
    return last;
}
```

`std::generate`

```
template<class ForwardIt, class Generator>
void generate(ForwardIt first, ForwardIt last, Generator g) {
    while (first != last)
        *first++ = g();
}
```

- `swap(v1, v2)` Swaps the values of two objects
- `min(x, y)` Finds the minimum value between x and y
- `max(x, y)` Finds the maximum value between x and y
- `min_element(begin, end)` (returns a pointer)
Finds the minimum element in the range [begin, end)
- `max_element(begin, end)` (returns a pointer)
Finds the maximum element in the range [begin, end)
- `minmax_element(begin, end)` C++11 (returns pointers <min,max>)
Finds the minimum and the maximum element in the range [begin, end)

- `equal(begin1, end1, begin2)`

Determines if two sets of elements are the same in
[begin1, end1), [begin2, begin2 + end1 - begin1)

- `mismatch(begin1, end1, begin2)` (returns pointers <pos1,pos2>)

Finds the first position where two ranges differ in
[begin1, end1), [begin2, begin2 + end1 - begin1)

- `find(begin, end, value)` (returns a pointer)

Finds the first element in the range [begin, end) equal to value

- `count(begin, end, value)`

Counts the number of elements in the range [begin, end) equal to value

- `sort(begin, end)` (in-place)
Sorts the elements in the range `[begin, end)` in ascending order
- `merge(begin1, end1, begin2, end2, output)`
Merges two sorted ranges `[begin1, end1)`, `[begin2, end2)`, and store the results in `[output, output + end1 - start1)`
- `unique(begin, end)` (in-place)
Removes consecutive duplicate elements in the range `[begin, end)`
- `binary_search(begin, end, value)`
Determines if an element value exists in the (sorted) range `[begin, end)`
- `accumulate(begin, end, value)`
Sums up the range `[begin, end)` of elements with initial value (common case equal to zero)
- `partial_sum(begin, end)` (in-place)
Computes the inclusive prefix-sum of the range `[begin, end)`

- `fill(begin, end, value)`
Fills a range of elements `[begin, end)` with `value`
- `iota(begin, end, value)` C++11
Fills the range `[begin, end)` with successive increments of the starting value
- `copy(begin1, end1, begin2)`
Copies the range of elements `[begin1, end1)` to the new location `[begin2, begin2 + end1 - begin1)`
- `swap_ranges(begin1, end1, begin2)`
Swaps two ranges of elements `[begin1, end1)`, `[begin2, begin2 + end1 - begin1)`
- `remove(begin, end, value)` (in-place)
Removes elements equal to `value` in the range `[begin, end)`
- `includes(begin1, end1, begin2, end2)`
Checks if the (sorted) set `[begin1, end1)` is a subset of `[begin2, end2)`

- `set_difference(begin1, end1, begin2, end2, output)`
Computes the difference between two (sorted) sets
- `set_intersection(begin1, end1, begin2, end2, output)`
Computes the intersection of two (sorted) sets
- `set_symmetric_difference(begin1, end1, begin2, end2, output)`
Computes the symmetric difference between two (sorted) sets
- `set_union(begin1, end1, begin2, end2, output)`
Computes the union of two (sorted) sets
- `make_heap(begin, end)` Creates a max heap out of the range of elements
- `push_heap(begin, end)` Adds an element to a max heap
- `pop_heap(begin, end)` Remove an element (top) to a max heap

Algorithm Library - Other Examples

```
#include <algorithm>

int a      = std::max(2, 5); // a = 5
int array1[] = {7, 6, -1, 6, 3};
int array2[] = {8, 2, 0, 3, 7};

int b = *std::max_element(array1, array1 + 5); // b = 7
auto c = std::minmax_element(array1, array1 + 5);
//c.first = -1, c.second = 7
bool d = std::equal(array1, array1 + 5, array2); // d = false

std::sort(array1, array1 + 5);           // [-1, 3, 6, 6, 7]
std::unique(array1, array1 + 5);          // [-1, 3, 6, 7]
int e = accumulate(array1, array1 + 5, 0); // 15
std::partial_sum(array1, array1 + 5);     // [-1, 2, 8, 15]
std::iota(array1, array1 + 5, 2);          // [2, 3, 4, 5, 6]
std::make_heap(array2, array2 + 5);       // [8, 7, 0, 3, 2]
```

C++20 Ranges

C++20 Ranges

***Ranges** are an abstraction that allows to operate on elements of data structures uniformly. They are an extension of the standard *iterators**

A **range** is an object that provides `begin()` and `end()` methods (an *iterator* + a *sentinel*)

`begin()` returns an *iterator*, which can be incremented until it reaches `end()`

```
template<typename T>
concept range = requires(T& t) {
    ranges::begin(t);
    ranges::end(t);
};
```

-
- An Overview of Standard Ranges
 - Range, Algorithms, Views, and Actions - A Comprehensive Guide
 - Eric Niebler - Range v3
 - Range by Example

Key Concepts

Range View is a *range* defined on top of another *range*

Range Adaptors are utilities to transform a *range* into a *view*

Range Factory is a *view* that contains no elements

Range Algorithms are library-provided functions that directly operate on ranges
(corresponding to std iterator algorithm)

Range Action is an object that modifies the underlying data of a range

A **range view** is a *range* defined on top of another *range* that transforms the underlying way to access internal data

- Views do not own any data
- *copy, move, assignment* operations perform in constant time
- Views are *composable*
- Views are *lazy evaluated*

Syntax:

```
range/view | view
```

```
#include <iostream>
#include <ranges>
#include <vector>

std::vector<int> v{1, 2, 3, 4};

for (int x : v | std::views::reverse)
    std::cout << x << " "; // print: "4, 3, 2, 1"

auto rv2 = v | std::views::reverse; // cheap, it does not copy "v"

auto rv3 = v | std::views::drop(2) | // drop the first two elements
            std::views::reverse;
for (int x : rv3) // lazy evaluated
    std::cout << x << " "; // print: "4, 3"
```


Range Adaptors are utilities to transform a *range* into a *view* with custom behaviors

- *Range adaptors* produce lazily evaluated *views*
- *Range adaptors* can be chained or composed (pipeline)

Syntax:

```
adaptor(range/view, args...)
adaptor(args...)(range/view)
range/view | adaptor(args...) // preferred syntax
```

```
#include <iostream>
#include <ranges>
#include <vector>

std::vector<int> v{1, 2, 3, 4};

for (int x : v | std::ranges::reverse_view(v))    // @\textbf{adaptor}@
    std::cout << x << " "; // print: "4, 3, 2, 1"

auto rv2 = std::ranges::reverse_view(v); // cheap, it does not copy "v"

auto rv3 = std::ranges::reverse_view(
    std::ranges::drop_view(2, v)); // drop the first two elements
for (int x : rv3) // lazy evaluated
    std::cout << x << " "; // print: "4, 3"
```

Range Factory

Range Factory produces a *view* that contains no elements

```
#include <iostream>
#include <ranges>

for (int x : std::ranges::iota_view{1, 4}) // factory (adaptor)
    std::cout << x << " ";                // print: "1, 2, 3, 4"

for (int x : std::view::repeat('a', 4))    // factory (view)
    std::cout << x << " ";                // print: "a, a, a, a"
```

Range Algorithms

The **range algorithms** are almost identical to the corresponding *iterator-pair* algorithms in the `std` namespace, except that they have *concept*-enforced constraints and accept *range* arguments

- *Range algorithms* are immediately evaluated
- *Range algorithms* can work directly on containers (`begin()` , `end()` are no more explicitly needed) and *view*

```
#include <algorithm>
#include <vector>

std::vector<int> vec{3, 2, 1};
std::ranges::sort(vec); // 1, 2, 3
```

Algorithm Operators and Projections

```
#include <algorithm>
#include <vector>

struct Data {
    char value1;
    int value2;
};

std::vector<int> vec{4, 2, 5};
auto cmp = [](auto a, auto b) { return a > b; }; // Unary boolean predicate
std::ranges::sort(vec, cmp); // 5, 4, 2

std::vector<Data> vec2{{'a', 4}, {'b', 2}, {'c', 5}};
std::ranges::sort(vec2, {}, &Data::value2); // Projection: 2, 4, 5
                                           // {'b', 2}, {'a', 4}, {'c', 5}
```

Algorithms and Views

```
// sum of the squares of the first 'count' numbers  
auto sum_of_squares(int count) {  
    auto squares = std::views::iota(1, count) |  
        std::views::transform([](int x) { return x * x; });  
    return std::accumulate(squares, 0);  
}
```

The **range actions** mimic *std algorithms* and *range algorithms* adding the **composability** property

- *Range actions* are *eager* evaluated
- *Range algorithms* work directly on *ranges*
- Not included in the `std` library

```
#include <algorithm>
#include <vector>

std::vector<int> vec{3, 5, 6, 3, 5}
// in-place
vec = vec | actions::sort    // 3, 3, 5, 5, 6
      | actions::unique; // 3, 5, 6

vec |= actions::sort    // 3, 3, 5, 5, 6
      | actions::unique; // 3, 5, 6
// out-of-place
auto vec2 = std::move(vec) | actions::sort    // 3, 3, 5, 5, 6
                          | actions::unique; // 3, 5, 6
```