Modern C++ Programming

18. Containers, Iterators, Ranges, and Algorithms

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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

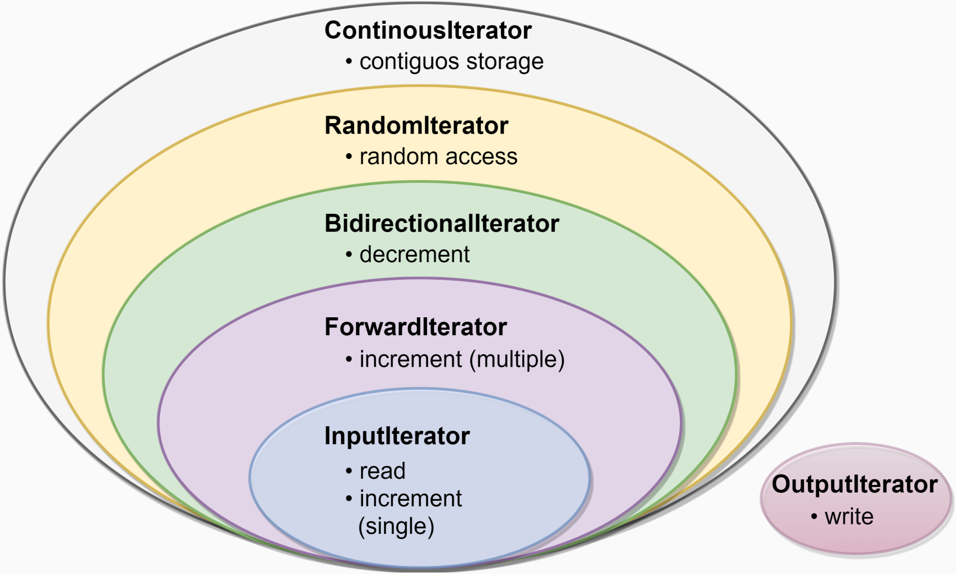
STL containers provide the following methods to get iterator objects:

- `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	`*it`
Write	`*it =`
Increment	`it++`
Decrement	`it--`
Comparison	`it1 < it2`
Random access	`it + 4`, `it[2]`

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_value& operator[](int index)`

anderberg.me/2016/07/04/c-custom-iterators/

Sequence Containers

Overview

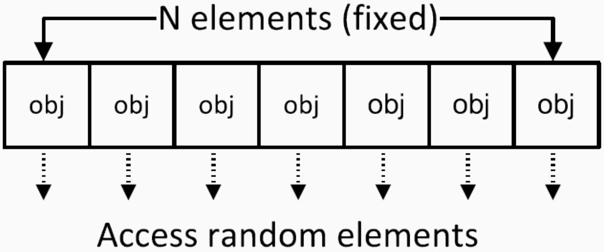
Sequence containers are data structures storing objects of the same data type in a linear mean manner

The *STL Sequence Container* types are:

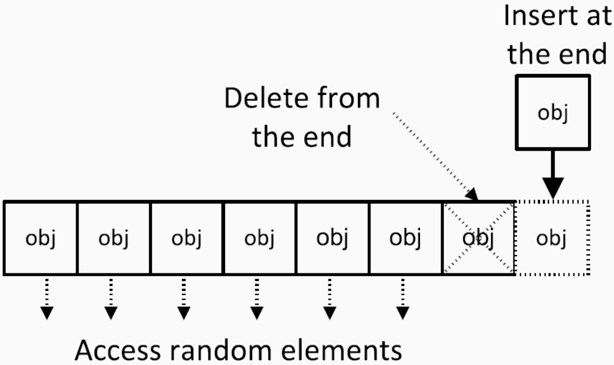
- `std::array` provides a *fixed-size* contiguous array (on stack)
- `std::vector` provides a *dynamic* contiguous array (`constexpr` in C++20)
- `std::list` provides a *double-linked list*
- `std::deque` provides a *double-ended queue* (implemented as array-of-array)
- `std::forward_list` provides a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

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

std::array



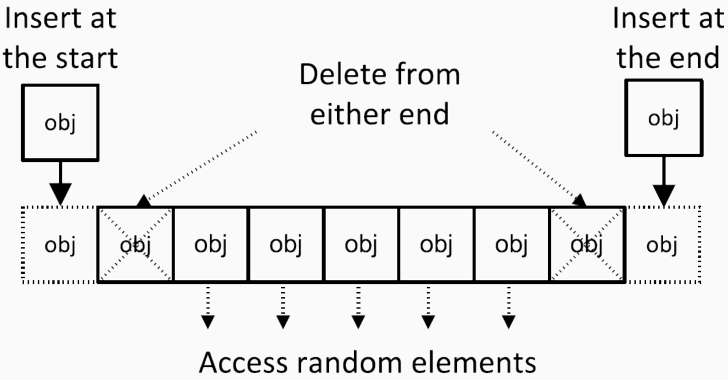
N elements (fixed)
obj
obj
obj
obj
obj
obj
obj
Access random elements



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)

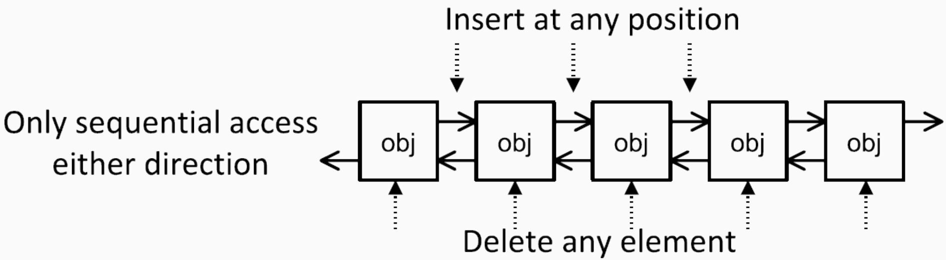
`std::deque`



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)

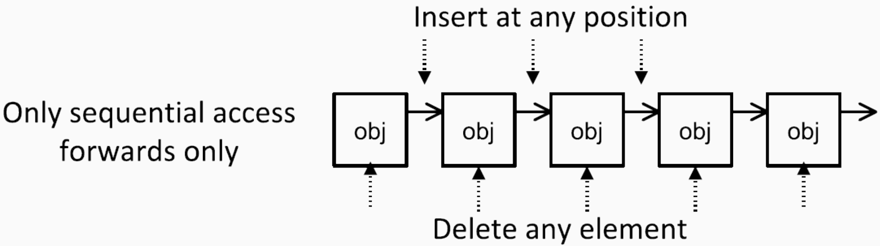
std::list



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

std::forward_list



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

```cpp
#include <algorithm> // std::sort
#include <array>
// std::array supports initialization only through 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

```cpp
#include <vector>
#include <algorithm> // std::fill

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]

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

```cpp
#include <list>
#include <algorithm> // std::fill

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>
#include <algorithm> // std::fill

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];                                  // retuns 5
```

std::forward_list example

```cpp
#include <forward_list>
#include <algorithm> // std::fill

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

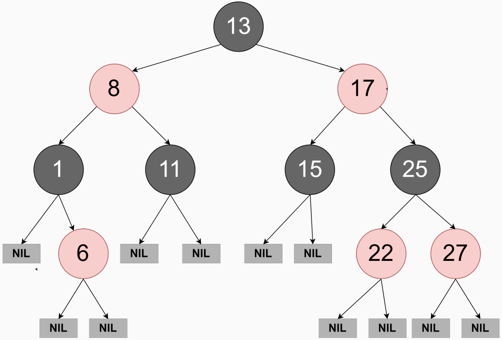
- `std::set` is a collection of sorted unique elements (`operator<`)
- `std::unordered_set` is a collection of unsorted unique keys
- `std::map` is a collection of unique <key, value> pairs, sorted by keys
- `std::unordered_map` is a collection of unique <key, value> pairs, unsorted

Multiple entries for the same key are permitted

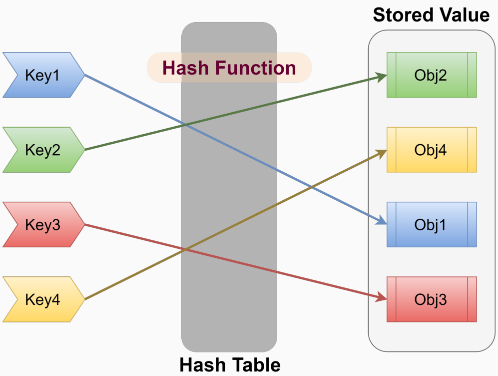
- `std::multiset` is a collection of sorted elements (`operator<`)
- `std::unordered_multiset` is a collection of unsorted elements
- `std::multimap` is a collection of <key, value> pairs, sorted by keys

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

Supported Operations and Complexity

CONTAINERS	insert	erase	count	find	lower_bound upper_bound
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.
- `operator[]` if the key is not found, it returns a new element
- `at()` if the key is not found, raises an exception

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 = map1.find("jj");      // iterator
cout << (search != map1.end());     // true
auto it = map1.lower_bound("bb");
cout << (*it).second;               // 5
```

std::multiset example

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

std::multiset<int>    mset1 {1, 2, 5, 2, 2}; // 1, 2, 2, 2, 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(5);          // iterator
cout << *it;                      // 5

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

Container Adaptors

Overview

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>          // <-- also 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]
```

Implement a Custom Iterator

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

```
#include <iostream>
#include <algorithm>
// !! 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`

```cpp
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
};
```

```cpp
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
}
```

Implement a Simple Iterator (Iterator declaration)

```
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& itB);

    It& operator++();      // Pre-increment

    It operator++(int);    // Post-increment

// !! Type traits here
};
```

Implement a Simple Iterator (Iterator definition) 5/6

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

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

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

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

---

internalpointers.com/post/writing-custom-iterators-modern-cpp

Preparation for std::iterator Being Deprecated

Iterator Notes

Common Errors

Modify a container with a “active” iterators

```
#include <vector>

std::vector<int> vec{1, 2, 3, 4, 5};
for (auto x : vec)
    vec.push_back(x);   // iterator invalidation!!
```

Iterator Utility Methods

Iterator Operations

- `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

Iterator Operations

- `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

```cpp
#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

```cpp
#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
}
```

Iterator Traits

`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

Iterator Traits

```cpp
#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

```cpp
#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());
}
```

```cpp
#include <algorithm> // it includes also std::multiplies
#include <vector>
#include <cstdlib>   // std::rand
#include <numeric>   // std::accumulate
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::generate(vector.begin(), vector.end(), std::rand);
    // now vector has 4 random values

    // remove all values > 100 using Erase-remove idiom
    auto new_end = std::remove_if(vector.begin(), vector.end(), Unary());
    // elements are removed, but vector size is still unchanged
    vector.erase(new_end, vector.end()); // shrink vector to finish removal
}
```

STL Algorithms Library (Possible Implementations)

std::find

```cpp
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

```cpp
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)`

en.cppreference.com/w/cpp/algorithm

- `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, output)` (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`)

Algorithm Library

- `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

```cpp
#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 = std::accumulate(array1, array1 + 4, 0); // 15
std::partial_sum(array1, array1 + 4, array1);   // [-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 Nielbler - 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

Range View

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
```

```cpp
#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
```

Range Adaptor

```cpp
#include <ranges>
#include <vector>

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

for (int x : std::ranges::reverse_view(v))      // adaptor
    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
    cout << x << " ";  // print: "4, 3"
```

Range Factory

Range Factory produces a *view* that contains no elements

```
#include <ranges>

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

for (int x : std::views::repeat('a', 4))   // factory (view)
    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*

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

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

Algorithm Operators and Projections

```cpp
#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::ranges::fold_left_first(squares, std::plus{});
}
```

Range Actions

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

```cpp
#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
```