CS100 Lecture 22

Contents

Standard Template Library (STL)

- Overview
- Sequence containers and iterators
- Algorithms and function objects (aka "functors")
- Associative containers

Overview of STL

Standard Template Library

Added into C++ in 1994.

- Containers
- Iterators
- Algorithms
- Function objects
- Some other adapters, like container adapters and iterator adapters
- Allocators

Containers

- Sequence containers
  - `vector`, `list`, `deque`, `array` (since C++11), `forward_list` (since C++11)
- Associative containers
  - `set`, `map`, `multiset`, `multimap` (often implemented with *binary search trees*)
- Unordered associative containers (since C++11)
  - `unordered_set`, `unordered_map`, `unordered_multiset`, `unordered_multimap` (implemented with *hash tables*)
- Container adapters: provide a different interface for sequential containers, but they are not containers themselves.
  - `stack`, `queue`, `priority_queue`
  - (since C++23) `flat_set`, `flat_map`, `flat_multiset`, `flat_multimap`

Iterators

Without iterators:

- Traverse an array

  ```cpp
  for (int i = 0; i != sizeof(a) / sizeof(a[0]); ++i)
    do_something(a[i]);
  ```

- Traverse a `vector`

  ```cpp
  for (std::size_t i = 0; i != v.size(); ++i)
    do_something(v[i]);
  ```

- Traverse a linked-list?

  ```cpp
  for (ListNode *p = l.head(); p; p = p->next)
    do_something(p->data);
  ```

Iterators

A generalization of pointers, used to access elements in different containers **in a uniform manner**.

With iterators:

The following works no matter whether `c` is an array, a `std::string`, or any container.

```
for (auto it = std::begin(c); it != std::end(c); ++it)
  do_something(*it);
```

Equivalent way: range-based for loops

```
for (auto &x : c) do_something(x);
```

Algorithms

The algorithms library defines functions for a variety of purposes:

- searching, sorting, counting, manipulating, ...

Examples:

```cpp
// assign every element in `a` with the value `x`.
std::fill(a.begin(), a.end(), x);
// sort the elements in `b` in ascending order.
std::sort(b.begin(), b.end());
// find the first element in `b` that is equal to `x`.
auto pos = std::find(b.begin(), b.end(), x);
// reverse the elements in `c`.
std::reverse(c.begin(), c.end());
```

Algorithms

Example: Map every number in `data` to its rank. ("离散化")

```cpp
auto remap(const std::vector<int> &data) {
  auto tmp = data;
  std::sort(tmp.begin(), tmp.end()); // sort
  auto pos = std::unique(tmp.begin(), tmp.end()); // drop duplicates
  auto ret = data;
  for (auto &x : ret)
    x = std::lower_bound(tmp.begin(), pos, x) - tmp.begin(); // binary search
  return ret;
}
```

Function objects

Things that look like "functions": *Callable*

- functions, and also function pointers
- objects of a class type that has an overloaded `operator()` (the function-call operator)
- lambda expressions

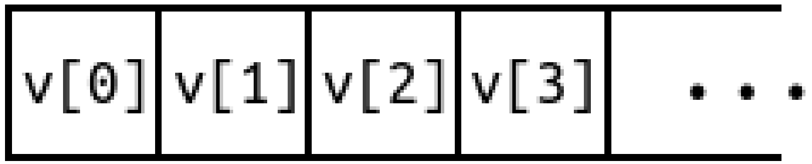
More in later lectures ...

Sequence containers and iterators

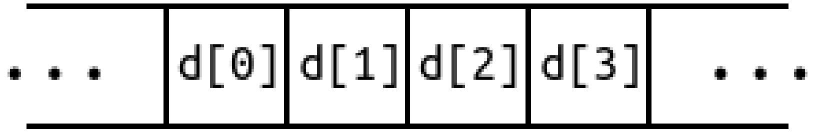
Note: `string` is not treated as a container but behaves much like one.

Sequence containers

- `std::vector<T>`: dynamic contiguous array (we are quite familiar with)



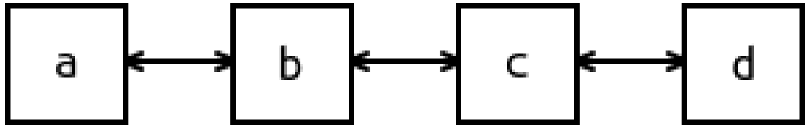
- `std::deque<T>`: **d**ouble-**e**nded **que**ue (often pronounced as "deck")
  - `std::deque<T>` supports fast insertion and deletion **at both its beginning and its end**. (`push_front`, `pop_front`, `push_back`, `pop_back`)



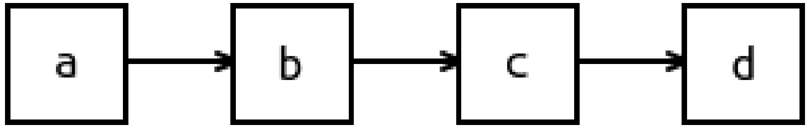
- `std::array<T, N>`: same as `T[N]`, it is a **container**
  - It will never decay to `T *`.
  - Container interfaces are provided: `.at(i)`, `.front()`, `.back()`, `.size()`, ..., as well as iterators.

Sequence containers

- `std::list<T>`: doubly-linked list
  - `std::list<T>` supports fast insertion and deletion **anywhere in the container**,
  - but fast random access is not supported (i.e. no `operator[]`).
  - Bidirectional traversal is supported.



- `std::forward_list<T>`: singly-linked list
  - Intended to save time and space (compared to `std::list`).
  - Only forward traversal is supported.



Interfaces

STL containers have consistent interfaces. See here for a full list.

Element access:

- `c.at(i)`, `c[i]`: access the element indexed `i`. `at` performs bounds checking, and throws `std::out_of_range` if `i` exceeds the valid range.
- `c.front()`, `c.back()`: access the front/back element.

Interfaces

Size and capacity: `c.size()` and `c.empty()` are what we already know.

- `c.resize(n)`, `c.resize(n, x)`: adjust the container to be with exactly `n` elements. If `n > c.size()`, `n - c.size()` elements will be appended.
  - `c.resize(n)`: Appended elements are **value-initialized**.
  - `c.resize(n, x)`: Appended elements are copies of `x`.
- `c.capacity()`, `c.reserve(n)`, `c.shrink_to_fit()`: only for `string` and `vector`.
  - `c.capacity()` returns the capacity (number of elements that *can* be stored in the current storage)
  - `c.reserve(n)`: reserves space for at least `n` elements.
  - `c.shrink_to_fit()`: requests to remove the unused capacity, so that `c.capacity() == c.size()`.

Interfaces

Modifiers:

- `c.push_back(x)`, `c.emplace_back(args...)`, `c.pop_back()`: insert/delete elements at the end of the container.
- `c.push_front(x)`, `c.emplace_front(args...)`, `c.pop_front()`: insert/delete elements at the beginning of the container.
- `c.clear()` removes all the elements in `c`.

Interfaces

Modifiers:

- `c.insert(...)`, `c.emplace(...)`, `c.erase(...)`: insert/delete elements at a specified location.
  - **Warning**: For containers that need to maintain contiguous storage (`string`, `vector`, `deque`), insertion and deletion somewhere in the middle can be **very slow** ($O(n)$).
  - These functions have a lot of overloads. Remember a few common ones, and STFW (Search The Friendly Web) when you need to use them.

Interfaces

Some of these member functions are not supported on some containers, **depending on the underlying data structure**. For example:

- Any operation that modifies the length of the container is not allowed for `array`.
- `push_front`, `emplace_front` and `pop_front` are not supported on `string`, `vector` and `array`.
- `size` is not supported on `forward_list` in order to save time and space.
- `operator[]` and `at` are not supported on linked-lists.

This table tells you everything.

Iterators

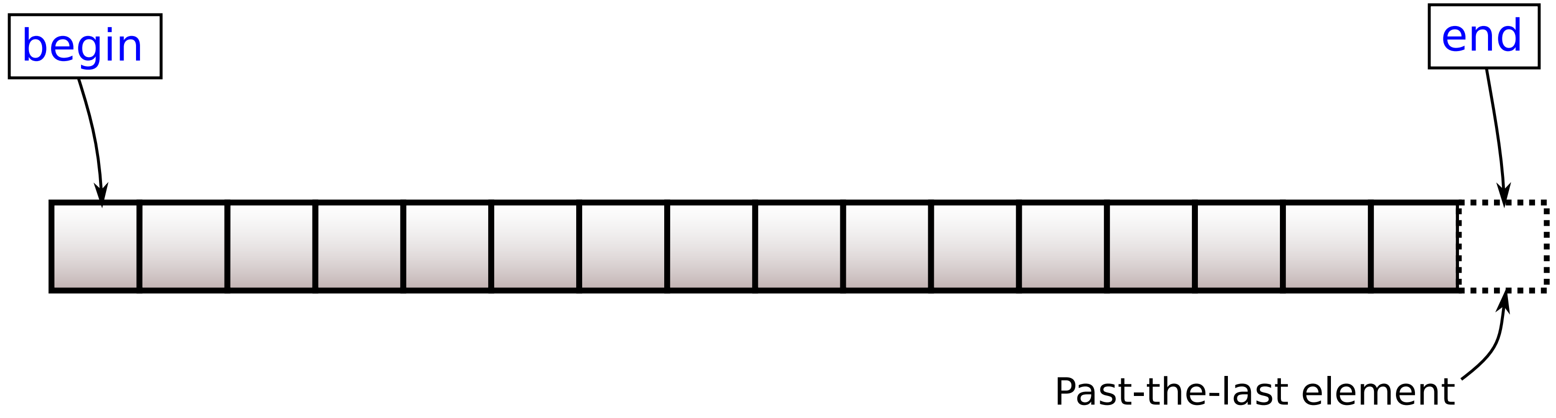
A generalized "pointer" used for accessing elements in different containers.

Every container has its iterator: `Container::iterator`. e.g. `std::vector<int>::iterator`, `std::forward_list<std::string>::iterator`

- `auto` comes to our rescue!

`c.begin()` returns the iterator to the first element of `c`.

`c.end()` returns the iterator to **the element following the last element** of `c`.



Iterators

A pair of iterators (`b`, `e`) is often used to indicate a range `[b, e)`.

Such ranges are **left-inclusive**. Benefits:

- `e - b` is the **length** of the range, i.e. the number of elements. There is no extra `+1` or `-1`.
- If `b == e`, the range is empty.

Iterators

Basic operations, supported by almost all kinds of iterators:

- `*it`: returns a reference to the element that `it` refers to.
- `it->mem`: equivalent to `(*it).mem`.
- `++it`, `it++`: moves `it` one step forward, so that `it` refers to the "next" element.
  - `++it` returns a reference to `it`, while `it++` returns a copy of `it` before incrementation.
- `it1 == it2`: checks whether `it1` and `it2` refer to the same position in the container.
- `it1 != it2`: equivalent to `!(it1 == it2)`.

These are supported by the iterators of all sequence containers, as well as `string`.

Iterators

Use the basic operations to traverse a sequence container:

```cpp
void swapcase(std::string &str) {
  for (auto it = str.begin(); it != str.end(); ++it) {
    if (std::islower(*it))
      *it = std::toupper(*it);
    else if (std::isupper(*it))
      *it = std::tolower(*it);
  }
}
void print(const std::list<int> &lst) {
  for (auto it = lst.begin(); it != lst.end(); ++it)
    std::cout << *it << ' ';
}
```

Iterators

Built-in pointers are also iterators: They are the iterator for built-in arrays.

For an array `Type a[N]`:

- The "begin" iterator is `a`.
- The "end" (off-the-end) iterator is `a + N`.

The standard library functions `std::begin(c)` and `std::end(c)` (defined in `<iterator>` and many other header files):

- return `c.begin()` and `c.end()` if `c` is a container;
- return `c` and `c + N` if `c` is an array of length `N`.

Range-for demystified

The range-based for loop

```
for (@declaration : container)
  @loop_body
```

is equivalent to

```
{
  auto b = std::begin(container);
  auto e = std::end(container);
  for (; b != e; ++b) {
    @declaration = *b;
    @loop_body
  }
}
```

Iterators: dereferenceable

Like pointers, an iterator can be dereferenced (`*it`) only when it refers to an existing element. ("**dereferenceable**")

- `*v.end()` is undefined behavior.
- `++it` is undefined behavior if `it` is not dereferenceable. In other words, moving an iterator out of the range `[begin, off_the_end]` is undefined behavior.

Iterators: invalidation

```
Type *storage = new Type[n];
Type *iter = storage;
delete[] storage;
// Now `iter` does not refer to any existing element.
```

Some operations on some containers will **invalidate** some iterators:

- make these iterators not refer to any existing element.

For example:

- `push_back(x)` on a `vector` may cause the reallocation of storage. All iterators obtained previously are invalidated.
- Deleting an element in a `list` will invalidate the iterator referring to that element.

More operations on iterators

The iterators of containers that support `*it`, `it->mem`, `++it`, `it++`, `it1 == it2` and `it1 != it2` are ForwardIterators.

BidirectionalIterator: a ForwardIterator that can be moved in both directions

- supports `--it` and `it--`.

RandomAccessIterator: a BidirectionalIterator that can be moved to point to any element in constant time.

- supports `it + n`, `n + it`, `it - n`, `it += n`, `it -= n` for an integer `n`.
- supports `it[n]`, equivalent to `*(it + n)`.
- supports `it1 - it2`, returns the **distance** of two iterators.
- supports `<`, `<=`, `>`, `>=`.

Iterator categories

ForwardIterators: supports `*it`, `it->mem`, `++it`, `it++`, `it1 == it2`, `it1 != it2`

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*** Which category is the built-in pointer in?**

Iterator categories

ForwardIterators: supports `*it`, `it->mem`, `++it`, `it++`, `it1 == it2`, `it1 != it2`

BidirectionalIterator: a ForwardIterator that can be moved in both directions

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- supports `it + n`, `n + it`, `it - n`, `it += n`, `it -= n` for an integer `n`.
- supports `it[n]`, equivalent to `*(it + n)`.
- supports `it1 - it2`, returns the **distance** of two iterators.
- supports `<`, `<=`, `>`, `>=`.

* **Which category is the built-in pointer in?** - RandomAccessIterator.

Iterator categories

ForwardIterators: an iterator that can be moved forward.

- `forward_list<T>::iterator`

BidirectionalIterator: a ForwardIterator that can be moved in both directions

- `list<T>::iterator`

RandomAccessIterator: a BidirectionalIterator that can be moved to point to any element in constant time.

- `string::iterator`, `vector<T>::iterator`, `deque<T>::iterator`, `array<T,N>::iterator`

Iterator categories

To know the category of an iterator of a container, consult its type alias member `iterator_category`.

```
using vec_iter = std::vector<int>::iterator;
using category = vec_iter::iterator_category;
```

Put your mouse on `category`, and the IDE will tell you what it is.

It is one of the following tags: `std::forward_iterator_tag`, `std::bidirectional_iterator_tag`, `std::random_access_iterator_tag`.

Note: There are two other categories: InputIterator and OutputIterator. They may (or may not) be covered in later lectures.

Constructors of containers

All sequence containers can be constructed in the following ways:

- `Container c(b, e)`, where `[b, e)` is an **iterator range**.
  - Copies elements from the iterator range `[b, e)`.
- `Container c(n, x)`, where `n` is a nonnegative integer and `x` is a value.
  - Initializes the container with `n` copies of `x`.
- `Container c(n)`, where `n` is a nonnegative integer.
  - Initializes the container with `n` elements. All elements are **value-initialized**.
  - This is not supported by `string`. (Why?)

Constructors of containers

All sequence containers can be constructed in the following ways:

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  - Initializes the container with `n` copies of `x`.
- `Container c(n)`, where `n` is a nonnegative integer.
  - Initializes the container with `n` elements. All elements are **value-initialized**.
  - This is not supported by `string`, because it is meaningless to have `n` value-initializes `char`s (all of them will be `'\0'`)!

Algorithms and function objects

Algorithms

Full list of standard library algorithms can be found here.

No one can remember all of them, but some are quite commonly used.

Algorithms: interfaces

Parameters: The STL algorithms accept pairs of iterators to represent "ranges":

```
int a[N], b[N]; std::vector<int> v;
std::sort(a, a + N);
std::sort(v.begin(), v.end());
std::copy(a, a + N, b); // copies elements in [a, a+N) to [b, b+N)
std::sort(v.begin(), v.begin() + 10); // Only the first 10 elements are sorted.
```

(since C++20) `std::ranges::xxx` can be used, which has more modern interfaces

```
std::ranges::sort(a);
std::ranges::copy(a, b);
```

Algorithms: interfaces

Parameters: The algorithms suffixed `_n` use **a beginning iterator** `begin` **and an integer** `n` **to represent a range** `[begin, begin + n)`.

Example: Use STL algorithms to rewrite the constructors of `Dynarray`:

```
Dynarray::Dynarray(const int *begin, const int *end)
    : m_storage{new int[end - begin]}, m_length{end - begin} {
  std::copy(begin, end, m_storage);
}
Dynarray::Dynarray(const Dynarray &other)
    : m_storage{new int[other.size()]}, m_length{other.size()} {
  std::copy_n(other.m_storage, other.size(), m_storage);
}
Dynarray::Dynarray(std::size_t n, int x = 0)
    : m_storage{new int[n]}, m_length{n} {
  std::fill_n(m_storage, m_length, x);
}
```

Algorithms: interfaces

Return values: "Position" is typically represented by an iterator. For example:

```cpp
std::vector<int> v = someValues();
auto pos = std::find(v.begin(), v.end(), 42);
assert(*pos == 42);
auto maxPos = std::max_element(v.begin(), v.end());
```

- `pos` is an **iterator** pointing to the first occurrence of `42` in `v`.
- `maxPos` is an **iterator** pointing to the max element in `v`.

"Not found"/"No such element" is often indicated by returning `end`.

Algorithms: requirements

An algorithm may have **requirements** on

- the iterator categories of the passed-in iterators, and
- the type of elements that the iterators point to.

Typically, `std::sort` requires *RandomAccessIterator*s, while `std::copy` allows any *InputIterator*s.

Typically, all algorithms that need to compare elements rely only upon `operator<` and `operator==` of the elements.

- You don't have to define all the six comparison operators of `X` in order to `sort` a `vector<X>`. `sort` only requires `operator<`.

Algorithms

Since we pass **iterators** instead of **containers** to algorithms, **the standard library algorithms never modify the length of the containers**.

- STL algorithms never insert or delete elements in the containers (unless the iterator passed to them is some special *iterator adapter*).

For example: `std::copy` only **copies** elements, instead of inserting elements.

```
std::vector<int> a = someValues();
std::vector<int> b(a.size());
std::vector<int> c{};
std::copy(a.begin(), a.end(), b.begin()); // OK
std::copy(a.begin(), a.end(), c.begin()); // Undefined behavior!
```

Some common algorithms (`<algorithm>`)

Non-modifying sequence operations:

- `count(begin, end, x)`, `find(begin, end, x)`, `find_end(begin, end, x)`, `find_first_of(begin, end, x)`, `search(begin, end, pattern_begin, pattern_end)`

Modifying sequence operations:

- `copy(begin, end, dest)`, `fill(begin, end, x)`, `reverse(begin, end)`, ...
- `unique(begin, end)`: drop duplicate elements.
  - requires the elements in the range `[begin, end)` to be **sorted** (in ascending order by default).
  - **It does not remove any elements!** Instead, it moves all the duplicated elements to the end of the sequence, and returns an iterator `pos`, so that `[begin, pos)` has no duplicate elements.

Some common algorithms (`<algorithm>`)

Example: `unique`

```
std::vector v{1, 1, 2, 2, 2, 3, 5};
auto pos = std::unique(v.begin(), v.end());
// Now [v.begin(), pos) holds {1, 2, 3, 5},
// and [pos, v.end()) holds {1, 2, 2}, but the exact order is not known.
v.erase(pos, v.end()); // Typical use with the container's `erase` operation
// Now v holds {1, 2, 3, 5}.
```

`unique` does not remove the duplicate elements! To remove them, use the container's `erase` operation.

Some common algorithms (`<algorithm>`)

Partitioning, sorting and merging algorithms:

- `partition`, `is_partitioned`, `stable_partition`
- `sort`, `is_sorted`, `stable_sort`
- `nth_element`
- `merge`, `inplace_merge`

Binary search on sorted ranges:

- `lower_bound`, `upper_bound`, `binary_search`, `equal_range`

Heap algorithms:

- `is_heap`, `make_heap`, `push_heap`, `pop_heap`, `sort_heap`

Learn the underlying algorithms and data structures of these functions in CS101!

Some common algorithms

Min/Max and comparison algorithms: (`<algorithm>`)

- `min_element(begin, end)`, `max_element(begin, end)`, `minmax_element(begin, end)`
- `equal(begin1, end1, begin2)`, `equal(begin1, end1, begin2, end2)`
- `lexicographical_compare(begin1, end1, begin2, end2)`

Numeric operations: (`<numeric>`)

- `accumulate(begin, end, initValue)`: Sum of elements in `[begin, end)`, with initial value `initValue`.
  - `accumulate(v.begin(), v.end(), 0)` returns the sum of elements in `v`.
- `inner_product(begin1, end1, begin2, initValue)`: Inner product of two vectors $\mathbf{a}^T\mathbf{b}$, added with the initial value `initValue`.

Predicates

Consider the `Point2d` class:

```cpp
struct Point2d {
  double x, y;
};
std::vector<Point2d> points = someValues();
```

Suppose we want to sort `points` in ascending order of the `x` coordinate.

- `std::sort` requires `operator<` in order to compare the elements,
- but it is not recommended to overload `operator<` here! (What if we want to sort some `Point2d`s in another way?)

(C++20 modern way: `std::ranges::sort(points, {}, &Point2d::x);`)

Predicates

`std::sort` has another version that accepts another argument `cmp`:

```
bool cmp_by_x(const Point2d &lhs, const Point2d &rhs) {
  return lhs.x < rhs.x;
}
std::sort(points.begin(), points.end(), cmp_by_x);
```

`sort(begin, end, cmp)`

- `cmp` is a **Callable** object. When called, it accepts two arguments whose type is the same as the element type, and returns `bool`.
- `std::sort` will use `cmp(x, y)` instead of `x < y` to compare elements.
- After sorting, `cmp(v[i], v[i + 1])` is true for every `i` ∈ `[0, v.size()-1)`.

Predicates

To sort numbers in reverse (descending) order:

```
bool greater_than(int a, int b) { return a > b; }
std::sort(v.begin(), v.end(), greater_than);
```

To sort them in ascending order of absolute values:

```
bool abs_less(int a, int b) { return std::abs(a) < std::abs(b); } // <cmath>
std::sort(v.begin(), v.end(), abs_less);
```

Predicates

Many algorithms accept a Callable object. For example, `find_if(begin, end, pred)` finds the first element in `[begin, end)` such that `pred(element)` is true.

```
bool less_than_10(int x) {
  return x < 10;
}
std::vector<int> v = someValues();
auto pos = std::find_if(v.begin(), v.end(), less_than_10);
```

`for_each(begin, end, operation)` performs `operation(element)` for each element in the range `[begin, end)`.

```
void print_int(int x) { std::cout << x << ' '; }
std::for_each(v.begin(), v.end(), print_int);
```

Predicates

Many algorithms accept a Callable object. For example, `find_if(begin, end, pred)` finds the first element in `[begin, end)` such that `pred(element)` is true.

What if we want to find the first element less than `k`, where `k` is determined at run-time?

Predicates

What if we want to find the first element less than `k`, where `k` is determined at run-time?

```
struct LessThan {
  int k_;
  LessThan(int k) : k_{k} {}
  bool operator()(int x) const {
    return x < k_;
  }
};
auto pos = std::find_if(v.begin(), v.end(), LessThan(k));
```

- `LessThan(k)` constructs an object of type `LessThan`, with the member `k_` initialized to `k`.
- This object has an `operator()` overloaded: **the function-call operator**.
  - `LessThan(k)(x)` is equivalent to `LessThan(k).operator()(x)`, which is `x < k`.

Function objects

Modern way:

```
struct LessThan {
  int k_; // No constructor is needed, and k_ is public.
  bool operator()(int x) const { return x < k_; }
};
auto pos = std::find_if(v.begin(), v.end(), LessThan{k}); // {} instead of ()
```

A **function object** (aka "functor") is an object `fo` with `operator()` overloaded.

- `fo(arg1, arg2, ...)` is equivalent to `fo.operator()(arg1, arg2, ...)`. Any number of arguments is allowed.

Function objects

Exercise: use a function object to compare integers by their absolute values.

```cpp
struct AbsCmp {
  bool operator()(int a, int b) const {
    return std::abs(a) < std::abs(b);
  }
};
std::sort(v.begin(), v.end(), AbsCmp{});
```

Lambda expressions

Defining a function or a function object is not good enough:

- These functions or function objects are almost used only once, but
- too many lines of code is needed, and
- you have to add names to the global scope.

Is there a way to define an **unnamed**, immediate callable object?

Lambda expressions

To sort by comparing absolute values:

```
std::sort(v.begin(), v.end(),
          [](int a, int b) -> bool { return std::abs(a) < std::abs(b); });
```

To sort in reverse order:

```
std::sort(v.begin(), v.end(),
          [](int a, int b) -> bool { return a > b; });
```

To find the first element less than `k`:

```
auto pos = std::find_if(v.begin(), v.end(),
                        [k](int x) -> bool { return x < k; });
```

Lambda expressions

The return type can be omitted and deduced by the compiler.

```
std::sort(v.begin(), v.end(),
          [](int a, int b) { return std::abs(a) < std::abs(b); });
```

```
std::sort(v.begin(), v.end(), [](int a, int b) { return a > b; });
```

```
auto pos = std::find_if(v.begin(), v.end(), [k](int x) { return x < k; });
```

Lambda expressions

A lambda expression has the following syntax:

```
[capture_list](params) -> return_type { function_body }
```

The compiler will generate a function object according to it.

```cpp
int k = 42;
auto f = [k](int x) -> bool { return x < k; };
bool b1 = f(10); // true
bool b2 = f(100); // false
```

Lambda expressions

```
[capture_list](params) -> return_type { function_body }
```

It is allowed to write complex statements in `function_body`, just as in a function.

```cpp
struct Point2d { double x, y; };
std::vector<Point2d> points = somePoints();
// prints the l2-norm of every point
std::for_each(points.begin(), points.end(),
              [](const Point2d &p) {
                auto norm = std::sqrt(p.x * p.x + p.y * p.y);
                std::cout << norm << std::endl;
              });
```

Lambda expressions: capture

To capture more variables:

```cpp
auto pos = std::find_if(v.begin(), v.end(),
                        [lower, upper](int x) { return lower <= x && x <= upper;});
```

To capture by reference (so that copy is avoided)

```cpp
std::string str = someString();
std::vector<std::string> wordList;
// finds the first string that is lexicographically greater than `str`,
// but shorter than `str`.
auto pos = std::find_if(wordList.begin(), wordList.end(),
     [&str](const std::string &s) { return s > str && s.size() < str.size();});
```

Here `&str` indicates that `str` is captured by referece. **`&` here is not the address-of operator!**

More on lambda expressions

- *C++ Primer* Section 10.3
- *Effective Modern C++* Chapter 6 (Item 31-34)

Note that *C++ Primer (5th edition)* is based on C++11 and *Effective Modern C++* is based on C++14. Lambda expressions are evolving at a very fast pace in modern C++, with many new things added and many limitations removed.

More fancy ways of writing lambda expressions are not covered in CS100.

Back to algorithms

So many things in the algorithm library! How can we remember them?

- Remember the **conventions**:
  - No insertion/deletion of elements
  - Iterator range `[begin, end)`
  - Functions named with the suffix `_n` uses `[begin, begin + n)`
  - Pass functions, function objects, and lambdas for customized operations
  - Functions named with the suffix `_if` requires a boolean predicate
- Remember the common ones: `copy`, `find`, `for_each`, `sort`, ...
- Look them up in cppreference before use.

Associative containers

Motivation: set

Represent a "set":

- Quick insertion, lookup and deletion of elements.
- Order does not matter.

Sequence containers do not suffice:

- Lookup of elements is $O(n)$.
- Quick insertion/deletion only happens at certain positions for some containers.
    - e.g. `vector` only supports quick insertion/deletion at the end.
- The order of elements is preserved, which is not important.

You will learn the appropriate data structures in CS101.

`std::set`

Defined in `<set>`.

- `std::set<T>` is a set whose elements are of type `T`. **`operator<(const T, const T)` should be supported**, because it is usually implemented as Red-black trees.
- `std::set<T, Cmp>` is also available. `x < y` will be replaced with `cmp(x, y)`, where `cmp` is a function object of type `Cmp`.

```cpp
std::set<int> s1; // An empty set of ints
std::set<std::string> s2{"hello", "world"}; // A set of strings,
                                            // initialized with two elements
struct Student { std::string name; int id; };
std::set<Student> s3; // No operator< for Student is available.
                      // This line alone does not cause error, but you cannot
                      // insert elements into it.
s3.insert(Student{"Alice", 42}); // Error: No operator< available.
```

`std::set`

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```cpp
struct Student { std::string name; int id; };
struct CmpStudentByName {
  bool operator()(const Student &a, const Student &b) const {
    return a.name < b.name;
  }
};
std::set<Student, CmpStudentByName> students; // OK
students.insert(Student{"Alice", 42}); // OK
```

`std::set`

Constructors

```cpp
std::set<Type> s1{a, b, c, ...};
std::set<Type> s2(begin, end); // An iterator range [begin, end)
```

C++17 CTAD (Class Template Argument Deduction) also applies:

```cpp
std::set s1{a, b, c, ...}; // Element type is deduced according to the list
std::set s2(begin, end); // Element type is deduced according to
                         // the type of elements pointed by `begin` and `end`.
```

Besides, `std::set` is copy-constructible, copy-assignable, move-constructible and move-assignable, just as the sequence containers we have learned.

`std::set` does not contain duplicate elements. These constructors will ignore duplicate elements.

`std::set`: operations

Common operations: `s.empty()`, `s.size()`, `s.clear()`.

Insertion: `insert` and `emplace`. **Duplicate elements will not be inserted.**

- `s.insert(x)`, `s.insert({a, b, ...})`, `s.insert(begin, end)`.

```
std::set s{3, 2, 5, 5, 1}; // {1, 2, 3, 5}. The duplicate 5 is removed.
std::cout << s.size() << std::endl; // 4
s.insert(42); // {1, 2, 3, 5, 42}
s.insert(42); // Nothing is inserted. (No errors.)
int a[]{10, 20, 30};
s.insert(a, a + 3); // An iterator range.
                    // s now contains {1, 2, 3, 5, 10, 20, 30, 42}.
s.insert({11, 12}); // {1, 2, 3, 5, 10, 11, 12, 20, 30, 42}.
```

`std::set`: insertion

Insertion: `insert` and `emplace`. **Duplicate elements will not be inserted.**

- `s.emplace(args...)`. **Forwards** the arguments `args...` to the constructor of the element type, and constructs the element in-place.

```cpp
std::set<std::string> s;
s.emplace(10, 'c'); // inserts a string "cccccccccc"
```

`s.insert(x)` and `s.emplace(args...)` returns **`std::pair<iterator, bool>`**:

- On success, `.first` is an `iterator` pointing to the inserted element, and `.second` is `true`.
- On failure, `.first` is an `iterator` pointing to the element that prevented the insertion, and `.second` is `false`.

`std::set`: iterators

`s.begin()`, `s.end()`: Begin and off-the-end iterators.

The iterator of `std::set` is **BidirectionalIterator**:

- Supports `*it`, `it->mem`, `++it`, `it++`, `--it`, `it--`, `it1 == it2`, `it1 != it2`.

The elements are in ascending order: The following assertion always succeeds (if both `tmp` and `iter` are dereferenceable).

```cpp
auto tmp = iter;
++iter;
assert(*tmp < *iter);
```

`std::set`: iterators

Elements in a `set` cannot be modified directly: `*iter` returns a reference-to-`const`.

- The elements are stored in specific positions in the red-black tree, according to their values.
- You cannot change their values arbitrarily.

`std::set`: traversal

Range-for still works!

```
std::set<int> s{5, 5, 7, 3, 20, 12, 42};
for (auto x : s)
  std::cout << x << ' ';
std::cout << std::endl;
```

Output: `3, 5, 7, 12, 20, 42 `. The elements are in ascending order.

Equivalent way: Use iterators

```
for (auto it = s.begin(); it != s.end(); ++it)
  std::cout << *it << ' ';
std::cout << std::endl;
```

`std::set`: deletion

Delete elements: `erase`

- `s.erase(x)`, `s.erase(pos)`, `s.erase(begin, end)`, where `pos` is an iterator pointing to some element in `s`, and `[begin, end)` is an iterator range in `s`.
- `s.erase(x)` removes the element that is equivalent to `x`, **if any**.
  - returns `0` or `1`, indicating the number of elements removed.

```
std::set<int> s{5, 5, 7, 3, 20, 12, 42};
std::cout << s.erase(42) << std::endl; // 42 is removed. output: 1
// s is now {3, 5, 7, 12, 20}.
s.erase(++++s.begin()); // 7 is removed.
```

`std::set`: element lookup

`s.find(x)`, `s.count(x)`, and some other functions.

`s.find(x)` returns an iterator pointing to the element equivalent to `x` (if found), or `s.end()` (if not found).

```
std::set<int> s = someValues();
if (s.find(x) != s.end()) // x is found
  // ...
```

`std::set`: pros and cons

The time complexity of insertion, deletion, and lookup of elements in a `std::set`: **logarithmic in the size of the container**. ($O(\log n)$)

- Compared to sequence containers, this is (almost) a huge improvement.

Elements are sorted automatically.

Fast random access like `v[i]` is not supported.

Other kinds of sets:

Sets based on red-black trees:

- `std::set`
- `std::multiset`: allows duplicate elements

Sets based on hash-tables: (since C++11)

- `std::unordered_set`: hash-table version of `std::set`
- `std::unordered_multiset`: allows duplicate elements

Sets based on hash-tables provides (average-case) $O(1)$ time operations, but requires the data to be hashable.

Motivation: map