

Modern C++ Programming

14. CONTAINERS, ITERATORS, AND ALGORITHMS

Federico Busato

University of Verona, Dept. of Computer Science
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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 to write 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)

Iterator support 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>

Sequence Containers

Overview

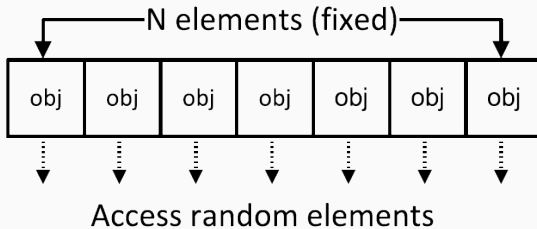
Sequence containers are data structures storing objects of the same data type in a linear manner

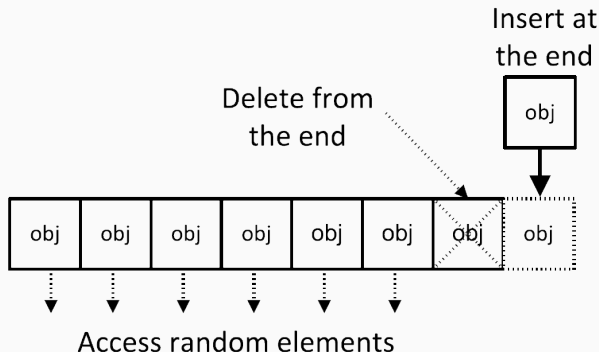
The *STL Sequence Container* types are:

- `std::array` provides a *fixed-size* contiguous array (on stack)
- `std::vector` provides a *dynamic* contiguous array
- `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

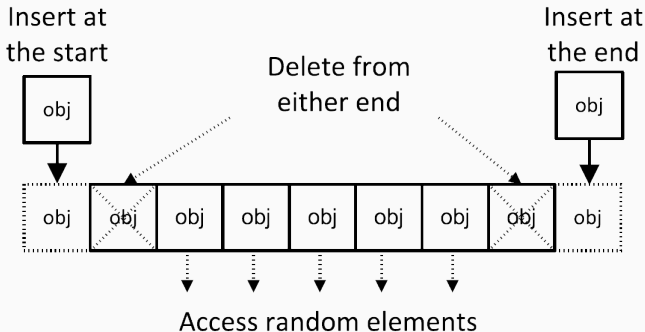
`std::array`





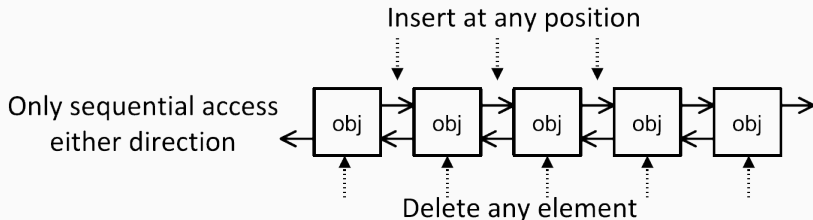
Other methods:

- `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)



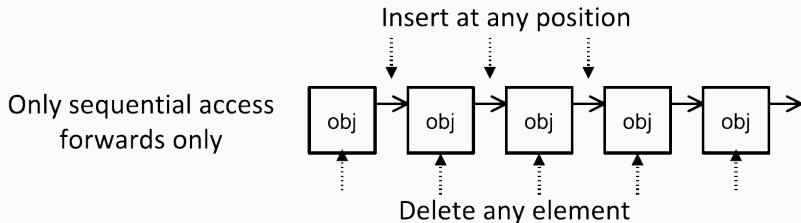
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- `clear()` removes all elements from the container (no reallocation)



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:

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- `shrink_to_fit()` reallocate to remove unused capacity
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Supported Operations and Complexity

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

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

* Amortized time † Worst case (middle insertion)

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

std::array example

```
#include <array>      // <--
#include <iostream>    // std::array supports initialization
int main() {          // 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 }; // run-time 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
    std::cout << (arr1 > arr2);                  // true

    std::cout << sizeof(arr1);                    // 12
    std::cout << arr1.size();                     // 3
    for (const auto& it : arr1)
        std::cout << it << ", ";                // 2, 3, 5

    std::cout << arr1[0];                         // 2
    std::cout << arr1.at(0);                      // 2 (safe)
    std::cout << arr1.data()[0]                   // 2 (raw array)
}
```

std::vector example

```
#include <vector>      // <--
#include <iostream>

int main() {
    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]

    vec5.fill(3);                      // equal to { 3, 3, 3 }
    std::cout << sizeof(vec1);          // 24
    std::cout << vec1.size();            // 3
    for (const auto& it : vec1)
        std::cout << it << ", ";      // 2, 3, 5

    std::cout << vec1[0];                // 2
    std::cout << vec1.at(0);              // 2 (safe)
    std::cout << vec1.data()[0]           // 2 (raw array)
    vec1.push_back(5);                  // [2, 3, 4, 5]
}
```

std::list example

```
#include <list>          // <--
#include <iostream>

int main() {
    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]
    list5.fill(3);                // [3, 3]

    list1.push_back(5);            // [2, 3, 2, 5]
    list1.merge(arr5);             // [2, 3, 2, 5, 3, 3]
    list1.remove(2);               // [3, 5, 3, 3]
    list1.unique();                // [3, 5, 3]
    list1.sort();                 // [3, 3, 5]
    list1.reverse();              // [5, 3, 3]
}
```

std::deque example

```
#include <deque>           // <--
#include <iostream>

int main() {
    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]
    queue5.fill(3);           // [3, 3]

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

std::forward_list example

```
#include <forward_list>      // <--
#include <iostream>

int main() {
    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]
    flist5.fill(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(), 0);  // [5, 2, 3, 2]
    flist1.remove(2);                      // [3, 5, 3, 3]
    flist1.unique();                       // [3, 5, 3]
    flist1.sort();                         // [3, 3, 5]
    flist1.reverse();                     // [5, 3, 3]
    flist1.merge(flist5);                 // [5, 3, 3, 4, 4]
}
```

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

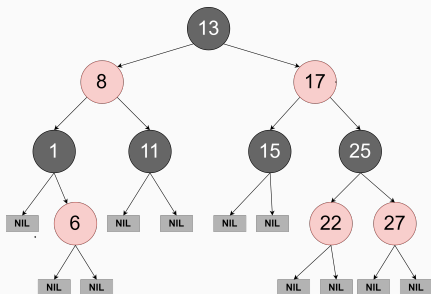
- `std::set` is a collection of sorted unique elements (`operator<`)
- `std::unordered_set` is a collection of unsorted unique keys
- `std::map` is a collection of unique `<key, value>` pairs, sorted by keys
- `std::unordered_map` is a collection of unique `<key, value>` pairs, unsorted

Multiple entries for the same key are permitted

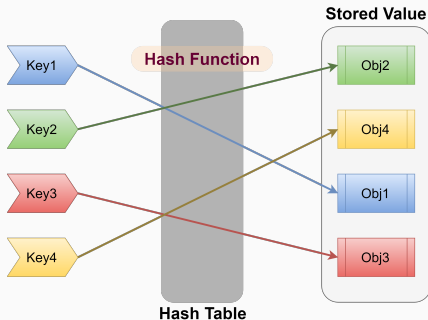
- `std::multiset` is a collection of sorted elements (`operator<`)
- `std::unordered_multiset` is a collection of unsorted elements
- `std::multimap` is a collection of `<key, value>` pairs, sorted by keys
- `std::unordered_multimap` is a collection of `<key, value>` pairs

Internal Representation

Note: sorted associative containers are typically implemented using *red-black trees*, while unsorted associative containers (C++11) are implemented using *hash tables*



Red-Black Tree



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>
Sorted Containers	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$	$\mathcal{O}(\log(n))$	
Unsorted Containers	$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	$\mathcal{O}(1)^*$	$\mathcal{O}(\log(n))$

* $\mathcal{O}(n)$ 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

Sorted/Unsorted 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

Unsorted 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>           // <--
#include <iostream>

int main() {
    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)
        std::cout << it << " ";        // 2, 3, 5, 7 (sorted)

    auto search = set1.find(2);           // iterator
    std::cout << search != set1.end();   // true
    auto it      = set1.lower_bound(4);
    std::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>           // <--
#include <iostream>

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

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

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

std::multiset example

```
#include <multiset>           // <--
#include <iostream>

int main() {
    std::multiset<int>    mset1 {1, 2, 5, 2, 2};
    std::multiset<double> mset2;    // empty map

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

    auto it = mset1.find(3);        // iterator
    std::cout << *it << " " << *(it + 1); // prints 5, 5

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

Container Adaptors

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

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

The *STL Container Adapters* 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 Adapters 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 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> // <--
#include <iostream>

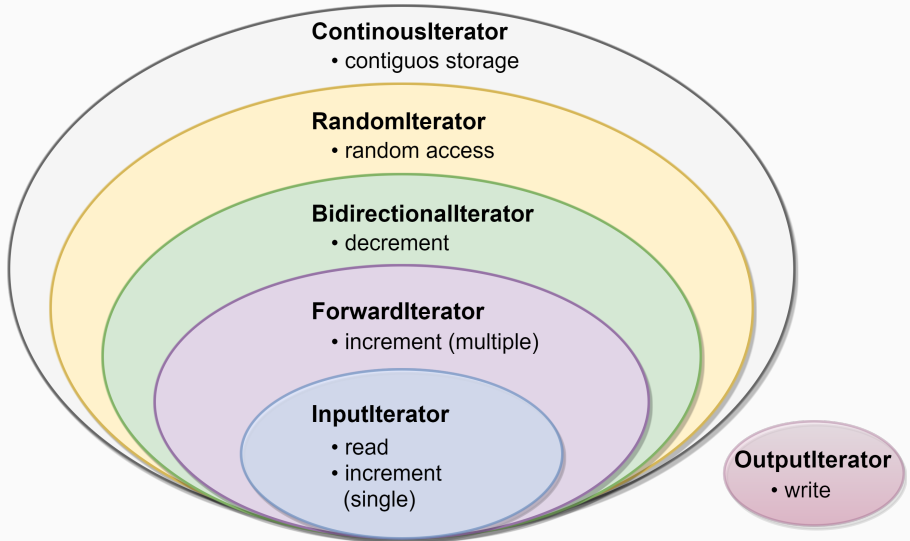
int main() {
    std::stack<int> stack1;
    stack1.push(1); stack1.push(4);    // [1, 4]
    stack1.top();    // 4
    stack1.pop();    // [1]

    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); queue1.push(5); queue1.push(4);    // [5, 4, 1]
    pqueue1.top();    // 5
    pqueue1.pop();    // [4, 1]
}
```

Implement a Custom Iterator

Iterator Categories/Tags



Iterator

- CopyConstructible `It(const It&)`
- CopyAssignable `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)`

Goal: implement a simple iterator to iterate over a `List` 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(int value) {  
    if (head == nullptr) { // empty list  
        head = new Node(); // head is updated  
        tail = head;  
    }  
    else {  
        tail->_next = new Node();  
        tail      = tail->_next; // tail is updated  
    }  
    tail->_data = value;  
    tail->_next = nullptr; // very important to match end() method!!  
}
```

```
#include <iterator> // for "std::iterator", outside List declaration

struct It : public std::iterator<std::input_iterator_tag,
                                value_t> { // dereferencing type
    Node* _ptr;          // internal pointer

    It(Node* ptr);      // Constructor

    int& operator*(); // Deferencing

    friend bool operator!=(const It& itA, const It& itA); // Not equal

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

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

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

int& 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;
}
```

Implement a Simple Iterator (properties)

Without extending `std::iterator`. Needed by `std` algorithms

```
#include <iterator>

struct It {
    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
}
```


Range Access Methods

C++11\C++14 provide 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
- `reference` defines a reference to the type iterated over
- `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 algorithms 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

```
#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();
}
```