Introduction to C++ STL (Standard Template Library)

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What is the C++ STL?

Alexander Stepanov

The Standard Template Library (**STL**) is a **C++** framework consisting in **template-based** classes and algorithms that implement mostly used data structures and common tasks.

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Roughly speaking:

16 containers (data structures)

~90 algorithms

+ utilities

Why we care about STL

- Because we will use `C++` in this course.
- You do not have to re-invent the wheel.
- Learn more about `C++`.

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You **must** consult sources like:
http://www.cplusplus.com/
http://en.cppreference.com/

STL goal

Generic programming: code once, re-use many times.

Increase correctness.

Wider range of uses.

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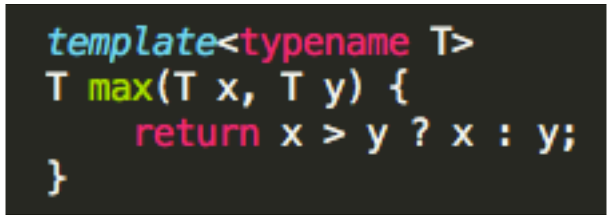
C++ templates

function templates



```
template<typename T>
T max(T x, T y) {
    return x > y ? x : y;
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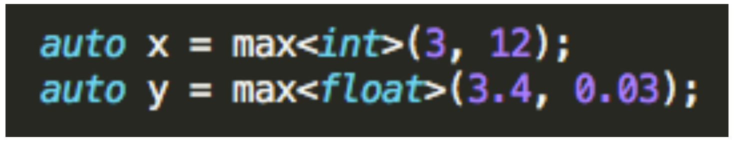
```



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auto x = max<int>(3, 12);
auto y = max<float>(3.4, 0.03);
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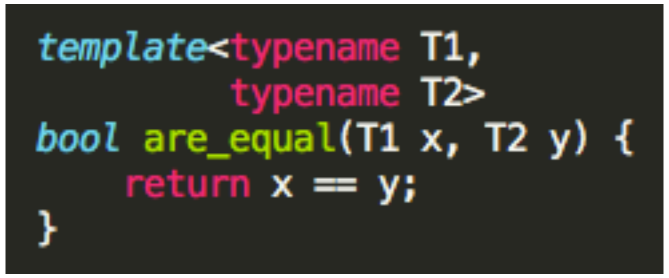

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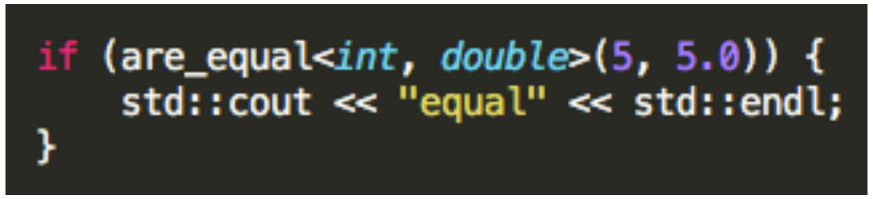

```
if (are_equal<int, double>(5, 5.0)) {
    std::cout << "equal" << std::endl;
}
```

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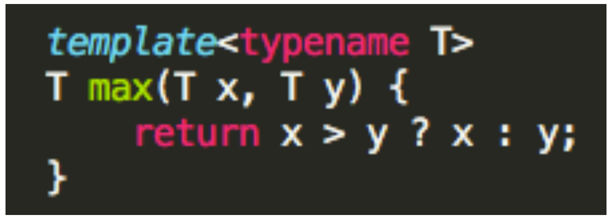
C++ templates

function templates ← **C++ templates** → **class** templates



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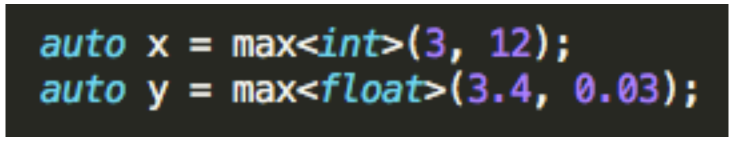

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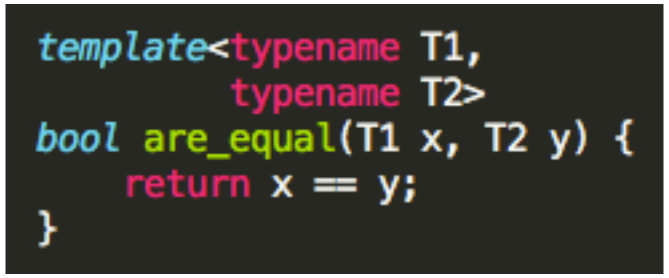

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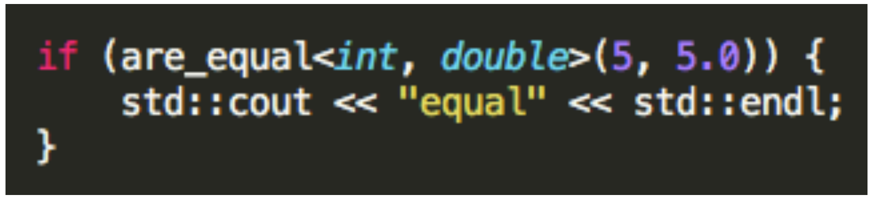

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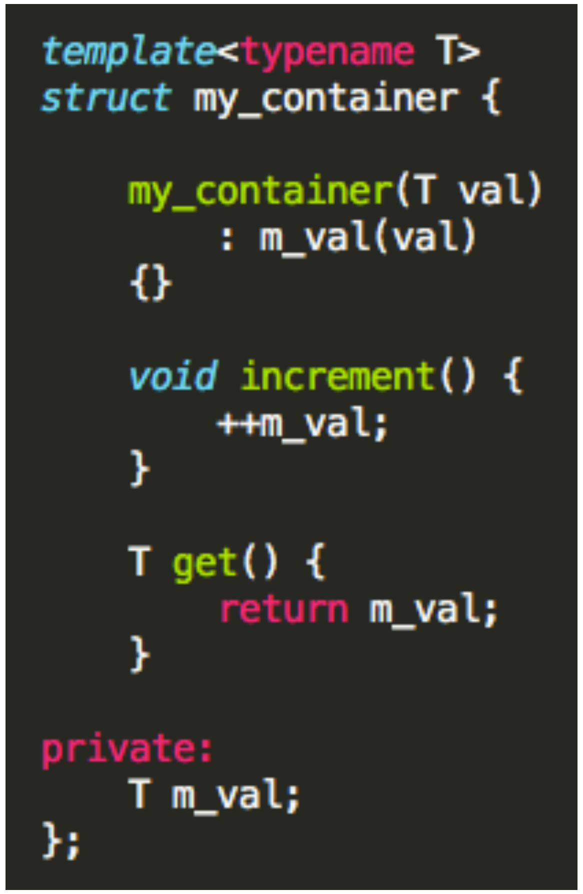

```
template<typename T>
struct my_container {

    my_container(T val)
        : m_val(val)
    {}

    void increment() {
        ++m_val;
    }

    T get() {
        return m_val;
    }

private:
    T m_val;
};
```

STL goal

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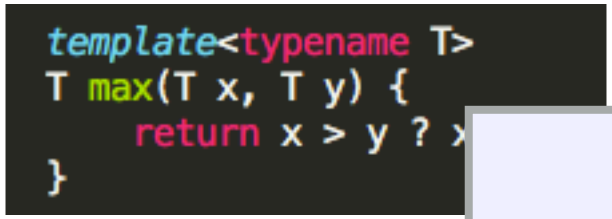

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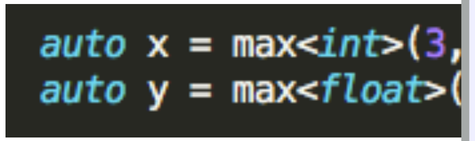

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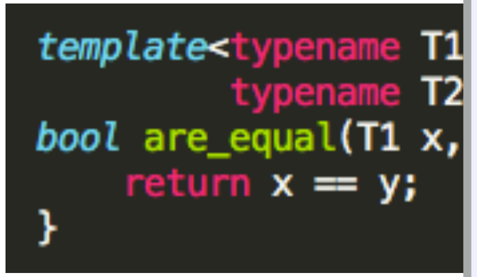

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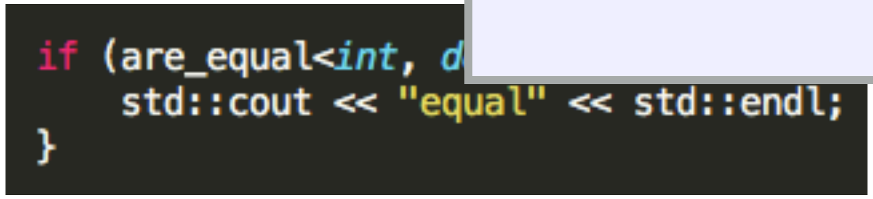

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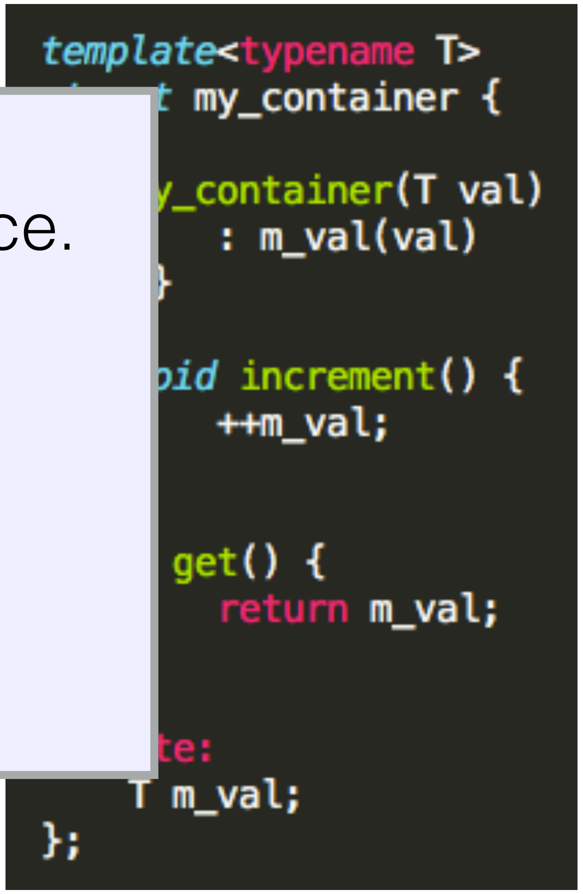
class templates



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Trade-off between reusability and performance.

Experiment by yourself.
Try to understand **why**.

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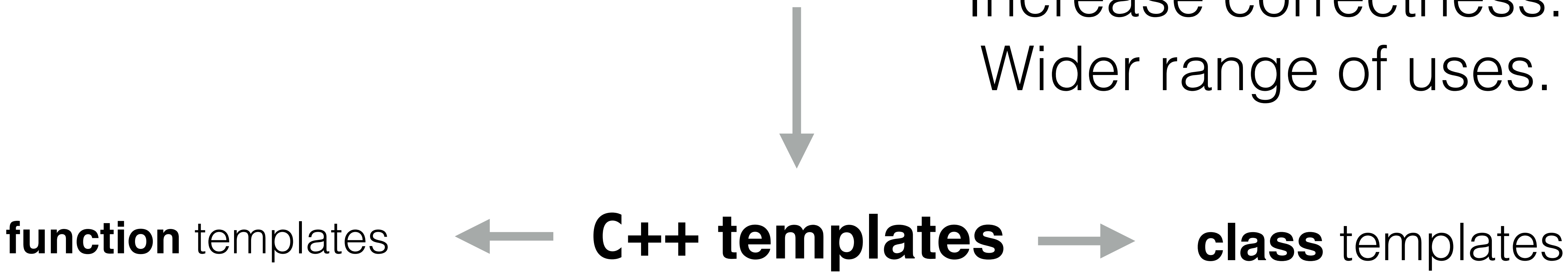

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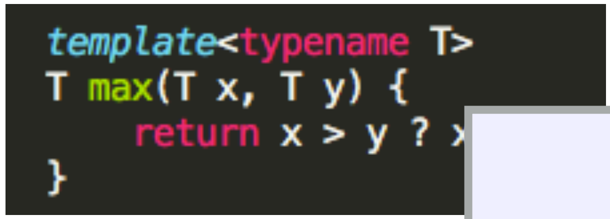

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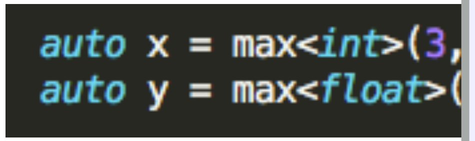

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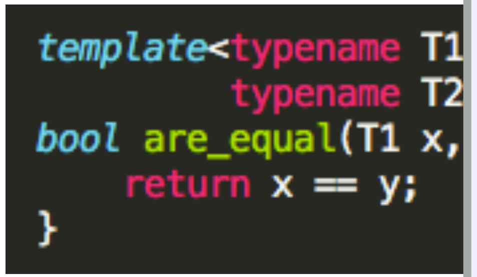

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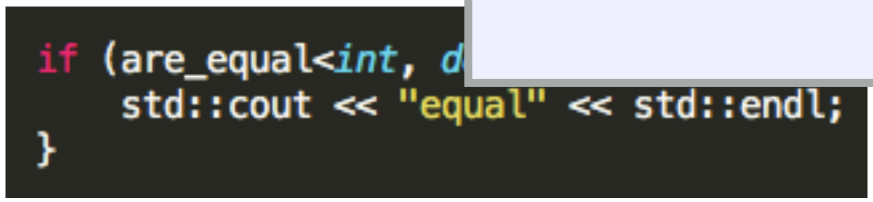

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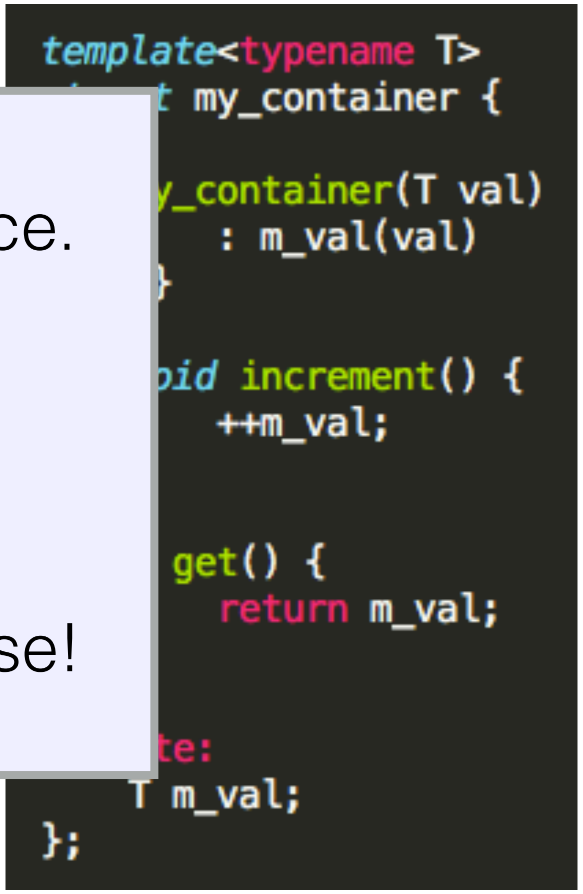

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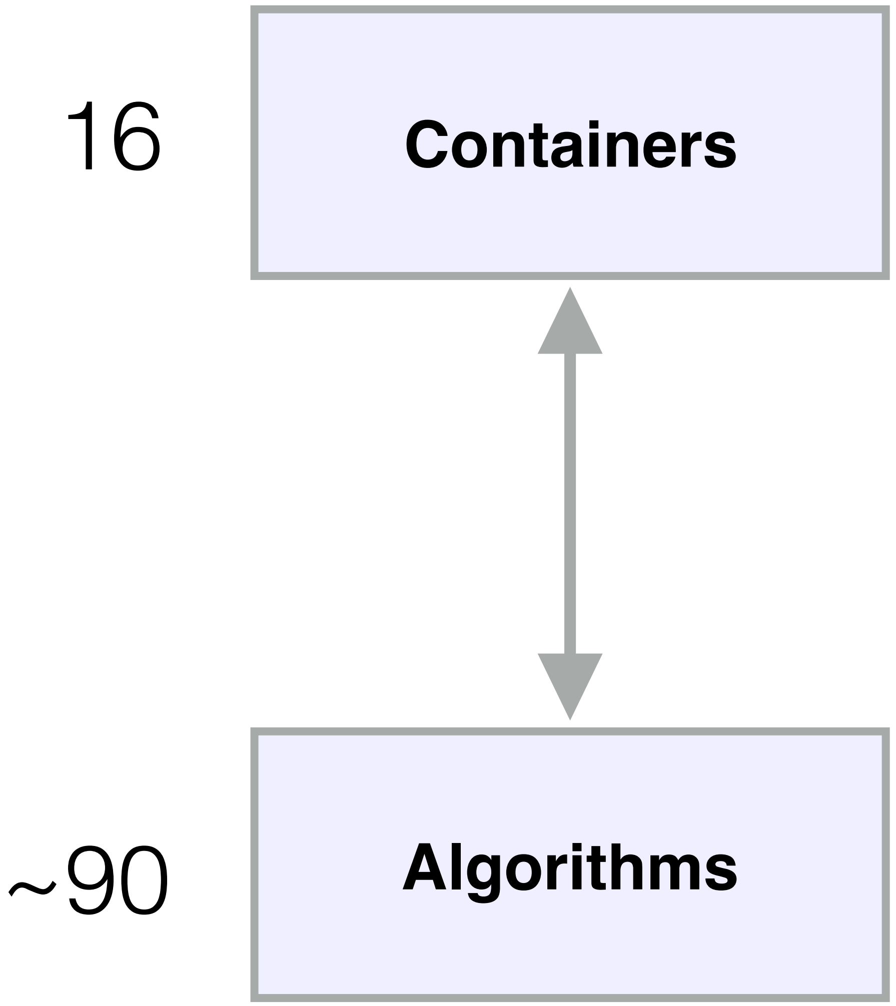
Try to understand **why**.

Indeed one of the goals of ours for this course!

STL basic model

Separation of concerns



16

Containers

Store data;
do not know
about algorithms.

~90

Algorithms

Manipulate data;
do not know
about containers.

STL basic model

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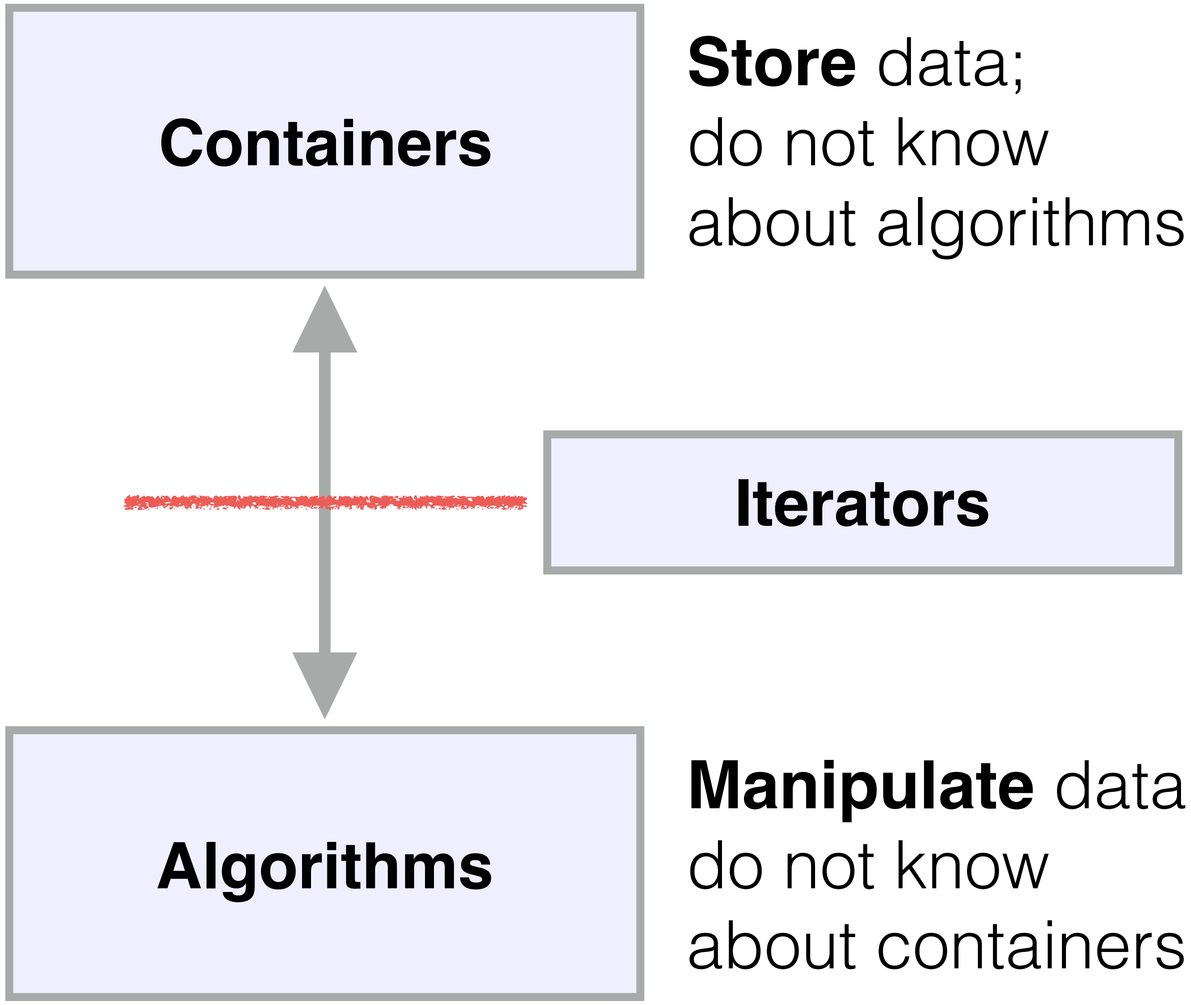

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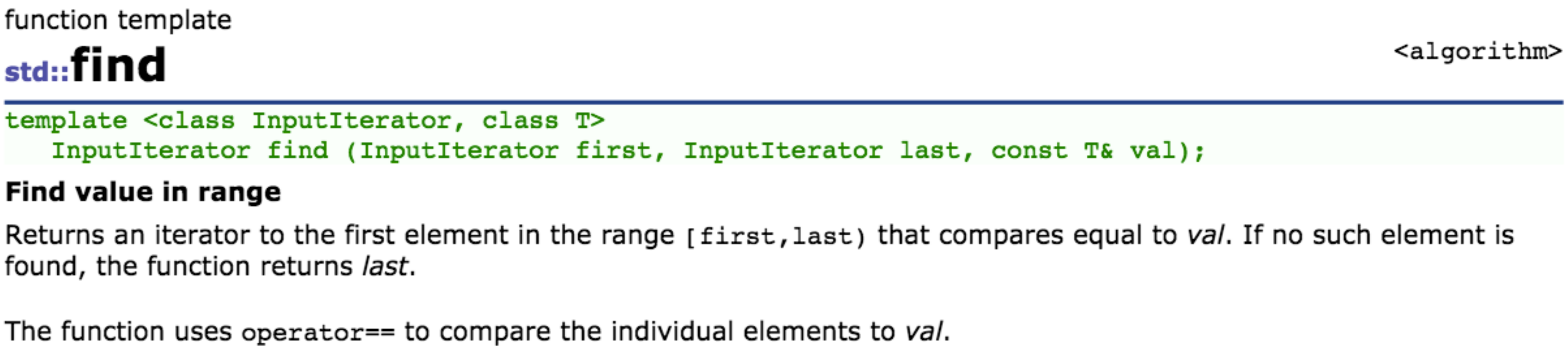
An example

[source: http://www.cplusplus.com]



function template

std::find

<algorithm>

```
template <class InputIterator, class T>
   InputIterator find (InputIterator first, InputIterator last, const T& val);
```

Find value in range

Returns an iterator to the first element in the range `[first,last)` that compares equal to *val*. If no such element is found, the function returns *last*.

The function uses `operator==` to compare the individual elements to *val*.

An example

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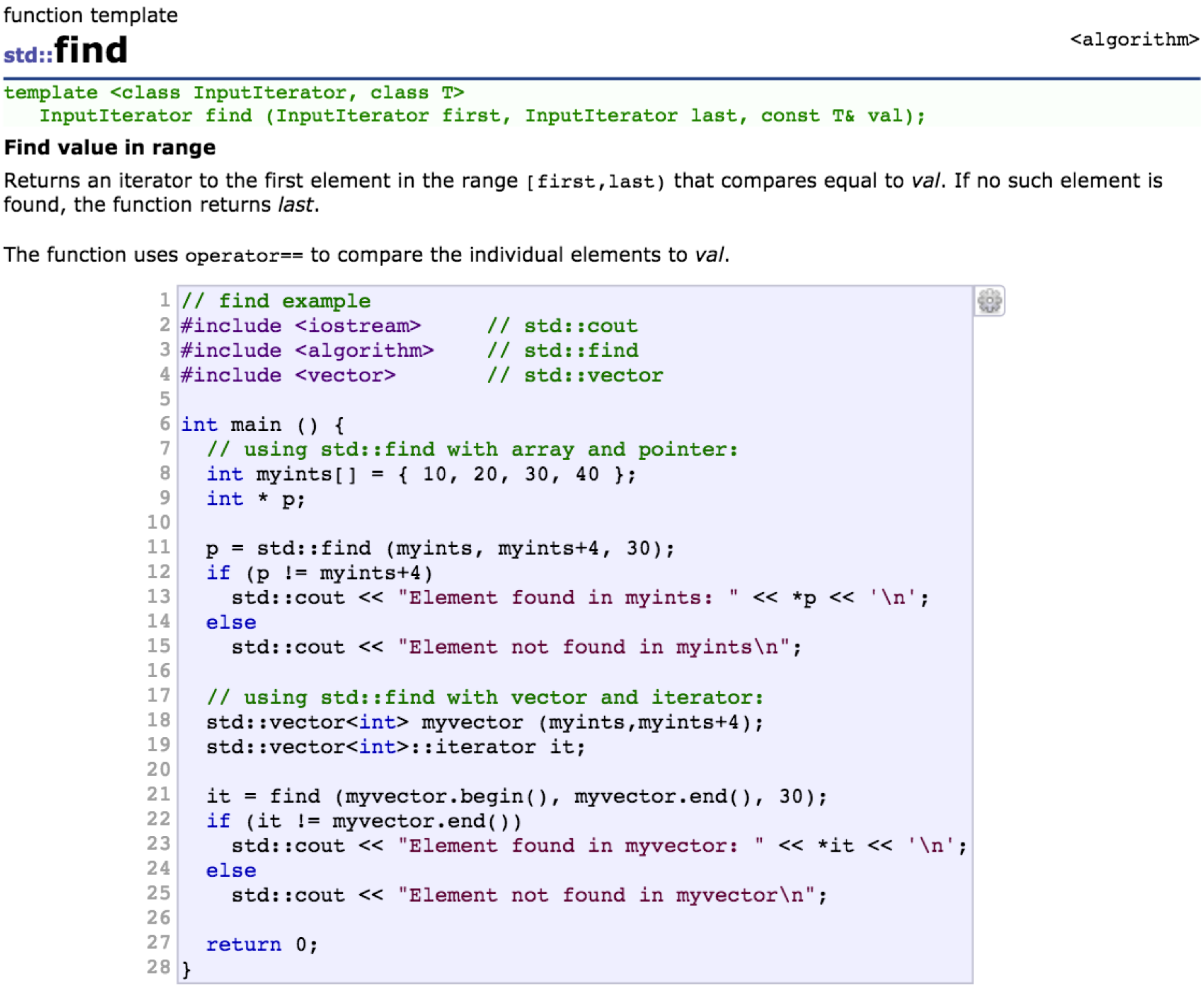

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```
// find example
#include <iostream>     // std::cout
#include <algorithm>    // std::find
#include <vector>       // std::vector

int main () {
  // using std::find with array and pointer:
  int myints[] = { 10, 20, 30, 40 };
  int * p;

  p = std::find (myints, myints+4, 30);
  if (p != myints+4)
    std::cout << "Element found in myints: " << *p << '\n';
  else
    std::cout << "Element not found in myints\n";

  // using std::find with vector and iterator:
  std::vector<int> myvector (myints,myints+4);
  std::vector<int>::iterator it;

  it = find (myvector.begin(), myvector.end(), 30);
  if (it != myvector.end())
    std::cout << "Element found in myvector: " << *it << '\n';
  else
    std::cout << "Element not found in myvector\n";

  return 0;
}
```

Containers

A container is a holder object that stores a **collection** of other objects (its elements). These are implemented as **class templates**.
The container manages the **storage space** for its elements and provides member functions to access them, either directly or through iterators.

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deque
list
```

```
set
multiset
map
multimap
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stack
queue
priority_queue
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sequential

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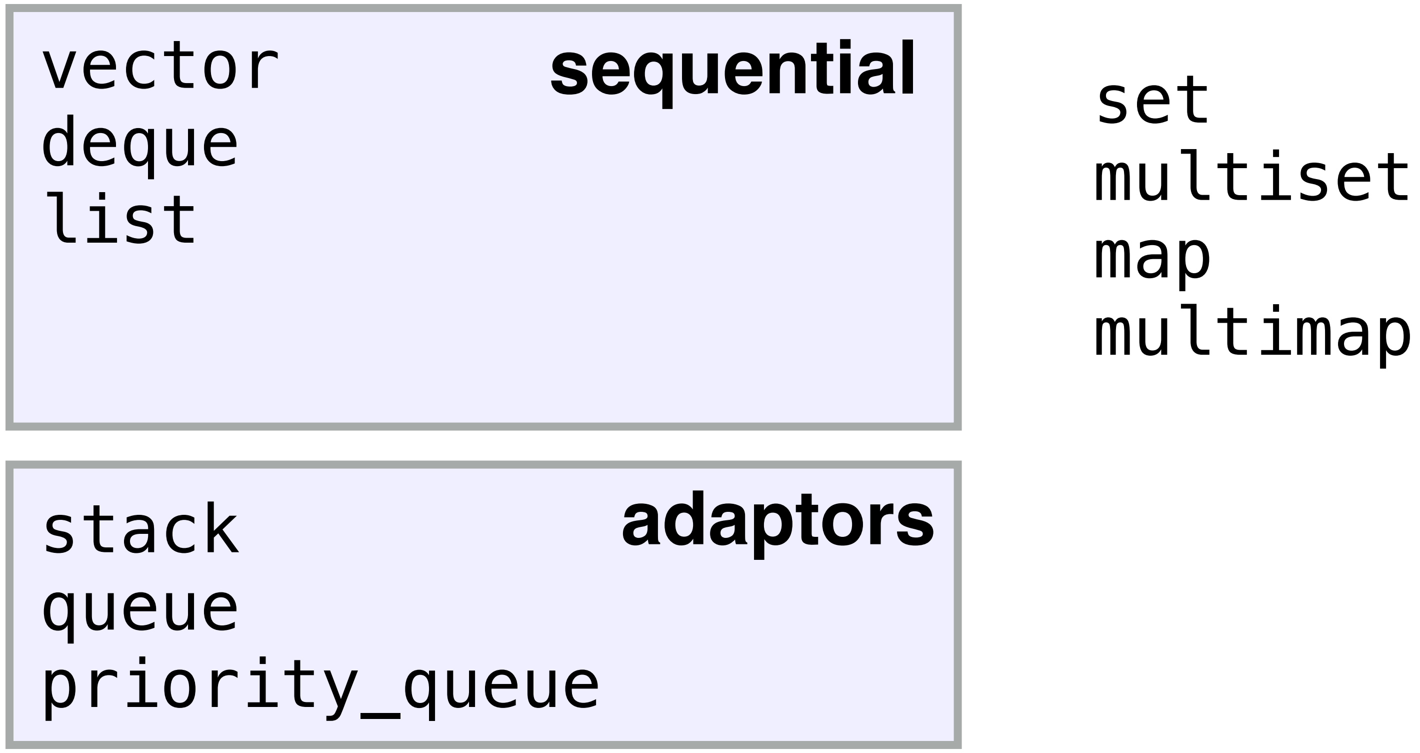

sequential

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+ 6 containers with `C++11`

sequential

`vector`
`deque`
`list`
`array`
`forward_list`

adaptors

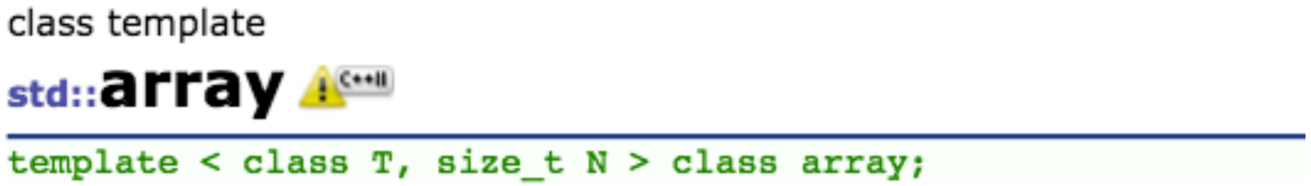
`stack`
`queue`
`priority_queue`

associative

`set`
`multiset`
`map`
`multimap`
`unordered_set`
`unordered_multiset`
`unordered_map`
`unordered_multimap`

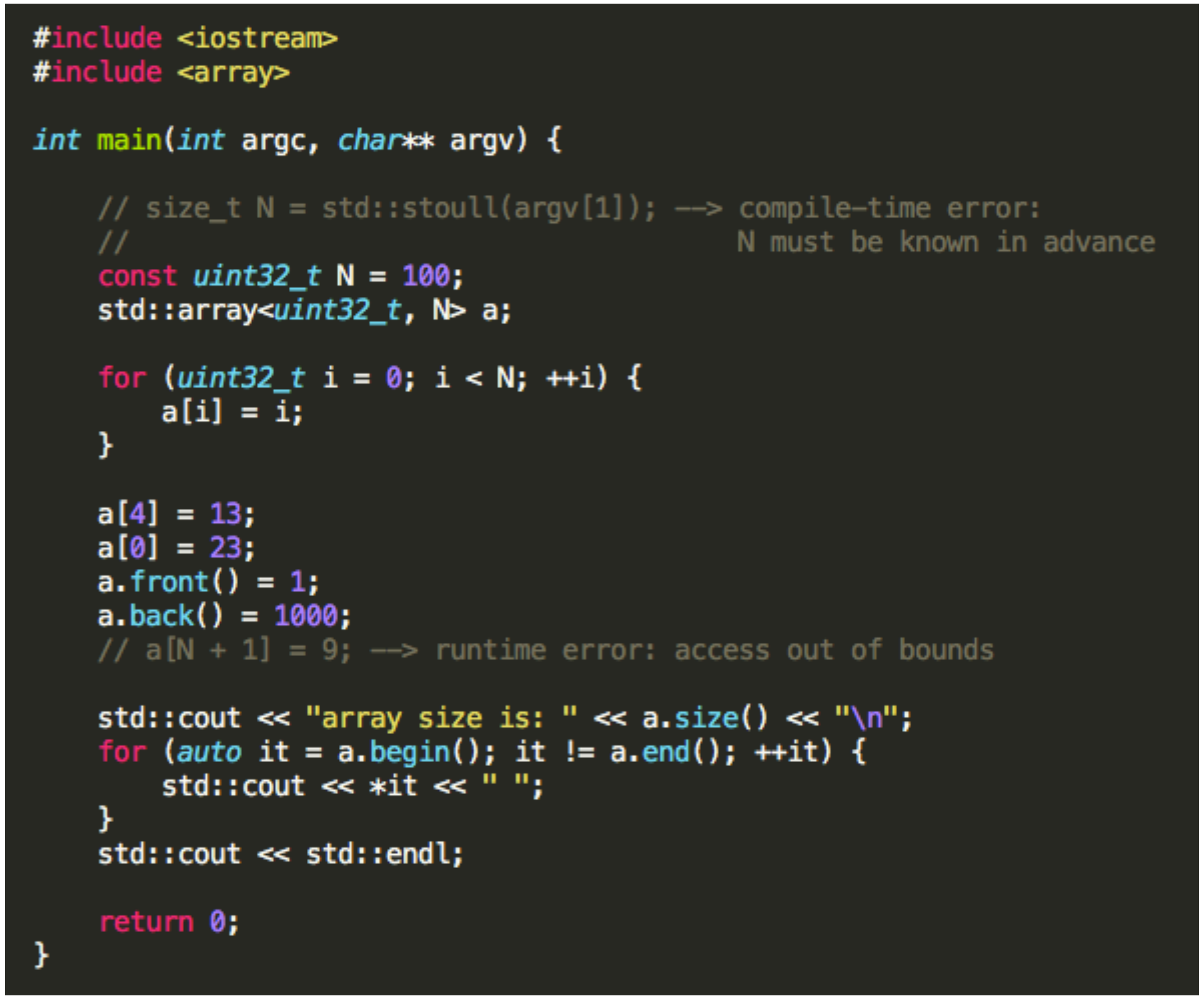
Sequential containers

random access: O(1)
other operations: O(N)



class template
std::array
template < class T, size_t N > class array;

Arrays are **fixed-size** sequence containers: they hold a specific number of elements ordered in a strict linear sequence. A wrap class around the an ordinary array declared with the language's bracket syntax ([]).



```
#include <iostream>
#include <array>

int main(int argc, char** argv) {

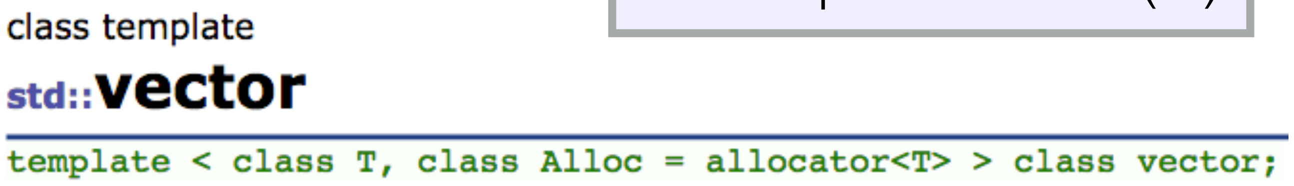
    // size_t N = std::stoull(argv[1]); --> compile-time error:
    //                                       N must be known in advance
    const uint32_t N = 100;
    std::array<uint32_t, N> a;

    for (uint32_t i = 0; i < N; ++i) {
        a[i] = i;
    }

    a[4] = 13;
    a[0] = 23;
    a.front() = 1;
    a.back() = 1000;
    // a[N + 1] = 9; --> runtime error: access out of bounds

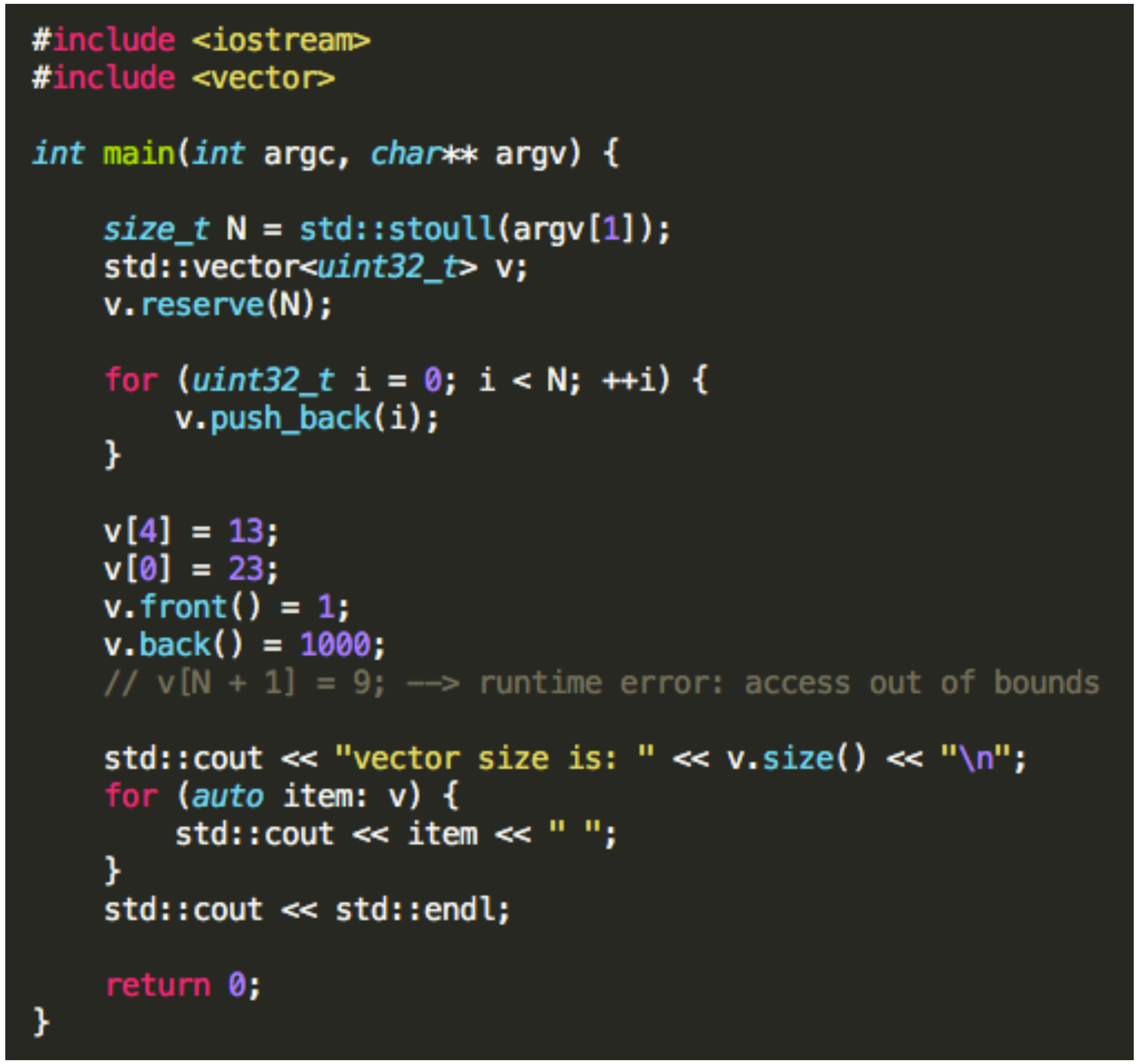
    std::cout << "array size is: " << a.size() << "\n";
    for (auto it = a.begin(); it != a.end(); ++it) {
        std::cout << *it << " ";
    }
    std::cout << std::endl;

    return 0;
}
```



class template
std::vector
template < class T, class Alloc = allocator<T> > class vector;

Just like arrays, vectors use contiguous storage locations for their elements but unlike arrays, **their size can change dynamically**, with their storage being handled automatically by the container.



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#include <iostream>
#include <vector>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    v[4] = 13;
    v[0] = 23;
    v.front() = 1;
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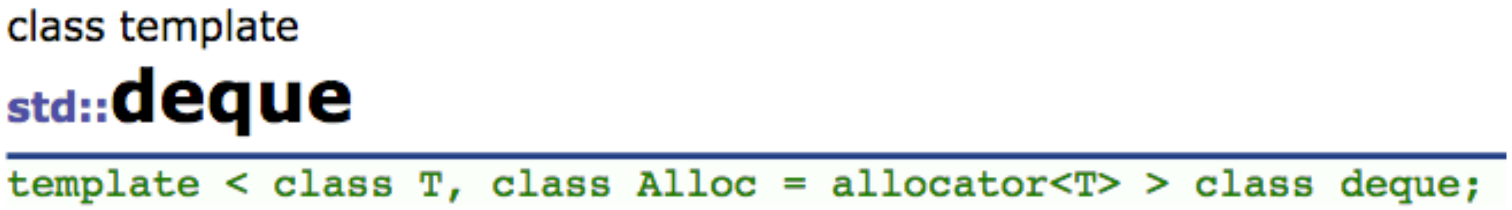
    // v[N + 1] = 9; --> runtime error: access out of bounds

    std::cout << "vector size is: " << v.size() << "\n";
    for (auto item: v) {
        std::cout << item << " ";
    }
    std::cout << std::endl;

    return 0;
}
```

Sequential containers



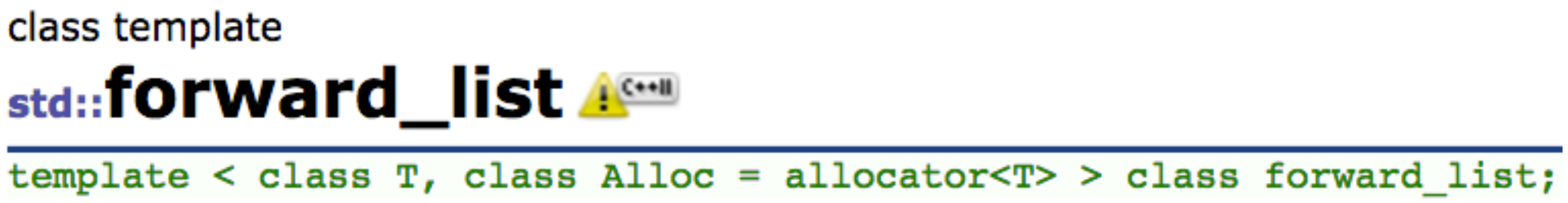
class template

std::deque

```
template < class T, class Alloc = allocator<T> > class deque;
```

Deque is a **d**ouble-**e**nded **que**ue. Double-ended queues are sequence containers with dynamic sizes that can be expanded or contracted on **both ends** (either its front or its back). Behaviour similar to that of vectors.

random access: O(1)
other operations: O(N)



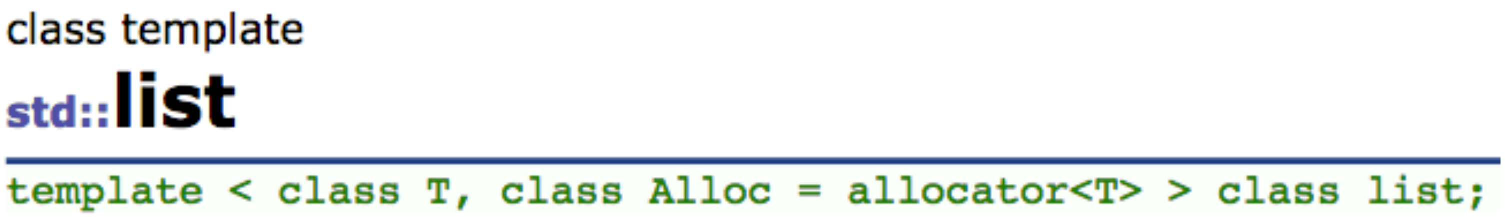
class template

std::forward_list C++11

```
template < class T, class Alloc = allocator<T> > class forward_list;
```

Forward lists are implemented as **singly-linked lists**. Singly linked lists can store each of the elements they contain in **different and unrelated storage locations**. The ordering is kept by the association to each element of a link to the next element in the sequence.

random access: O(N)
insert/delete: O(1)



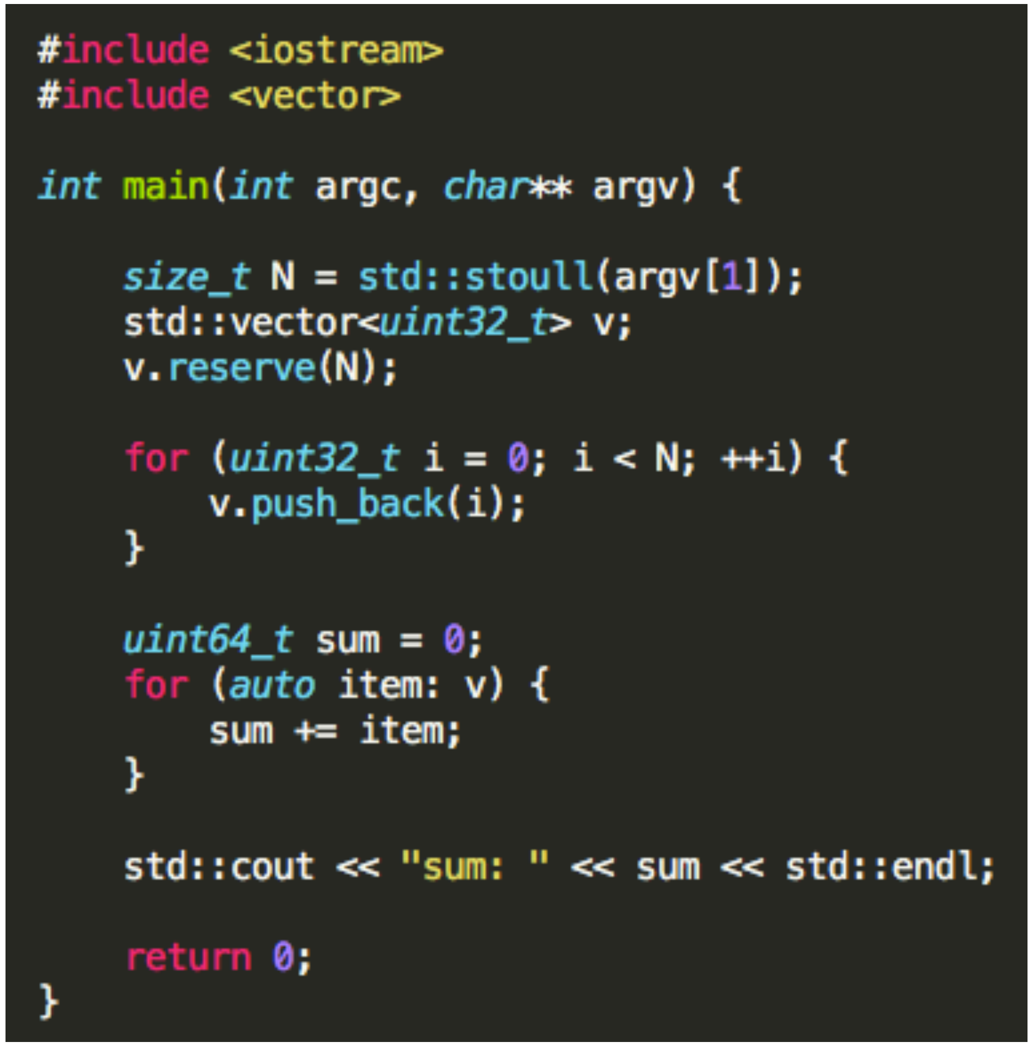
class template

std::list

```
template < class T, class Alloc = allocator<T> > class list;
```

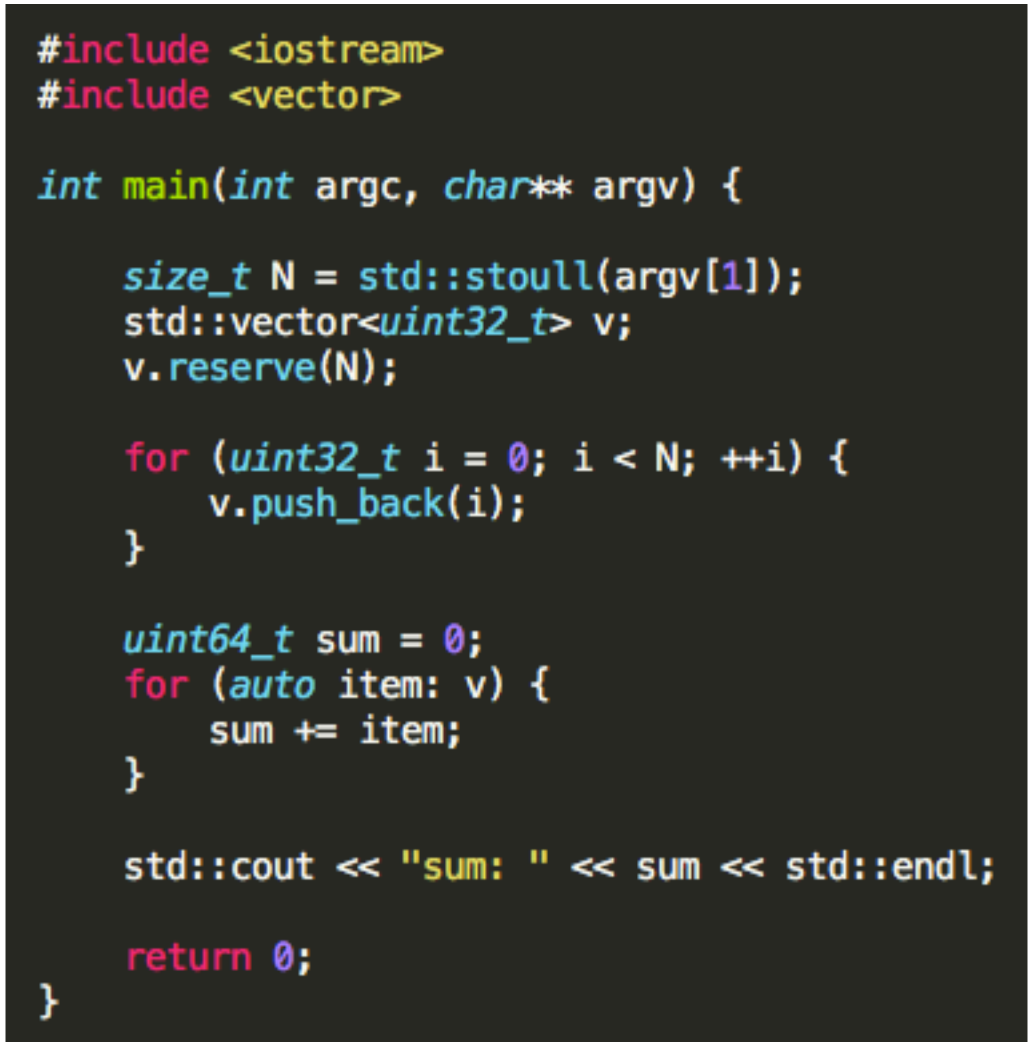
List containers are implemented as **doubly-linked lists**.

Sequential containers



```cpp
#include <iostream>
#include <vector>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```

Sequential containers



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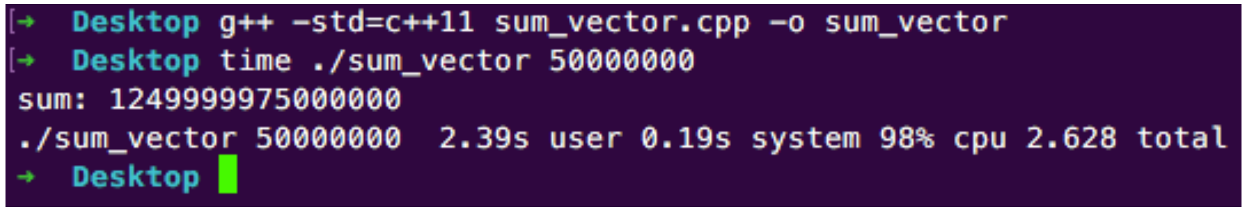
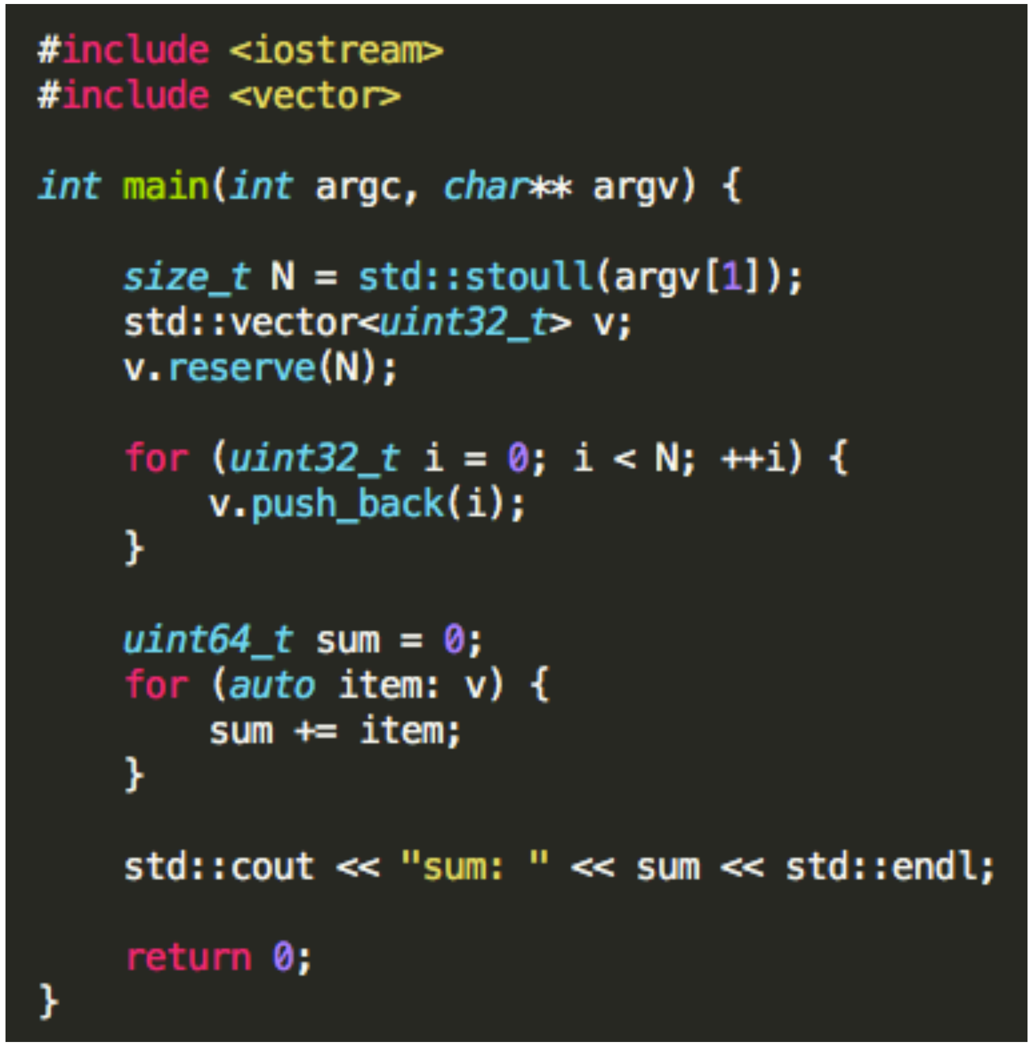
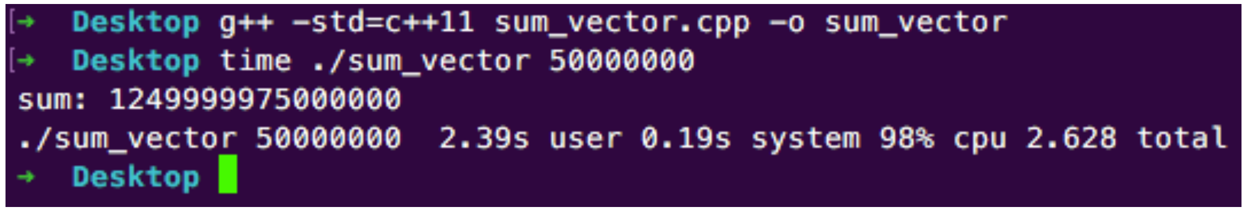


```
[→  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
[→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→  Desktop
```

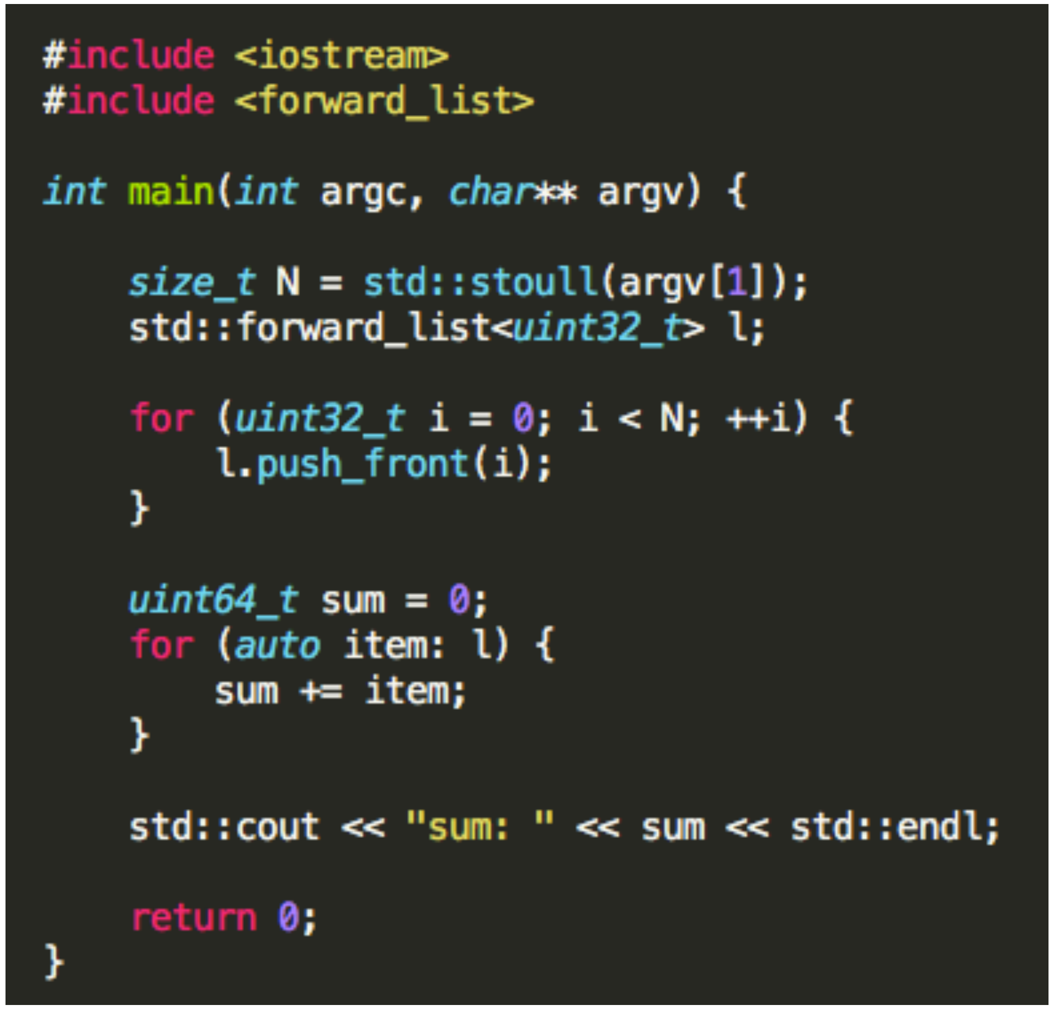
Sequential containers



```cpp
#include <iostream>
#include <vector>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



```
[→  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
[→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→  Desktop █
```



```cpp
#include <iostream>
#include <forward_list>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

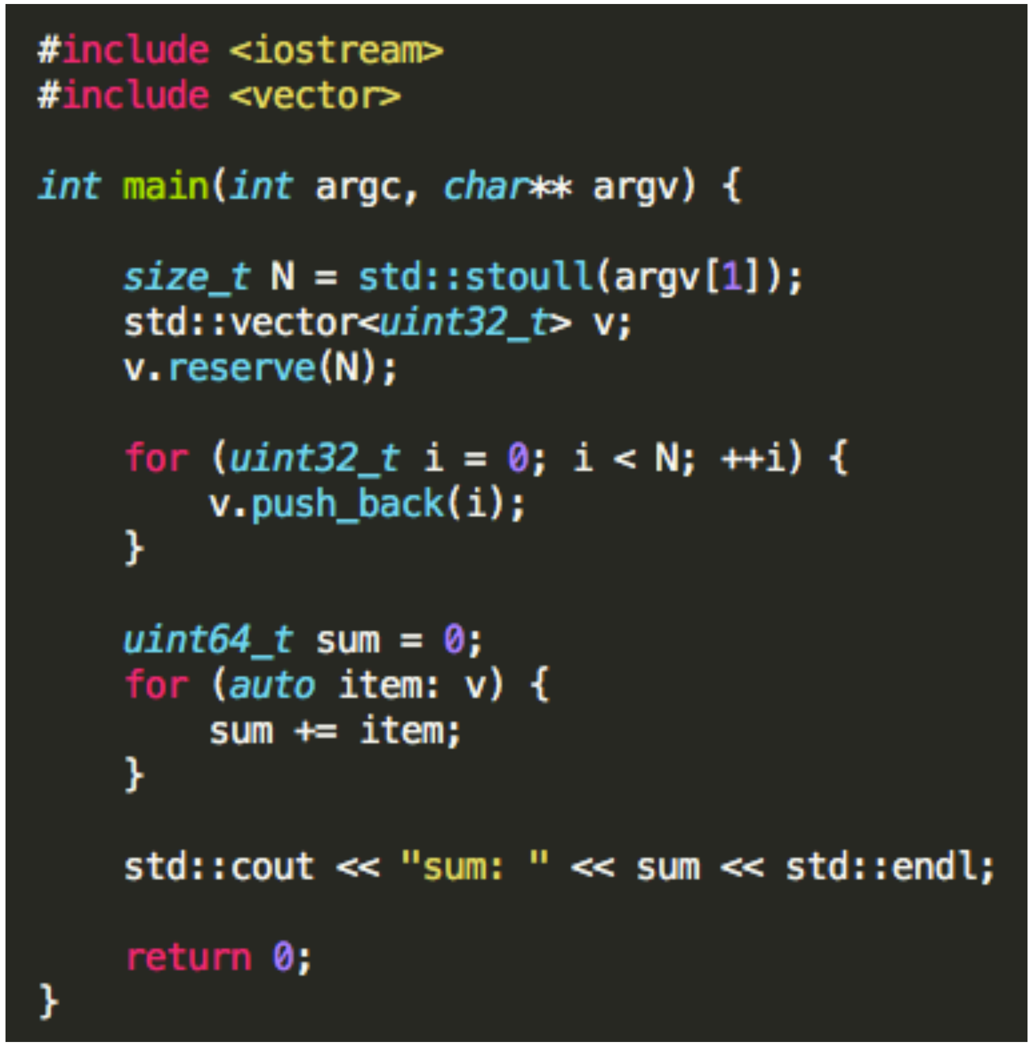
    for (uint32_t i = 0; i < N; ++i) {
        l.push_front(i);
    }

    uint64_t sum = 0;
    for (auto item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```

Sequential containers



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    std::vector<uint32_t> v;
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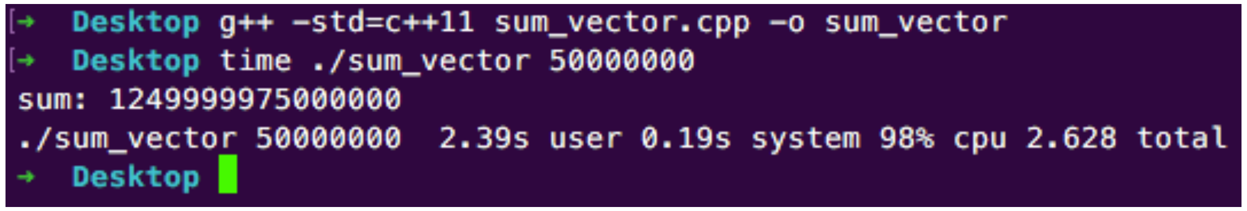
        v.push_back(i);
    }

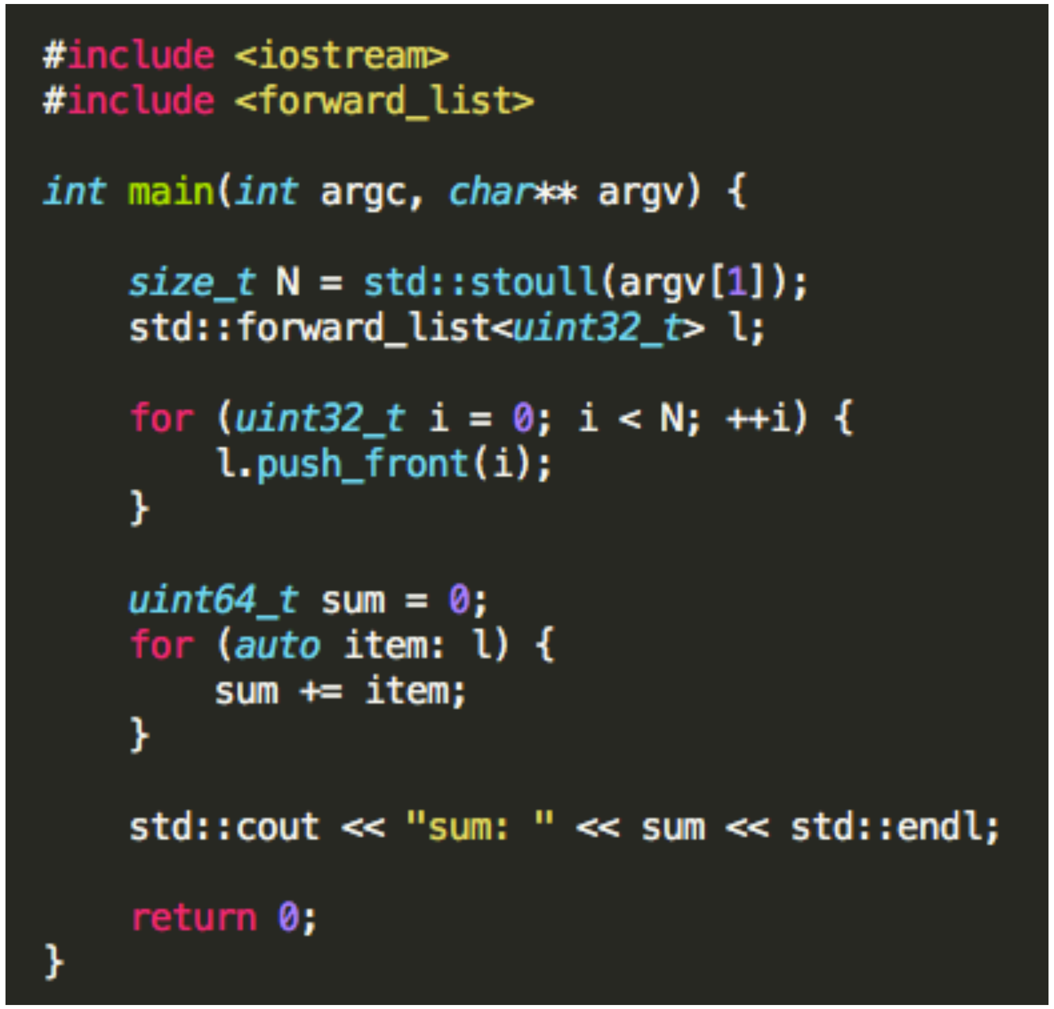
    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

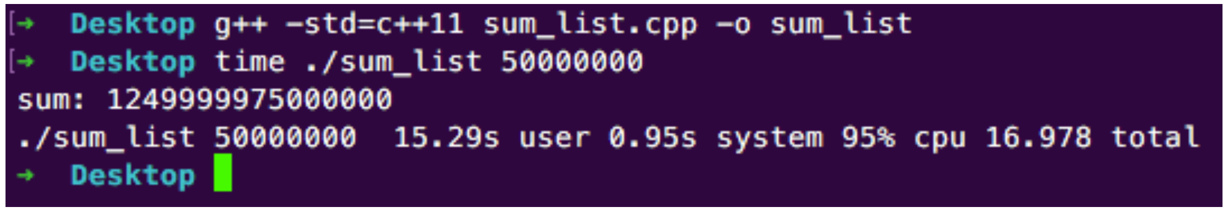
    return 0;
}
```



```
[→  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
[→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→  Desktop █
```

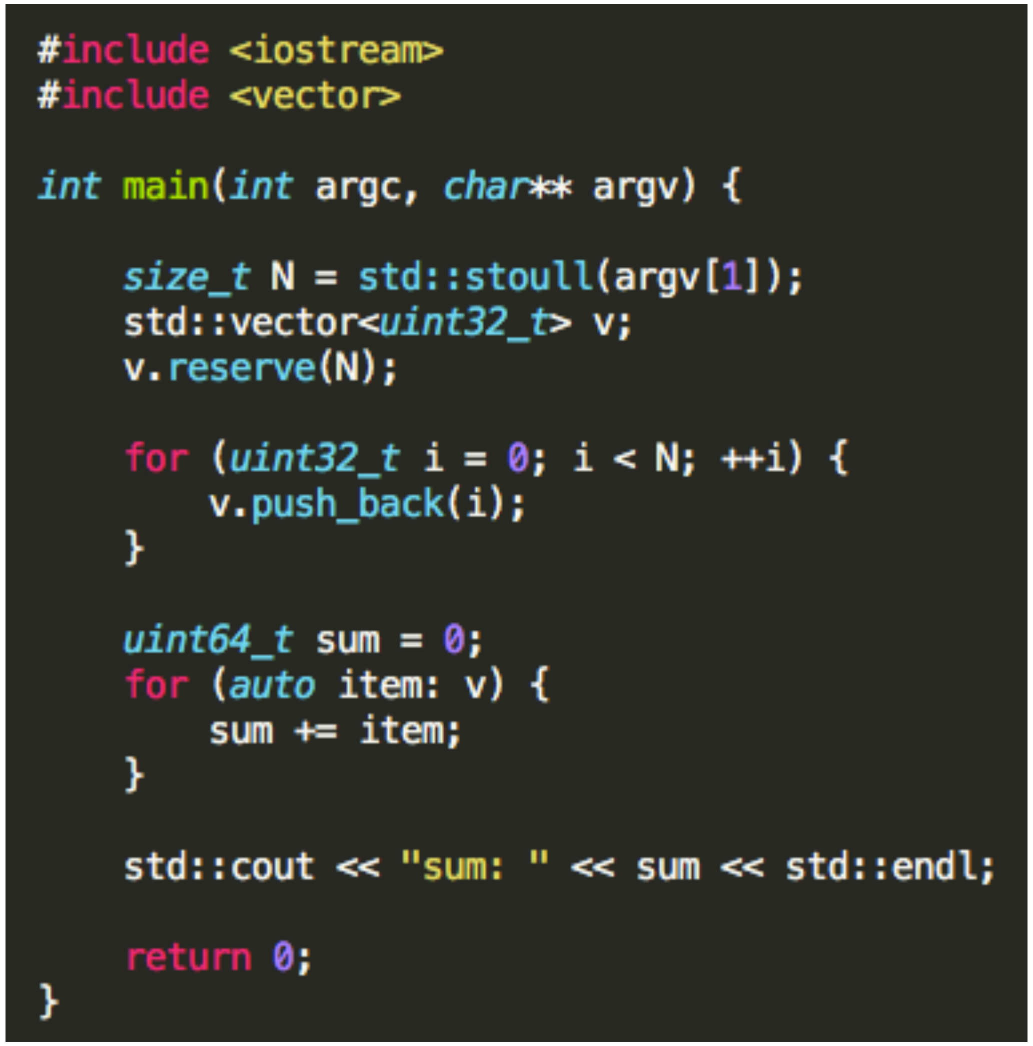


```cpp
#include <iostream>
#include <forward_list>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

    for (uint32_t i = 0; i < N; ++i) {
        l.push_front(i);
    }

    uint64_t sum = 0;
    for (auto item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



```
[→  Desktop g++ -std=c++11 sum_list.cpp -o sum_list
[→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
→  Desktop █
```

Sequential containers



```cpp
#include <iostream>
#include <vector>

int main(int argc, char** argv) {

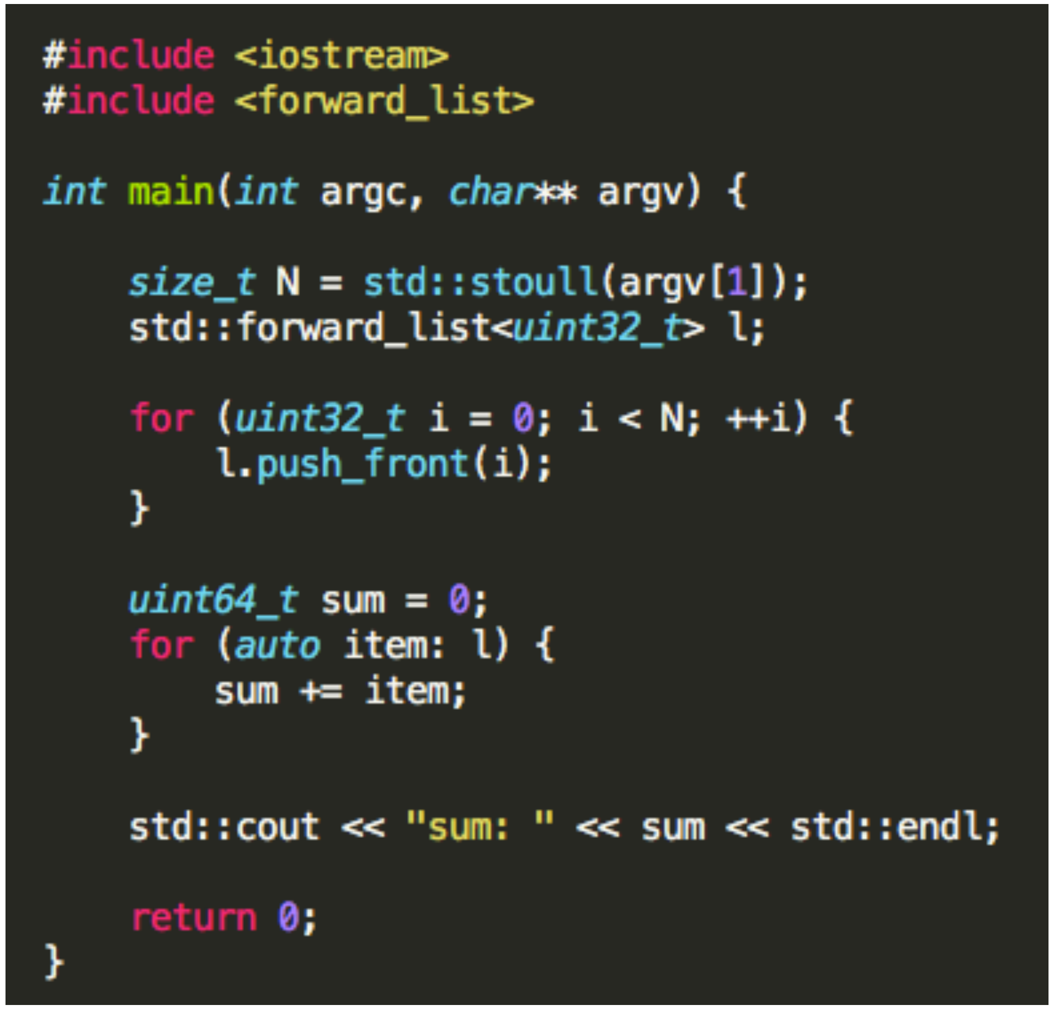
    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



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#include <iostream>
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int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

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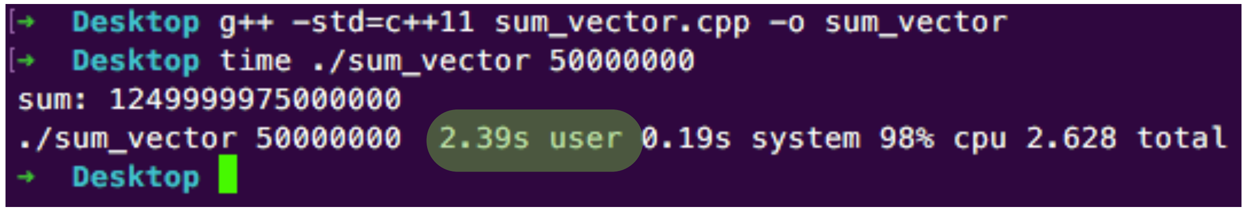
        l.push_front(i);
    }

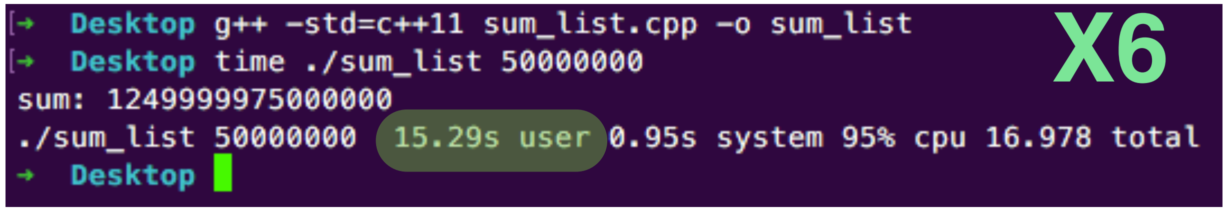
    uint64_t sum = 0;
    for (auto item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



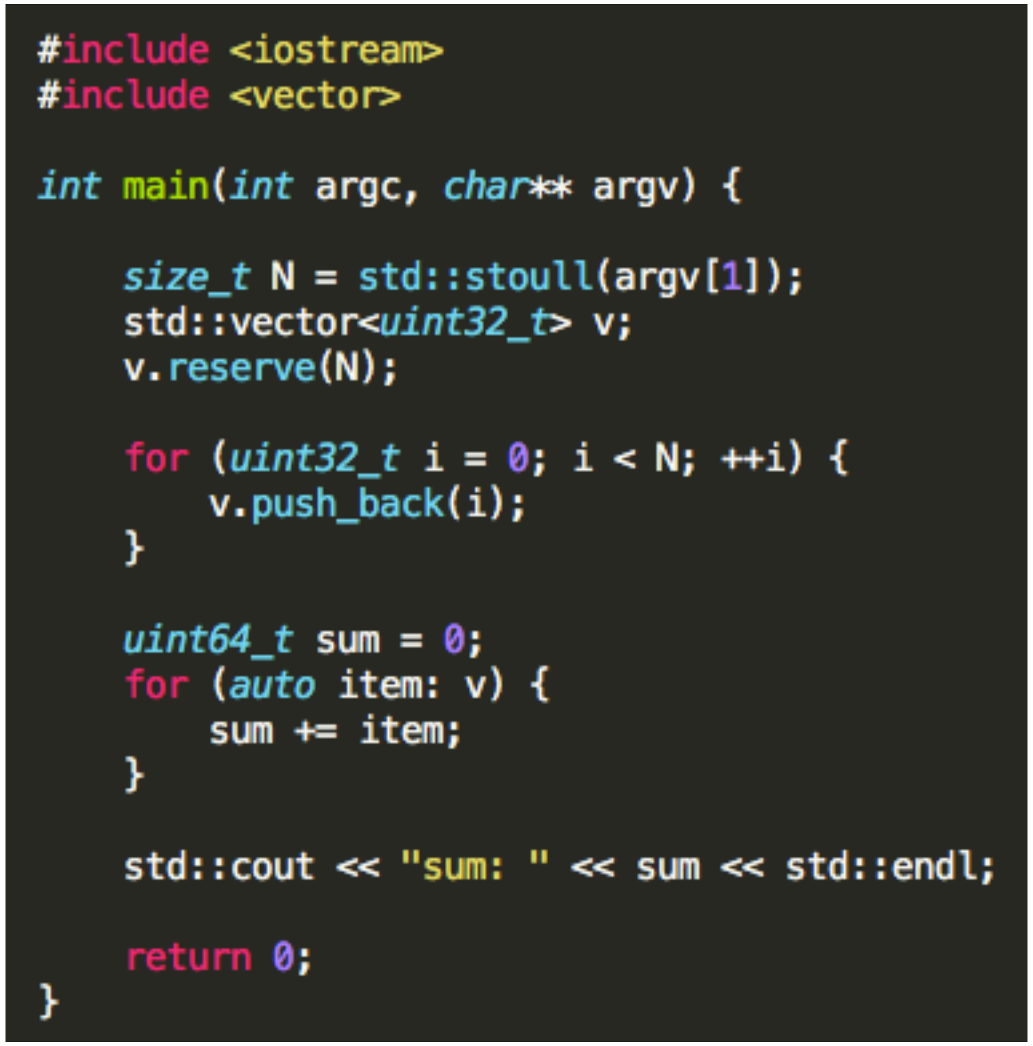
```
[➜  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
[➜  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
➜  Desktop █
```



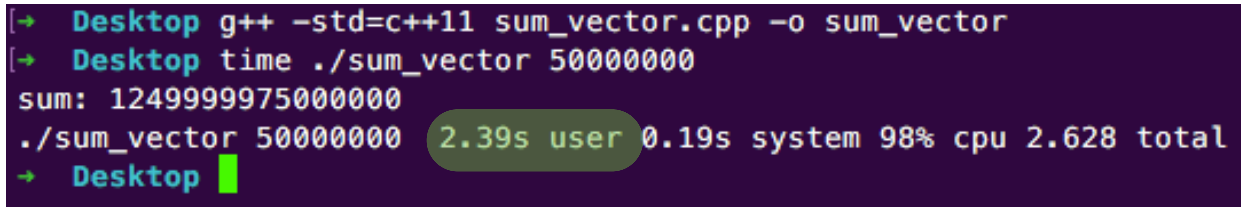
```
[➜  Desktop g++ -std=c++11 sum_list.cpp -o sum_list
[➜  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
➜  Desktop █
```

X6

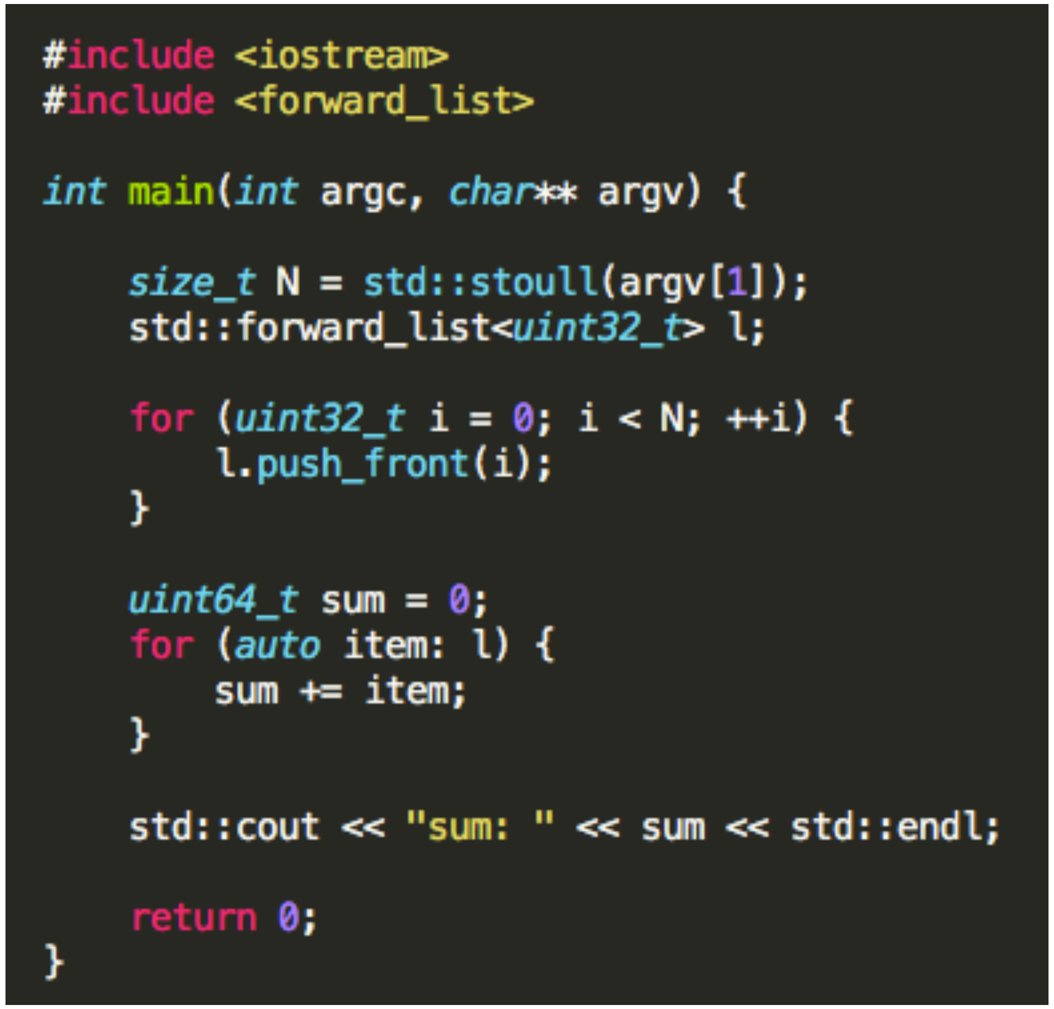
Sequential containers



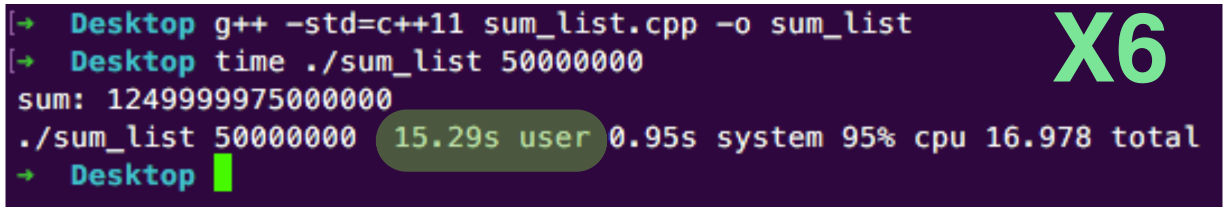
```cpp
#include <iostream>
#include <vector>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



```
→  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→  Desktop
```

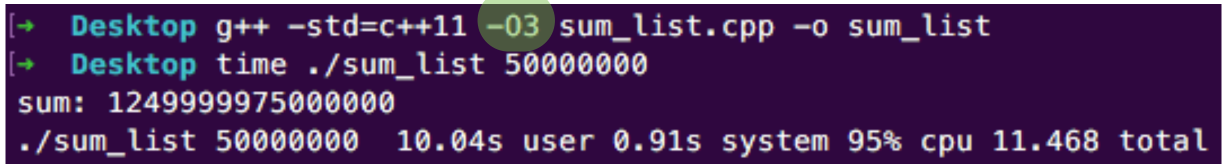


```cpp
#include <iostream>
#include <forward_list>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

    for (uint32_t i = 0; i < N; ++i) {
        l.push_front(i);
    }

    uint64_t sum = 0;
    for (auto item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



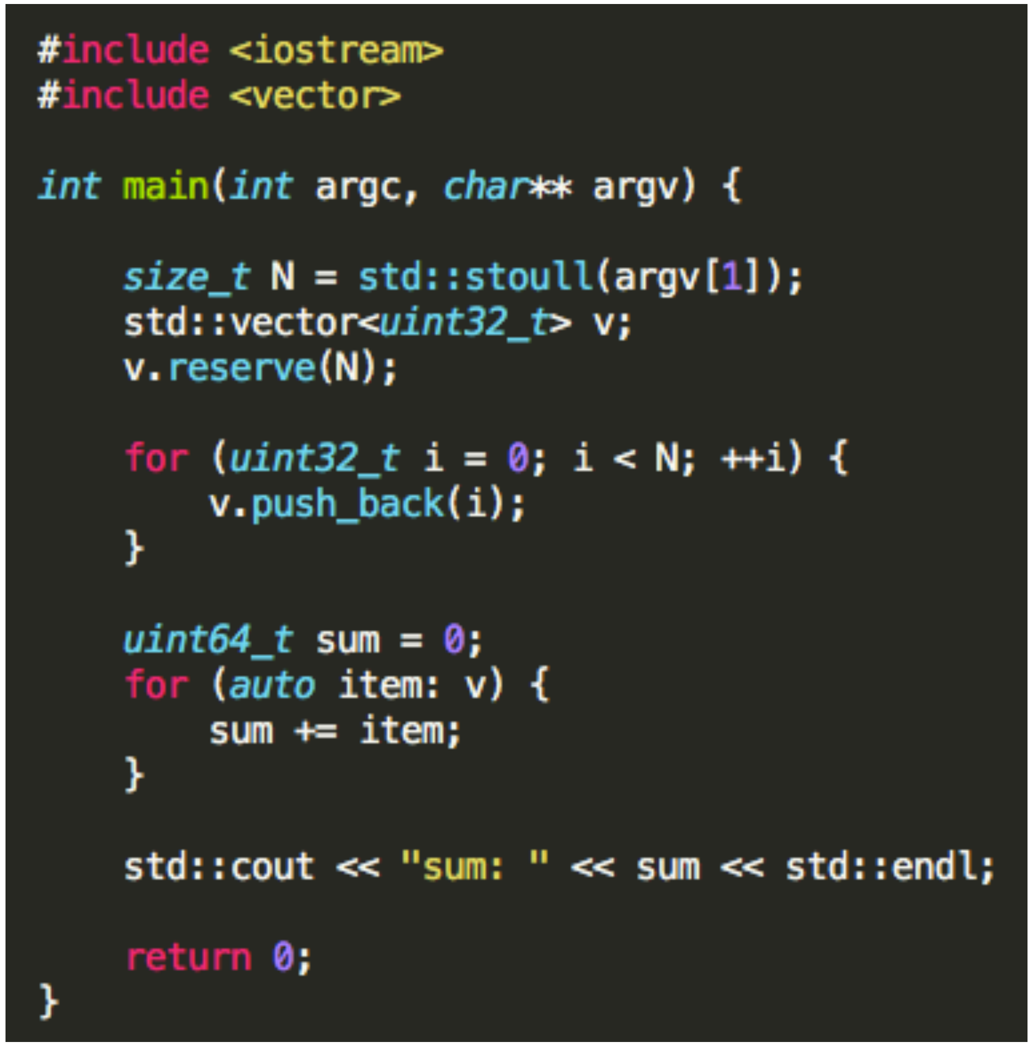
```
→  Desktop g++ -std=c++11 sum_list.cpp -o sum_list
→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
→  Desktop
```

X6



```
→  Desktop g++ -std=c++11 -O3 sum_list.cpp -o sum_list
→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  10.04s user 0.91s system 95% cpu 11.468 total
```

Sequential containers



```cpp
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#include <vector>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```

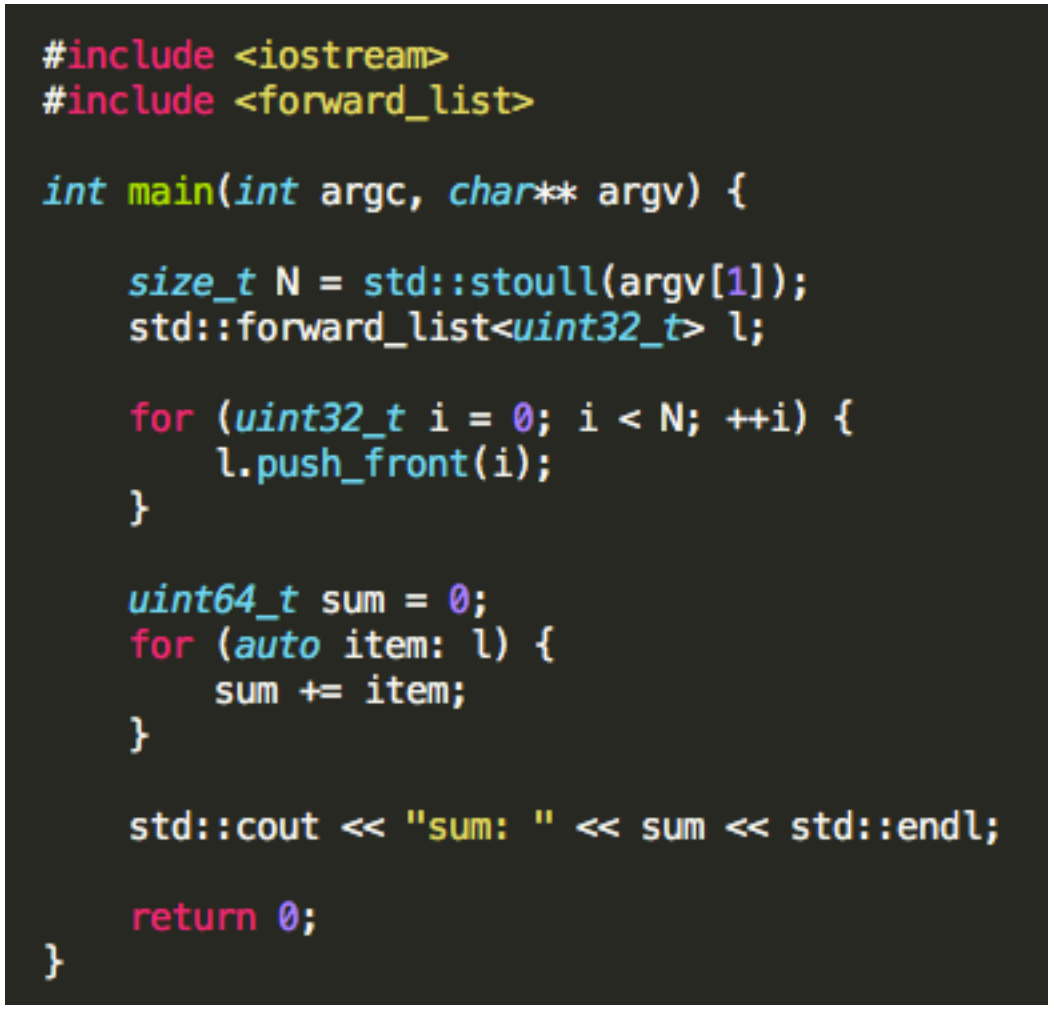

```cpp
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int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

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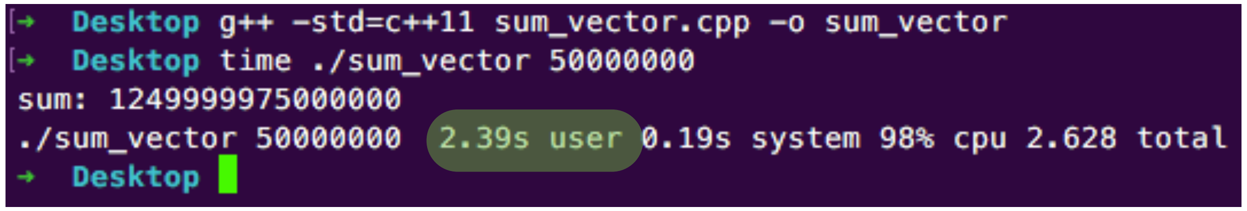
        l.push_front(i);
    }

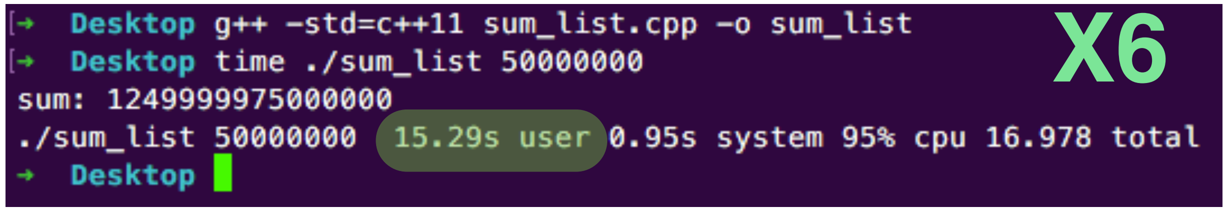
    uint64_t sum = 0;
    for (auto item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



```
[→  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
[→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→  Desktop
```



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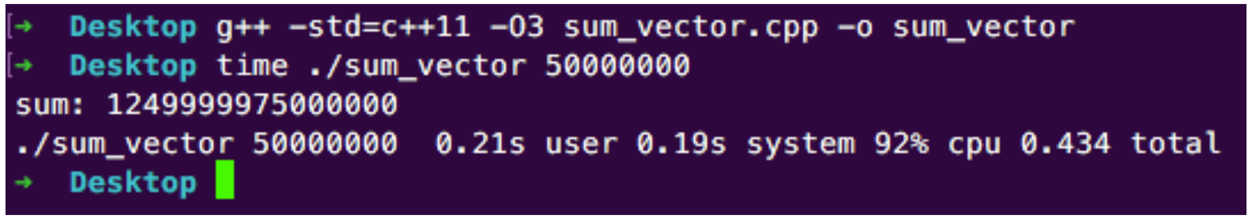
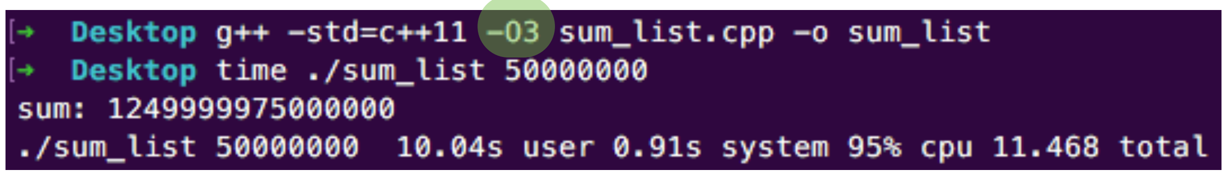
[→  Desktop g++ -std=c++11 sum_list.cpp -o sum_list
[→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
→  Desktop
```

X6

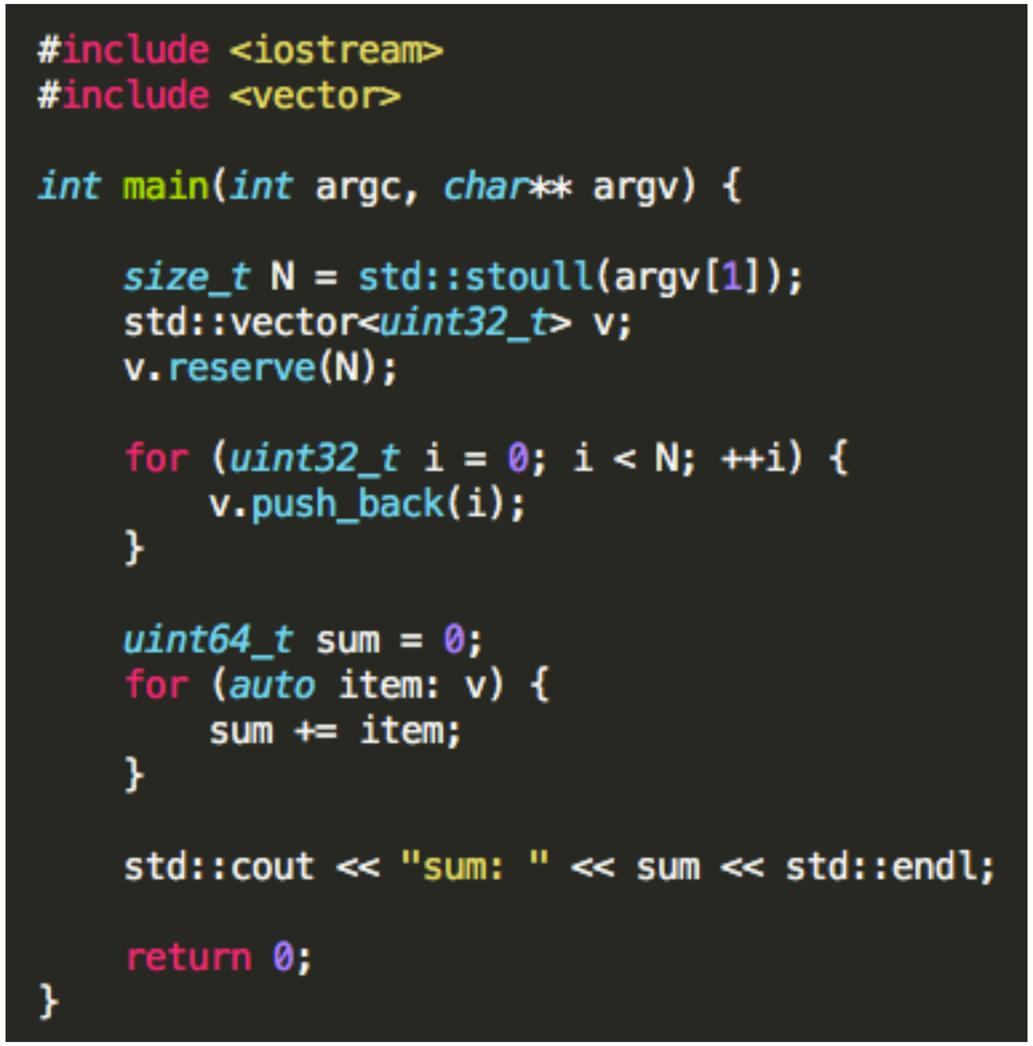


```
[→  Desktop g++ -std=c++11 -O3 sum_vector.cpp -o sum_vector
[→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  0.21s user 0.19s system 92% cpu 0.434 total
→  Desktop
```



```
[→  Desktop g++ -std=c++11 -O3 sum_list.cpp -o sum_list
[→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  10.04s user 0.91s system 95% cpu 11.468 total
```

Sequential containers



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#include <vector>

int main(int argc, char** argv) {

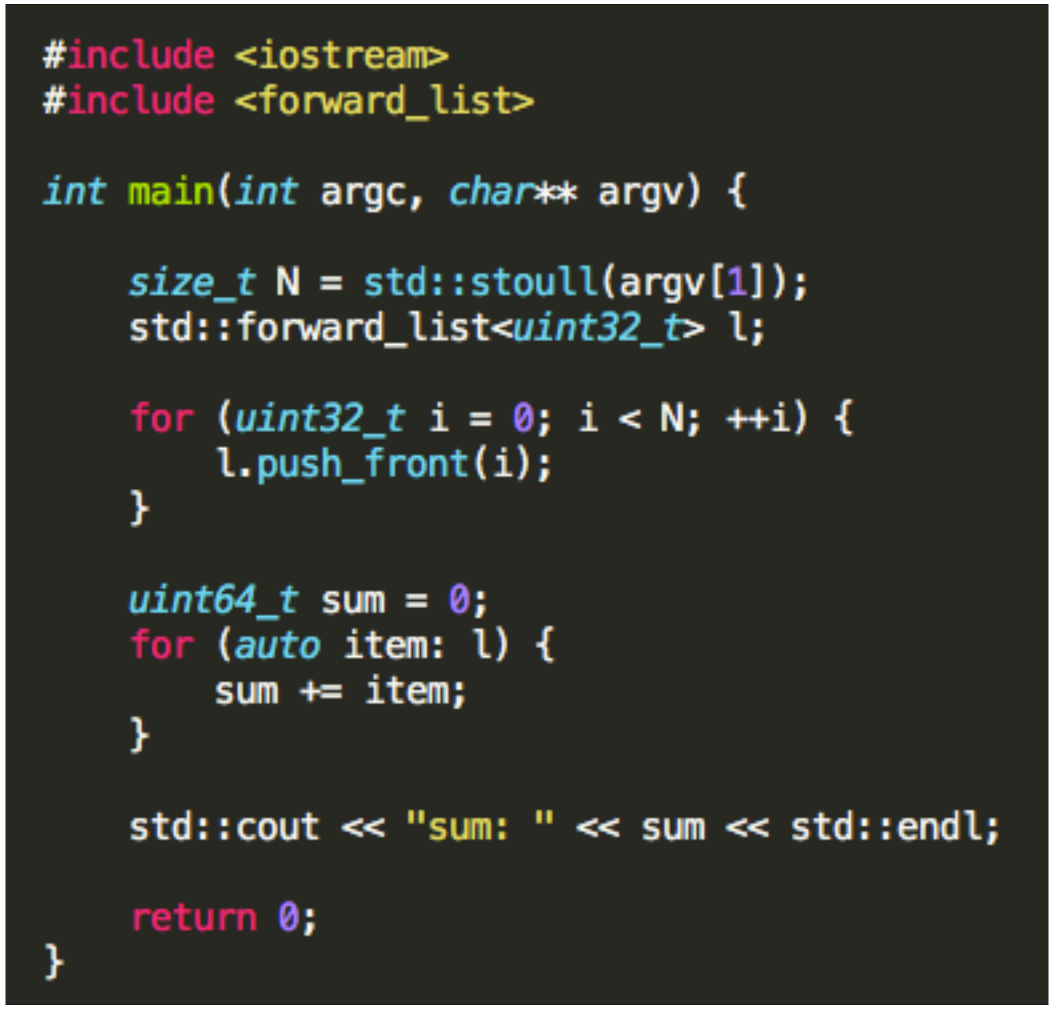
    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; ++i) {
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



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int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
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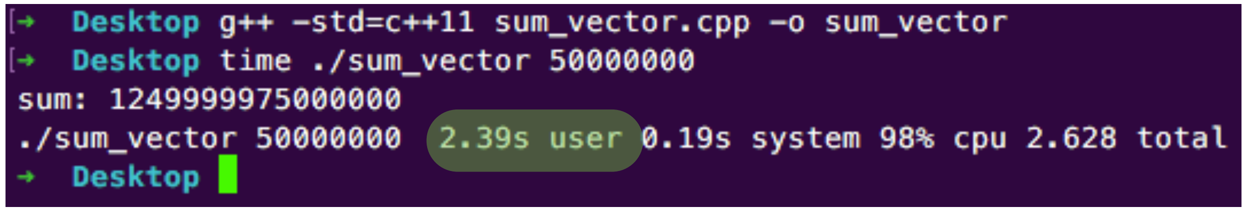
    for (uint32_t i = 0; i < N; ++i) {
        l.push_front(i);
    }

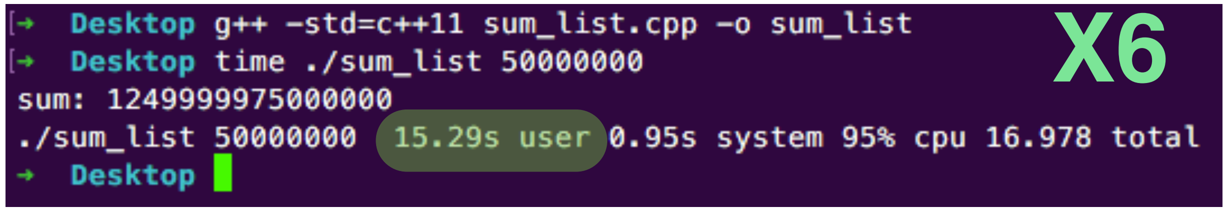
    uint64_t sum = 0;
    for (auto item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```

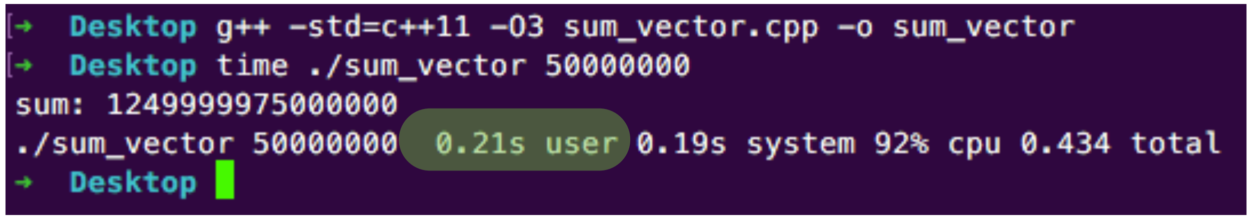


```
➜  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
➜  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
➜  Desktop
```

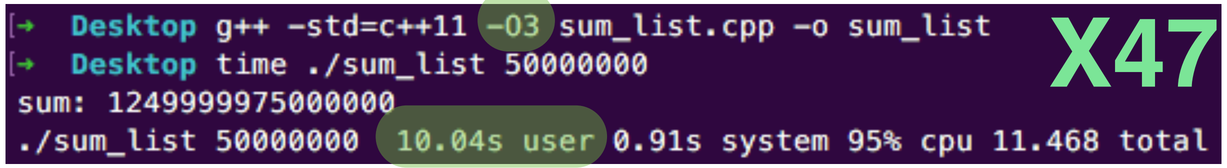


```
➜  Desktop g++ -std=c++11 sum_list.cpp -o sum_list
➜  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
➜  Desktop
```

X6



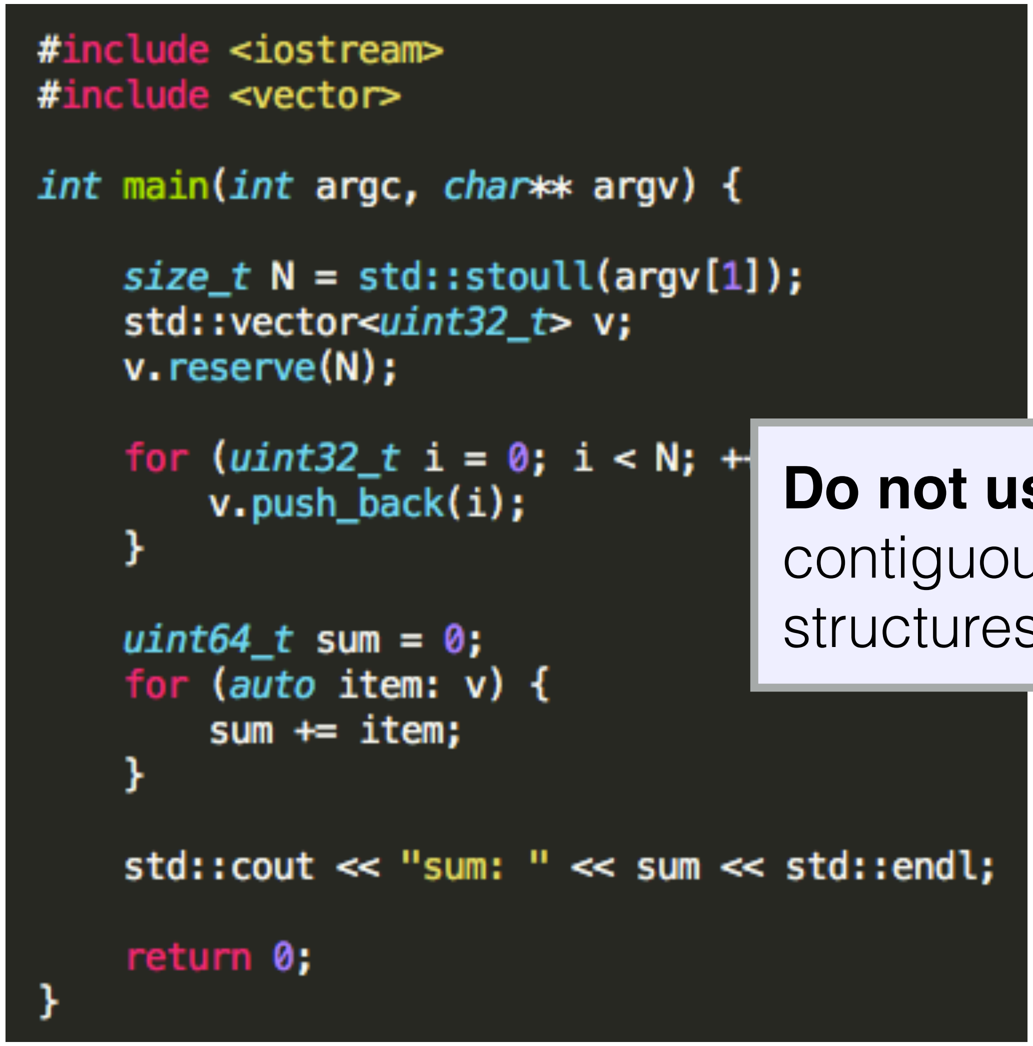
```
➜  Desktop g++ -std=c++11 -O3 sum_vector.cpp -o sum_vector
➜  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  0.21s user 0.19s system 92% cpu 0.434 total
➜  Desktop
```



```
➜  Desktop g++ -std=c++11 -O3 sum_list.cpp -o sum_list
➜  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  10.04s user 0.91s system 95% cpu 11.468 total
```

X47

Sequential containers



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

int main(int argc, char** argv) {

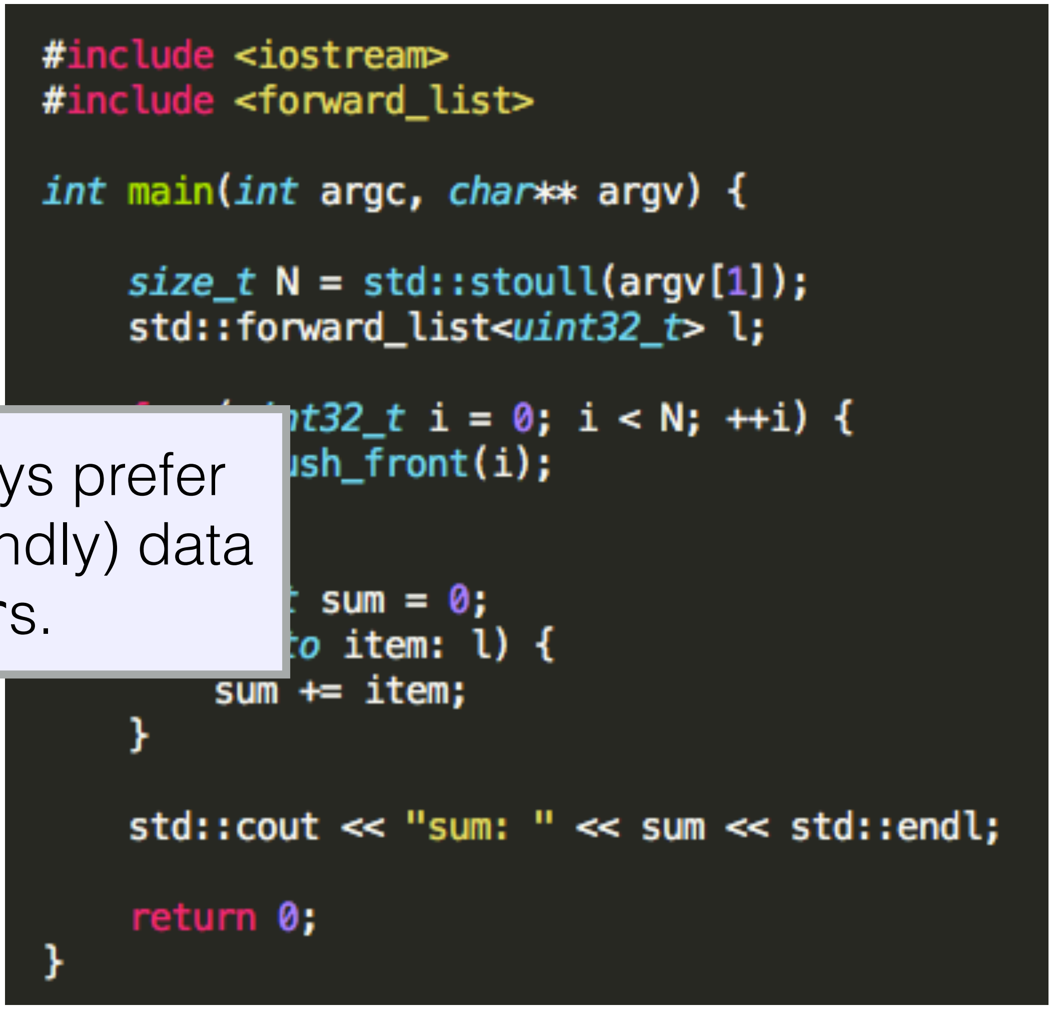
    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; +
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



```
#include <iostream>
#include <forward_list>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

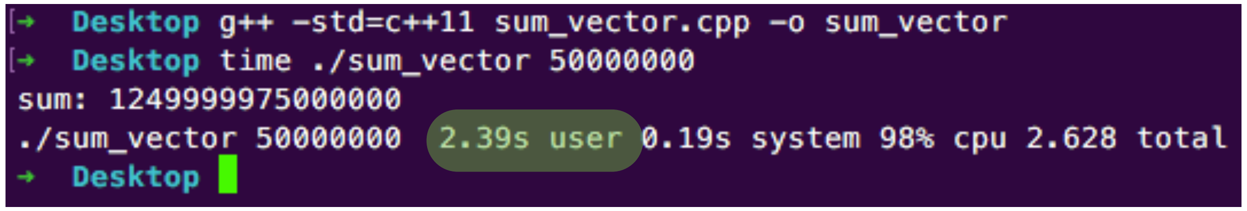
              nt32_t i = 0; i < N; ++i) {
              ush_front(i);

              t sum = 0;
              to item: l) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```

Do not use lists. Always prefer contiguous (cache-friendly) data structures, like `vectors`.



```
[→  Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
[→  Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→  Desktop
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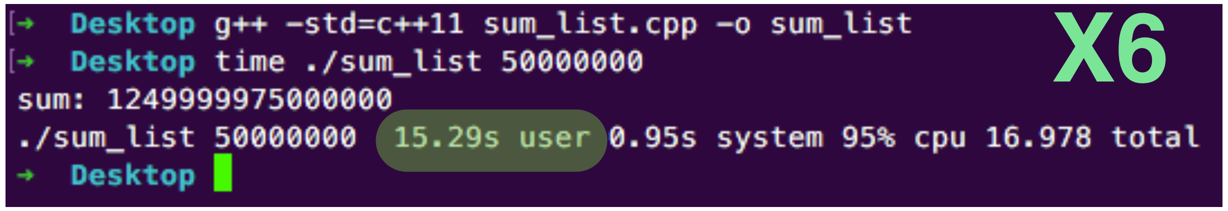
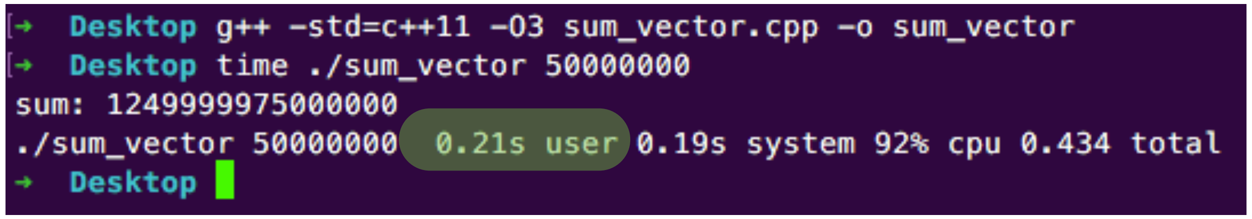


```
[→  Desktop g++ -std=c++11 sum_list.cpp -o sum_list
[→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
→  Desktop
```

X6



```
[→  Desktop g++ -std=c++11 -O3 sum_vector.cpp -o sum_vector
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sum: 1249999975000000
./sum_vector 50000000  0.21s user 0.19s system 92% cpu 0.434 total
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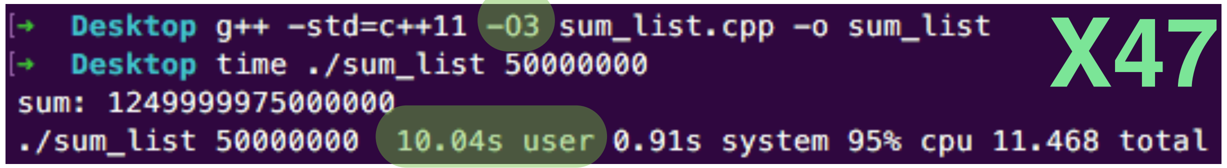
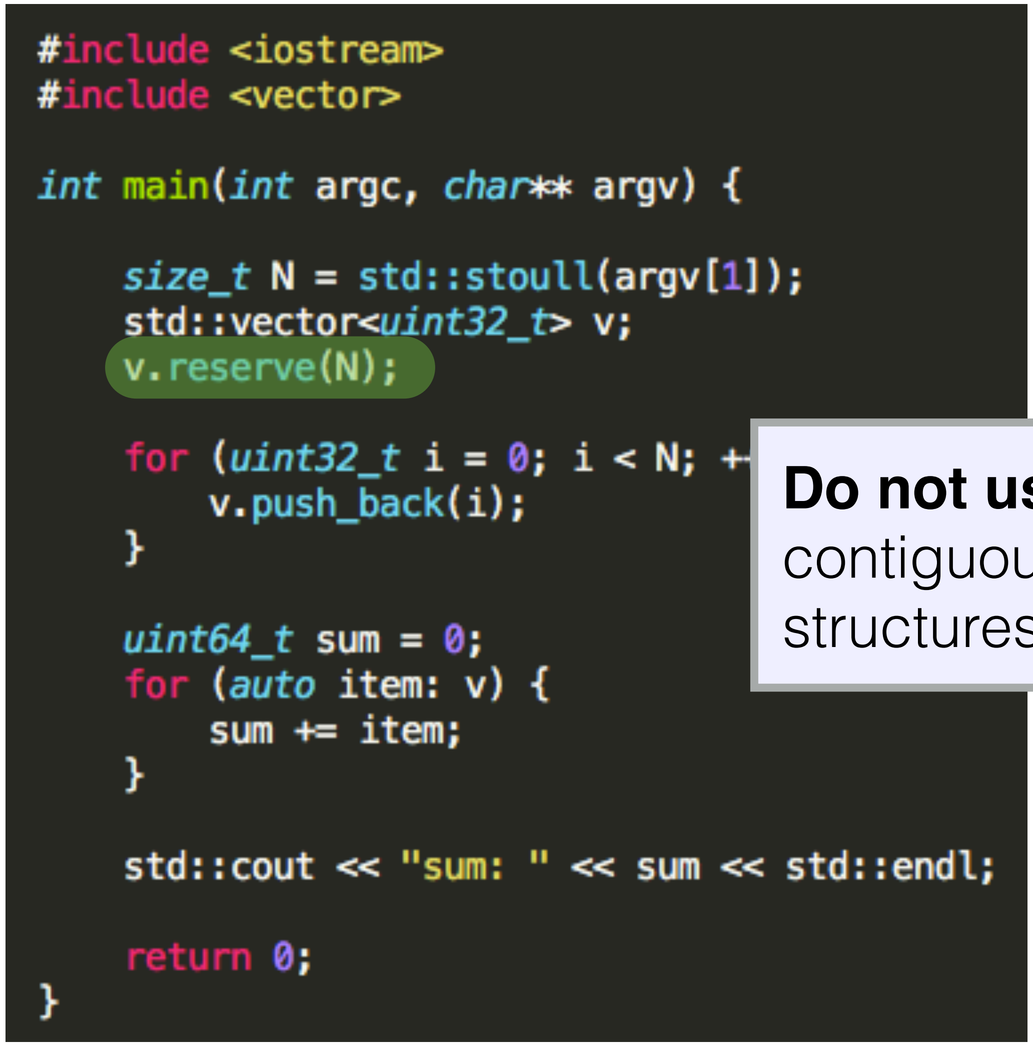


```
[→  Desktop g++ -std=c++11 -O3 sum_list.cpp -o sum_list
[→  Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  10.04s user 0.91s system 95% cpu 11.468 total
```

X47

Sequential containers



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

int main(int argc, char** argv) {

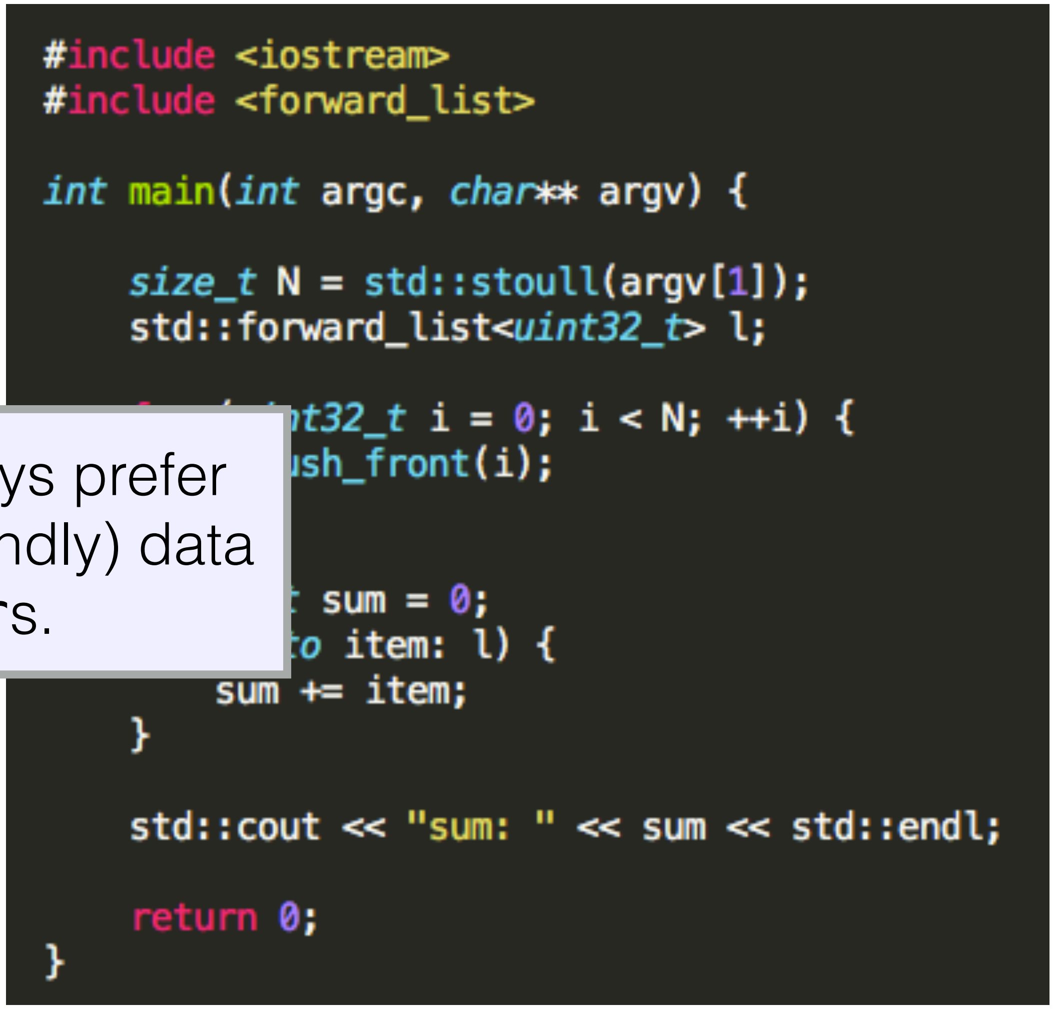
    size_t N = std::stoull(argv[1]);
    std::vector<uint32_t> v;
    v.reserve(N);

    for (uint32_t i = 0; i < N; +
        v.push_back(i);
    }

    uint64_t sum = 0;
    for (auto item: v) {
        sum += item;
    }

    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```



```
#include <iostream>
#include <forward_list>

int main(int argc, char** argv) {

    size_t N = std::stoull(argv[1]);
    std::forward_list<uint32_t> l;

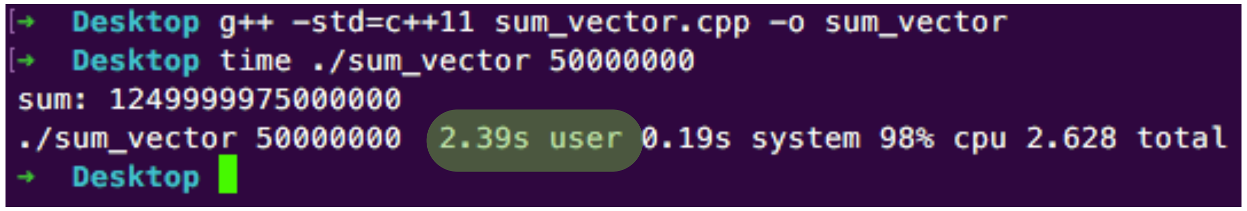
              t32_t i = 0; i < N; ++i) {
              sh_front(i);

              t sum = 0;
              o item: l) {
        sum += item;
    }

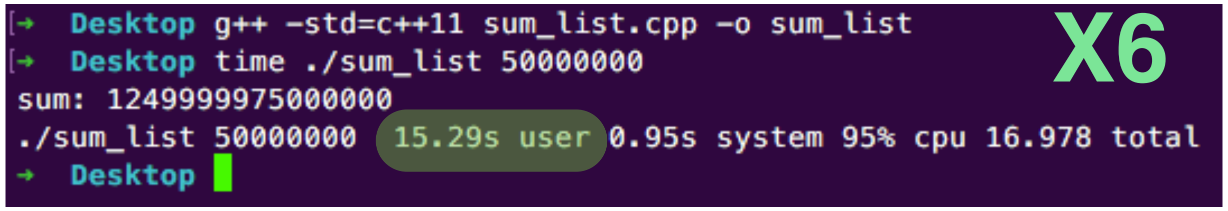
    std::cout << "sum: " << sum << std::endl;

    return 0;
}
```

Do not use lists. Always prefer contiguous (cache-friendly) data structures, like `vectors`.

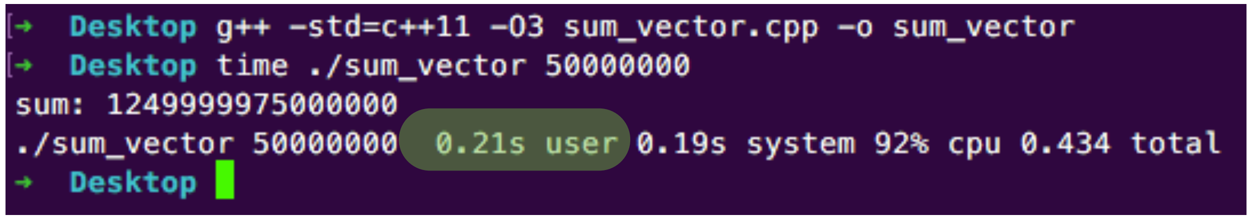


```
→ Desktop g++ -std=c++11 sum_vector.cpp -o sum_vector
→ Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  2.39s user 0.19s system 98% cpu 2.628 total
→ Desktop █
```

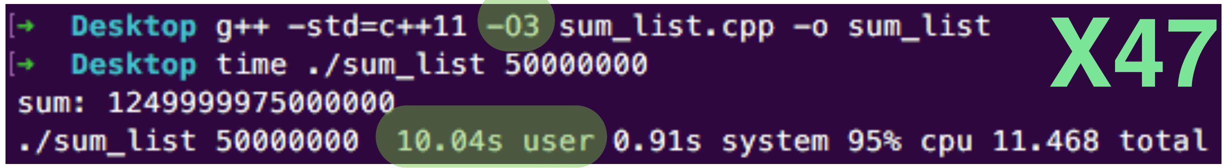


```
→ Desktop g++ -std=c++11 sum_list.cpp -o sum_list
→ Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  15.29s user 0.95s system 95% cpu 16.978 total
→ Desktop █
```

X6



```
→ Desktop g++ -std=c++11 -O3 sum_vector.cpp -o sum_vector
→ Desktop time ./sum_vector 50000000
sum: 1249999975000000
./sum_vector 50000000  0.21s user 0.19s system 92% cpu 0.434 total
→ Desktop █
```

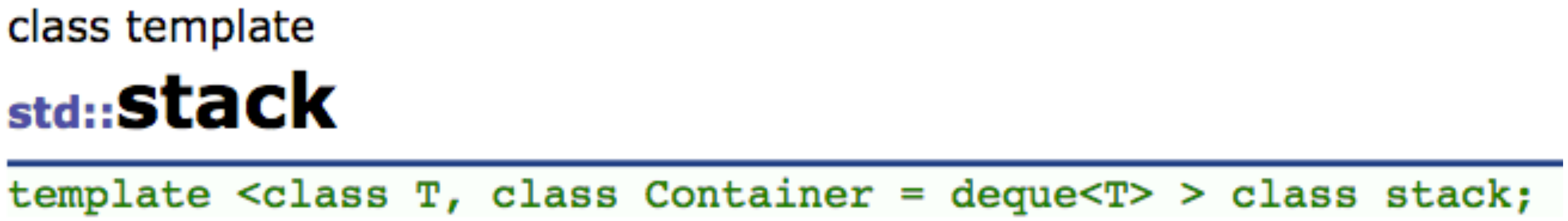


```
→ Desktop g++ -std=c++11 -O3 sum_list.cpp -o sum_list
→ Desktop time ./sum_list 50000000
sum: 1249999975000000
./sum_list 50000000  10.04s user 0.91s system 95% cpu 11.468 total
```

X47

Container adaptors

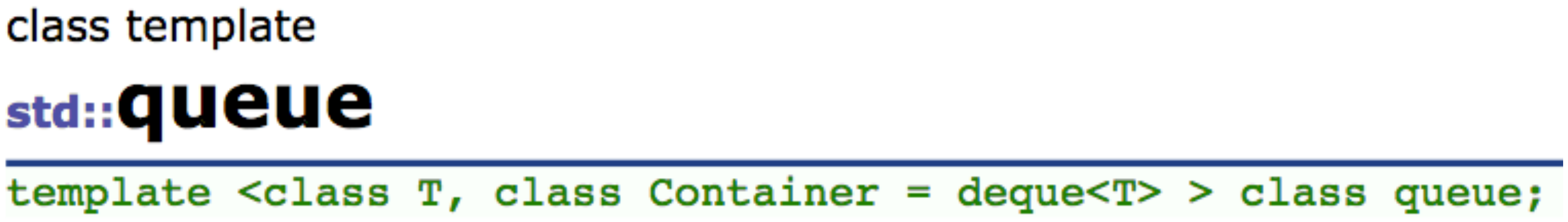
Containers adaptors are classes that use an encapsulated object of a specific container class as its **underlying container**, providing a specific set of member functions to access its elements.



class template

std::**stack**

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



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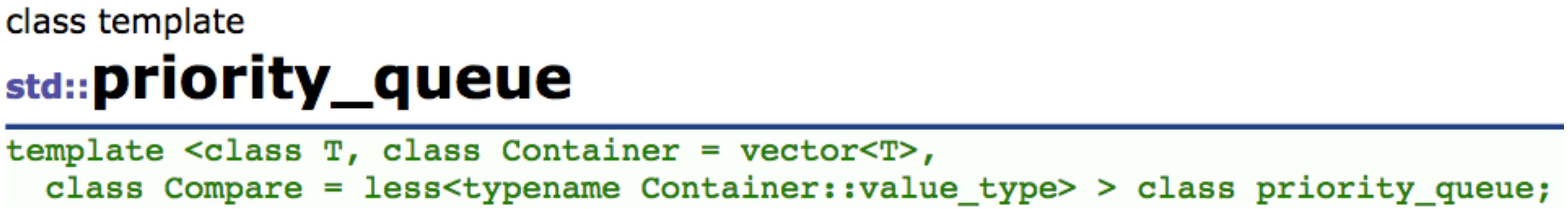

class template

std::**priority_queue**

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template <class T, class Container = vector<T>,
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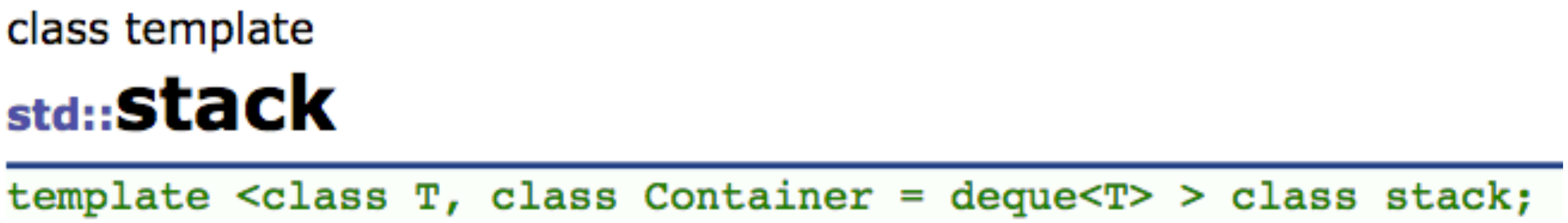
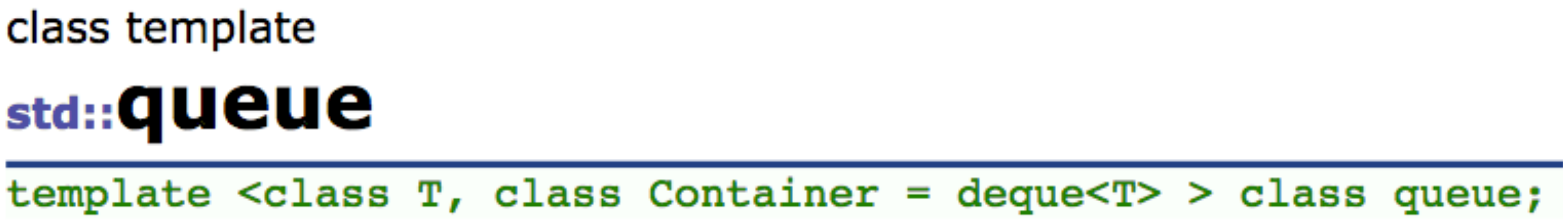


class template

std::stack

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

LIFO policy
push/pop: O(1)



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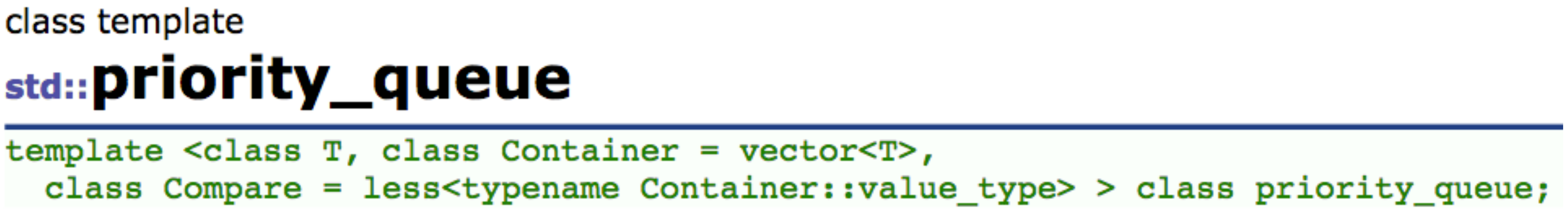

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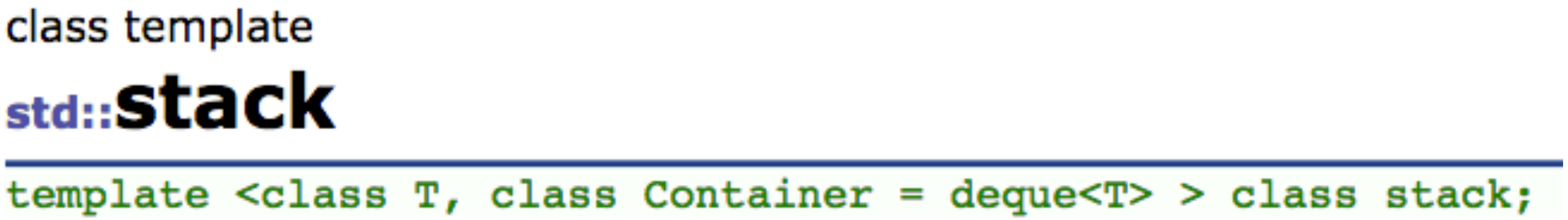

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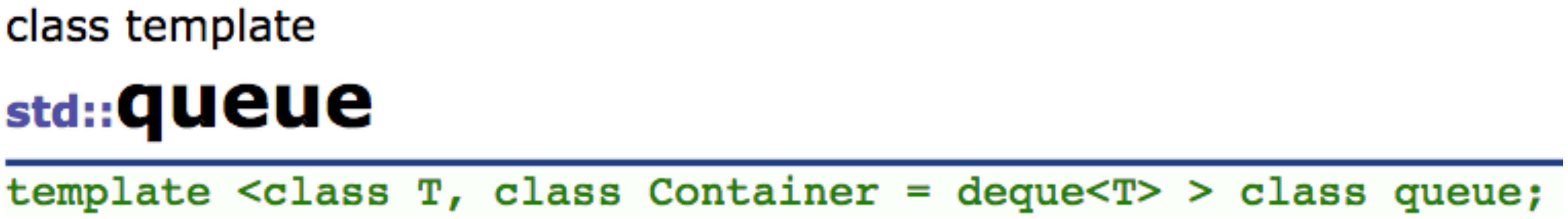

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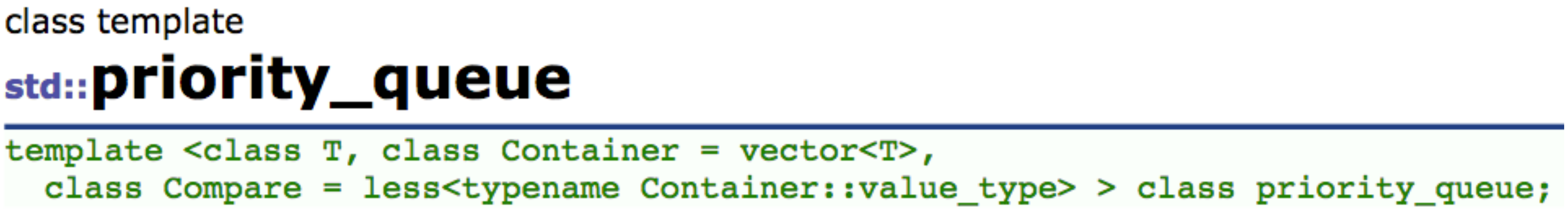

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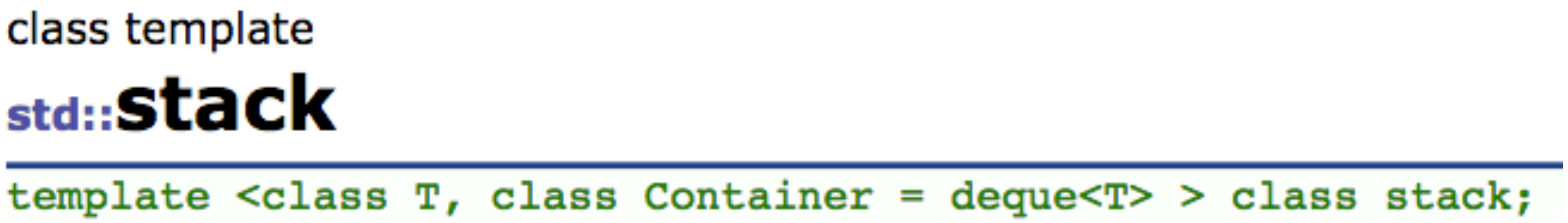

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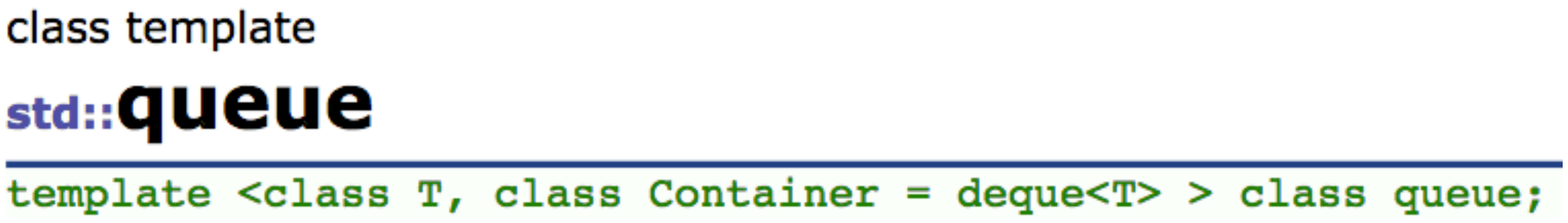

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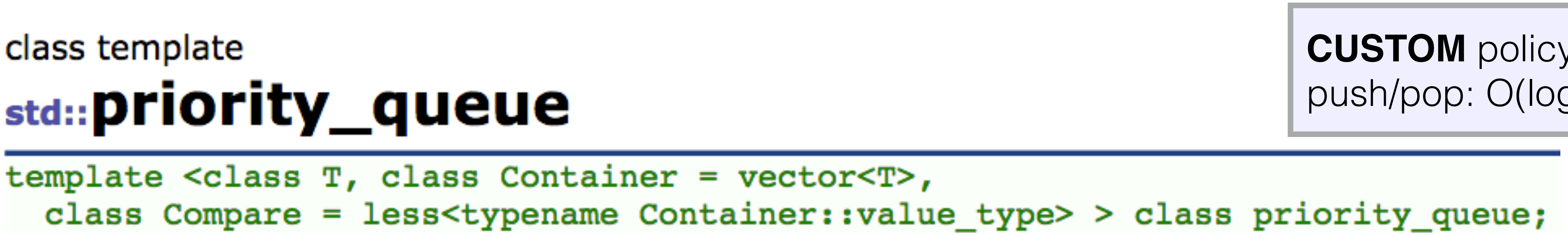

class template

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```
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  class Compare = less<typename Container::value_type> > class priority_queue;
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CUSTOM policy
push/pop: O(log N)

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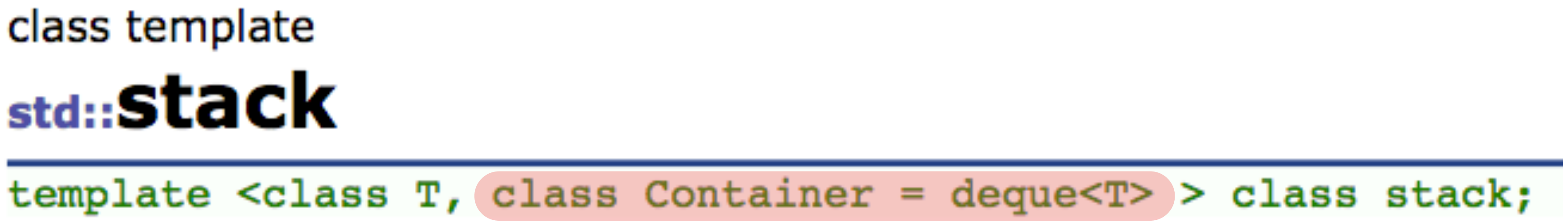

class template

std::**stack**

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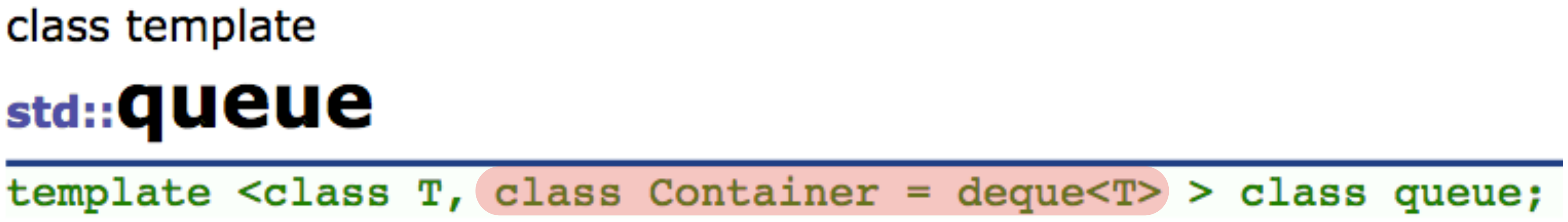
LIFO policy
push/pop: O(1)



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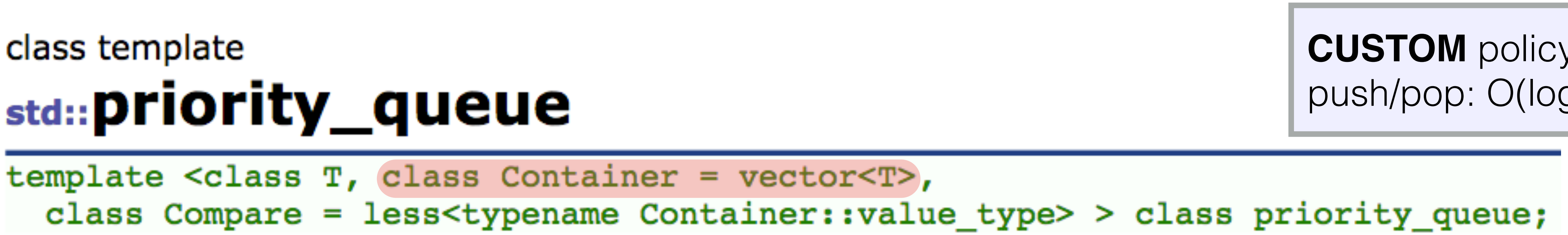

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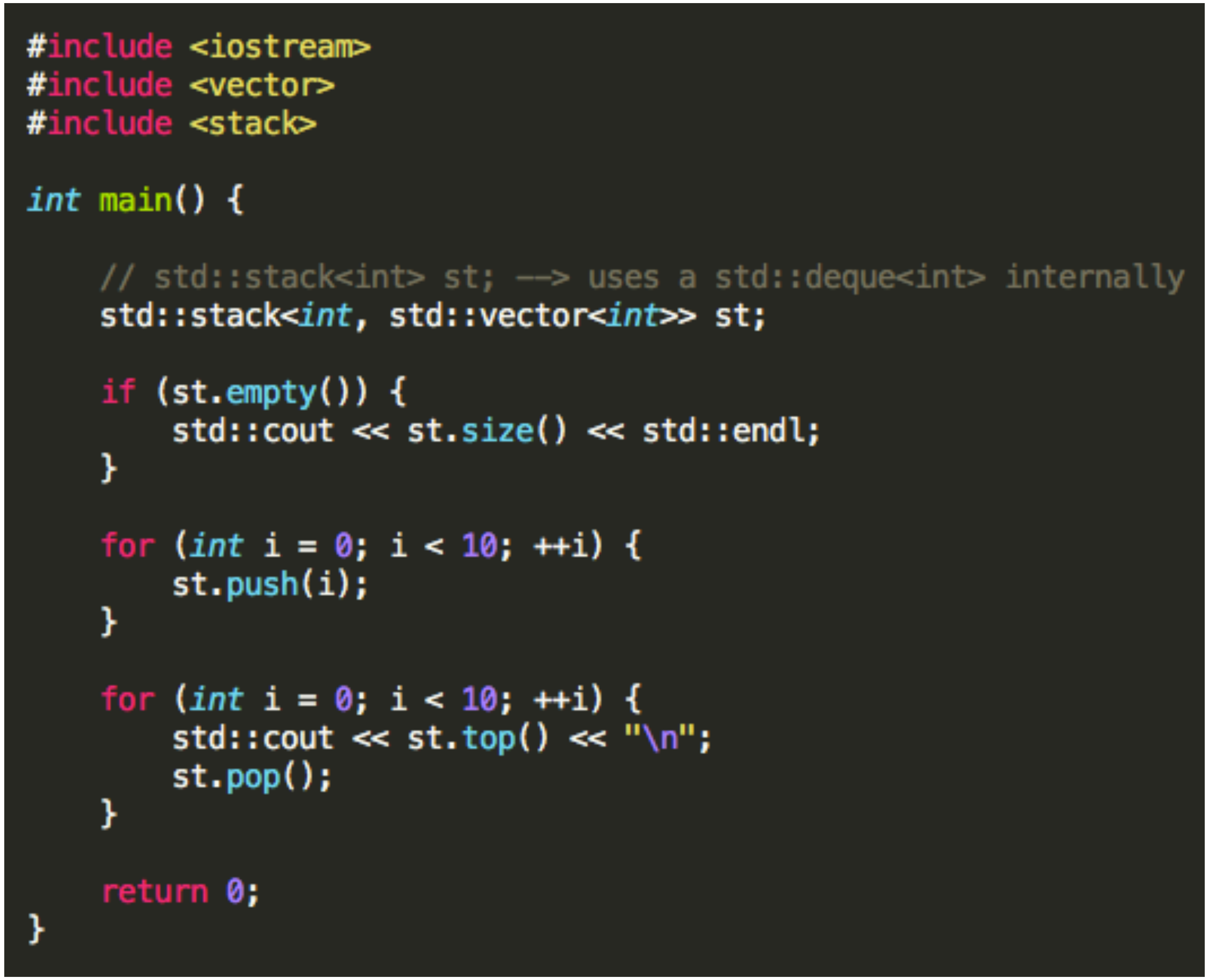
```

CUSTOM policy
push/pop: O(log N)

`vector`, `deque` and `list` can be used here

Container adaptors



```cpp
#include <iostream>
#include <vector>
#include <stack>

int main() {

    // std::stack<int> st; --> uses a std::deque<int> internally
    std::stack<int, std::vector<int>> st;

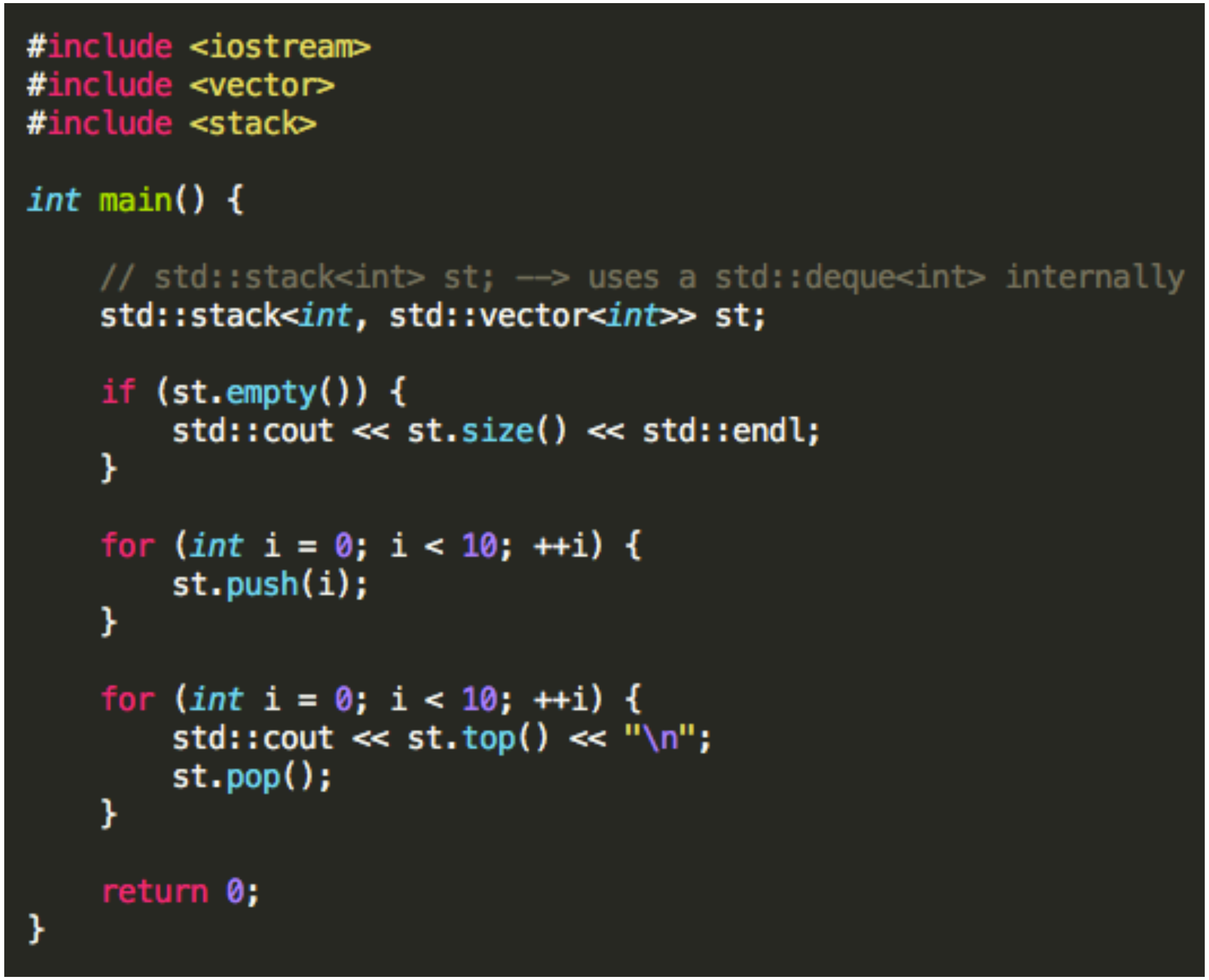
    if (st.empty()) {
        std::cout << st.size() << std::endl;
    }

    for (int i = 0; i < 10; ++i) {
        st.push(i);
    }

    for (int i = 0; i < 10; ++i) {
        std::cout << st.top() << "\n";
        st.pop();
    }

    return 0;
}
```

Container adaptors



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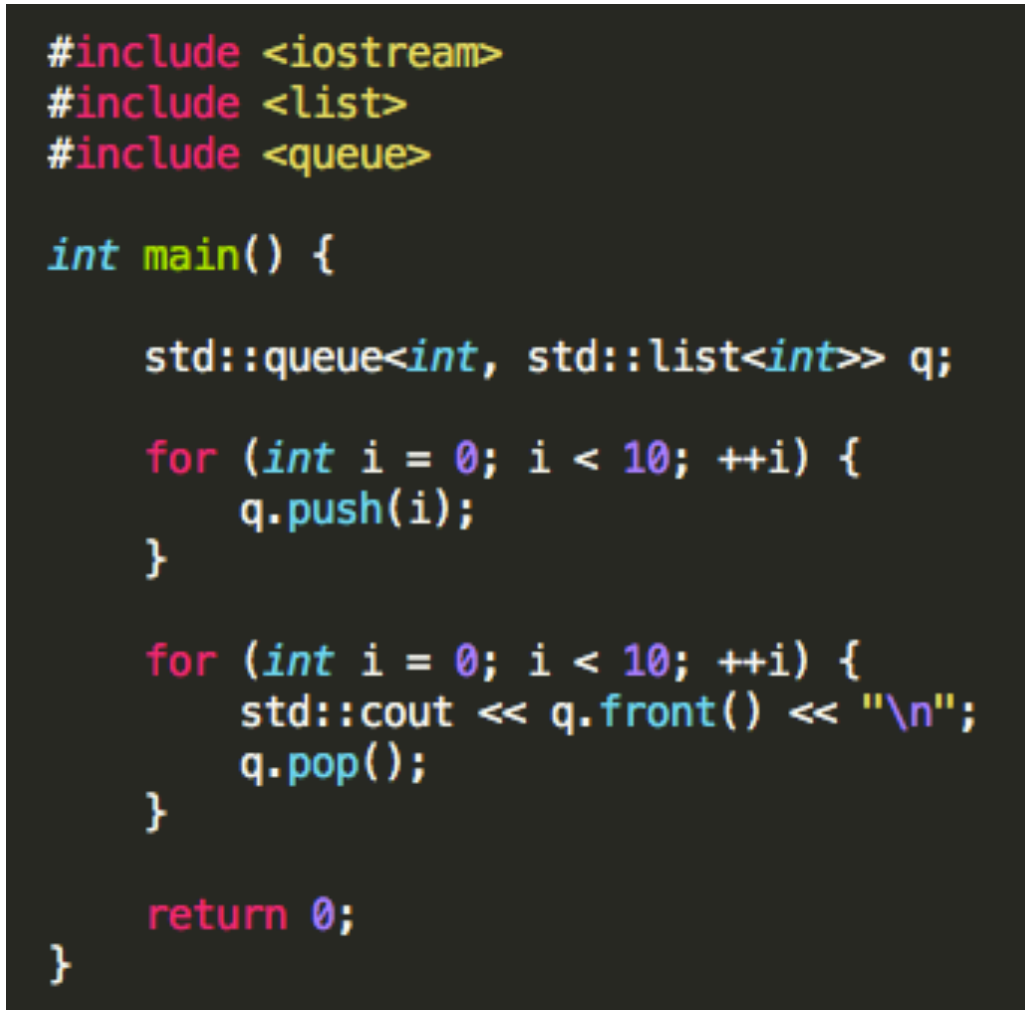
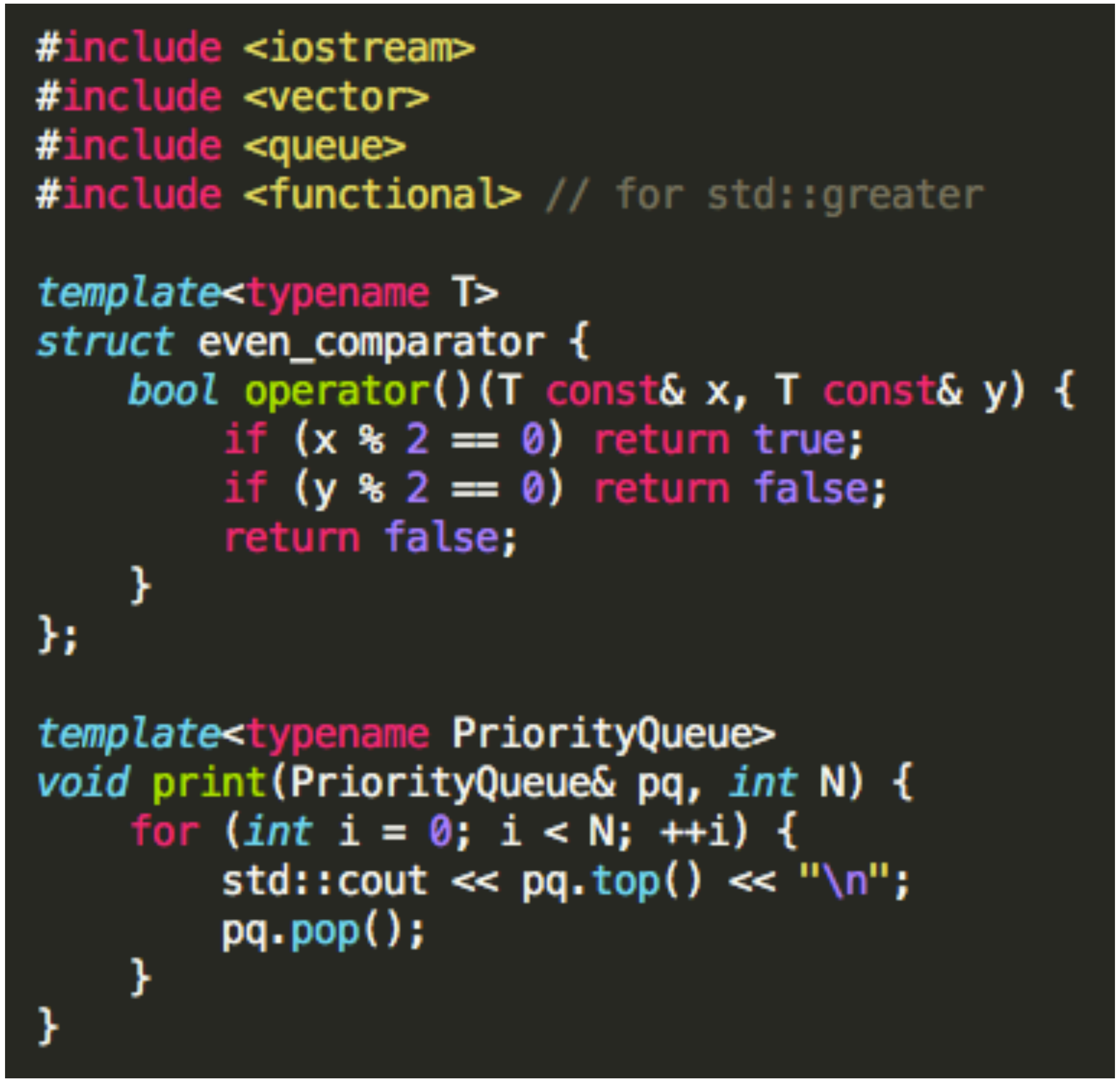
        st.pop();
    }

    return 0;
}
```

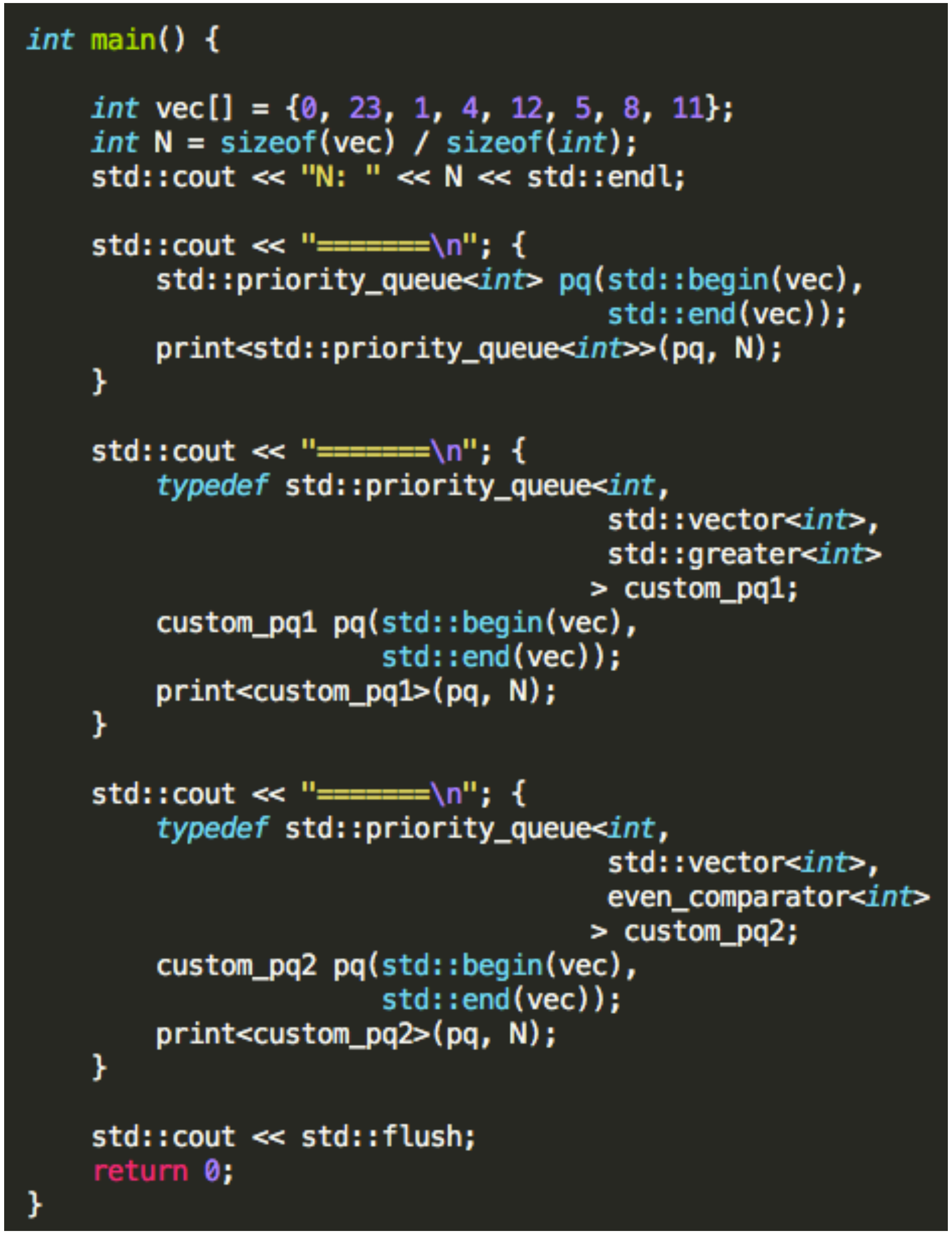


```cpp
#include <iostream>
#include <list>
#include <queue>

int main() {

    std::queue<int, std::list<int>> q;

    for (int i = 0; i < 10; ++i) {
        q.push(i);
    }

    for (int i = 0; i < 10; ++i) {
        std::cout << q.front() << "\n";
        q.pop();
    }

    return 0;
}
```

Container adaptors



```cpp
#include <iostream>
#include <vector>
#include <queue>
#include <functional> // for std::greater

template<typename T>
struct even_comparator {
    bool operator()(T const& x, T const& y) {
        if (x % 2 == 0) return true;
        if (y % 2 == 0) return false;
        return false;
    }
};

template<typename PriorityQueue>
void print(PriorityQueue& pq, int N) {
    for (int i = 0; i < N; ++i) {
        std::cout << pq.top() << "\n";
        pq.pop();
    }
}
```



```cpp
int main() {

    int vec[] = {0, 23, 1, 4, 12, 5, 8, 11};
    int N = sizeof(vec) / sizeof(int);
    std::cout << "N: " << N << std::endl;

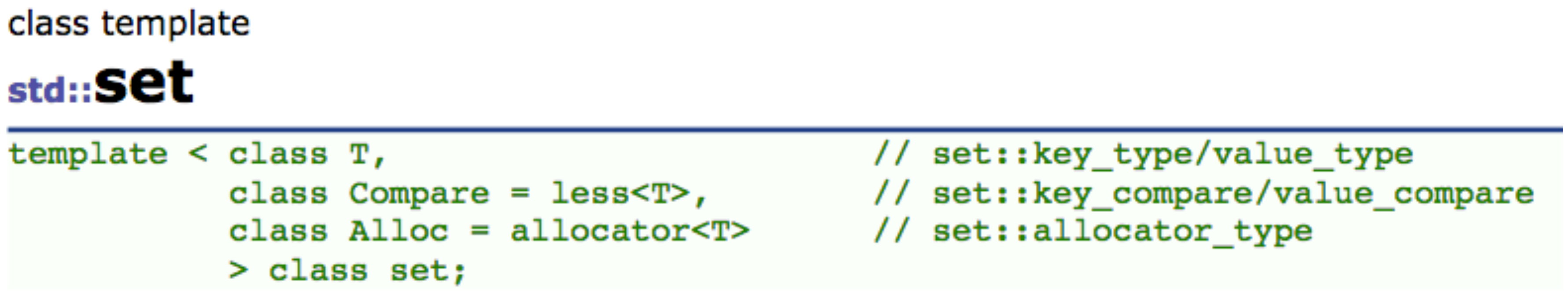
    std::cout << "=======\n"; {
        std::priority_queue<int> pq(std::begin(vec),
                                    std::end(vec));
        print<std::priority_queue<int>>(pq, N);
    }

    std::cout << "=======\n"; {
        typedef std::priority_queue<int,
                                    std::vector<int>,
                                    std::greater<int>
                                   > custom_pq1;
        custom_pq1 pq(std::begin(vec),
                      std::end(vec));
        print<custom_pq1>(pq, N);
    }

    std::cout << "=======\n"; {
        typedef std::priority_queue<int,
                                    std::vector<int>,
                                    even_comparator<int>
                                   > custom_pq2;
        custom_pq2 pq(std::begin(vec),
                      std::end(vec));
        print<custom_pq2>(pq, N);
    }

    std::cout << std::flush;
    return 0;
}
```

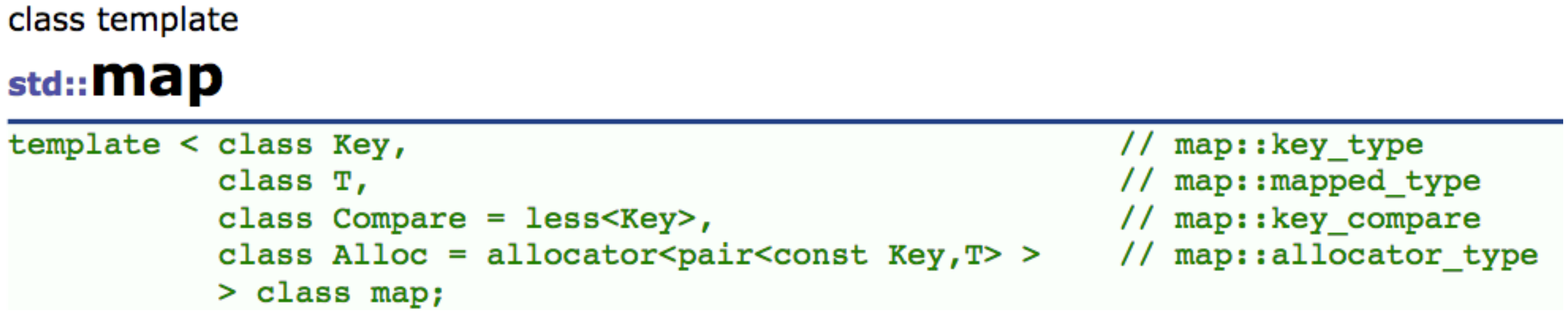
Associative containers



class template

std::set

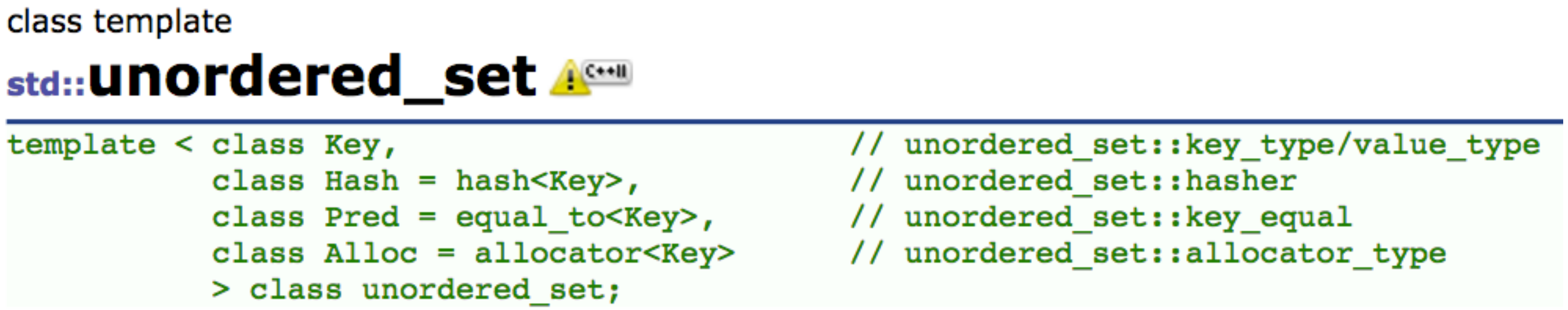
```
template < class T,                        // set::key_type/value_type
           class Compare = less<T>,        // set::key_compare/value_compare
           class Alloc = allocator<T>      // set::allocator_type
           > class set;
```



class template

std::map

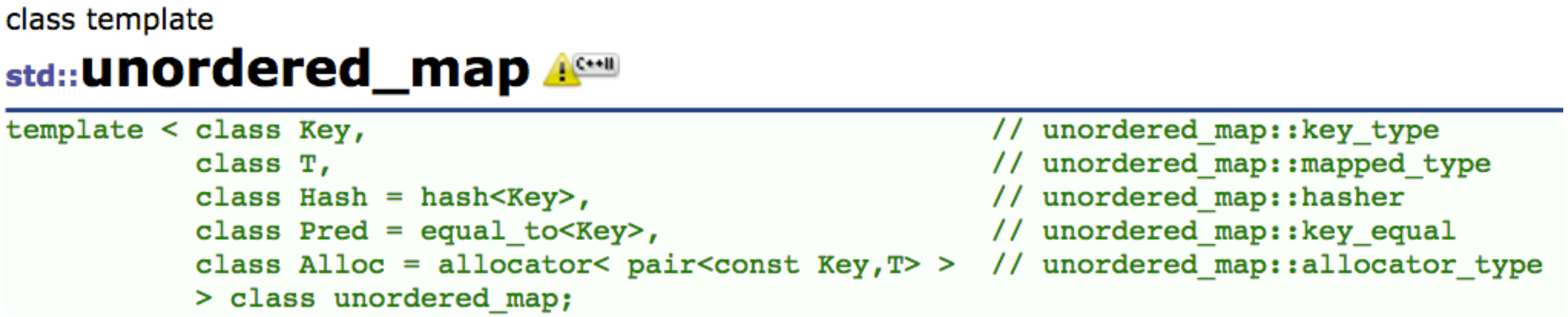
```
template < class Key,                                     // map::key_type
           class T,                                       // map::mapped_type
           class Compare = less<Key>,                     // map::key_compare
           class Alloc = allocator<pair<const Key,T> >    // map::allocator_type
           > class map;
```



class template

std::unordered_set C++11

```
template < class Key,                        // unordered_set::key_type/value_type
           class Hash = hash<Key>,           // unordered_set::hasher
           class Pred = equal_to<Key>,       // unordered_set::key_equal
           class Alloc = allocator<Key>      // unordered_set::allocator_type
           > class unordered_set;
```



class template

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```
template < class Key,                                    // unordered_map::key_type
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           class Hash = hash<Key>,                       // unordered_map::hasher
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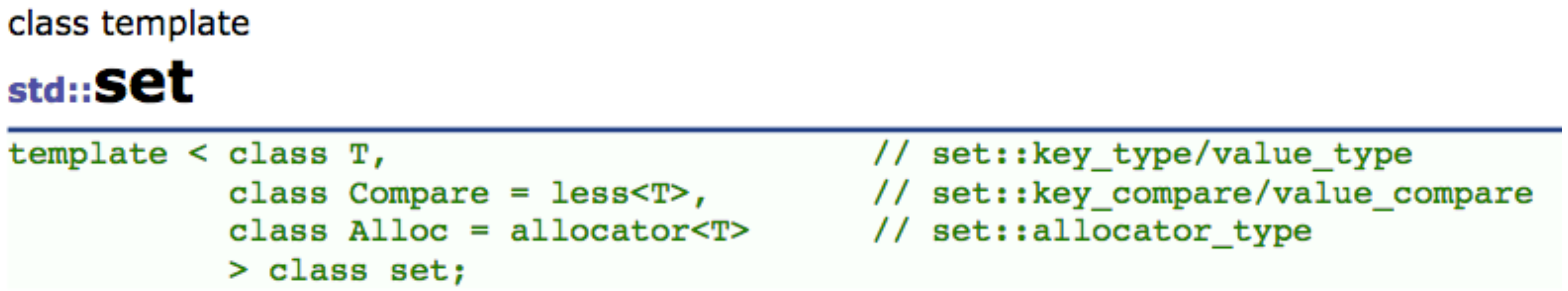
           class Alloc = allocator< pair<const Key,T> >  // unordered_map::allocator_type
           > class unordered_map;
```

Associative containers



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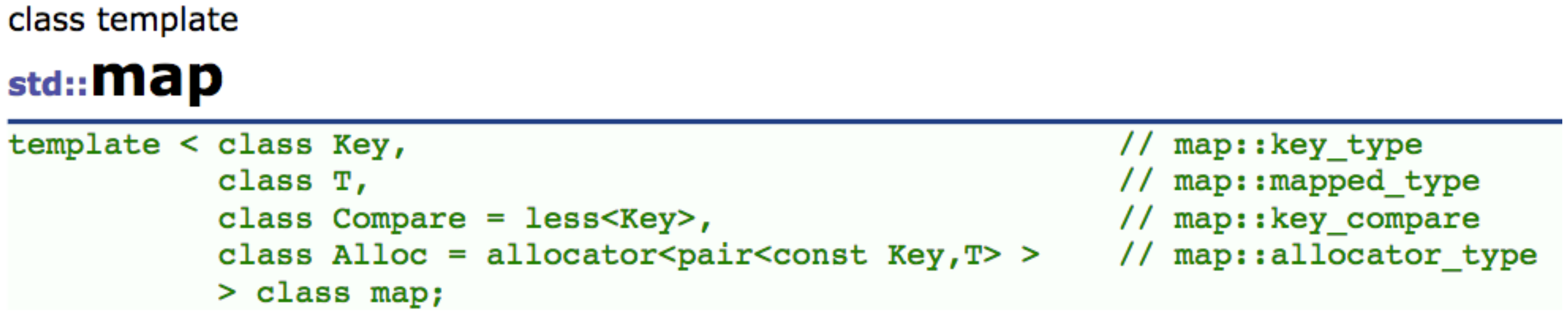

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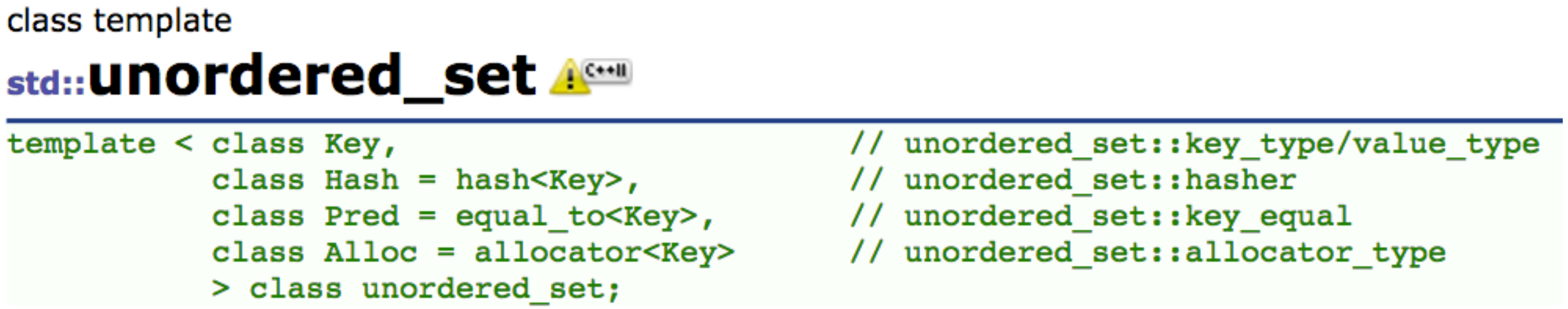
```

based on (balanced) **binary search trees**

insert/delete: O(log N)
range queries: O(|range|)



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           > class unordered_set;
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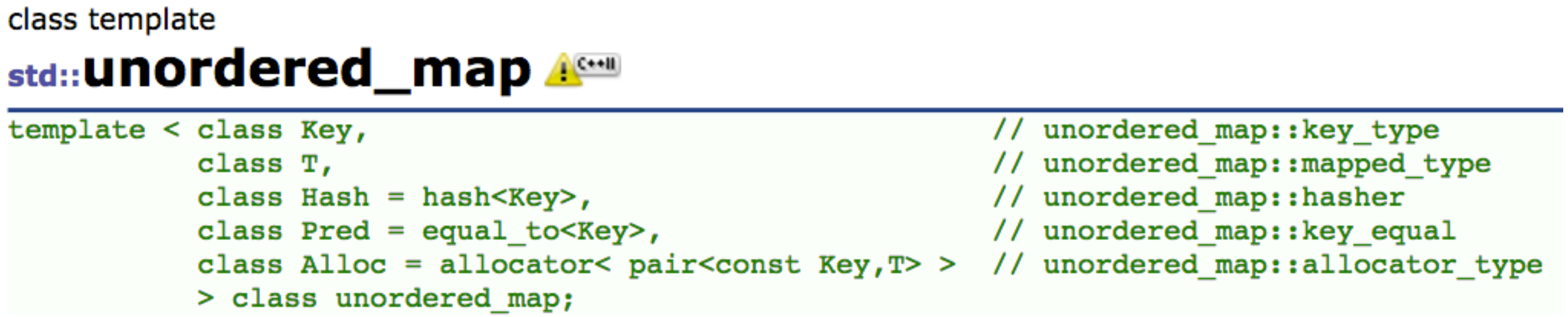

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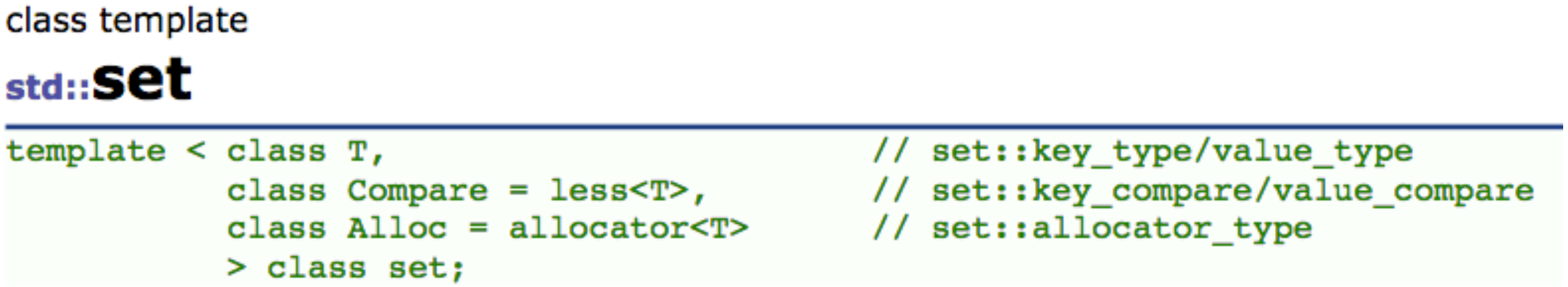

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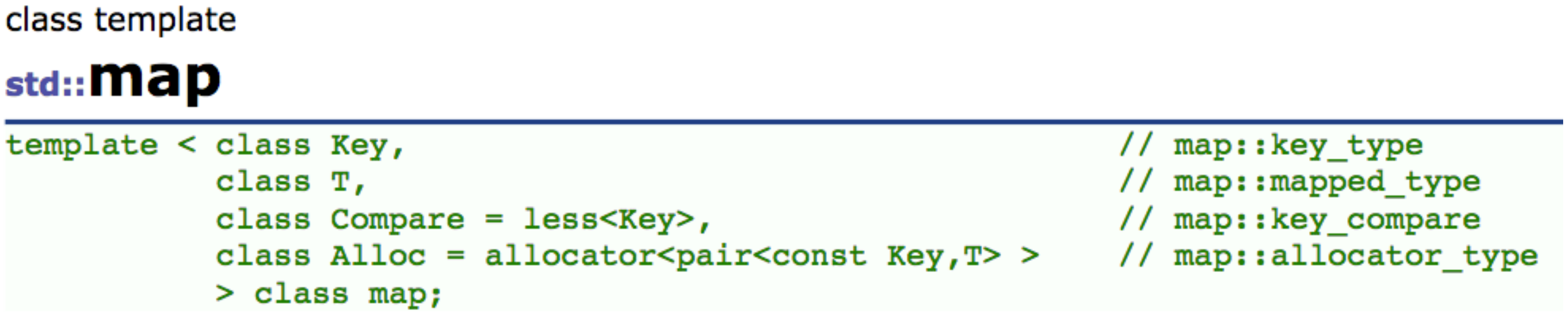

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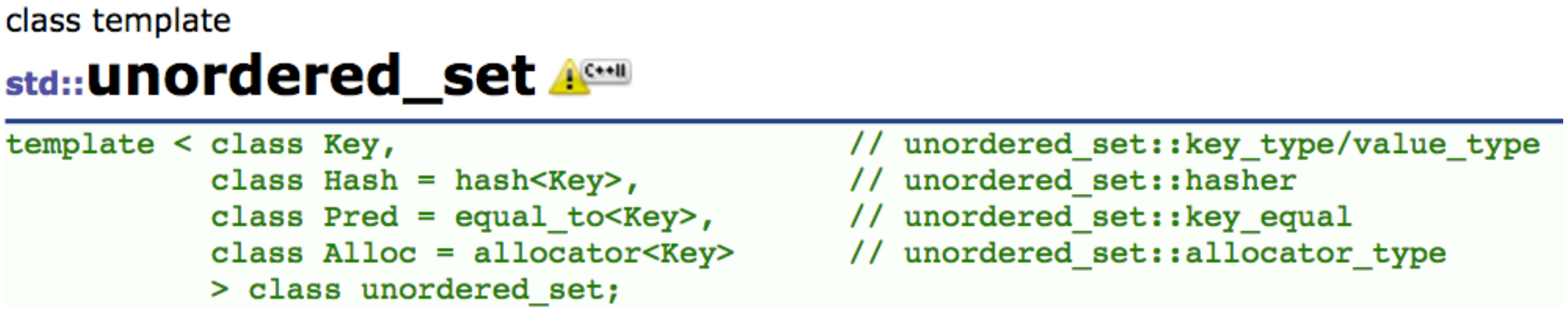

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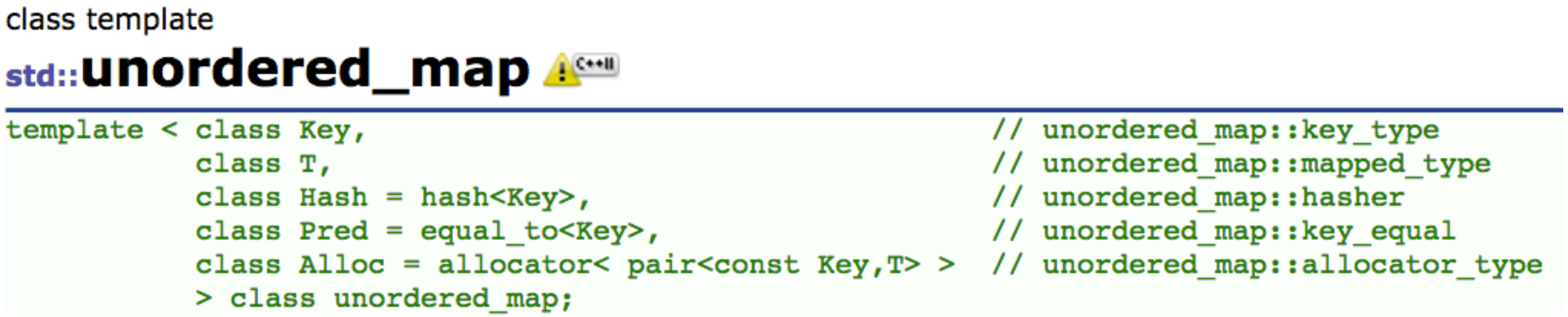
           class Alloc = allocator<Key>      // unordered_set::allocator_type
           > class unordered_set;
```



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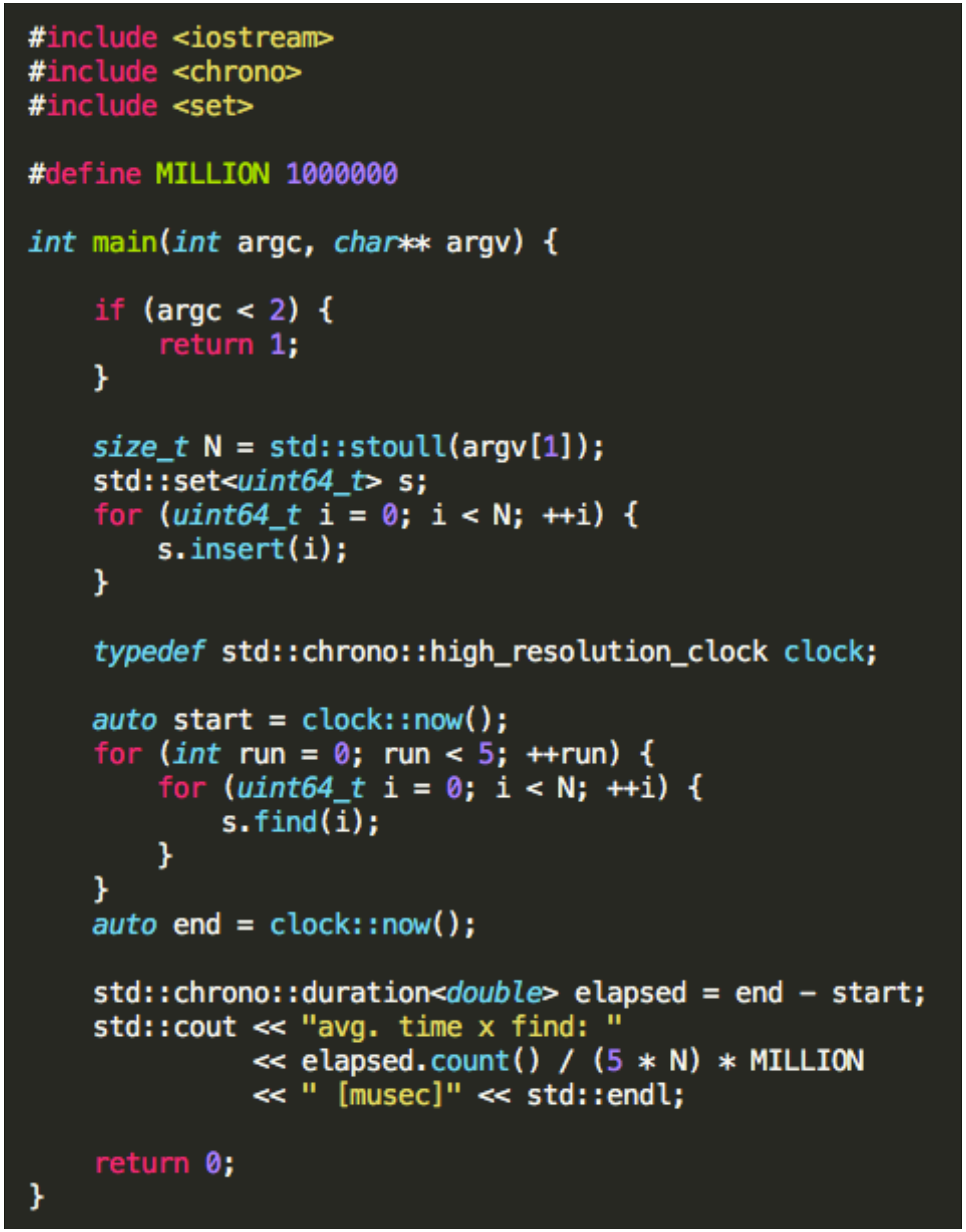
           > class unordered_map;
```

based on **hashing**

insert/delete: O(1) exp.
range queries: ——

Associative containers



```cpp
#include <iostream>
#include <chrono>
#include <set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

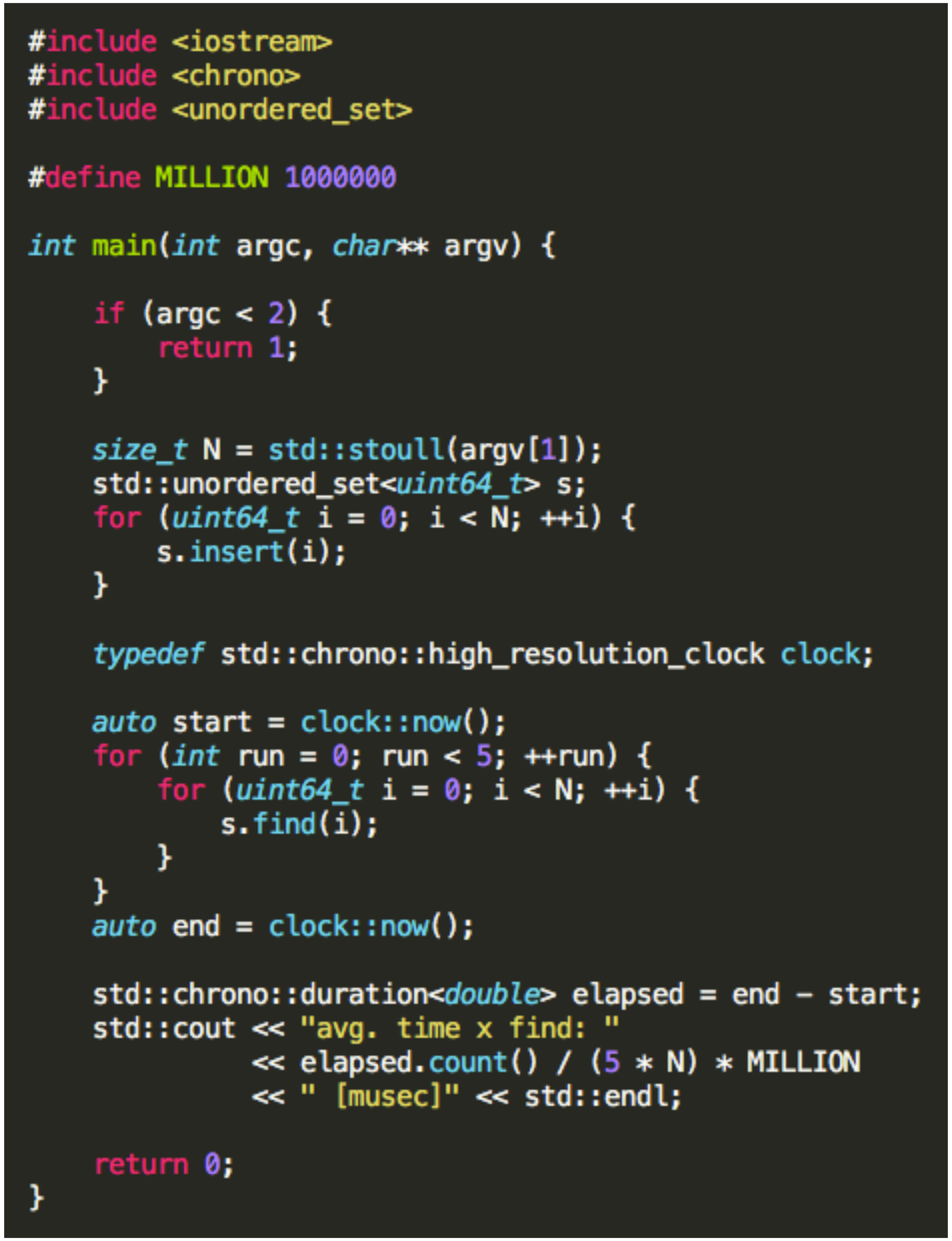
    size_t N = std::stoull(argv[1]);
    std::set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << " [musec]" << std::endl;

    return 0;
}
```



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#include <chrono>
#include <unordered_set>

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int main(int argc, char** argv) {

    if (argc < 2) {
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    }

    size_t N = std::stoull(argv[1]);
    std::unordered_set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

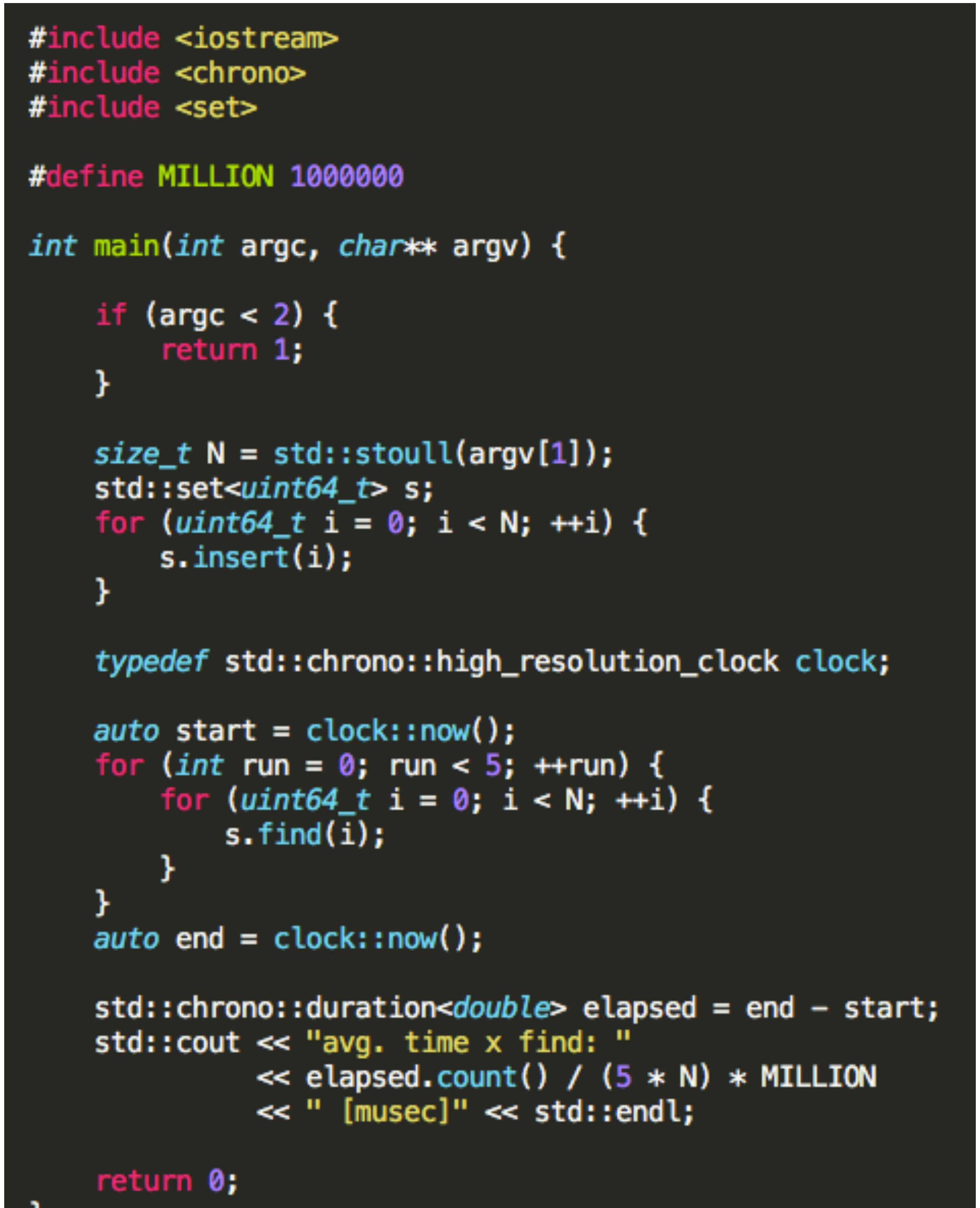
    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

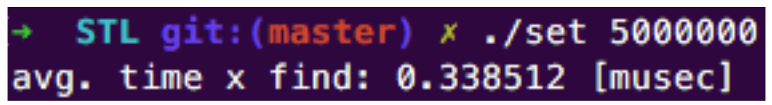
    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << " [musec]" << std::endl;

    return 0;
}
```

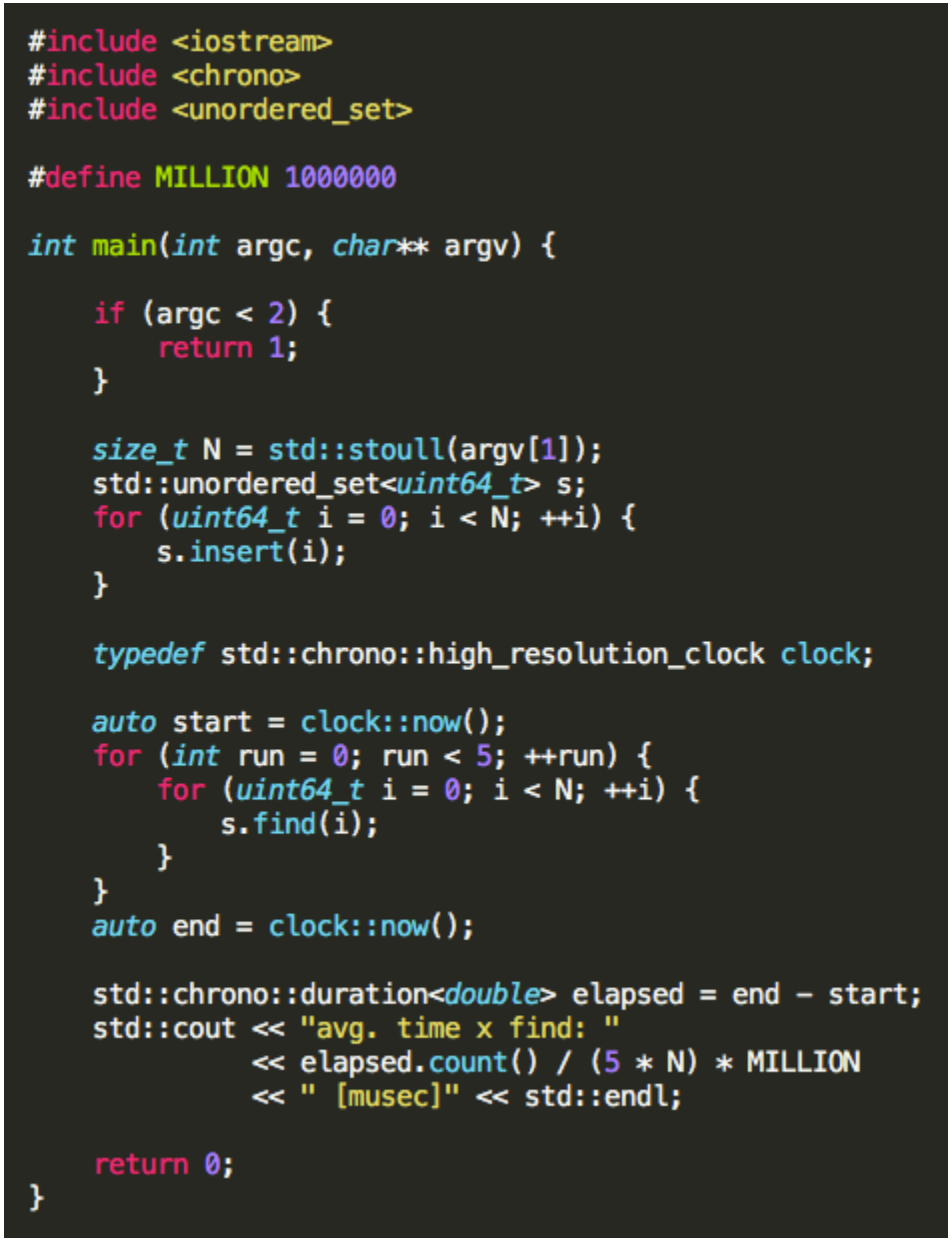
Associative containers



```cpp
#include <iostream>
#include <chrono>
#include <set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

    size_t N = std::stoull(argv[1]);
    std::set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << " [musec]" << std::endl;

    return 0;
}
```

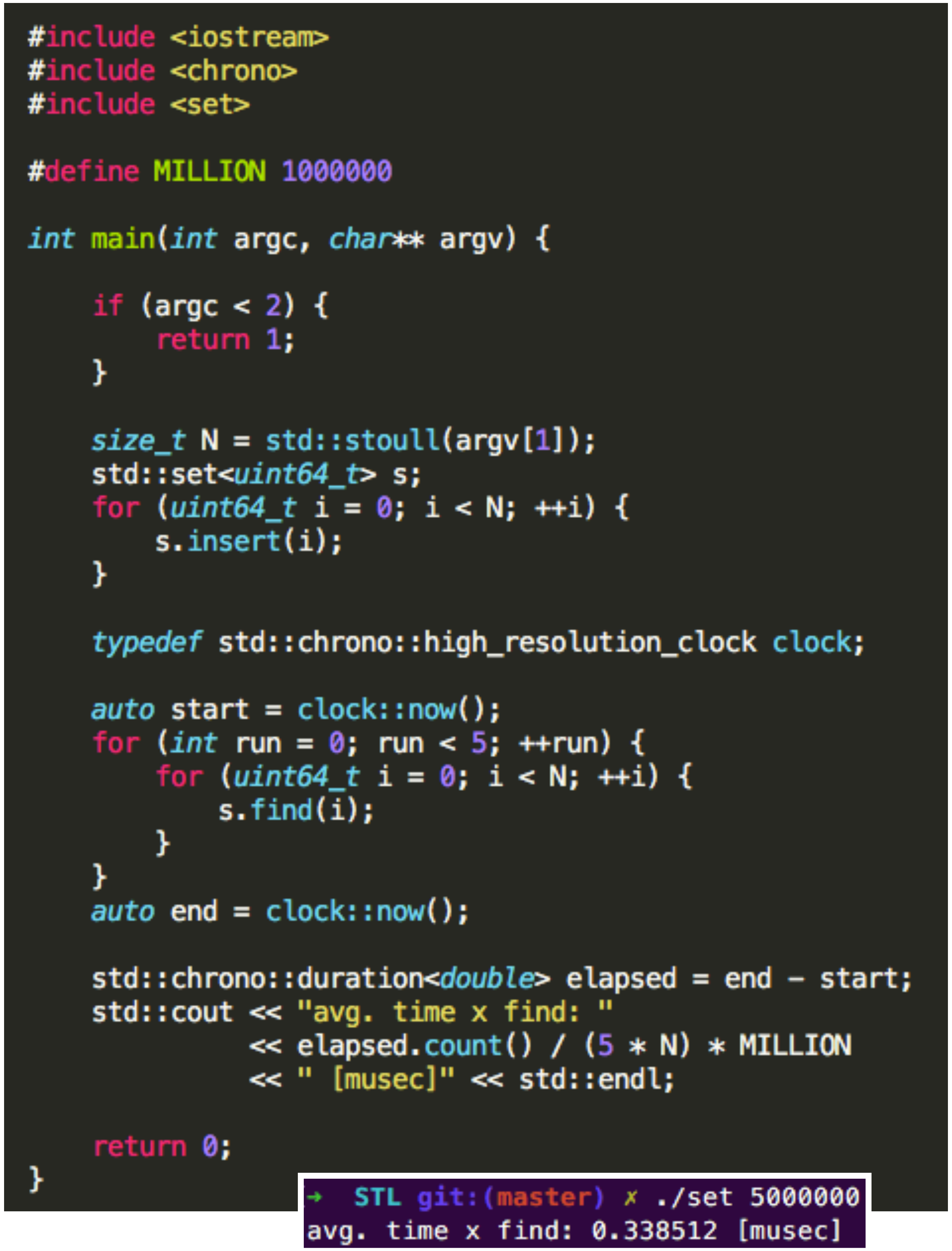


```
→  STL git:(master) ✗ ./set 5000000
avg. time x find: 0.338512 [musec]
```



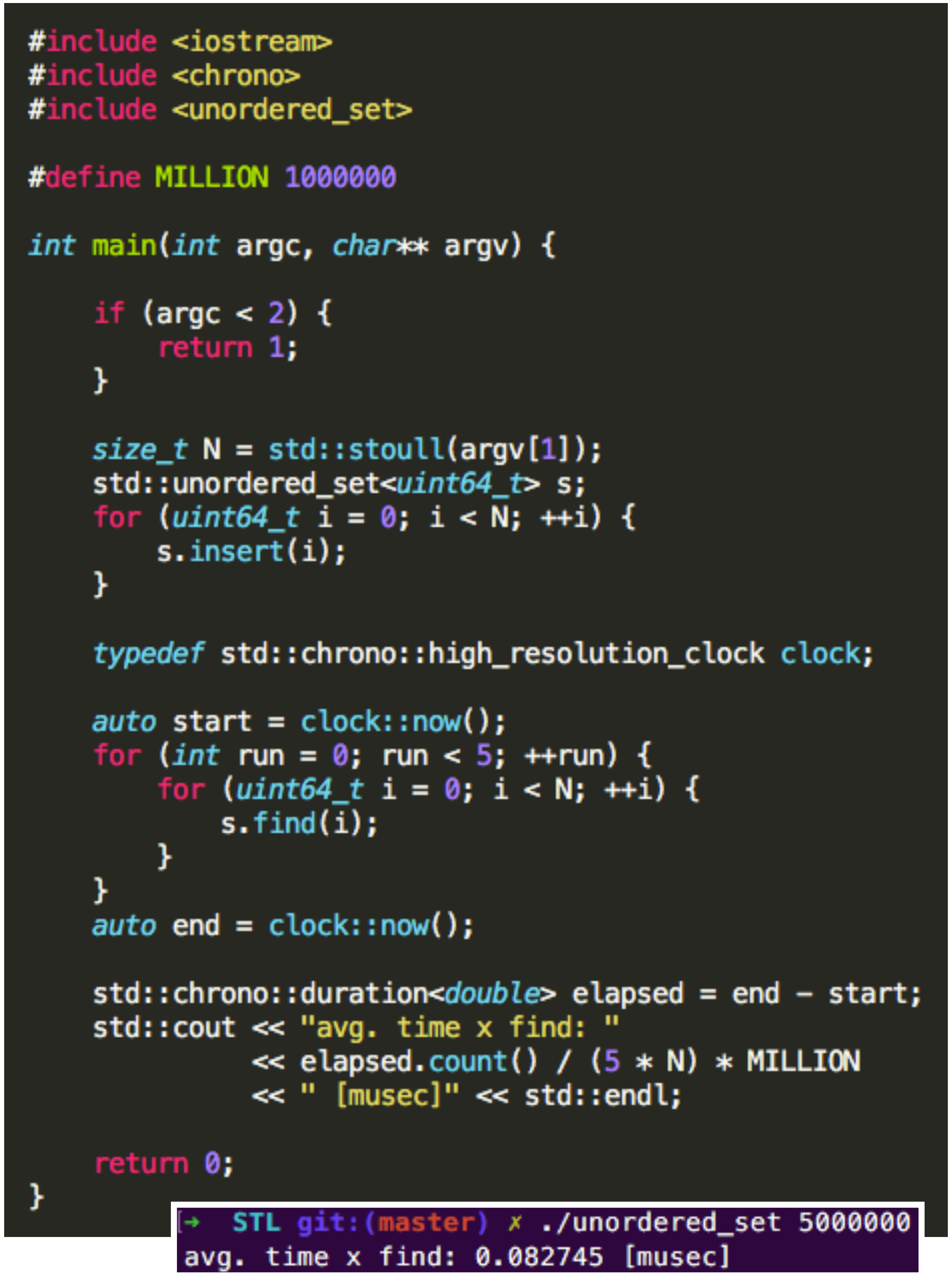
```cpp
#include <iostream>
#include <chrono>
#include <unordered_set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

    size_t N = std::stoull(argv[1]);
    std::unordered_set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << " [musec]" << std::endl;

    return 0;
}
```

Associative containers



```cpp
#include <iostream>
#include <chrono>
#include <set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

    size_t N = std::stoull(argv[1]);
    std::set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << "  [musec]" << std::endl;

    return 0;
}
```

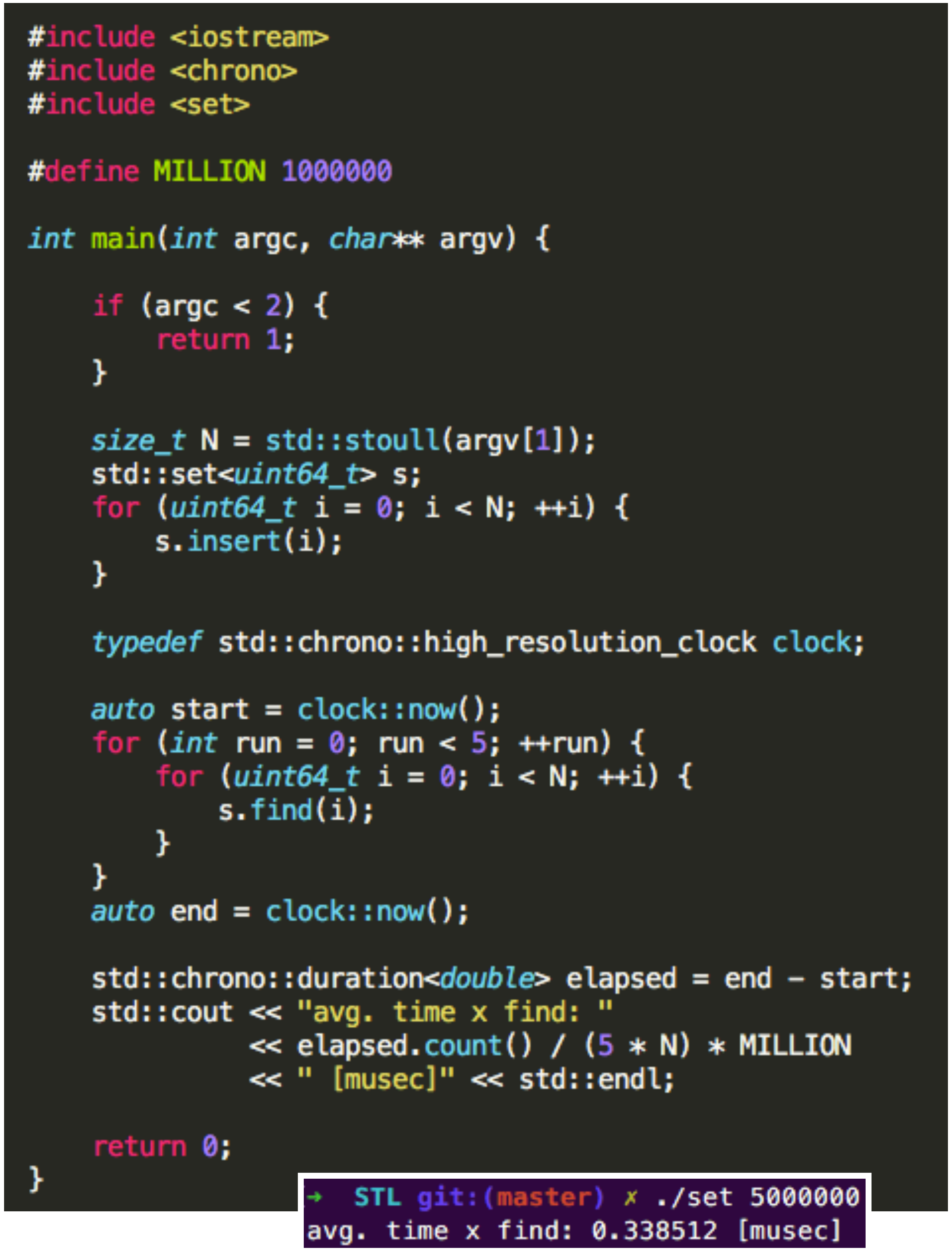
```
➜  STL git:(master) ✗ ./set 5000000
avg. time x find: 0.338512 [musec]
```



```cpp
#include <iostream>
#include <chrono>
#include <unordered_set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

    size_t N = std::stoull(argv[1]);
    std::unordered_set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << "  [musec]" << std::endl;

    return 0;
}
```

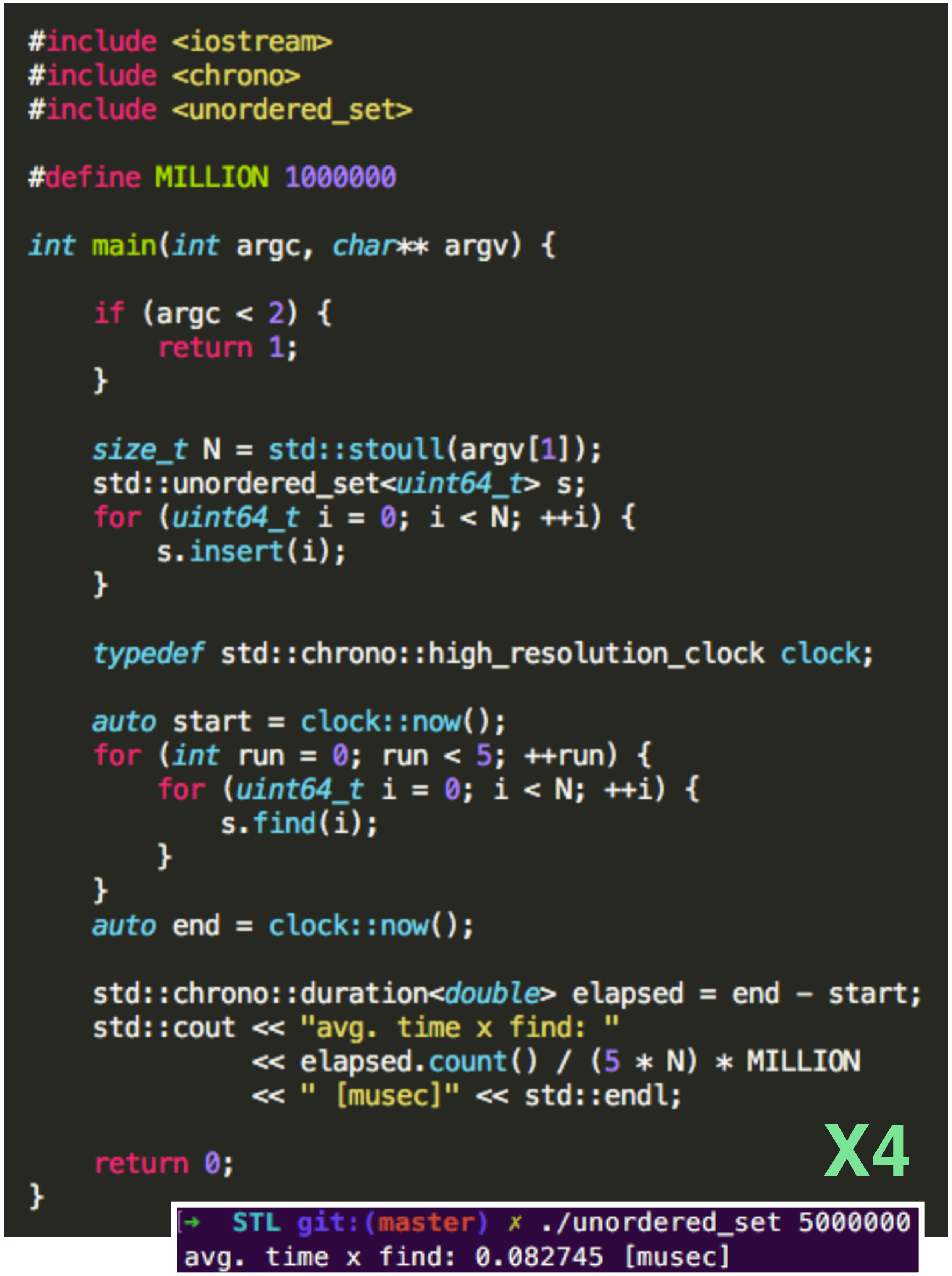
```
[➜  STL git:(master) ✗ ./unordered_set 5000000
avg. time x find: 0.082745 [musec]
```

Associative containers



```
#include <iostream>
#include <chrono>
#include <set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

    size_t N = std::stoull(argv[1]);
    std::set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << " [musec]" << std::endl;

    return 0;
}
```

```
→  STL git:(master) ✗ ./set 5000000
avg. time x find: 0.338512 [musec]
```



```
#include <iostream>
#include <chrono>
#include <unordered_set>

#define MILLION 1000000

int main(int argc, char** argv) {

    if (argc < 2) {
        return 1;
    }

    size_t N = std::stoull(argv[1]);
    std::unordered_set<uint64_t> s;
    for (uint64_t i = 0; i < N; ++i) {
        s.insert(i);
    }

    typedef std::chrono::high_resolution_clock clock;

    auto start = clock::now();
    for (int run = 0; run < 5; ++run) {
        for (uint64_t i = 0; i < N; ++i) {
            s.find(i);
        }
    }
    auto end = clock::now();

    std::chrono::duration<double> elapsed = end - start;
    std::cout << "avg. time x find: "
              << elapsed.count() / (5 * N) * MILLION
              << " [musec]" << std::endl;

    return 0;
}
```

X4

```
[→  STL git:(master) ✗ ./unordered_set 5000000
avg. time x find: 0.082745 [musec]
```

Iterators

An iterator is any **object** that, pointing to some element in a range of elements (such as an array or a container), has the ability to **iterate** through the elements of that range using a set of operators, at least the increment (++) and dereference (*) operators.

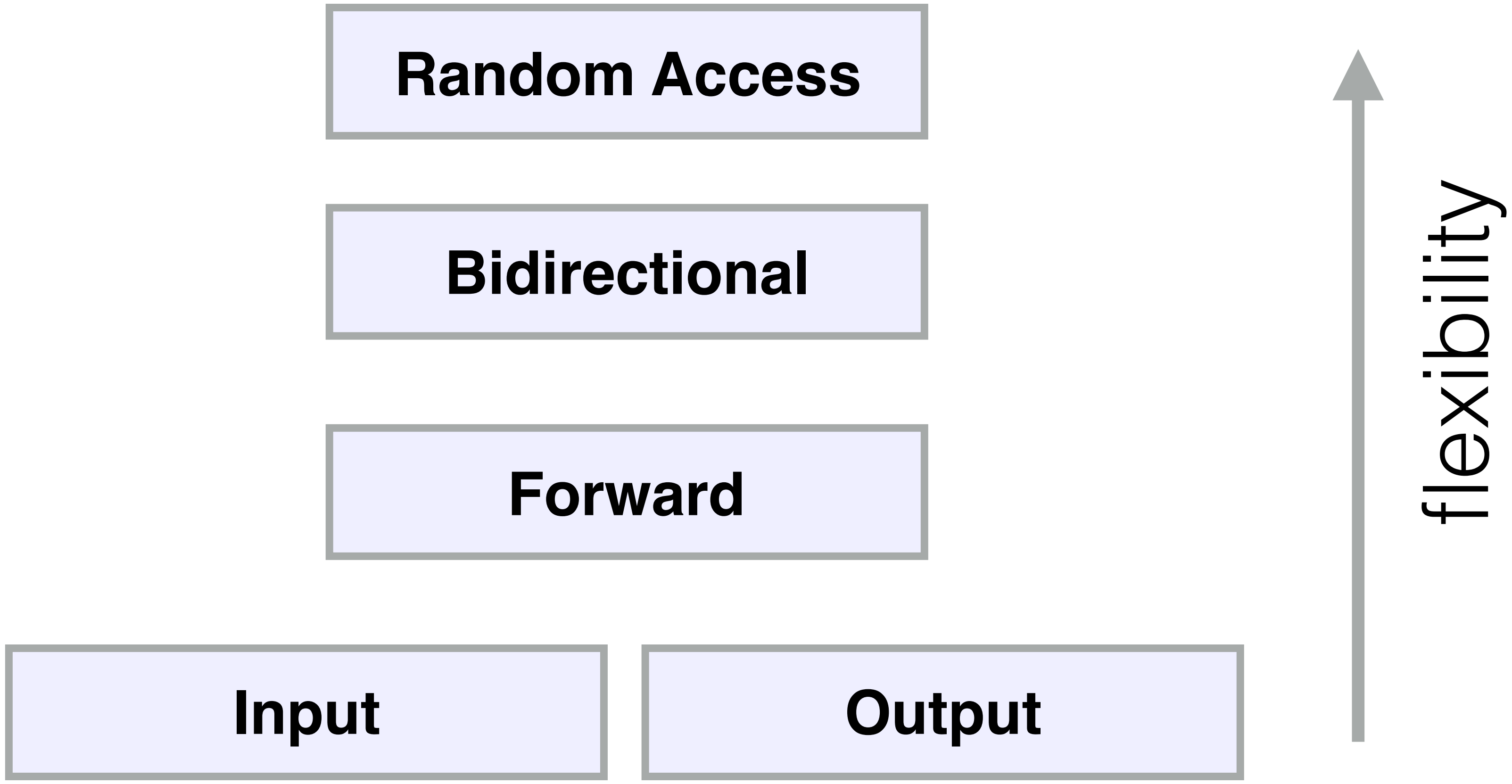
Operations:

```
advance
distance
begin
end
prev
next
```

Iterators

An iterator is any **object** that, pointing to some element in a range of elements (such as an array or a container), has the ability to **iterate** through the elements of that range using a set of operators, at least the increment (++) and dereference (∗) operators.

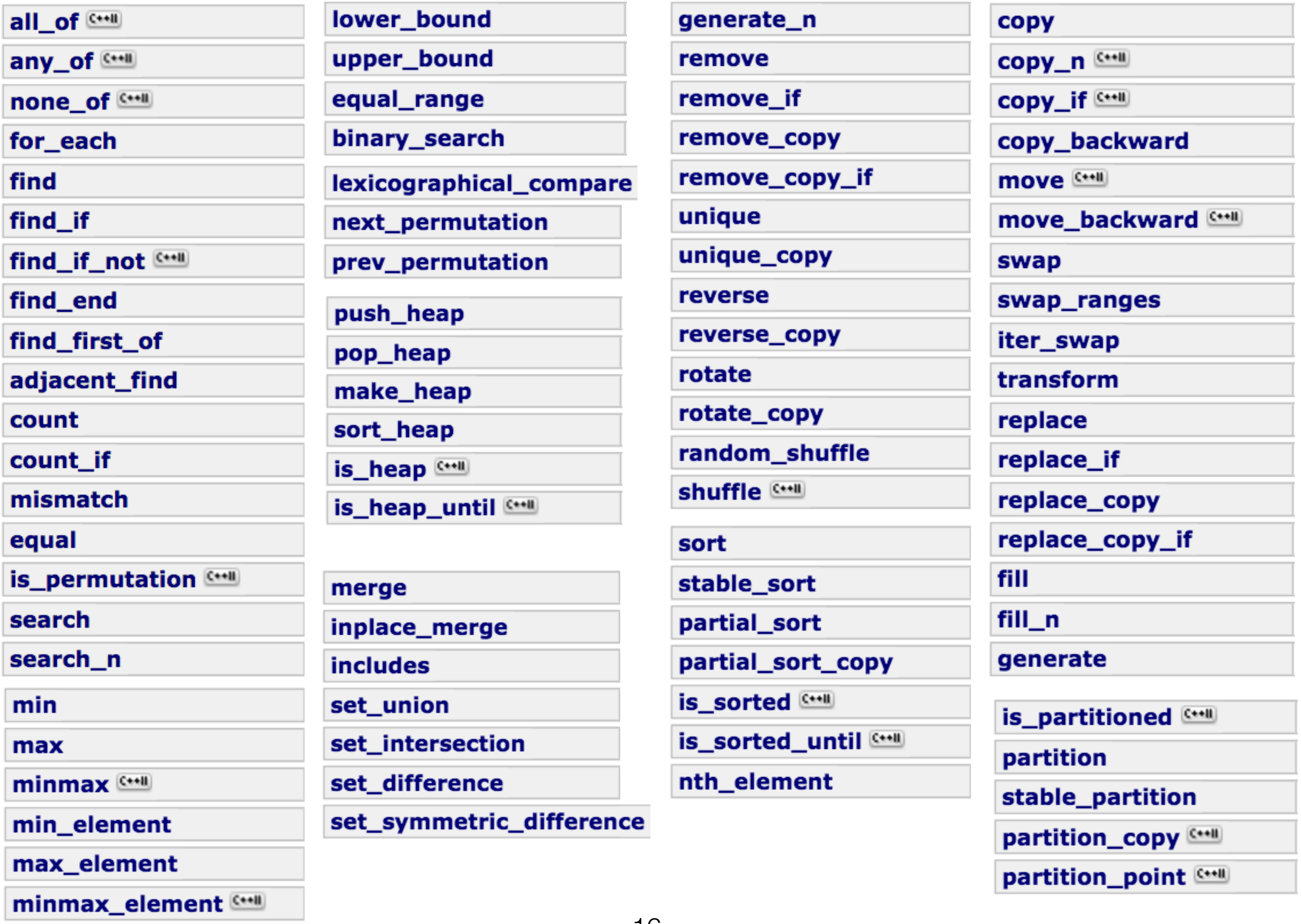
Operations:
`advance`
`distance`
`begin`
`end`
`prev`
`next`



`<algorithm>`

Algorithms

+ 20 with `C++11`



- all_of C++11
- any_of C++11
- none_of C++11
- for_each
- find
- find_if
- find_if_not C++11
- find_end
- find_first_of
- adjacent_find
- count
- count_if
- mismatch
- equal
- is_permutation C++11
- search
- search_n

- min
- max
- minmax C++11
- min_element
- max_element
- minmax_element C++11

- lower_bound
- upper_bound
- equal_range
- binary_search

- lexicographical_compare
- next_permutation
- prev_permutation

- push_heap
- pop_heap
- make_heap
- sort_heap
- is_heap C++11
- is_heap_until C++11

- merge
- inplace_merge
- includes
- set_union
- set_intersection
- set_difference
- set_symmetric_difference

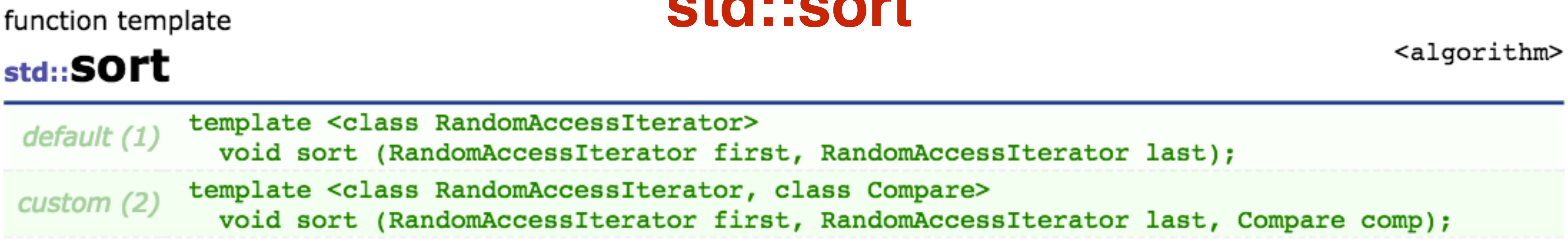
- generate_n
- remove
- remove_if
- remove_copy
- remove_copy_if
- unique
- unique_copy
- reverse
- reverse_copy
- rotate
- rotate_copy
- random_shuffle
- shuffle C++11

- sort
- stable_sort
- partial_sort
- partial_sort_copy
- is_sorted C++11
- is_sorted_until C++11
- nth_element

- copy
- copy_n C++11
- copy_if C++11
- copy_backward
- move C++11
- move_backward C++11
- swap
- swap_ranges
- iter_swap
- transform
- replace
- replace_if
- replace_copy
- replace_copy_if
- fill
- fill_n
- generate

- is_partitioned C++11
- partition
- stable_partition
- partition_copy C++11
- partition_point C++11

std::sort



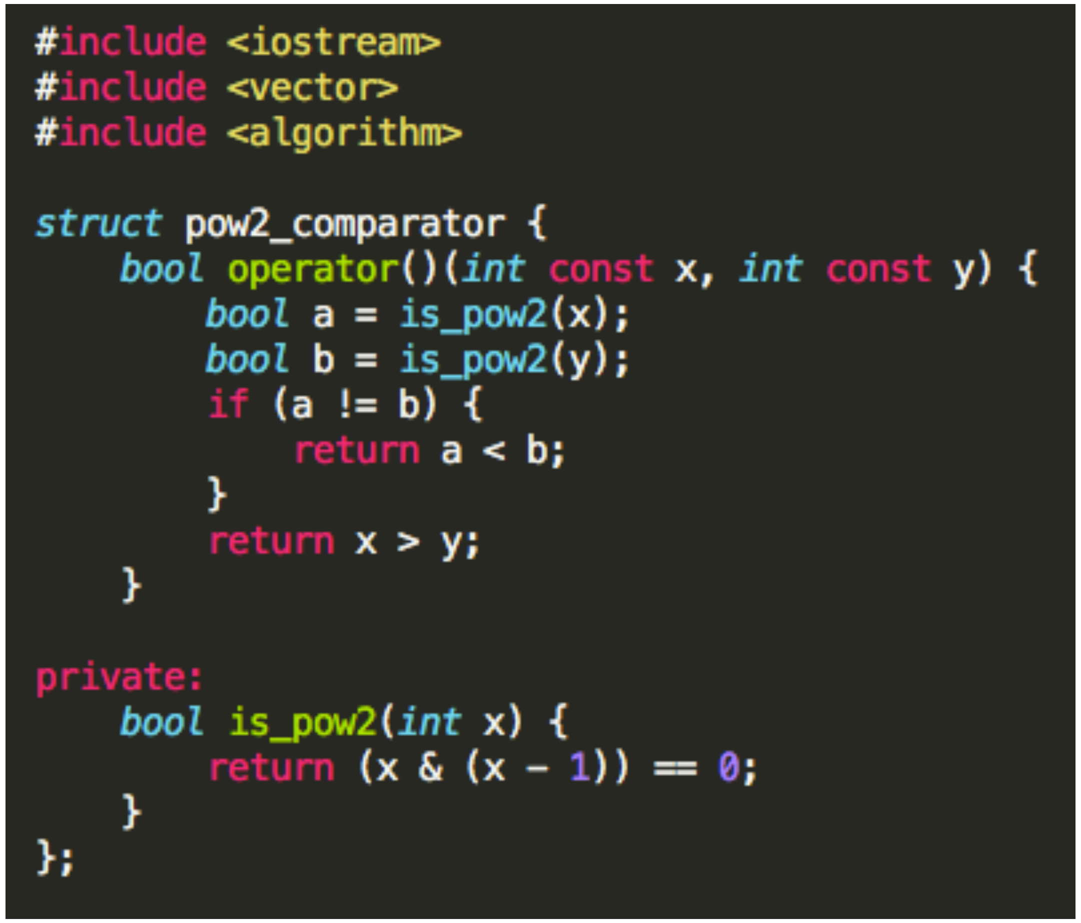
function template

std::sort

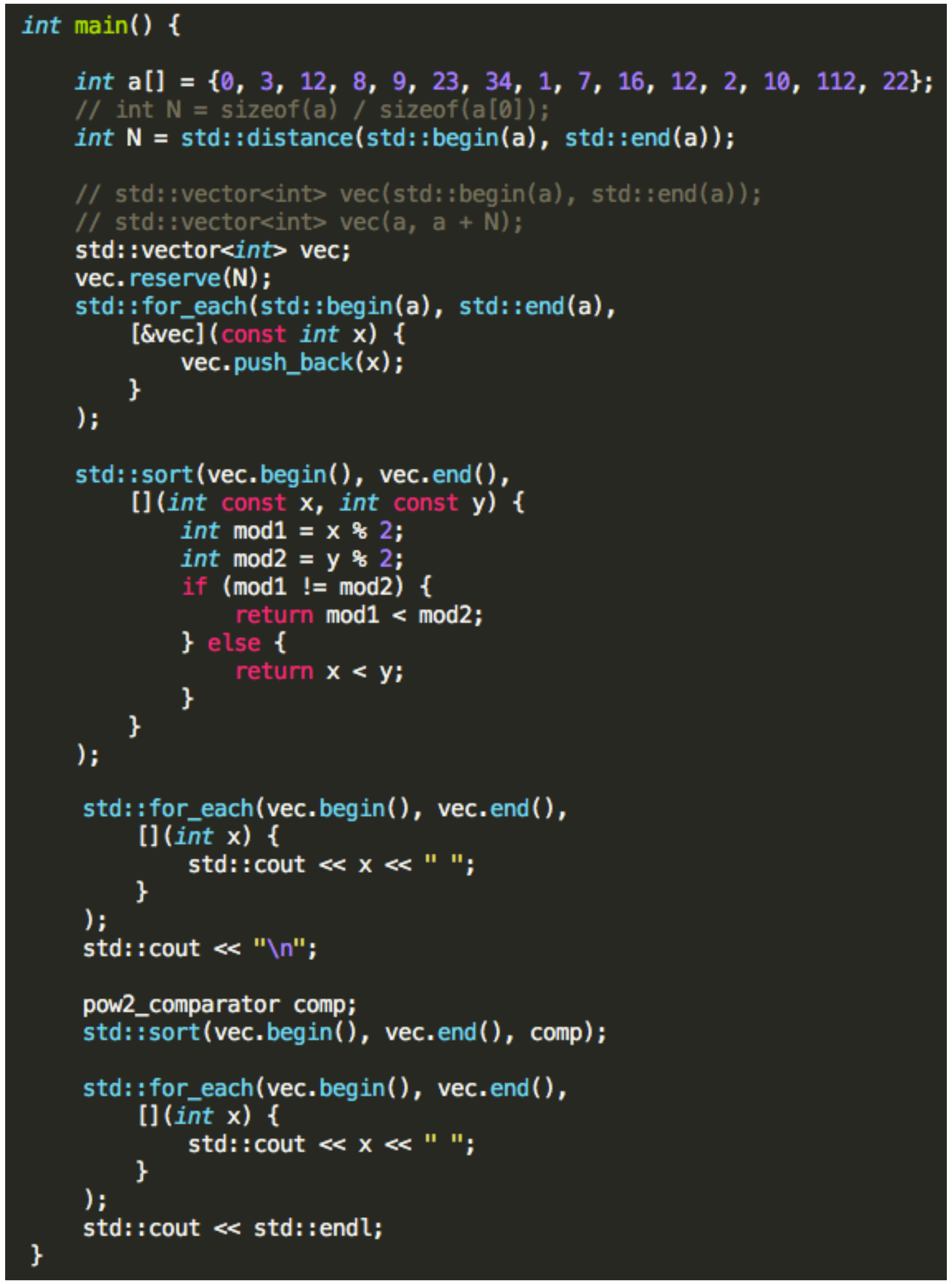
<algorithm>

default (1)	`template <class RandomAccessIterator>`
	`  void sort (RandomAccessIterator first, RandomAccessIterator last);`

custom (2)	`template <class RandomAccessIterator, class Compare>`
	`  void sort (RandomAccessIterator first, RandomAccessIterator last, Compare comp);`

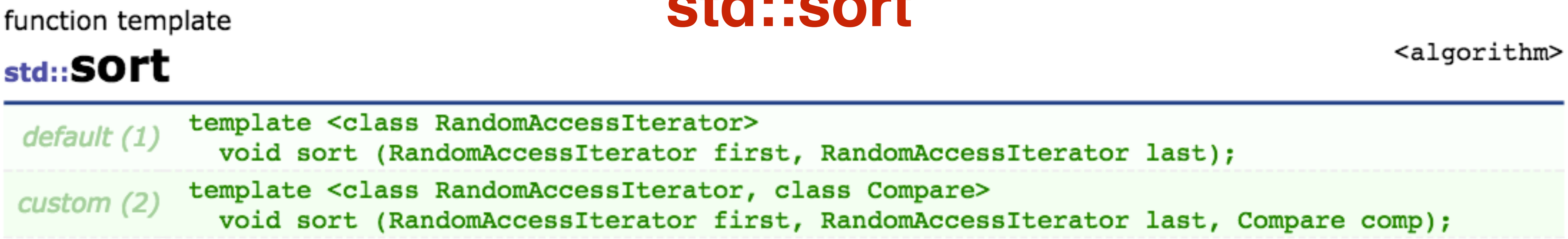


```cpp
#include <iostream>
#include <vector>
#include <algorithm>

struct pow2_comparator {
    bool operator()(int const x, int const y) {
        bool a = is_pow2(x);
        bool b = is_pow2(y);
        if (a != b) {
            return a < b;
        }
        return x > y;
    }

private:
    bool is_pow2(int x) {
        return (x & (x - 1)) == 0;
    }
};
```



```cpp
int main() {

    int a[] = {0, 3, 12, 8, 9, 23, 34, 1, 7, 16, 12, 2, 10, 112, 22};
    // int N = sizeof(a) / sizeof(a[0]);
    int N = std::distance(std::begin(a), std::end(a));

    // std::vector<int> vec(std::begin(a), std::end(a));
    // std::vector<int> vec(a, a + N);
    std::vector<int> vec;
    vec.reserve(N);
    std::for_each(std::begin(a), std::end(a),
        [&vec](const int x) {
            vec.push_back(x);
        }
    );

    std::sort(vec.begin(), vec.end(),
        [](int const x, int const y) {
            int mod1 = x % 2;
            int mod2 = y % 2;
            if (mod1 != mod2) {
                return mod1 < mod2;
            } else {
                return x < y;
            }
        }
    );

    std::for_each(vec.begin(), vec.end(),
        [](int x) {
            std::cout << x << " ";
        }
    );
    std::cout << "\n";

    pow2_comparator comp;
    std::sort(vec.begin(), vec.end(), comp);

    std::for_each(vec.begin(), vec.end(),
        [](int x) {
            std::cout << x << " ";
        }
    );
    std::cout << std::endl;
}
```

std::sort



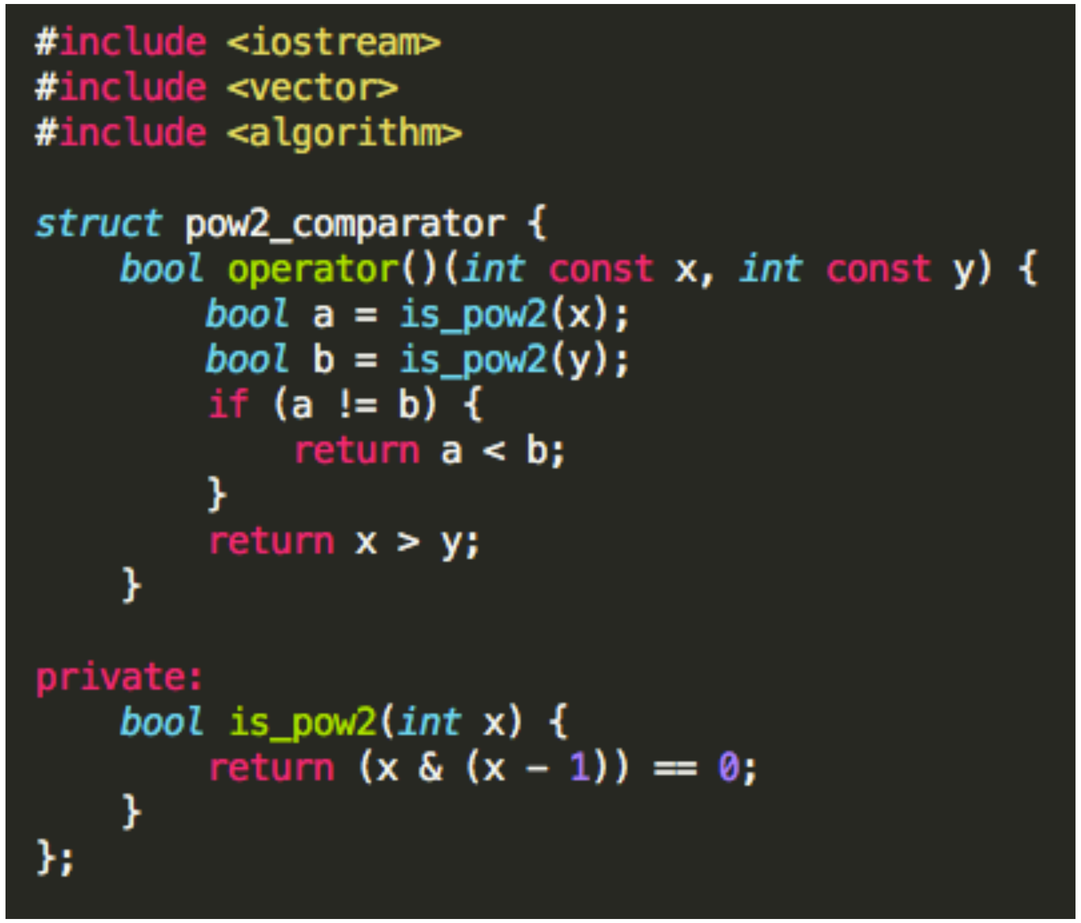
function template

std::sort

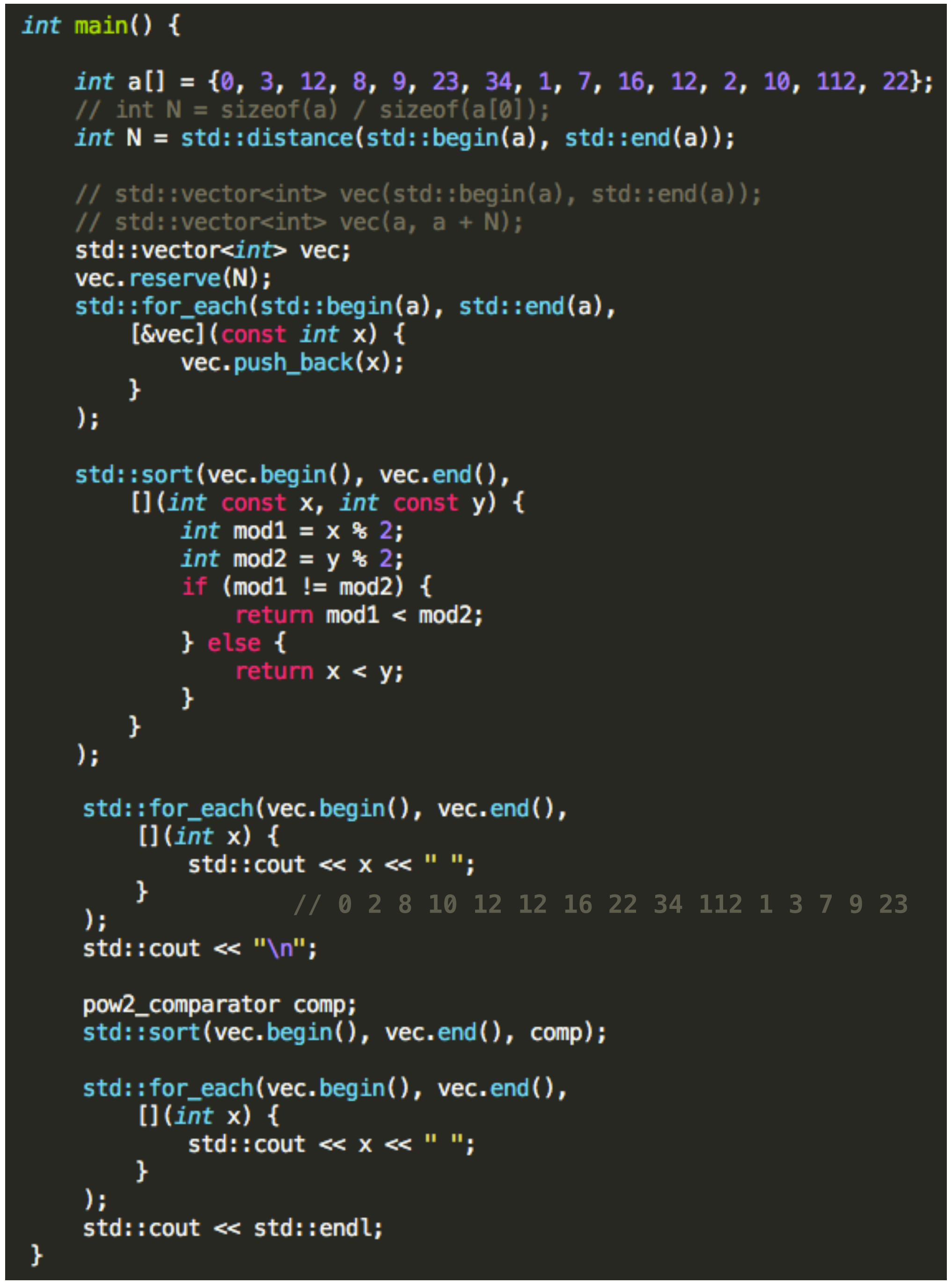
<algorithm>

default (1)	`template <class RandomAccessIterator>`
	`void sort (RandomAccessIterator first, RandomAccessIterator last);`

custom (2)	`template <class RandomAccessIterator, class Compare>`
	`void sort (RandomAccessIterator first, RandomAccessIterator last, Compare comp);`

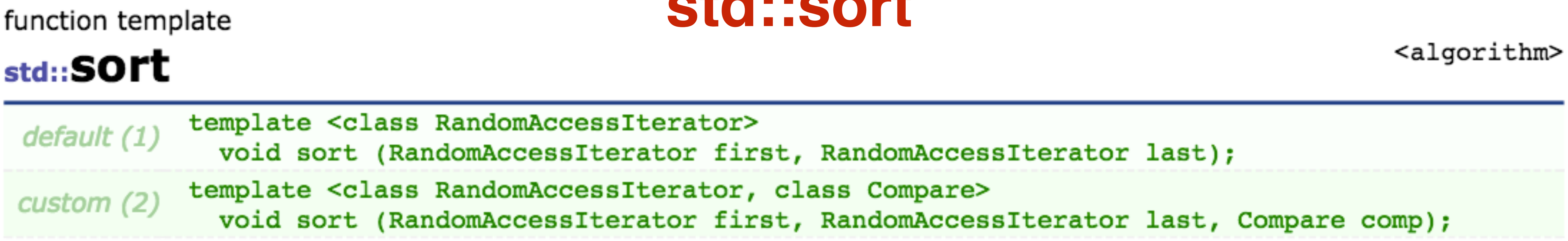


```cpp
#include <iostream>
#include <vector>
#include <algorithm>

struct pow2_comparator {
    bool operator()(int const x, int const y) {
        bool a = is_pow2(x);
        bool b = is_pow2(y);
        if (a != b) {
            return a < b;
        }
        return x > y;
    }

private:
    bool is_pow2(int x) {
        return (x & (x - 1)) == 0;
    }
};
```



```cpp
int main() {

    int a[] = {0, 3, 12, 8, 9, 23, 34, 1, 7, 16, 12, 2, 10, 112, 22};
    // int N = sizeof(a) / sizeof(a[0]);
    int N = std::distance(std::begin(a), std::end(a));

    // std::vector<int> vec(std::begin(a), std::end(a));
    // std::vector<int> vec(a, a + N);
    std::vector<int> vec;
    vec.reserve(N);
    std::for_each(std::begin(a), std::end(a),
        [&vec](const int x) {
            vec.push_back(x);
        }
    );

    std::sort(vec.begin(), vec.end(),
        [](int const x, int const y) {
            int mod1 = x % 2;
            int mod2 = y % 2;
            if (mod1 != mod2) {
                return mod1 < mod2;
            } else {
                return x < y;
            }
        }
    );

    std::for_each(vec.begin(), vec.end(),
        [](int x) {
            std::cout << x << " ";
        }            // 0 2 8 10 12 12 16 22 34 112 1 3 7 9 23
    );
    std::cout << "\n";

    pow2_comparator comp;
    std::sort(vec.begin(), vec.end(), comp);

    std::for_each(vec.begin(), vec.end(),
        [](int x) {
            std::cout << x << " ";
        }
    );
    std::cout << std::endl;
}
```

std::sort



function template

std::sort

<algorithm>

default (1)	`template <class RandomAccessIterator>`
	`void sort (RandomAccessIterator first, RandomAccessIterator last);`

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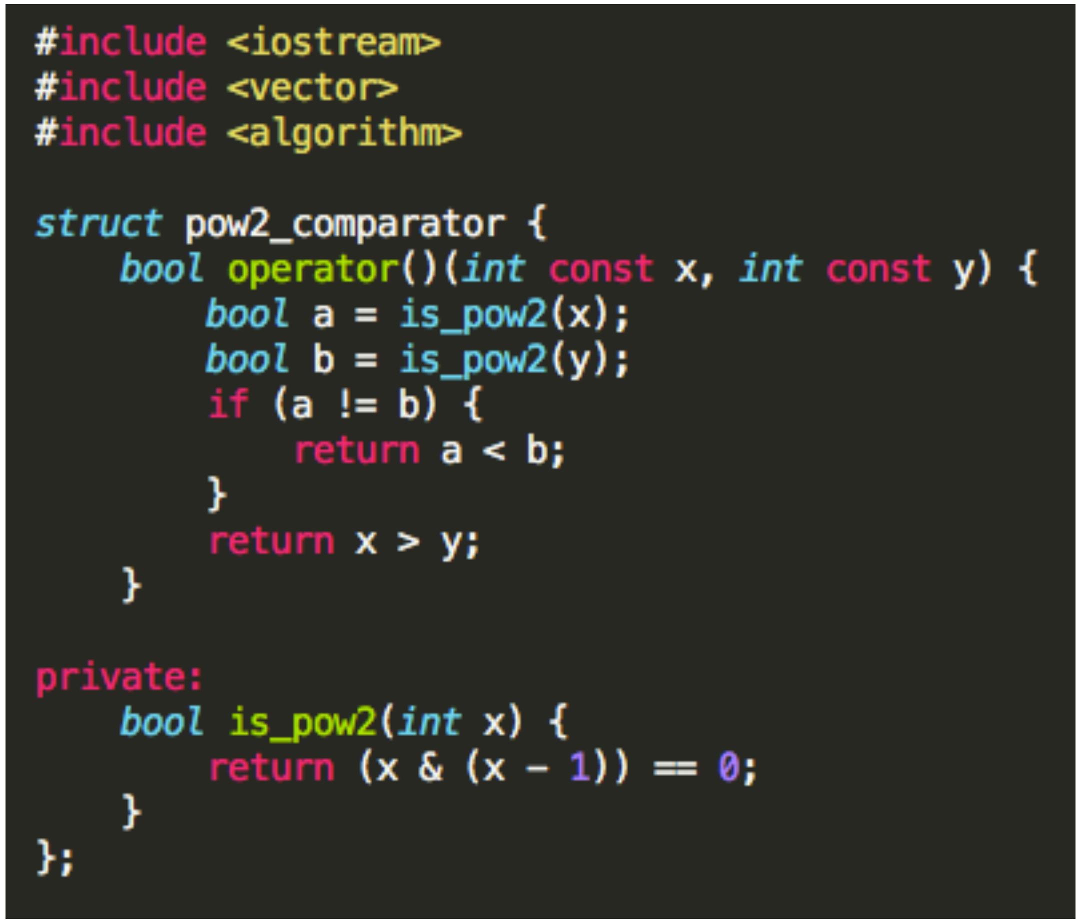
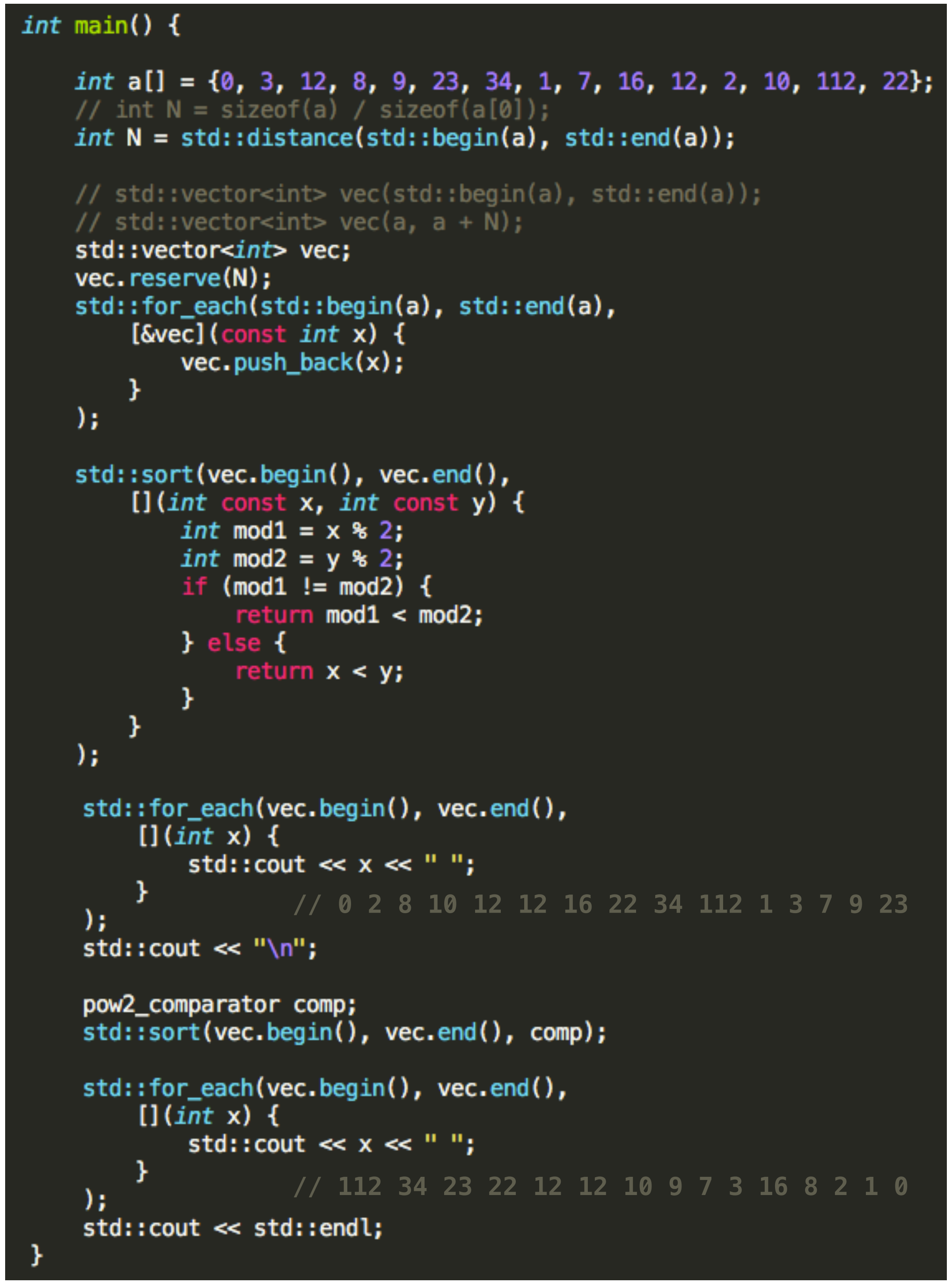
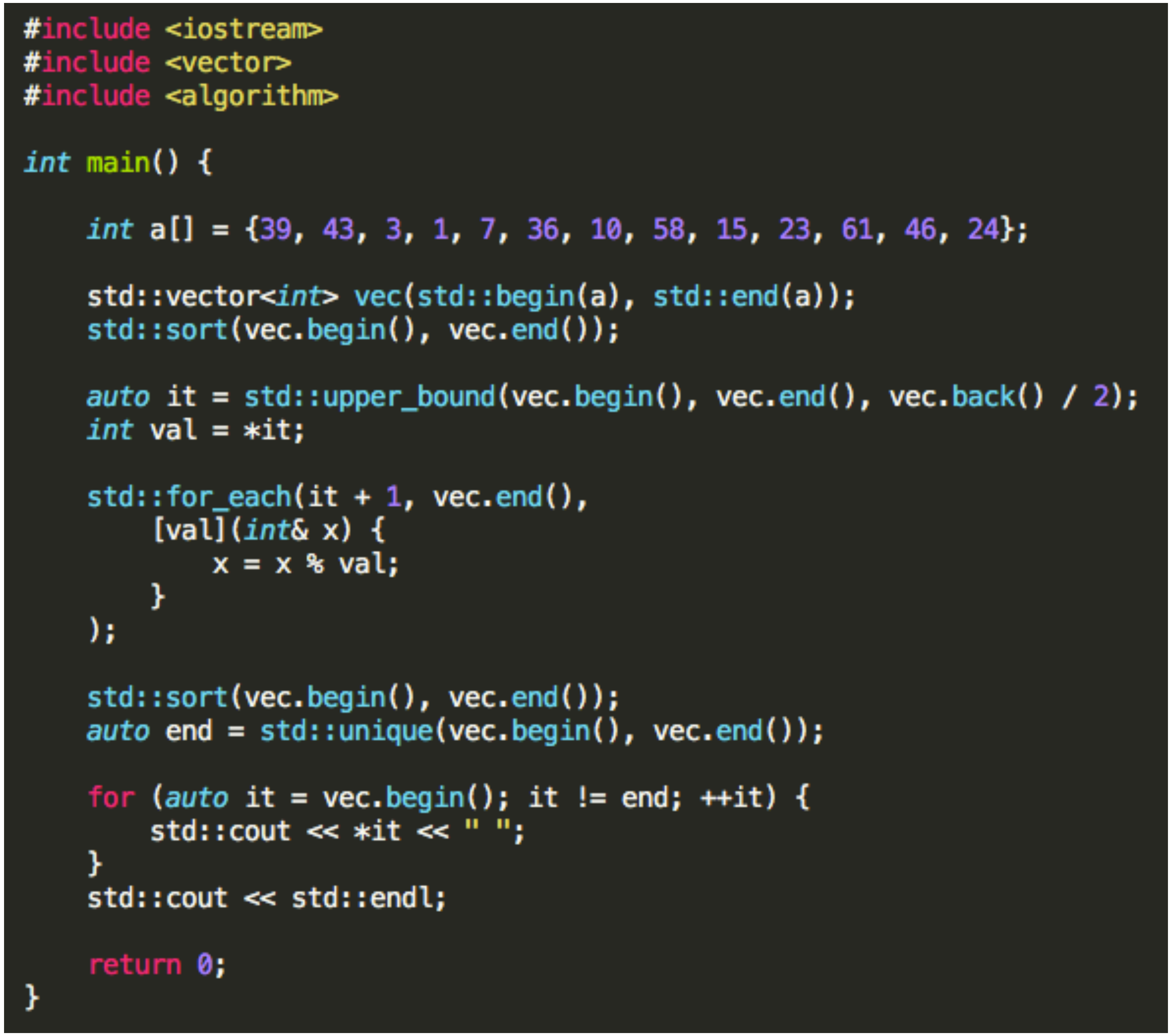


```cpp
#include <iostream>
#include <vector>
#include <algorithm>

struct pow2_comparator {
    bool operator()(int const x, int const y) {
        bool a = is_pow2(x);
        bool b = is_pow2(y);
        if (a != b) {
            return a < b;
        }
        return x > y;
    }

private:
    bool is_pow2(int x) {
        return (x & (x - 1)) == 0;
    }
};
```



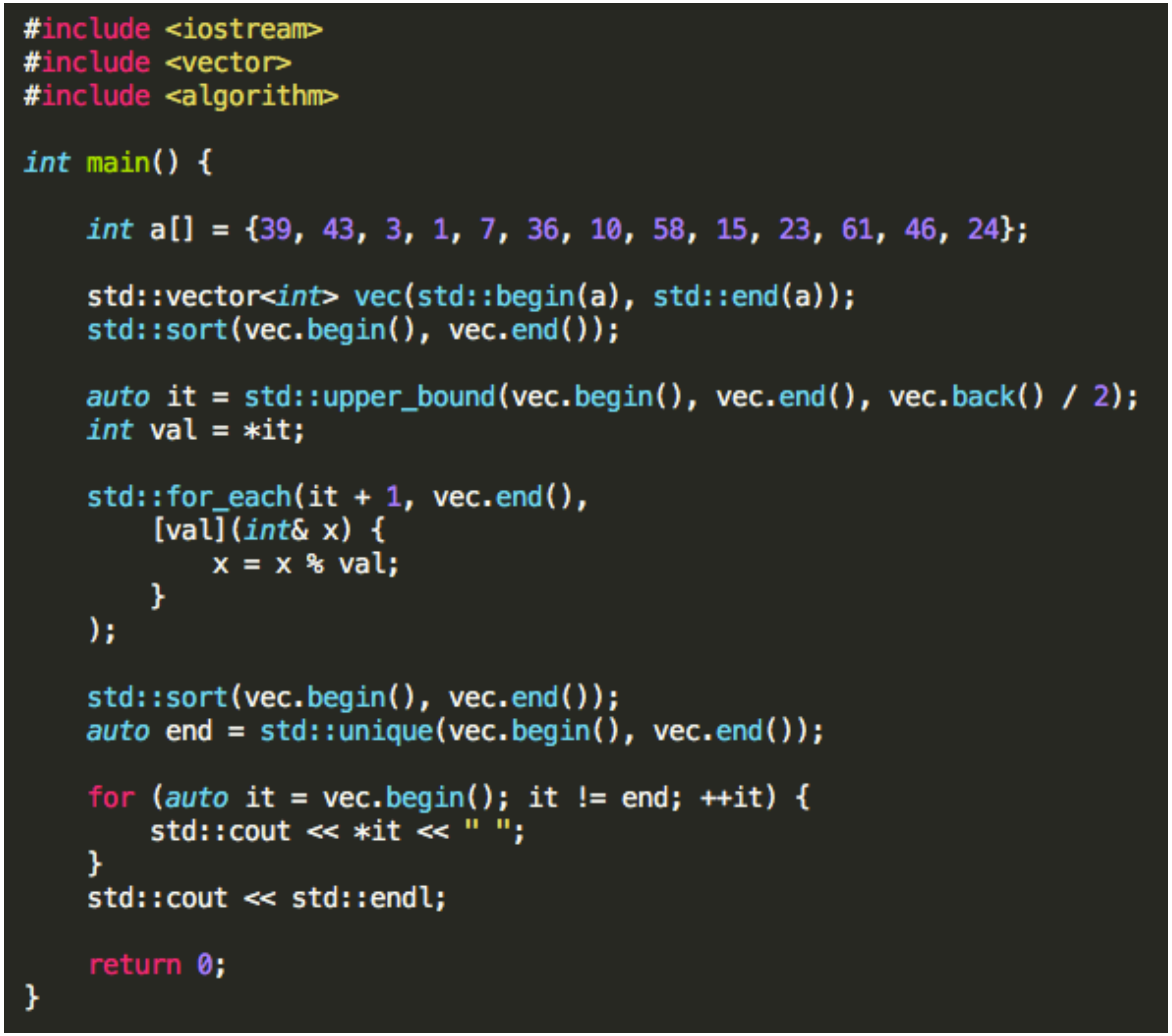
```cpp
int main() {

    int a[] = {0, 3, 12, 8, 9, 23, 34, 1, 7, 16, 12, 2, 10, 112, 22};
    // int N = sizeof(a) / sizeof(a[0]);
    int N = std::distance(std::begin(a), std::end(a));

    // std::vector<int> vec(std::begin(a), std::end(a));
    // std::vector<int> vec(a, a + N);
    std::vector<int> vec;
    vec.reserve(N);
    std::for_each(std::begin(a), std::end(a),
        [&vec](const int x) {
            vec.push_back(x);
        }
    );

    std::sort(vec.begin(), vec.end(),
        [](int const x, int const y) {
            int mod1 = x % 2;
            int mod2 = y % 2;
            if (mod1 != mod2) {
                return mod1 < mod2;
            } else {
                return x < y;
            }
        }
    );

    std::for_each(vec.begin(), vec.end(),
        [](int x) {
            std::cout << x << " ";
        }               // 0 2 8 10 12 12 16 22 34 112 1 3 7 9 23
    );
    std::cout << "\n";

    pow2_comparator comp;
    std::sort(vec.begin(), vec.end(), comp);

    std::for_each(vec.begin(), vec.end(),
        [](int x) {
            std::cout << x << " ";
        }               // 112 34 23 22 12 12 10 9 7 3 16 8 2 1 0
    );
    std::cout << std::endl;
}
```

Another example

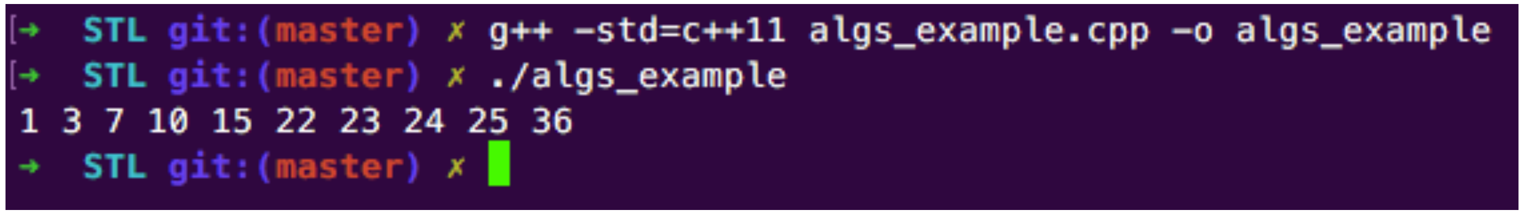


```
#include <iostream>
#include <vector>
#include <algorithm>

int main() {

    int a[] = {39, 43, 3, 1, 7, 36, 10, 58, 15, 23, 61, 46, 24};

    std::vector<int> vec(std::begin(a), std::end(a));
    std::sort(vec.begin(), vec.end());

    auto it = std::upper_bound(vec.begin(), vec.end(), vec.back() / 2);
    int val = *it;

    std::for_each(it + 1, vec.end(),
        [val](int& x) {
            x = x % val;
        }
    );

    std::sort(vec.begin(), vec.end());
    auto end = std::unique(vec.begin(), vec.end());

    for (auto it = vec.begin(); it != end; ++it) {
        std::cout << *it << " ";
    }
    std::cout << std::endl;

    return 0;
}
```

Another example



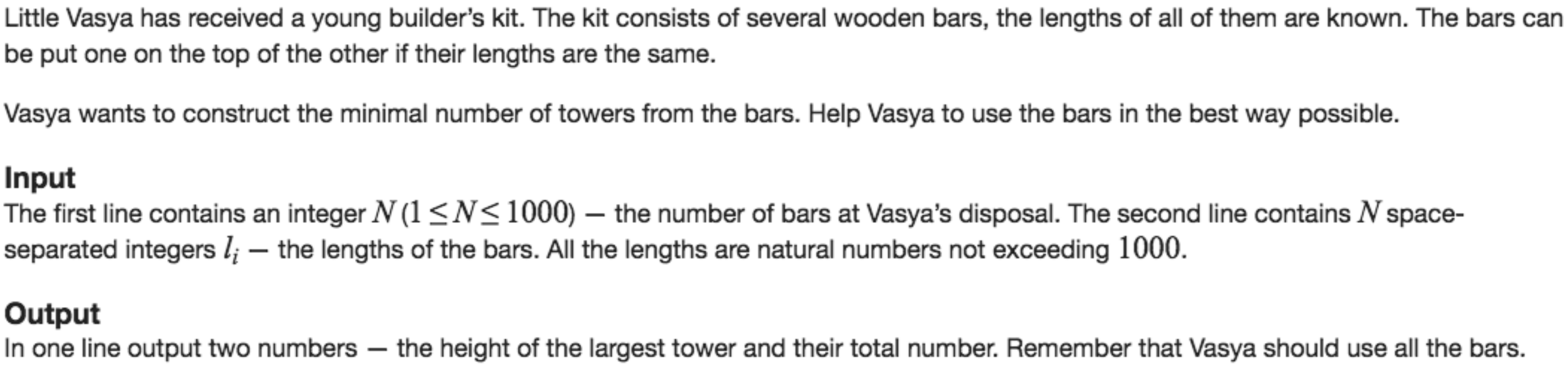
```cpp
#include <iostream>
#include <vector>
#include <algorithm>

int main() {

    int a[] = {39, 43, 3, 1, 7, 36, 10, 58, 15, 23, 61, 46, 24};

    std::vector<int> vec(std::begin(a), std::end(a));
    std::sort(vec.begin(), vec.end());

    auto it = std::upper_bound(vec.begin(), vec.end(), vec.back() / 2);
    int val = *it;

    std::for_each(it + 1, vec.end(),
        [val](int& x) {
            x = x % val;
        }
    );

    std::sort(vec.begin(), vec.end());
    auto end = std::unique(vec.begin(), vec.end());

    for (auto it = vec.begin(); it != end; ++it) {
        std::cout << *it << " ";
    }
    std::cout << std::endl;

    return 0;
}
```



```
[→  STL git:(master) ✗ g++ -std=c++11 algs_example.cpp -o algs_example
[→  STL git:(master) ✗ ./algs_example
1 3 7 10 15 22 23 24 25 36
→  STL git:(master) ✗ █
```

Exercises

1. Towers http://codeforces.com/problemset/problem/37/A?locale=en



Little Vasya has received a young builder's kit. The kit consists of several wooden bars, the lengths of all of them are known. The bars can be put one on the top of the other if their lengths are the same.

Vasya wants to construct the minimal number of towers from the bars. Help Vasya to use the bars in the best way possible.

Input

The first line contains an integer N ($1 \leq N \leq 1000$) — the number of bars at Vasya's disposal. The second line contains N space-separated integers l_i — the lengths of the bars. All the lengths are natural numbers not exceeding 1000.

Output

In one line output two numbers — the height of the largest tower and their total number. Remember that Vasya should use all the bars.

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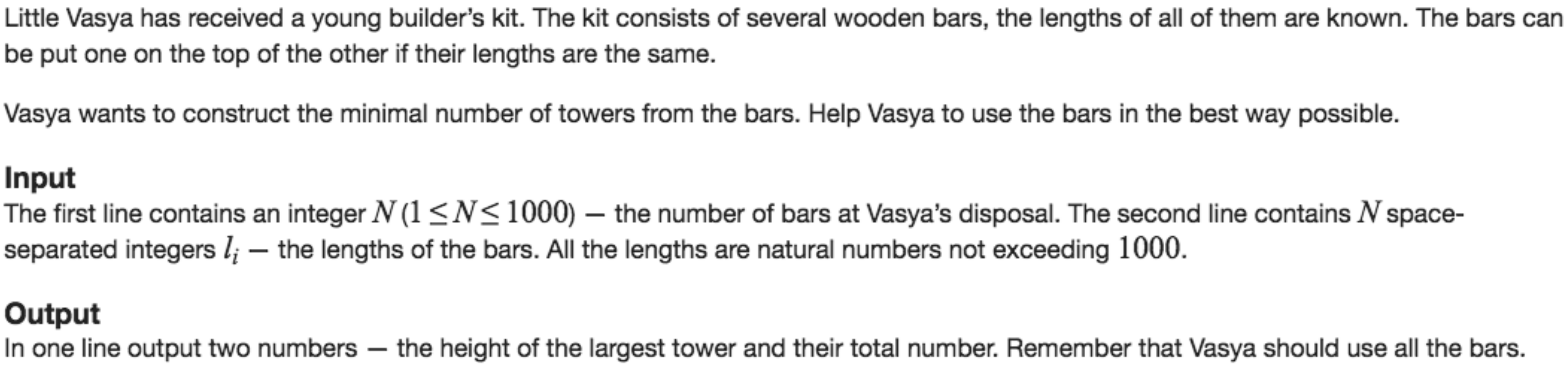

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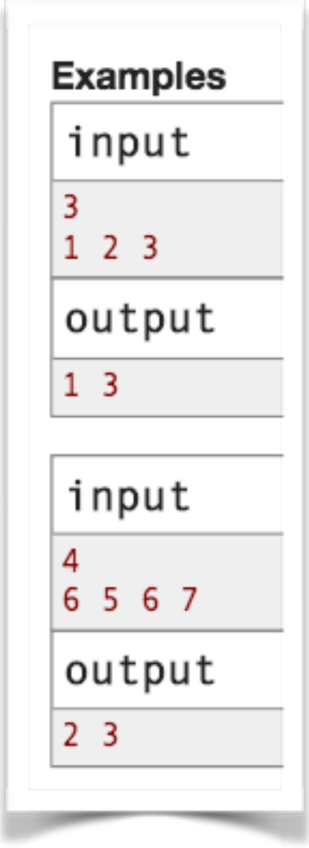


Examples

input

```
3
1 2 3
```

output

```
1 3
```

input

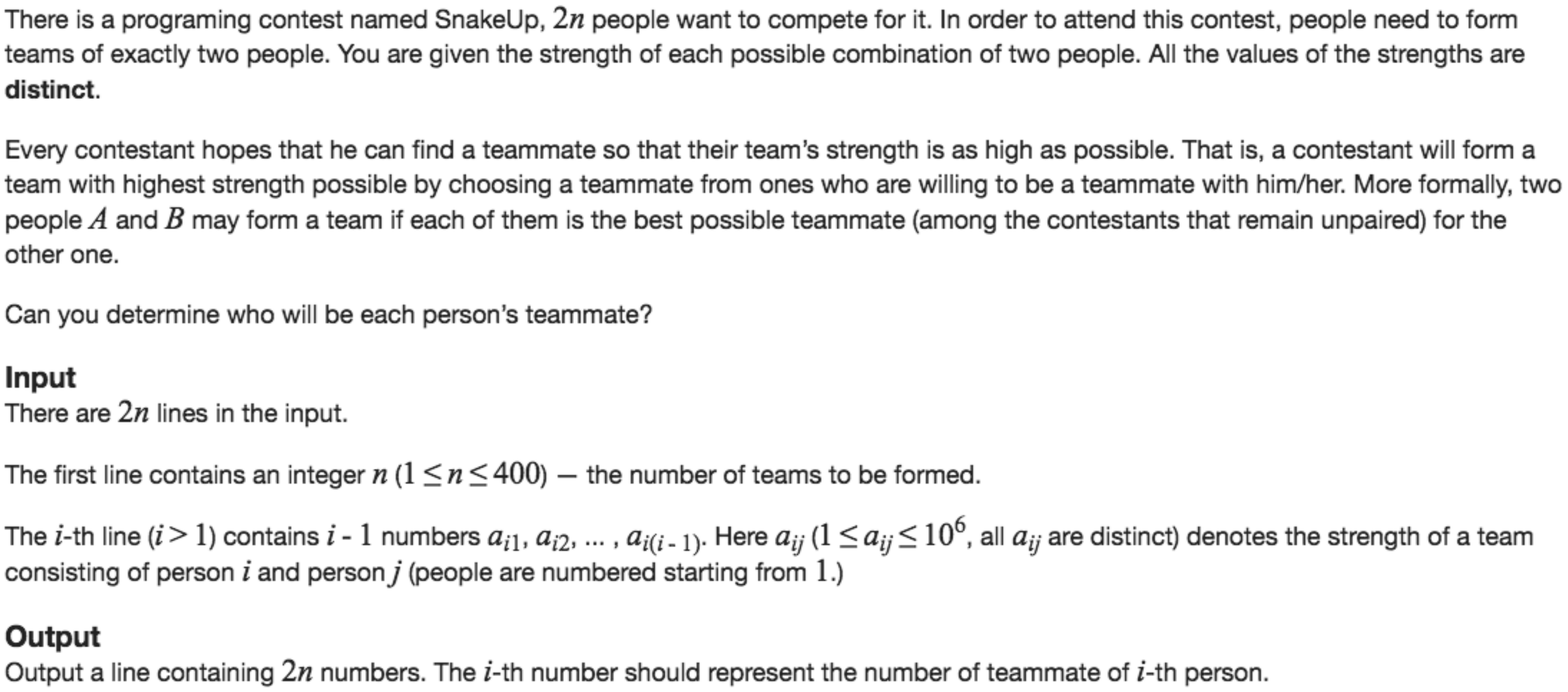
```
4
6 5 6 7
```

output

```
2 3
```

Exercises

2. Finding Team Member http://codeforces.com/problemset/problem/579/B?locale=en



There is a programing contest named SnakeUp, $2n$ people want to compete for it. In order to attend this contest, people need to form teams of exactly two people. You are given the strength of each possible combination of two people. All the values of the strengths are **distinct**.

Every contestant hopes that he can find a teammate so that their team's strength is as high as possible. That is, a contestant will form a team with highest strength possible by choosing a teammate from ones who are willing to be a teammate with him/her. More formally, two people A and B may form a team if each of them is the best possible teammate (among the contestants that remain unpaired) for the other one.

Can you determine who will be each person's teammate?

Input

There are $2n$ lines in the input.

The first line contains an integer n ($1 \le n \le 400$) — the number of teams to be formed.

The i-th line ($i > 1$) contains i - 1 numbers a_{i1}, a_{i2}, ... , $a_{i(i-1)}$. Here a_{ij} ($1 \le a_{ij} \le 10^6$, all a_{ij} are distinct) denotes the strength of a team consisting of person i and person j (people are numbered starting from 1.)

Output

Output a line containing $2n$ numbers. The i-th number should represent the number of teammate of i-th person.

Exercises

2. Finding Team Member

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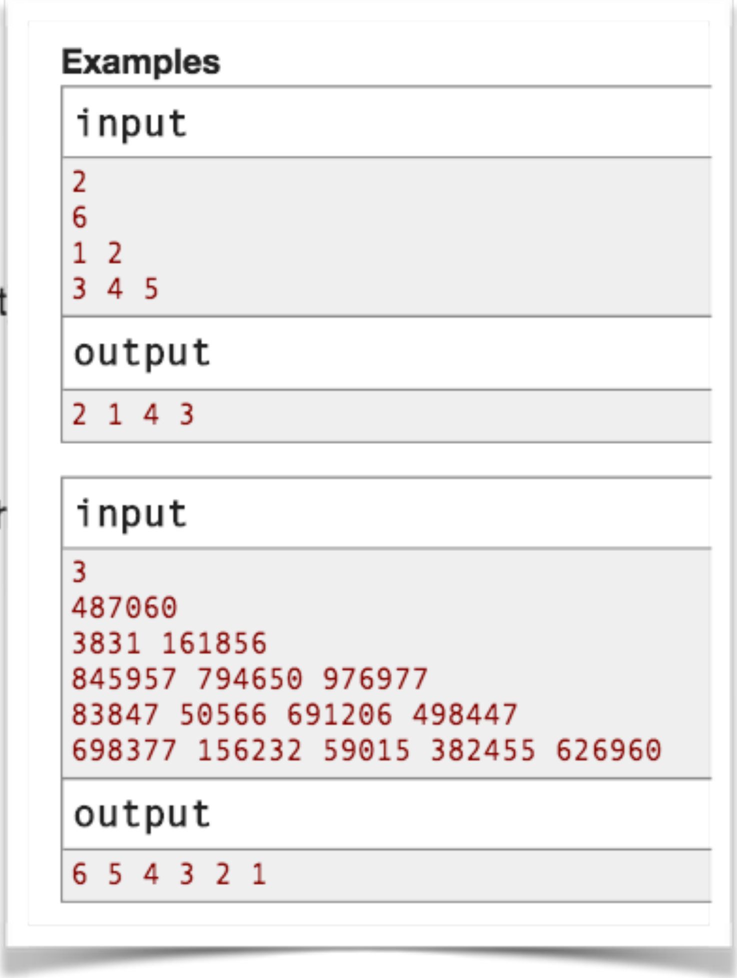


Examples

input

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

output

```
2 1 4 3
```

input

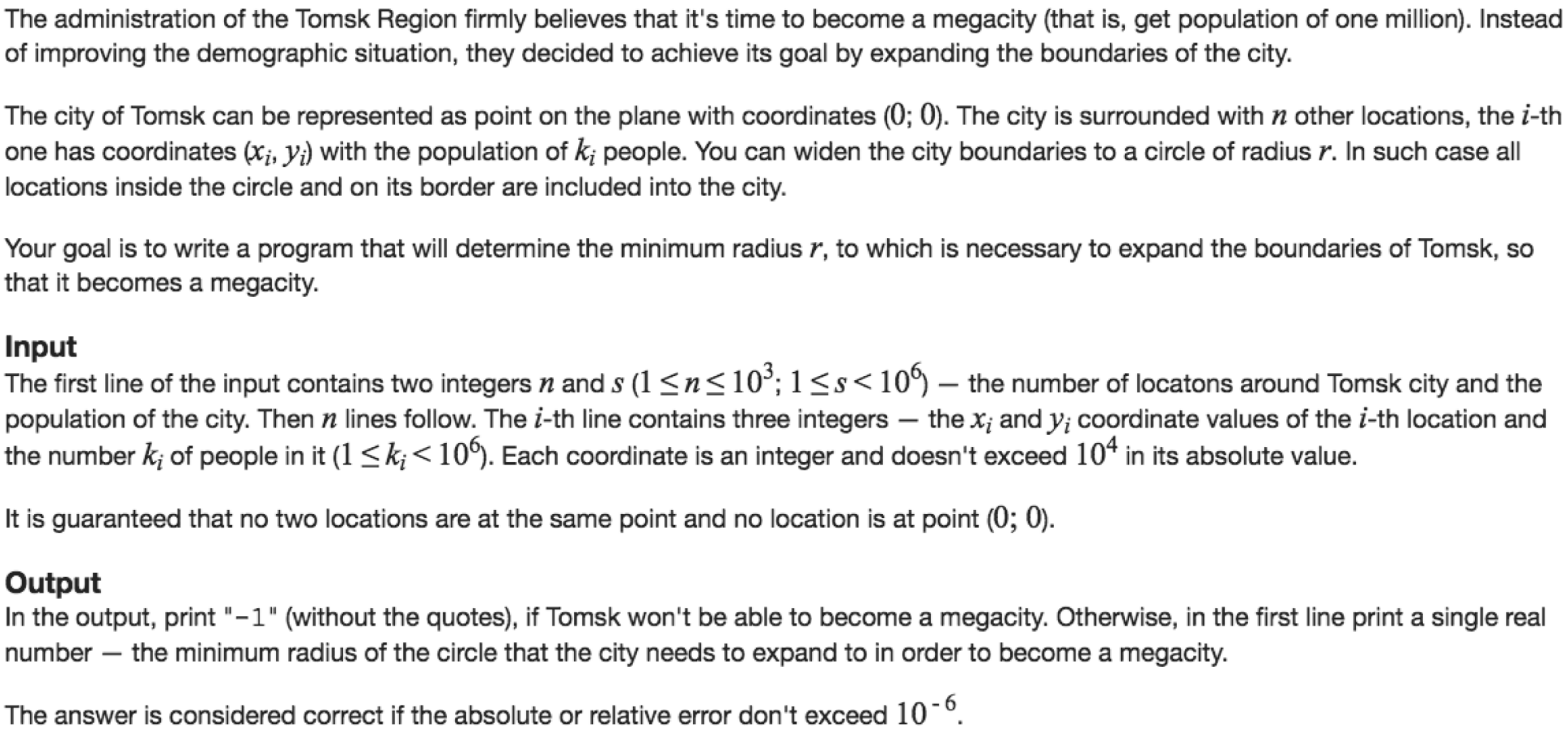
```
3
487060
3831 161856
845957 794650 976977
83847 50566 691206 498447
698377 156232 59015 382455 626960
```

output

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

Exercises

3. Megacity http://codeforces.com/problemset/problem/424/B?locale=en



The administration of the Tomsk Region firmly believes that it's time to become a megacity (that is, get population of one million). Instead of improving the demographic situation, they decided to achieve its goal by expanding the boundaries of the city.

The city of Tomsk can be represented as point on the plane with coordinates $(0; 0)$. The city is surrounded with n other locations, the i-th one has coordinates (x_i, y_i) with the population of k_i people. You can widen the city boundaries to a circle of radius r. In such case all locations inside the circle and on its border are included into the city.

Your goal is to write a program that will determine the minimum radius r, to which is necessary to expand the boundaries of Tomsk, so that it becomes a megacity.

Input

The first line of the input contains two integers n and s $(1 \le n \le 10^3; 1 \le s < 10^6)$ — the number of locatons around Tomsk city and the population of the city. Then n lines follow. The i-th line contains three integers — the x_i and y_i coordinate values of the i-th location and the number k_i of people in it $(1 \le k_i < 10^6)$. Each coordinate is an integer and doesn't exceed 10^4 in its absolute value.

It is guaranteed that no two locations are at the same point and no location is at point $(0; 0)$.

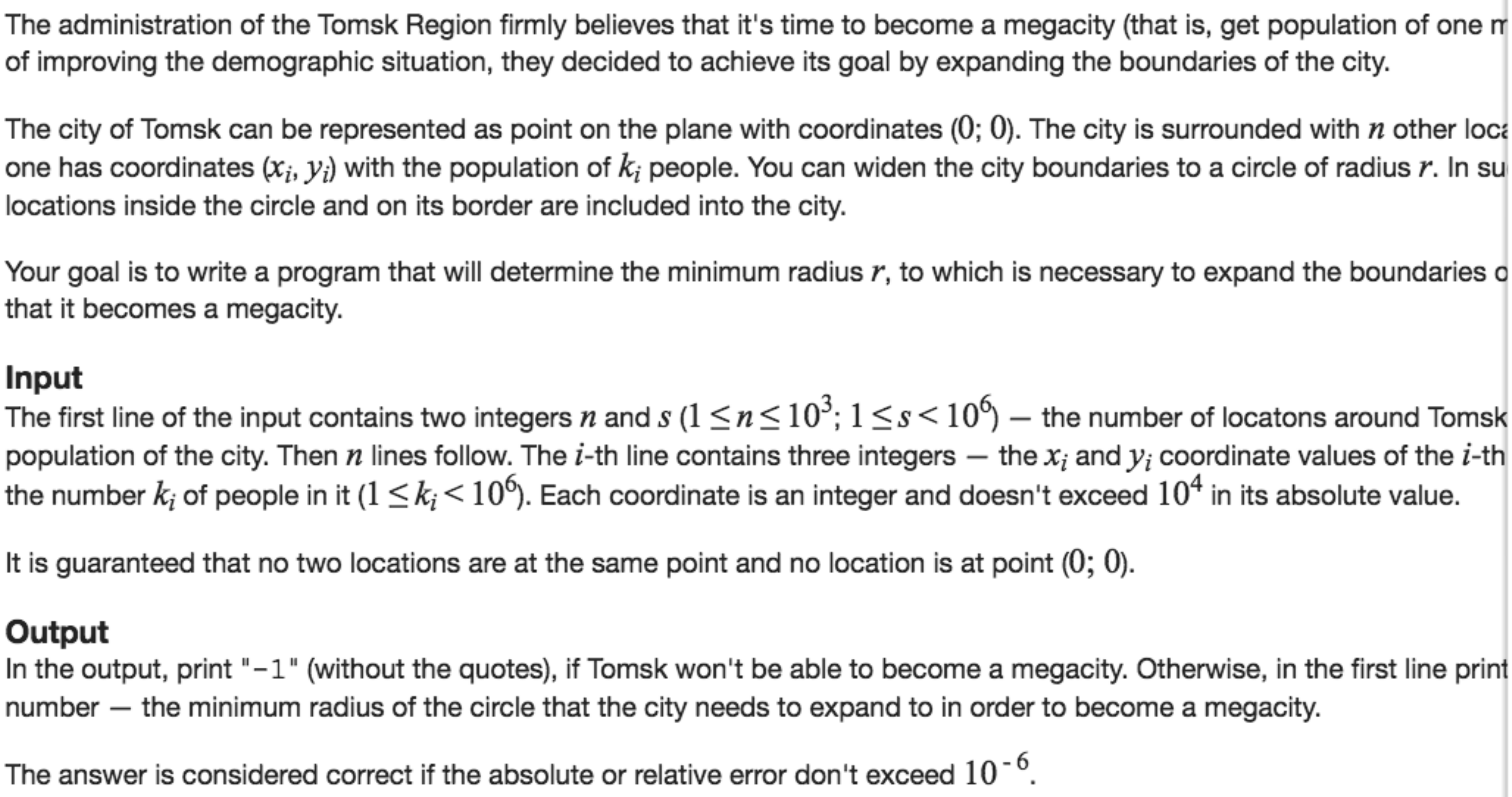
Output

In the output, print "-1" (without the quotes), if Tomsk won't be able to become a megacity. Otherwise, in the first line print a single real number — the minimum radius of the circle that the city needs to expand to in order to become a megacity.

The answer is considered correct if the absolute or relative error don't exceed 10^{-6}.

Exercises

3. Megacity http://codeforces.com/problemset/problem/424/B?locale=en



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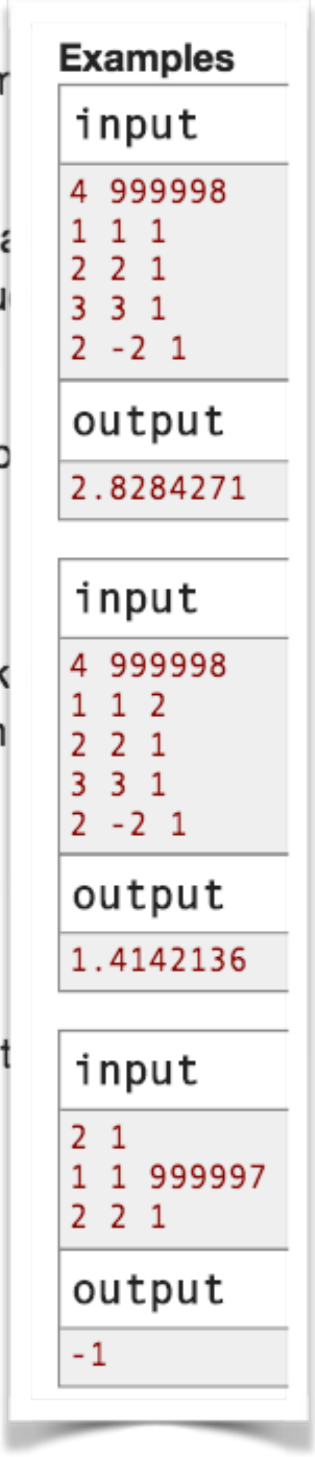
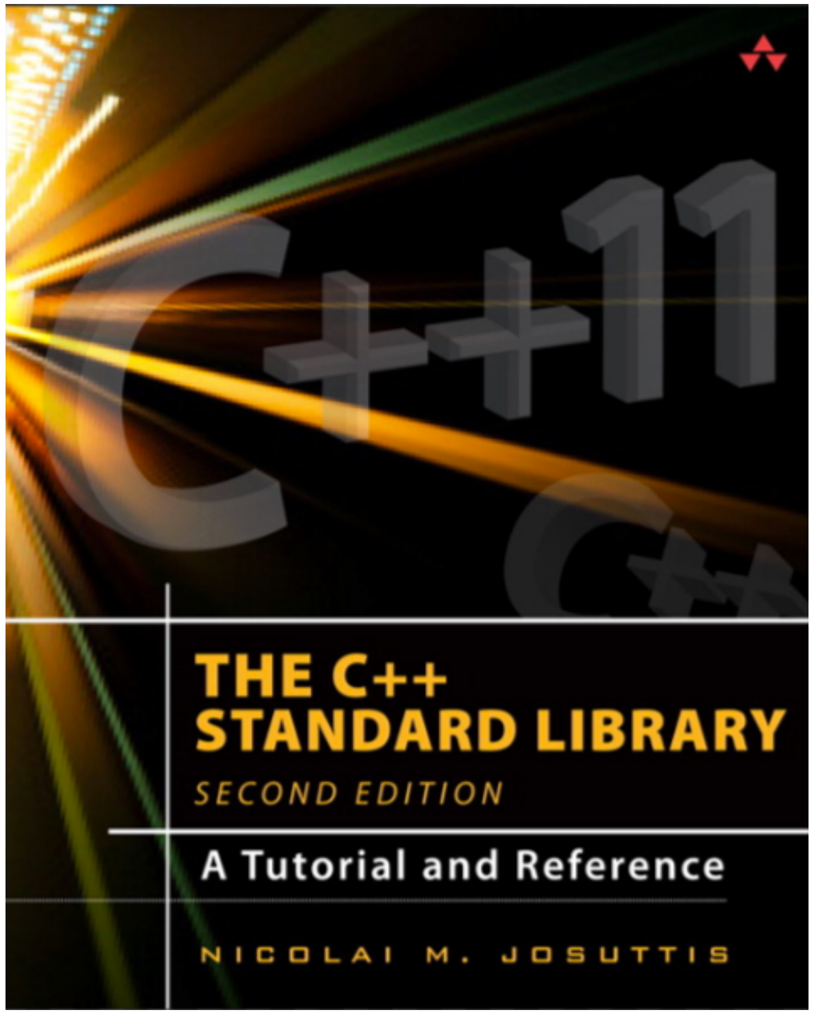


Examples

input
```
4 999998
1 1 1
2 2 1
3 3 1
2 -2 1
```
output
```
2.8284271
```
input
```
4 999998
1 1 2
2 2 1
3 3 1
2 -2 1
```
output
```
1.4142136
```
input
```
2 1
1 1 999997
2 2 1
```
output
```
-1
```

References

http://www.cplusplus.com/


C++11
THE C++
STANDARD LIBRARY
SECOND EDITION
A Tutorial and Reference
NICOLAI M. JOSUTTIS