CS100 Lecture 22

Contents

Standard Template Library (STL)

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

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

- Traverse a `vector`

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

- Traverse a linked-list?

```
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:

```
// 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")

```
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

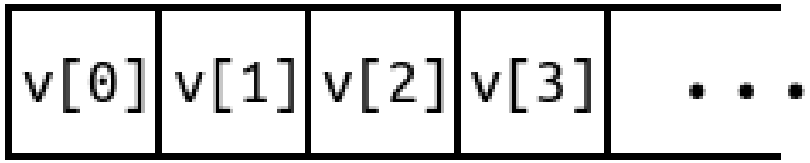
More in later lectures ...

Sequence containers and iterators

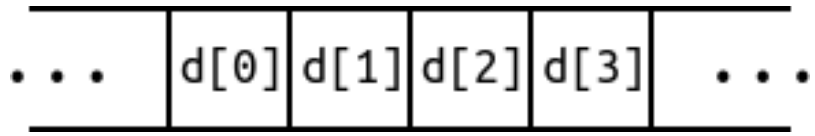
Note: `string` is not treated as a container but behaves much like one.

Sequence containers

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



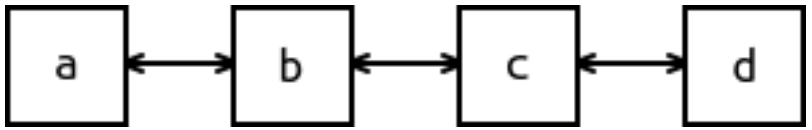
- `std::deque<T>`: **d**ouble-**e**nded **que**ue (often pronounced as "deck")
  - `std::deque<T>` supports fast insertion and deletion **at both its beginning and its end**. (`push_front`, `pop_front`, `push_back`, `pop_back`)



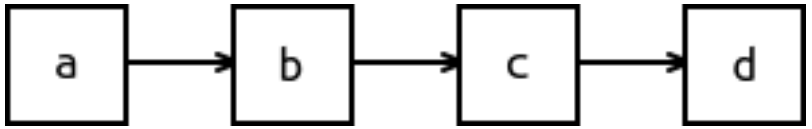
- `std::array<T, N>`: same as `T[N]`, it is a **container**
  - It will never decay to `T *`.
  - Container interfaces are provided: `.at(i)`, `.front()`, `.back()`, `.size()`, ..., as well as iterators.

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

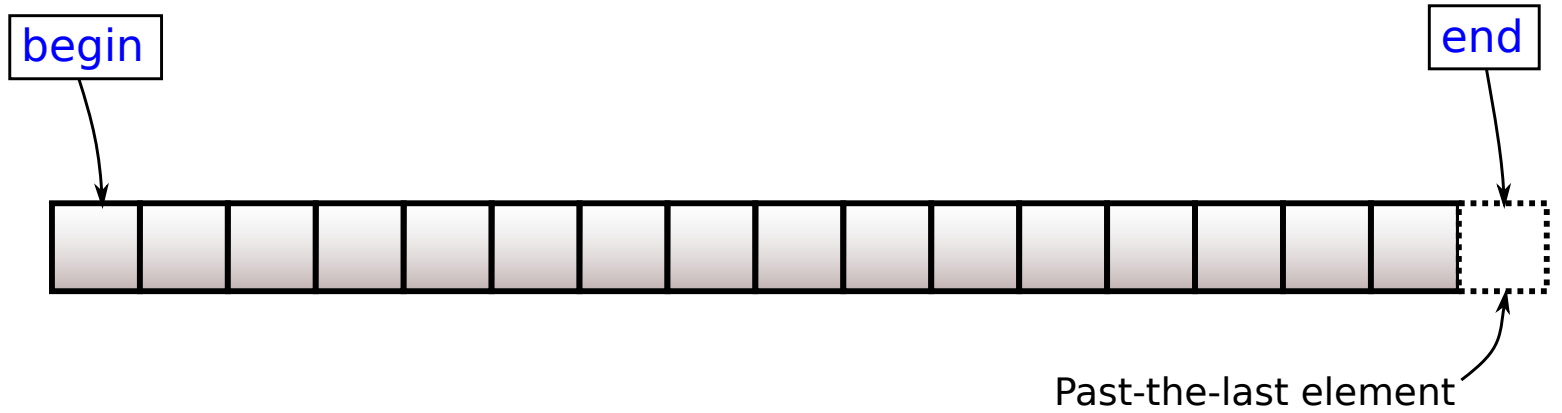
A generalized "pointer" used for accessing elements in different containers.

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:

```
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]`, 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.