

C++

程式語言（二）

Introduction to Programming (II)

Introduction to STL

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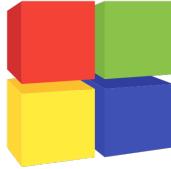
Platform/IDE

- Dev-C++



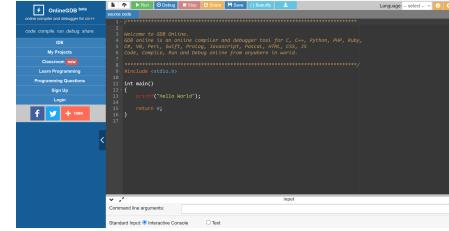
<https://www.pngegg.com/en/search?q=Dev-C>

- Codeblocks

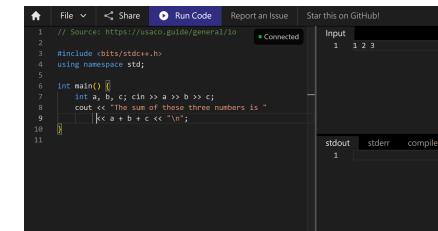


<https://icons8.com/icons/set/code-blocks>

- OnlineGDB (<https://www.onlinegdb.com/>)



- Real-Time Collaborative Online IDE (<https://ide.usaco.guide/>)



Textbooks (We focusing on C++11)

- *Learn C++ Programming by Refactoring* (由重構學習 C++ 程式設計). Pang-Feng Liu (劉邦鋒). NTU Press. 2023.
- *C++ Primer. 5th Edition*. Stanley B. Lippman, Josée Lajoie, Barbara E. Moo. 2019.
- *Effective C++*. Scott Meyers. O'Reilly. 2016.
- *Thinking in C++*. Vol. 1: *Introducing to Standard C++*. 2nd Edition. Bruce Eckel. Prentice Hall PTR. 2000.

Useful Resources

- Tutorialspoint
 - <https://www.tutorialspoint.com/cplusplus/index.htm>
 - Online C++ Compiler
- Programiz
 - <https://www.programiz.com/cpp-programming>
- LEARN C++
 - <https://www.learncpp.com/>
- MIT OpenCourseWare - Introduction to C++
 - <https://ocw.mit.edu/courses/6-096-introduction-to-c-january-iap-2011/pages/lecture-notes/>
- Learning C++ Programming
 - <https://www.programiz.com/cpp-programming>
- GeeksforGeeks
 - <https://www.geeksforgeeks.org/c-plus-plus/>

Standard Template Library (STL)

- Standard Template Library (STL) is a powerful library in C++ that provides a collection of **generic data structures** and **algorithms** to simplify common programming tasks.
 - It is based on **templates**.
 - **Goal:** Facilitate development of reusable and efficient codes.
- Key components:
 - **Containers** (+Adapters): Data structures that store objects.
 - **Algorithms**: Predefined functions or operations.
 - **Iterators**: Objects that help traverse elements in the containers.
 - **Functor**: Classes that overload operator () to work as functions.

Functor

- **Stateful:** functors can store data; it has a “state”.

```
struct Adder {
    int offset; // can keep data here
    Adder(int off) : offset(off) {}
    int operator()(int x) const { return x + offset; }
};

int main() {
    Adder add5(5);           // create a functor that adds 5
    cout << add5(10) << endl; // calls add5.operator()(10); 15
    Adder addMinus2(-2);
    cout << addMinus2(7) << endl; // prints 5
    return 0;
}
```

Functor

- **Stateful:** functors can store data; it has a “state”.
- **Inlinable:** The compiler can optimize calls better through **pointers-to-functions**.

```
int add(int a, int b) { return a + b; }
int (*fp)(int,int); // fp is a pointer to a function
fp = &add; // or fp = add;
int result = fp(2,3); // same as add(2,3)

int apply(int x, int y, int (*op)(int,int)) { // callback?
    return op(x, y);
}
int mul(int a, int b) { return a*b; }
int main() {
    cout << apply(6, 7, add) << "\n"; // prints 13
    cout << apply(6, 7, mul) << "\n"; // prints 42
}
```

Another example:
as a **comparator**

Functor

- **Stateful:** functors can store data; it has a “state”.
- **Inlinable:** The compiler can optimize calls better through pointers-to-functions.
- **Extensible:** Can be “templated” for generic behavior.

```
template<typename T>
struct Mul {
    T factor;
    Mul(T f) : factor(f) {}

    T operator()(T x) const {
        return x * factor;
    }
};
```

```
int main() {
    Mul<double> times2(2.0);
    cout << times2(3.5); // prints 7.0
}
```

Containers

- Sequence Containers:
 - `vector`, `deque`, `list`, `array`
- Associative Containers:
 - `set`, `map`, `multiset`, `multimap`
- Unordered Containers:
 - `unordered_set`, `unordered_map`
- Container Adapters:
 - `stack`, `queue`, `priority_queue`

Containers

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Due to the matter of time, we will only briefly discuss some of them.

Refer to the official documents for more details.

Sequence Containers:

Elements are stored in an ordered fashion!

vector (#include<vector>)

Task	Example: std::vector<int>
Create a vector; 8 copies of zero; 5 copies of 3	vector<int> v; vector<int> v(8); vector<int> v(5, 3);
Add k to the end of a vector v	v.push_back(k)
Remove the last element in a vector v	v.pop_back();
Clear the vector	v.clear();
Get the element at index i	w = v.at(i); w = v[i];

Note:

```
std::vector<int> v = { 9, 7 };  
v[2] = 5; // undefined; out of bound
```

vector (contd.)

Task	Example: <code>std::vector<int></code>
Check if the vector is empty	<code>if (v.empty())</code>
Insert <code>w</code> at some index <code>i</code> of the vector	<code>v.insert(v.begin() + i, k)</code>
Remove the element at index <code>i</code> of the vector	<code>v.erase(v.begin() + i)</code>
Get the sublist in indices <code>[i, j]</code>	<code>vector<int>c(v.begin() + i, v.begin() + j);</code>
Request capacity for a vector	<code>v.reserve(100000);</code>

Note:

`v.begin()` and `v.end()` are iterators (we will introduce them later).

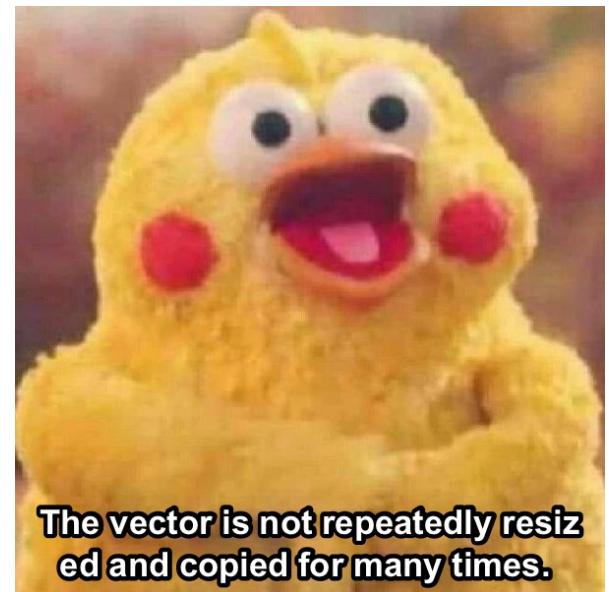
Benefit of `vector<T>.reserve()`

- **Example:** Create a vector of a large number of integers.

```
std::vector<int> v;
for (size_t i = 0; i < 1000000; ++i) {
    v.push_back(i);
}
```



```
std::vector<int> v;
v.reserve(1000000);
for (size_t i = 0; i < 1000000; ++i) {
    v.push_back(i);
}
```



deque: Similar to vector

```
(#include<deque>)
```

- deque (double-ended queue) supports faster insertion anywhere.

```
deque<int> dq{3, 4}; // {3, 4}
dq.push_front(2); // {2, 3, 4}
dq.pop_back(); // {2, 3}
dq[1] = 0; // {2, 0}
```

Note:

deque has push_front() and pop_front(), while vector doesn't.

array: fixed-size, contiguous container

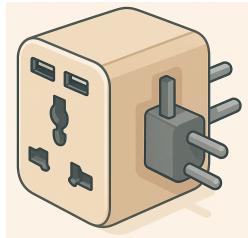
<https://en.cppreference.com/w/cpp/container/array>

- A container that encapsulates fixed size arrays.
- The size is part of its template type variable.

```
std::array<int, 5> a = {{1, 2, 3, 4, 5}};
```

- Functionality:
size(), empty(), front(), back(), operator[], at(),
and iterators—all in **constant time**.

Container Adapters



- A wrapper of an (other STL) object that changes **how external users can interact with that object.**
- It modifies or restricts the **interface** of existing sequence containers (vector, deque, list) to provide a **specialized behavior**.
- Examples: stack, queue, priority_queue
 - Will be introduced in *Data Structures* course in detail.

Stack

(#include<stack>)

<https://cplusplus.com/reference/stack/stack/>

- Implementation of LIFO (last-in-first-out) structure.

std::stack<T>

class template

std::stack

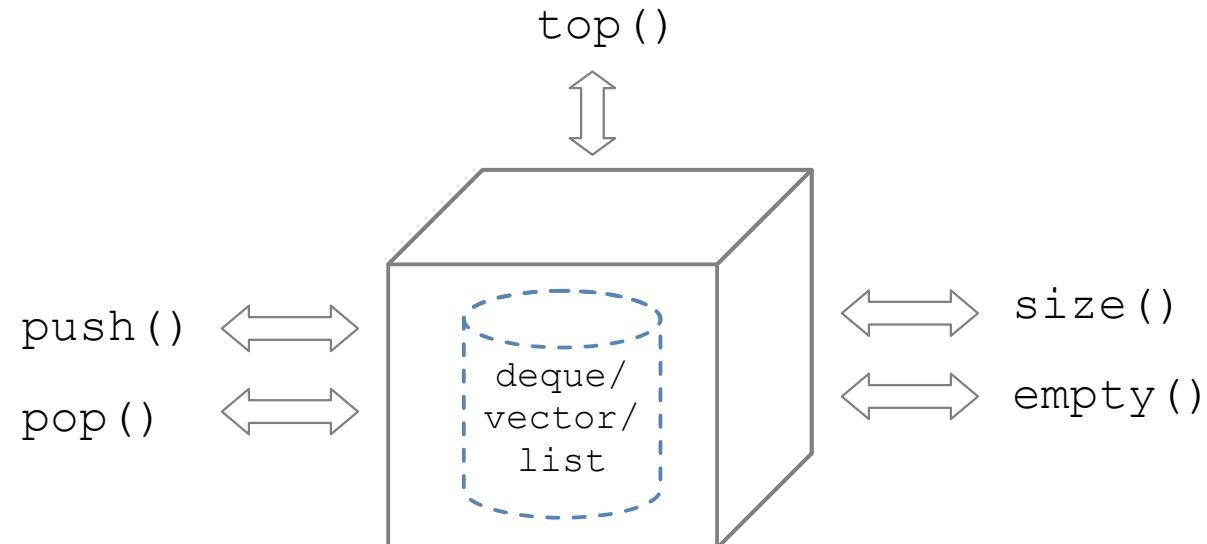
<stack>

template <class T, class Container = deque<T>> class stack;

LIFO stack

Stacks are a type of container adaptor, specifically designed to operate in a LIFO context (last-in first-out), where elements are inserted and extracted only from one end of the container.

Stacks are implemented as **container adaptors**, which are classes that use an encapsulated object of a specific container class as its **underlying container**, providing a specific set of member functions to access its elements. Elements are **pushed/popped** from the "**back**" of the specific container, which is known as the **top** of the stack.



Illustrating Examples

class template

std::stack

```
template <class T, class Container = deque<T> > class stack;
```

```
// Container = std::deque
std::stack<int> stack_deq;
// Container = std::vector
std::stack<int, std::vector<int>> stack_vec;
// Container = std::list
std::stack<int, std::list<int>> stack_list;
```

Queue

(#include<queue>)

<https://cplusplus.com/reference/queue/queue/>

- Implementation of FIFO (first-in-first-out) structure.

`std::queue<T>`

class template

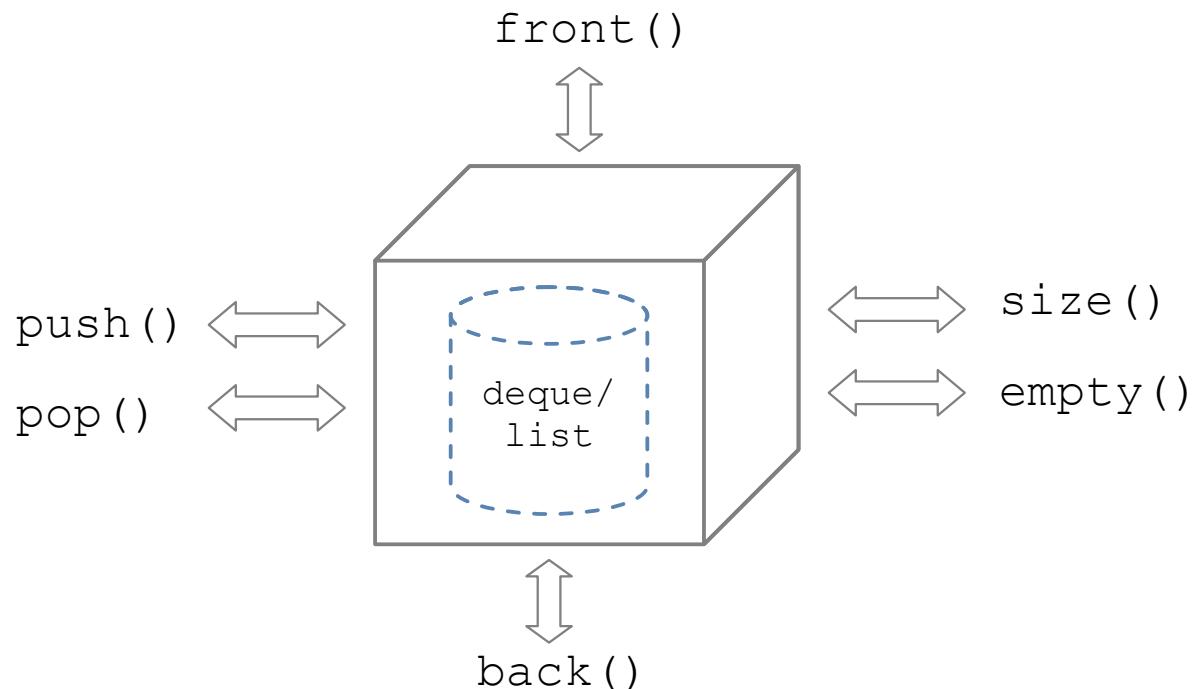
std::queue

template <class T, class Container = deque<T>> class queue;

FIFO queue

queues are a type of container adaptor, specifically designed to operate in a FIFO context (first-in first-out), where elements are inserted into one end of the container and extracted from the other.

queues are implemented as **containers adaptors**, which are classes that use an encapsulated object of a specific container class as its **underlying container**, providing a specific set of member functions to access its elements. Elements are **pushed** into the "**back**" of the specific container and **popped** from its "**front**".



priority_queue

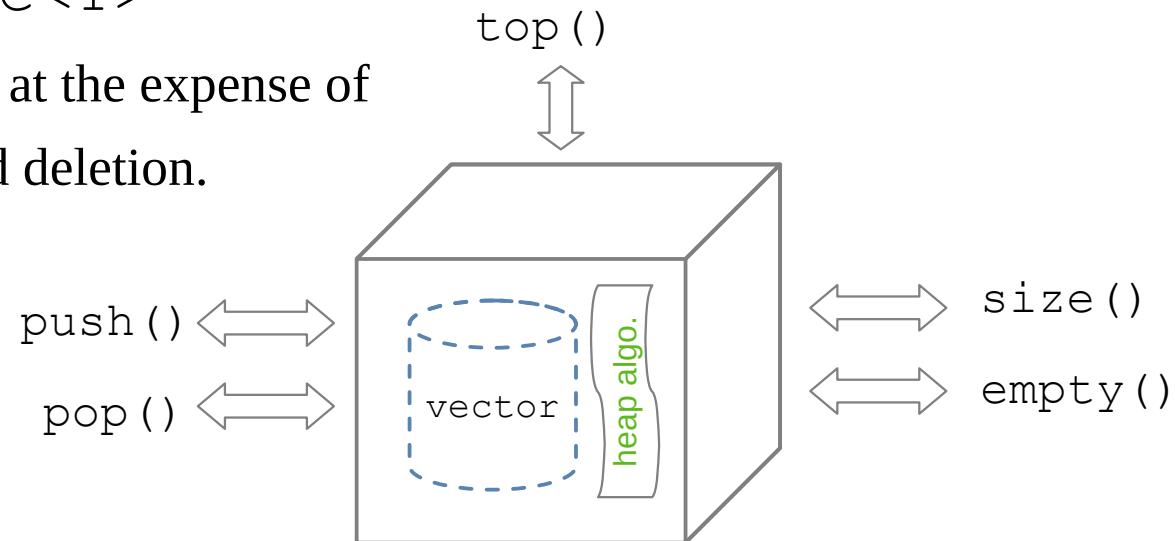
(#include<queue>)

https://cplusplus.com/reference/queue/priority_queue/?kw=priority_queue

- Implementation of heap-based priority queue structure.
 - Elements are ranked based on a certain priority.

`std::priority_queue<T>`

- It supports constant time lookup at the expense of logarithmic time of insertion and deletion.



priority_queue

https://cplusplus.com/reference/queue/priority_queue/

class template

std::priority_queue

<queue>

template <class T, class Container = vector<T>, class Compare = less<typename Container::value_type> > class priority_queue;

Priority queue

Priority queues are a type of container adaptors, specifically designed such that its first element is always the greatest of the elements it contains, according to some **strict weak ordering** criterion.

This context is similar to a **heap**, where elements can be inserted at any moment, and only the **max heap** element can be retrieved (the one at the top in the **priority queue**).

Priority queues are implemented as **container adaptors**, which are classes that use an encapsulated object of a specific container class as its **underlying container**, providing a specific set of member functions to access its elements. Elements are **popped** from the "**back**" of the specific container, which is known as the **top** of the priority queue.

Example: priority_queue of students

```
struct Student {  
    std::string name;  
    double math;  
    double science;  
    double english;  
  
    // Return the sum of the three scores.  
    double total() const {  
        return math + science + english;  
    }  
    // Define "<" based on the total score  
    // priority_queue puts the largest element on top  
    bool operator<(const Student &other) const {  
        return this->total() < other.total();  
    }  
};
```

Example (contd.)

```
int main() {
    std::vector<Student> students = {
        {"Alice",     85.5, 92.0, 78.0},
        {"Bob",       90.0, 88.5, 91.0},
        {"Charlie",   70.0, 75.0, 80.0},
        {"Diana",     95.0, 85.0, 89.5},
        {"Evan",      88.0, 90.5, 92.0}
    };

    // Use the default comparator which
    // will call Student::operator<
    // internally.
    std::priority_queue<Student> pq;
    for (const auto &s : students) {
        pq.push(s);
    }
}
```

```
// Extract and print the top 3 students
for (int r = 1; r <= 3 && !pq.empty(); ++r)
{
    const auto &s = pq.top();
    cout << rank << ". " << s.name
        << " (Total: " << s.total()
        << ") \n";
    pq.pop();
}
```

https://onlinegdb.com/pCE_M4FCF

Associative Containers:

Elements are organized and managed automatically using **keys**!

Elements are stored using a specific ordering mechanism so that it's more efficient for searching, insertion and deletion

map (#include<map>)

Task	Example: std::map<int, char>
Create a map	map<int, char> m;
Add key k with value v into the map	m.insert({k, v}); m[k] = v;
Remove key k from the map	m.erase(k);
Check if key k is in the map	if (m.count(k))
Check if the map is empty	if (m.empty())
Retrieve or overwrite value associated with key k	char c = m[k]; m[k] = v;
Find the index of an element	auto it = m.find(k);

Note: Actually, the underlying type stored in `std::map<K, V>` is `std::pair<const K, V>`

Comparison operator is required for map (also for set)

```
class Person {  
public:  
    std::string name;  
    int age;  
    Person(std::string n, int a) : name(n), age(a) {}  
};
```

```
std::map<int, int> map1; // OKAY - comparable  
std::map<Person, int> map2; // ERROR - not comparable  
// No operator < defined for Person!
```

A Solution

```
struct Person {
    std::string name;
    int age;
    Person(std::string n, int a) : name(n), age(a) {}

    bool operator<(Person const& other) const {
        if (name < other.name)           // compare names first
            return true;
        else if (other.name < name)     // if this name is greater
            return false;
        else                           // names are equal, compare ages
            return age < other.age;
    }
};
```

<https://onlinegdb.com/nIMMCpknXM>

Example

<https://onlinegdb.com/zLs4ysyUxK>

```
map<string,int> freq;
vector<string> words;
string tmp;
// reading some words
while (cin >> tmp) {
    words.push_back(tmp);
}

for (auto& w : words) {
    // freq[w] is 0 initially
    freq[w]++;
}

for (const auto& [key, count] : freq) {
    cout << key << " -> " << count
        << endl;
}
// structured bindings only available
// with '-std=c++17'
```

```
string query = "banana";
auto it = freq.find(query);

if (it != freq.end()) {
    cout << "Found \""
        << "\" : " << it->second
        << endl;
} else {
    cout << "\\" << query
        << "\\" not found\n";
}
// Erase the key "orange" from freq
freq.erase("orange");
```

Iterators

Have a look at looping over a collection

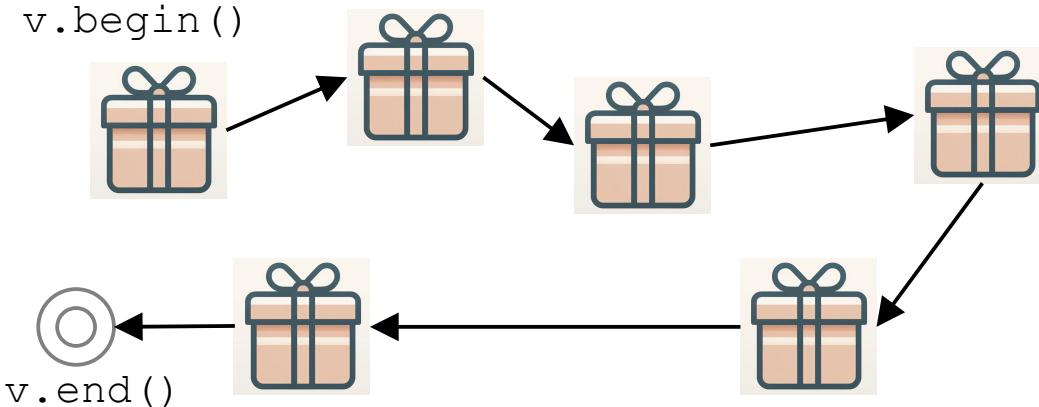
```
std::vector<int> v{5, 4, 3, 2, 1, 0};  
for (size_t i=0; i < v.size(); i++) { // looks good!  
    const auto& e = v[i];  
    cout << e << endl;  
}  
// The following way looks great, too.  
for (auto &e: v) {  
    cout << e << endl;  
}  
// But how about looping over a set or a map?  
// some_element++?? What does ++ mean here?
```

Note: Structured binding is available in C++17, not C++11.

```
std::map<int, char> m;  
for (const auto& [key, value]: m) // structure binding here  
    // work with key, value ...
```

Iterators

- Iterator can help in iterating over ANY container.
- It becomes more flexible and consistent to traverse and manipulate elements in a container (say v).
- The iterator always knows “the next element”.

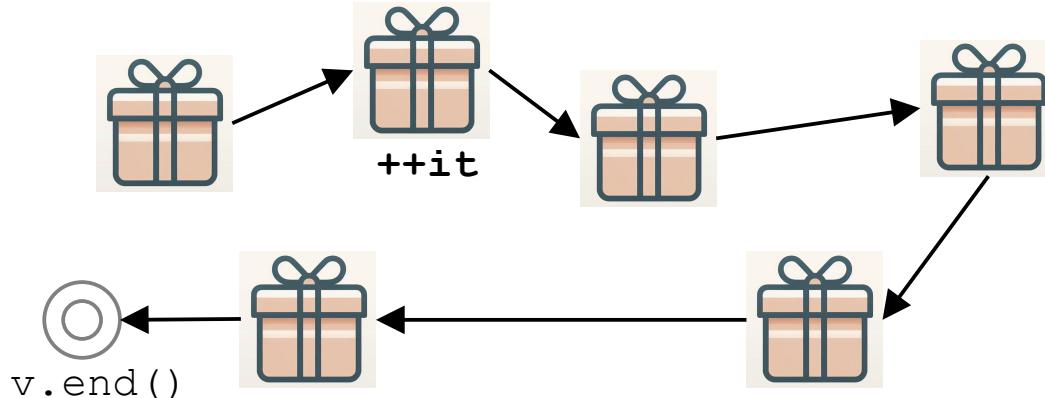


```
auto it = v.begin()
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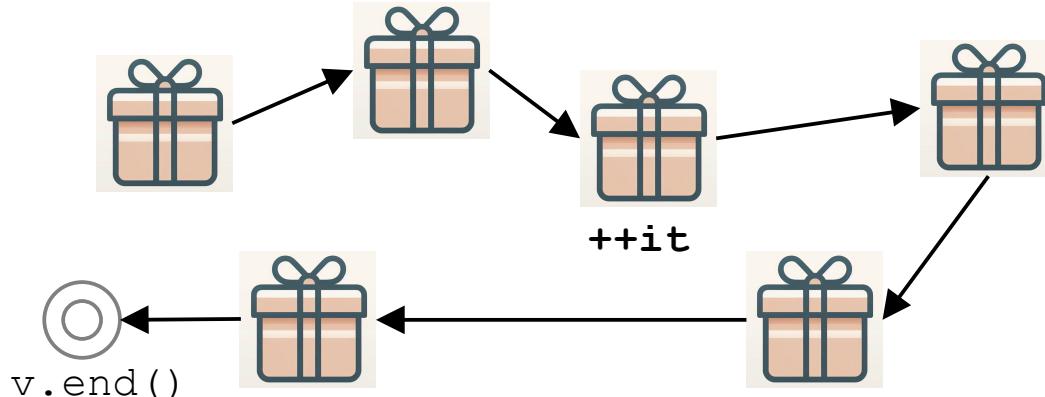


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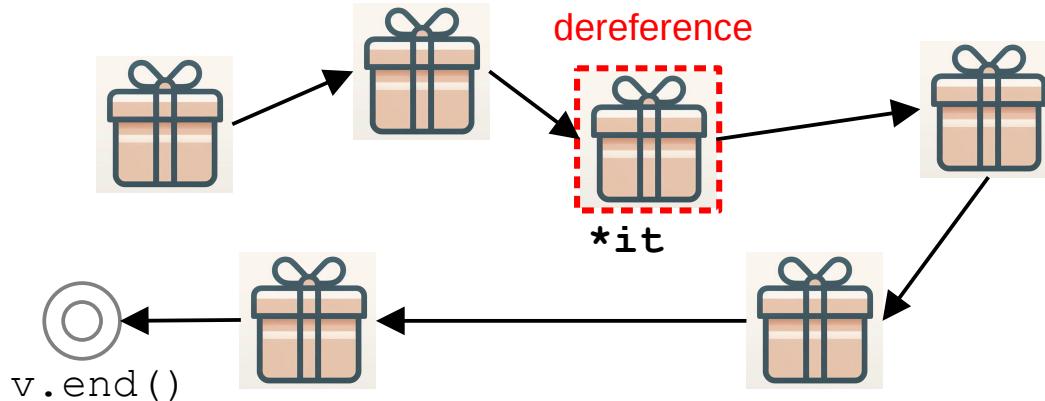


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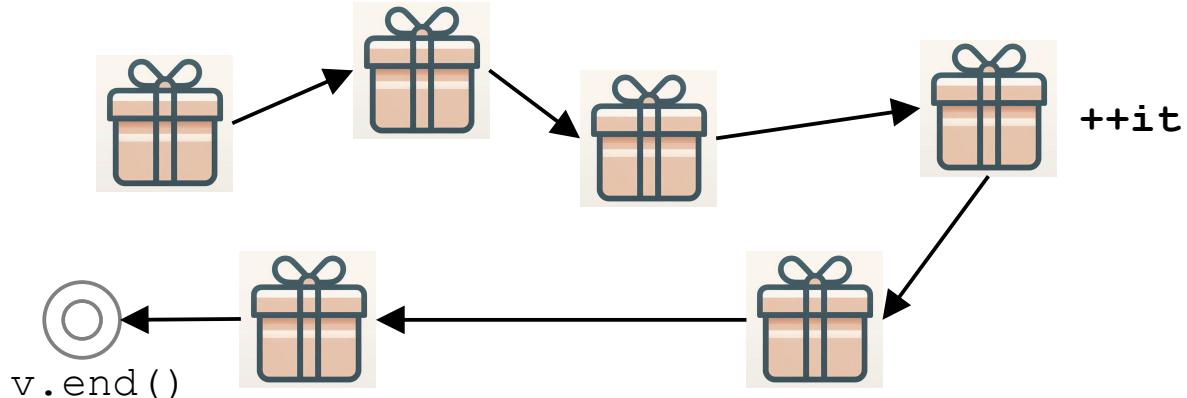


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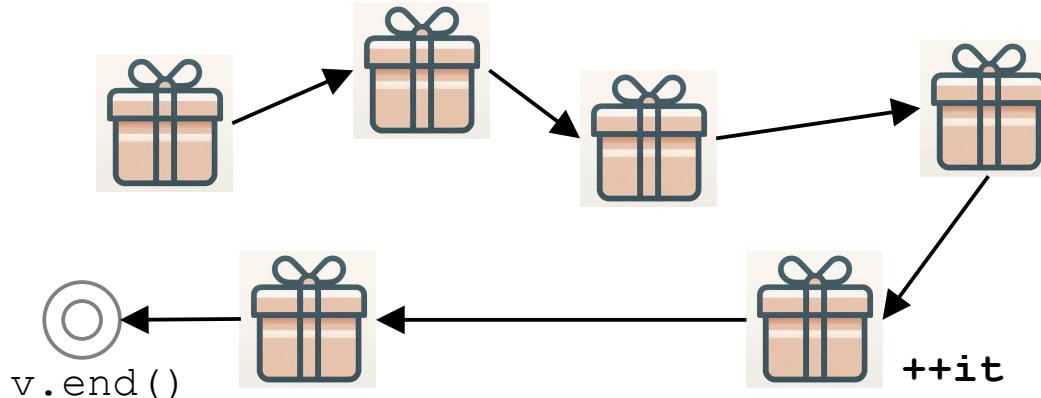


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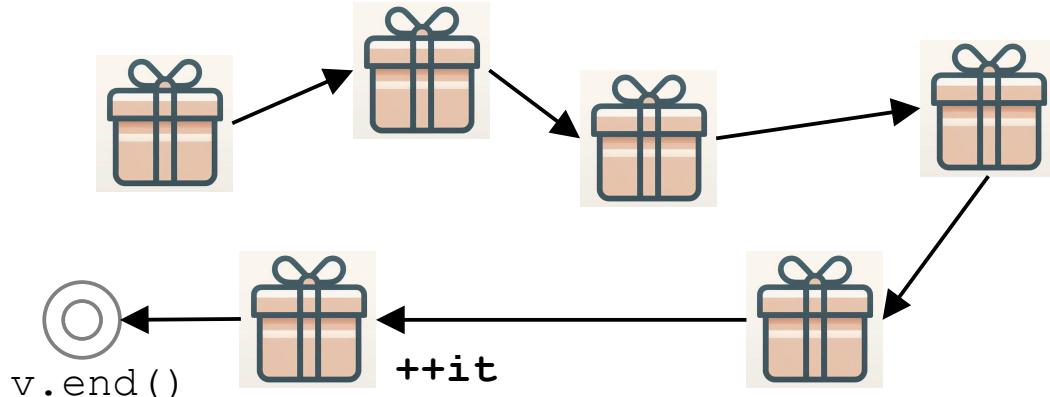


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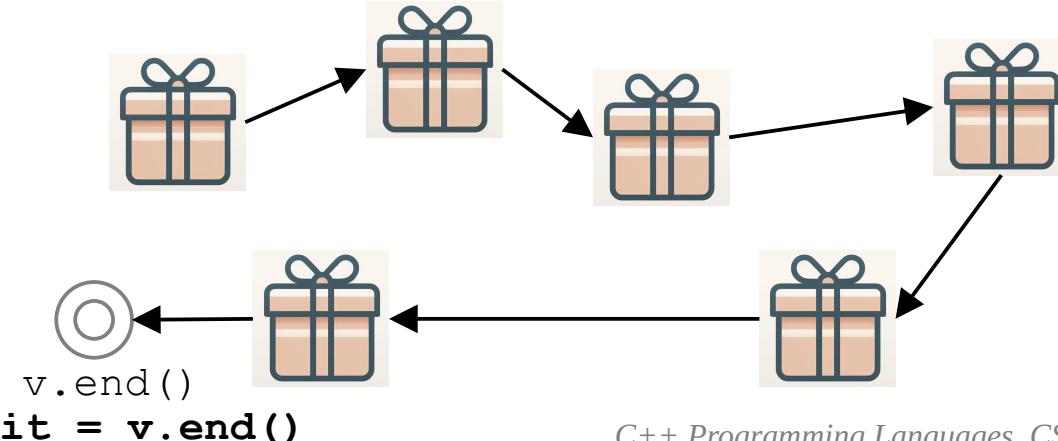


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```
auto it = v.begin()
```

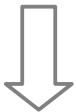


Why use `++it` instead of `it++`?

- `++it` increments the iterator first and then returns the updated iterator.
- `it++` returns the current iterator first, and then increments it.
 - An extra step is required here! We have to store a copy of the original iterator!
- However, it still depends on the scenario.

Example: Printing all elements in a map

```
std::map<int, int> map {{1, 6}, {1, 8}, {0, 3}, {3, 9}};
for (auto iter = map.begin(); iter != map.end(); ++iter) {
    const auto& [key, value] = *iter; // structured binding!
    cout << key << ":" << value << endl;
}
```



```
std::map<int, int> map {{1, 6}, {1, 8}, {0, 3}, {3, 9}};
for (auto iter = map.begin(); iter != map.end(); ++iter) {
    const auto& key = (*iter).first; //resolving the issue in C++11
    const auto& value = (*iter).second;
    cout << key << ":" << value << endl;
}
```

Example: 3Sum (LeetCode)

<https://leetcode.com/problems/3sum/>

15. 3Sum

Solved 

 Medium  Topics  Companies  Hint

Given an integer array `nums`, return all the triplets `[nums[i], nums[j], nums[k]]` such that `i != j`, `i != k`, and `j != k`, and `nums[i] + nums[j] + nums[k] == 0`.

Notice that the solution set must not contain duplicate triplets.

Example 1:

Input: `nums = [-1,0,1,2,-1,-4]`

Output: `[[-1,-1,2],[-1,0,1]]`

Explanation:

`nums[0] + nums[1] + nums[2] = (-1) + 0 + 1 = 0.`

`nums[1] + nums[2] + nums[4] = 0 + 1 + (-1) = 0.`

`nums[0] + nums[3] + nums[4] = (-1) + 2 + (-1) = 0.`

The distinct triplets are `[-1,0,1]` and `[-1,-1,2]`.

Notice that the order of the output and the order of the triplets does not matter.

Example 2:

Input: `nums = [0,1,1]`

Output: `[]`

Explanation: The only possible triplet does not sum up to 0.

Example 3:

Input: `nums = [0,0,0]`

Output: `[[0,0,0]]`

Explanation: The only possible triplet sums up to 0.



The screenshot shows a code editor window with a yellow border. The title bar says "Code". The language dropdown says "C++". The code area contains the following C++ code:

```
</> Code
C++ < Auto
1 class Solution {
2 public:
3     vector<vector<int>> threeSum(vector<int>& nums) {
4
5
6 }
```

Example: 3Sum (LeetCode)

- A brute-force solution

```
class Solution {
public:
    vector<vector<int>> threeSum(vector<int>& nums) {
        int len = nums.size();
        if(len==0 || len<3) // at least three elements needed
            return {};
        set<vector<int>> s; // "set" stores unique elements only
                             // duplicate triplets will not be added
        sort(nums.begin(),nums.end());
        // Compare all cases of group of three elements
        for(int i=0;i<len-2;i++){
            for(int j=i+1;j<len-1;j++) {
                for(int k=j+1;k<len;k++) {
                    if(nums[i]+nums[j]+nums[k]==0) {
                        s.insert({nums[i],nums[j],nums[k]});
                    }
                }
            }
        }
        // Insert all unique triplets in result vector
        vector<vector<int>> ans(s.begin(),s.end());
        return ans;
    }
};
```

Example: 3Sum (LeetCode)

<https://leetcode.com/problems/3sum/>

- <https://onlinegdb.com/q5n8kg7ku>

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

using namespace std;
```

- `upper_bound()`:
 - find the **first** element in a sorted range that is **strictly greater** than a given value

```
1 #include <iostream>
2 #include <vector>
3 #include <algorithm>
4
5 using namespace std;
6
7 class Solution {
8 public:
9     vector<vector<int>> threeSum(vector<int>& nums) {
10     //preprocessing
11     int countPos = 0, countNeg = 0, countZero = 0;
12     for (auto it = nums.begin(); it != nums.end(); ++it) {
13         if (*it > 0) {
14             countPos = 1;
15         } else if (*it < 0) {
16             countNeg = 1;
17         } else { // *it == 0
18             countZero++;
19         }
20     }
21     // after preprocessing
22     vector<int>::iterator start, fpos, searchEnd;
23     vector<vector<int>> result = {};
24     if (countPos + countNeg < 2) {
25         if (countZero > 2) return {{0,0,0}};
26         else return {};
27     }
28     sort(nums.begin(), nums.end());
29     for (auto start = nums.begin(); start < nums.end() - 2; ++start) {
30         searchEnd = nums.end();
31         if (start > nums.begin() && *start == *(start-1)) continue;
32         for (auto mid = start+1; mid < searchEnd - 1; ++mid) {
33             if (mid > start+1 && *mid == *(mid-1)) continue;
34             fpos = upper_bound(mid+1, searchEnd, -(*start)-(*mid));
35             if (*fpos == -(*start)-(*mid) && fpos > mid+1) {
36                 result.push_back({*start, *mid, -(*start)-(*mid)});
37                 searchEnd = fpos;
38             } //else searchEnd -= 1;
39             if (fpos <= mid+1) break;
40         }
41     }
42 }
43 return result;
44 }
```

Example: 3Sum (LeetCode)

<https://leetcode.com/problems/3sum/>

- <https://onlinegdb.com/q5n8kg7ku>

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

using namespace std;
```

- `upper_bound()`:
 - find the **first** element in a sorted range that is **strictly greater** than a given value

```
1 #include <iostream>
2 #include <vector>
3 #include <algorithm>
4
5 using namespace std;
6
7 class Solution {
8 public:
9     vector<vector<int>> threeSum(vector<int>& nums) {
10         //preprocessing
11         int countPos = 0, countNeg = 0, countZero = 0;
12         for (auto it = nums.begin(); it != nums.end(); ++it) {
13             if (*it > 0) {
14                 countPos = 1;
15             } else if (*it < 0) {
16                 countNeg = 1;
17             } else { // *it == 0
18                 countZero++;
19             }
20         }
21         // ...
22     }
23 }
```

Example: 3Sum (LeetCode)

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

using namespace std;
```

- `upper_bound()`:
 - find the **first** element in a sorted range that is **strictly greater** than a given value

```
21 // after preprocessing
22 vector<int>::iterator start, fpos, searchEnd;
23 vector<vector<int>> result = {};
24 if (countPos + countNeg < 2) {
25     if (countZero > 2) return {{0,0,0}};
26     else return {};
27 }
28 sort(nums.begin(), nums.end());
29 for (auto start = nums.begin(); start < nums.end()-2; ++start) {
30     searchEnd = nums.end();
31     if (start > nums.begin() && *start == *(start-1)) continue;
32     for (auto mid = start+1; mid < searchEnd - 1; ++mid) {
33         if (mid > start+1 && *mid == *(mid-1)) continue;
34         fpos = upper_bound(mid+1, searchEnd, -(*start)-(*mid));
35         if (*fpos-1) == -(*start)-(*mid) && fpos>mid+1) {
36             result.push_back({*start, *mid, -(*start)-(*mid)});
37             searchEnd = fpos;
38         } //else searchEnd -= 1;
39         if (fpos<=mid+1) break;
40     }
41 }
42 return result;
43 }
44 }
```

Example: 3Sum (LeetCode)

<https://leetcode.com/problems/3sum/>

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```
#include <iostream>
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- `upper_bound()`:
 - find the **first** element in a sorted range that is **strictly greater** than a given value

Accepted 314 / 314 testcases passed
josephcclin submitted at Apr 24, 2025 21:12

Editorial

Solution

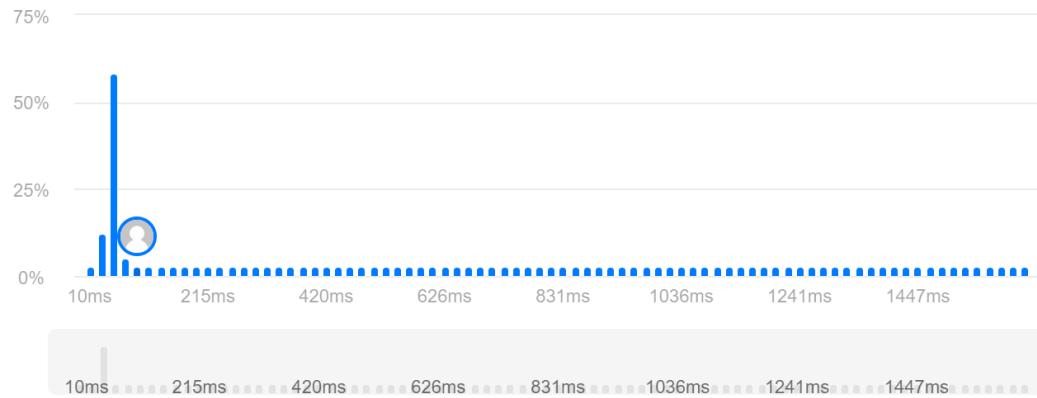
Runtime

110 ms | Beats 21.73%

Analyze Complexity

Memory

29.24 MB | Beats 43.67%



Example: 3Sum (LeetCode)

- Can be even efficient.
- Try on your own.



Exercise: Two Sum

- How about this easy exercises?

1. Two Sum

Easy Topics Companies Hint

Given an array of integers `nums` and an integer `target`, return *indices of the two numbers such that they add up to `target`*.

You may assume that each input would have **exactly one solution**, and you may not use the same element twice.

You can return the answer in any order.

Example 1:

Input: `nums = [2,7,11,15]`, `target = 9`
Output: `[0,1]`

Explanation: Because `nums[0] + nums[1] == 9`, we return `[0, 1]`.

Example 2:

Input: `nums = [3,2,4]`, `target = 6`
Output: `[1,2]`

Example 3:

Input: `nums = [3,3]`, `target = 6`
Output: `[0,1]`

Constraints:

- $2 \leq \text{nums.length} \leq 10^4$
- $-10^9 \leq \text{nums}[i] \leq 10^9$
- $-10^9 \leq \text{target} \leq 10^9$
- Only one valid answer exists.

<https://leetcode.com/problems/two-sum/description/?difficulty=EASY>

</> Code

C++ Auto

```
1 class Solution {
2 public:
3     vector<int> twoSum(vector<int>& nums, int target) {
4
5
6 };
```

Discussions & Questions