CS 247: Software Engineering Principles

STL Containers

Reading: Eckel, Vol. 2
Ch. 7 Generic Containers

The C++ Standard Template Library (STL)

The STL is a major component of the C++ Standard Library; it is a large collection of general-purpose generic classes, functions, and iterators:

1. Generic containers that take the element type as a parameter.
   - e.g., `vector, list, deque, set, stack, queue, …`
2. Different kinds of iterators that can navigate through the containers.
3. Algorithms that (via iterators) perform an interesting operation on a range of elements.
   - e.g., `sort, random_shuffle, transform, find`

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Design Philosophy of the STL

Generic containers that take the element type as a parameter.

- know (almost) nothing about the element type
  exception: ordered containers expect elements to have `operator<`
- operations are (mostly) limited to add, remove, and retrieve
- define their own iterators

Useful, efficient, generic algorithms that:

- know nothing about the data structures they operate on
- know (almost) nothing about the elements in the structures
- operate on range of elements accessed via iterators

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Design Philosophy of the STL

- STL algorithms are designed so that (almost) any algorithm can be used with any STL container, or any other data structure that supports iterators.
  - Element type must support copy constructor/assignment.
- For *ordered* containers, the element type must support `operator<` or you can provide a special *functor* (function-object) of your own.
- The STL assumes *value semantics* for its contained elements: elements are *copied* to/from containers more than you might realize.
- The container methods and algorithms are highly efficient; it is unlikely that you could do better.

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No Inheritance in the STL!

Basically, the primary designer (Alexander Stepanov) thinks that OOP (i.e., inheritance) is wrong, and generic programming is better at supporting polymorphism, flexibility and reuse.

- Templates provide a more flexible (“ad hoc”) kind of polymorphism.
- The containers are different enough that code reuse isn't really practical.
- Container methods are not virtual, to improve efficiency.

STL References

There are good on-line references:

C++ Reference

http://www.cplusplus.com/reference/stl/
http://www.cplusplus.com/reference/algorithm/

SGI Standard Template Library Programmer's Guide

http://www.sgi.com/tech/stl/

Review: Polymorphic Containers

Suppose we want to model a graphical Scene that has an ordered list of `Figures` (i.e., `Rectangles`, `Circles`, and maybe other concrete classes we haven't implemented yet).

- `Figure` is an abstract base class (ABC)
- `Rectangle`, `Circle`, etc. are derived classes

What should the list look like?

1. `vector <Figure>`
2. `vector <Figure&>`
3. `vector <Figure*>`

Containers of Objects or Pointers?

```
Circle c ("red");
vector<Figure>  figList;
figList.emplace_back(c);
```

Objects:

- copy operations could be expensive
- two red circles
- changes to one do not affect the other
- when `figList` dies, it will destroy its copy of red circle
- risk of static slicing

```
Circle c ("red");
vector<Figure*>  figList;
figList.emplace_back(&c);
```

Pointers:

- allows for polymorphic containers
- when `figList` dies, only pointers are destroyed
- client code must cleanup referents of pointer elements

```cpp
#include <iostream>
#include <string>
#include <vector>
using namespace std;
class Balloon {
  public :
     Balloon (string colour);
     Balloon (const Balloon& b);  // Copy constructor
     virtual ~Balloon();
     virtual void speak() const;
  private :
     string colour;
};
Balloon::Balloon(string colour) : colour{colour} {
    cout << colour << " balloon is born" << endl;
}
Balloon::Balloon(const Balloon& b) : colour{b.colour} {
    cout << colour << " copy balloon is born" << endl;
}
void Balloon::speak() const {
    cout << "I am a " << colour << " balloon" << endl;
}
Balloon::~Balloon() {
    cout << colour << " balloon dies" << endl;
}
```

```cpp
// How many Balloons are created?
int main (int argc, char* argv[]) {
    vector<Balloon> v;
    Balloon rb ("red");
    v.push_back(rb);
    Balloon gb ("green");
    v.push_back(gb);
    Balloon bb ("blue");
    v.push_back(bb);
}
```

STL Containers

C++98/03 defines three main data-container categories:

1. Sequence containers: `vector, deque, list`
2. Container adapters: `stack, queue, priority_queue`
3. Ordered associative containers: `[multi]set, [multi]map`

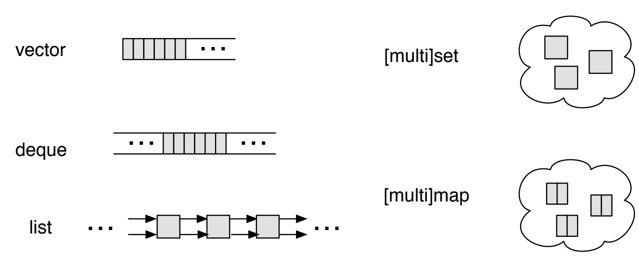
C++11 adds:

0. Addition of `emplace{_front,_back}`.
1. Sequence containers: `array, forward_list`
2. [nothing new]
3. [nothing new]
4. Unordered associative containers: `unordered_[multi]set, unordered_[multi]map`

C++14 adds:

1. Non-member `cbegin`/`cend`/`rbegin`/`rend`/`crbegin`/`crend`.

STL Containers: Conceptual View



Sequence containers

Ordered associative containers

	STL containers	*Some* useful operations
	all containers	size, empty, emplace, erase
Sequence	vector<T>	[], at, clear, insert, back, {emplace,push,pop}_back
Sequence	deque<T>	[], at, emplace{,_front,_back}, insert, {,push_,pop_}back, {,push_,pop_}front
Sequence	list<T>	insert, emplace, merge, reverse,splice, {,emplace_,push_,pop_}{back,front}, sort
Sequence	array<T>	[], at, front, back, max_size
Sequence	forward_list<T>	assign, front, max_size, resize, clear, {insert,erase,emplace}_after, {push,pop,emplace}_front
Associative	set<T>, multiset<T>	find, count, insert, clear, emplace, erase, {lower,upper}_bound
Associative	map<T1,T2>, multimap<T1,T2>	[]*, at*, find, count, clear, insert, emplace, erase, {lower,upper}_bound
Unordered Associative	unordered_set<T>, unordered_multiset<T>	find, count, insert, clear, emplace, erase, {lower,upper}_bound
Unordered Associative	unordered_map<T1,T2>, unordered_multimap<T1,T2>	[]*, at*, find, count, clear, insert, emplace, erase, hash_function
Container Adaptors	stack	top, push, pop, swap
Container Adaptors	queue	front, back, push, pop
Container Adaptors	priority_queue	top, push, pop, swap
Other	bitset (N bits)	[], count, any, all, none, set, reset, flip

Red means "there's also a stand-alone algorithm of this name"

Can't iterate over stack, queue, priority_queue.

* Not on multimap

1. Sequence Containers

There is a total ordering of contiguous values (i.e., no gaps) on elements based on the *order* in which they are added to the container.

They provide very similar basic functionality, but differ on:

1. Some access methods.
   - vector and deque allow random access to elements (via [] / at()), but list allows only sequential access (via iterators).
   - deque allows push_back *and* push_front (+ pop_front, + front).
2. Performance.
   - vector and deque are optimized for (random access) retrieval, whereas list is optimized for (positional) insertion/deletion.

vector<T>

Can think of as an expandable array that supports access with bounds checking, via vector<T>::at().

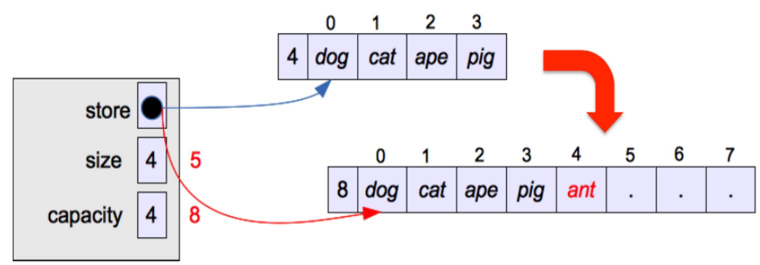
Vector elements must be stored contiguously according to the C++ standard, so pointer arithmetic will work and O(1) random access is guaranteed.

– So it pretty much has to be implemented using a C-style array .

Calling push_back when vector is at capacity forces a reallocation.

Access kind	Complexity	API support
random access	O(1)	operator[] or at()
append/delete last	O(1)*/O(1)	push_back/pop_back
prepend/delete first	O(N)	*not supported as API call*
random insert/delete	O(N)	insert/erase

(likely) vector Implementation



deque<T>

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== "double-ended queue"; similar to vectors, but allow fast insertion/ deletion at beginning and end.

Random access is "fast", but no guarantee that elements are stored contiguously.

- So pointer arithmetic won't work.
- `operator[]` and `at()` are overloaded to work correctly.

Access kind	Complexity	API support
random access	O(1)	`operator[]` or `at()`
append/delete last	O(1)*/O(1)	`push_back`/`pop_back`
prepend/delete first	O(1)*/O(1)	`push_front`/`pop_front`
random insert/delete	O(N)	`insert`/`erase`

deque implementation

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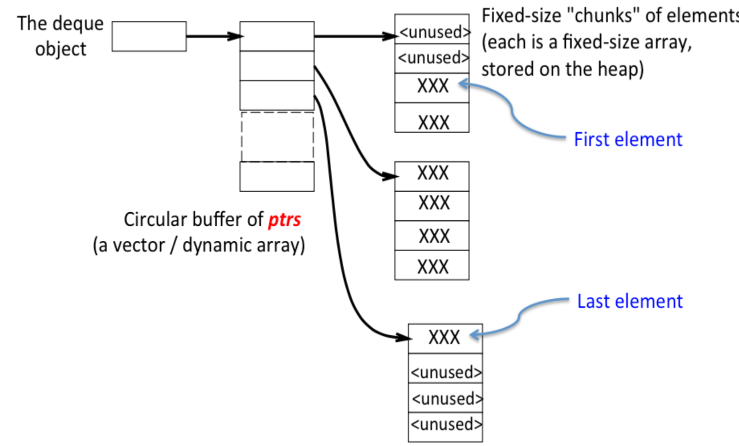

vector vs. deque

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So, in real life, should you use `vector` or `deque`?

- If you need to insert at the front, use `deque`.
- If you need to insert in the middle, use `list`.

Random access to elements is constant time in both, but a `vector` may be faster in reality.

Reallocations:

- take longer with a `vector`.
- `vector` invalidates external refs to elements, but not so with a `deque`.
- `vector` copies *elements* (which may be objects), whereas `deque` copies only *ptrs*.

Integrity of External References

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```
#include <vector>
#include <deque>
using namespace std;

int main (int argc, char* argv[]) {
    cout << "\nWith a vector:" << endl;
    vector<int> v;
    v.push_back(4);     v.push_back(3);
    v.push_back(37);    v.push_back(15);
    int* p = &v.back();
    cout << *p << " " << v.at(3) << "  " // Must be same
        << p << " " << &v.at(3) << endl; // Must be same
    v.push_back(99);              // Causes a reallocation
    cout << *p << " " << v.at(3) << "  " // May be different**
        << p << " " << &v.at(3) << endl; // Probably different
```

** p is no longer pointing to v[3], but the old value of 15 may still "be there"

Integrity of External References

```
    cout << "\nWith a deque:" << endl;
    deque<int> d;
    d.push_back(4);   d.push_back(3);
    d.push_back(37);  d.push_back(15);
    p = &d.back();
    cout << *p << " " << d.at(3) << "  "    // Must be same
        << p << " " << &d.at(3) << endl;    // Must be same
    d.resize(32767);              // Probably causes realloc
    cout << *p << " " << d.at(3) << "  "    // Must be same
        << p << " " << &d.at(3) << endl;    // Must be same
}
// My output below, YMMV but comments above will hold
With a vector:
15 15  0x7ff87bc039cc 0x7ff87bc039cc
15 15  0x7ff87bc039cc 0x7ff87bc039ec
With a deque:
15 15  0x7ff87c00220c 0x7ff87c00220c
15 15  0x7ff87c00220c 0x7ff87c00220c
```


list<T>

Implemented as a (plain old) doubly-linked list (PODLL)
Designed for fast insertion and deletion.

Supports only sequential access to elements via iterators.
- No random access via indexing `operator[]` or `at()`.

Access kind	Complexity	API support
random access	O(N)	*not supported as an API call*
append/delete last	O(1)	`push_back/pop_back`
prepend/delete first	O(1)	`push_front/pop_front`
random insert/delete	O(1) (once you've arrived at the elt; O(N) to get there)	`insert/erase`

(C++11) std::array

Effectively, a very thin wrapper around a C++ array, to make it a little more like a fixed-size `vector`.

C++ array vs. `std::array`

- not implicitly converted by compiler into a pointer
- supports many useful functions like
  - an `at()` method, for safe, bounds-checked accessing
  - a `size()` method that returns the extent of the array (which you set when you instantiated the array)

`std::array` vs. `std::vector`

- strong typing: if you know the array size should be fixed, enforce it!
- array contents may be stored on the stack rather than the heap
- `std::array` is faster and more space efficient

(C++11) std::forward_list

Basically, a plain-old singly-linked list.

`std::forward_list` vs. `std::list`

- more space efficient, and insertion/deletion operators are slightly faster
- no immediate access to the end of the list
  - no `push_back()`, `back()`
- no ability to iterate backwards
- no `size()` method

2. Container Adapters

Usually a trivial wrapping of a sequence container, to provide a specialized interface with ADT-specific operations to add/remove elements.

- `stack, queue, priority_queue`

You can specify in the constructor call which container you want to be used in the underlying implementation:

```
stack: vector, deque*, list
queue: deque*, list
priority_queue: vector*, deque
```

[* means default choice]

STL Container Adapters

Implemented using the adapter design pattern.

1. Define the interface you really want.
   e.g., for `stack`, we want `push(), pop()`
2. Instantiate (don't inherit) a private data-member object from the "workhorse" container class that will do the actual heavy lifting (e.g., `vector`).
3. Define operations by delegating to operations from the workhorse class.


```
template <typename T>
class Stack {
  public :
    Stack ();
    virtual ~Stack();
    void push (T val);
    void pop ();
    T top ();
    void print ();
    bool isEmpty();
  private :
    vector<T> s;
};
```

Note that the STL provides its own definition of Stack: please use that one! This is just an ad hoc example.

```
template <typename T>
Stack<T>::Stack(): s() {}

template <typename T>
Stack<T>::~Stack () {}

template <typename T>
void Stack<T>::push(T val){
  s.push_back(val);
}

template <typename T>
void Stack<T>::pop () {
  assert (!isEmpty());
  s.pop_back();
}
// … etc
```

"The STL Way"

"The STL Way" encourages you to define your own adapter classes, based on the STL container classes, if you have special-purpose needs that are *almost* satisfied by an existing STL class.

- STL doesn't use inheritance or define any methods as `virtual`.
- Encourages reuse via *adaptation*, rather than inheritance.
- Interface can be exactly what you want, not constrained by inheritance.

Inheritance vs. Adaptation

Suppose we would like to implement a card game and we want to model a pile of playing cards.

– Actually, a pile of `Card*`, since the cards will be a shared resource and will get passed around.

We want it to support natural `CardPile` capabilities, like `addCard`, `discard`, `merge`, `print`, etc.

We also want the client programmer to be able to treat a `CardPile` like a sequential polymorphic container: `iterate, find, insert, erase`.

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Inheriting from an STL Container

```
// legal, but is it a good idea?
class CardPile : public vector<Card*> {
    public:
        // Constructors and destructor
        CardPile ();
        virtual ~CardPile ();
        // Accessors
        void print () const;
        int getHeartsValue () const;
        // Mutators
        void add (Card* card);
        void add (CardPile & otherPile);
        void remove (Card* card);
        void shuffle ();
};
```

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Traditional STL Adaptation

```
class CardPile {

  public:
   // Constructors and destructor
   CardPile();
   virtual ~CardPile();

   // Accessors
   void print() const;
   int getHeartsValue() const;

   // Mutator ops ("natural" for CardPile)
   void add( Card * card );
   void add( CardPile & otherPile );
   void remove( Card * card );
   void shuffle();

   // If want shuffling to be repeatable, pass in a random
   // number generator.
   void shuffle( std::mt19937 & gen );
```

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Traditional STL adaptation (cont)

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```
   // Wrapped container methods and types
   using iterator = std::vector<Card*>::iterator;
   using const_iterator = std::vector<Card*>::const_iterator;
   CardPile::iterator begin();
   CardPile::const_iterator begin() const;
   CardPile::iterator end();
   CardPile::const_iterator end() const;
   int size() const;
   Card * at(int i) const;
   void pop_back();
   Card * back() const;
   bool empty() const;
private:
   std::vector<Card*> pile;
};
// Example of function wrapper
void CardPile::add( CardPile & otherPile ) {
   for ( auto card: otherPile ) pile.emplace_back( card );
   otherPile.pile.clear();
} // CardPile::add
```

But there is another way...

Public inheritance:

```
class Circle : public Figure{ …
```

- Inside the class definition of `Circle`, we have direct access to all non-private members of `Figure`.
- `Circle` is a subtype of `Figure`, and it provides a superset of the `Figure`'s public interface.

Private inheritance:

```
class Circle : private Figure{ …
```

- Inside the class definition of `Circle`, we have direct access to all non-private members of `Figure`.
- `Circle` is ***not*** a subtype of `Figure`; it does not support `Figure`'s public interface.
- Client code that instantiates a `Circle` cannot treat it polymorphically as if it were a `Figure`.
  - Cannot invoke any `Figure` public methods.
  - Cannot instantiate a `Circle` to a `Figure*`.

private Inheritance

Private inheritance is used to allow reuse of a base class's *implementation* without having to support the base class's interface.

All of the inherited `public` (and `protected`) members of the base class are `private` in the child class and can be used to implement child class methods; but they are not exported to the public.

We can selectively make some of the methods of the base class visible to the client code using using, as in

- `using Figure::getColour;`
- called promotion.

Private Inheritance of STL Container

```
class CardPile : private std::vector<Card*> {

  public:
   // Constructors and destructor
   CardPile();
   virtual ~CardPile();

   // Accessors
   void print() const;
   int getHeartsValue() const;

   // Mutator ops ("natural" for CardPile)
   void add( Card * card );
   void add( CardPile & otherPile );
   void remove( Card * card );
   void shuffle();

   // If want shuffling to be repeatable, pass in a random
   // number generator.
   void shuffle( std::mt19937 & gen );
```


Private Inheritance of STL Container (cont)

```
    // "Promoted" container methods and types
    using std::vector<Card*>::iterator;
    using std::vector<Card*>::const_iterator;
    using std::vector<Card*>::begin;
    using std::vector<Card*>::end;
    using std::vector<Card*>::size;
    using std::vector<Card*>::at;
    using std::vector<Card*>::pop_back;
    using std::vector<Card*>::back;
    using std::vector<Card*>::empty;

};
```

private Inheritance

This approach is safe *because* it breaks polymorphism!

- Cannot instantiate a `CardPile` to a `vector<Card*>`, so there is no risk of a call to the wrong destructor causing a memory leak.
- The client code cannot accidentally call the wrong version of an inherited non-virtual method.
  - None of the inherited functions are visible to clients unless explicitly made so by using `using` (in which case, the parent definition is used).
  - If you *redefine* an inherited function, the client code will get that version, since they can't see the parent version .

Private inheritance is not conceptually very different from adaptation.

- It requires a little less typing.
- It encourages reuse of the parent class's interface where applicable.

3. Associative Containers

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Ordered associative containers

`[multi]map, [multi]set`

- The ordering of the elements is based on a *key* value (a piece of the element, e.g., employee records sorted by SIN or name or …)
  - and not by the order of insertion.
- Implemented using a kind of binary search tree => lookup is O(log N).
- Can iterate through container elements "in order".

Unordered associative containers [new in C++11]

`unordered_[multi]map, unordered[multi]set`

- No ordering assumed among the elements.
- Implemented using hash tables => lookup is O(1).
- Can iterate through container elements, but no particular ordering is assumed.

set<T>

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A set is a collection of (unique) values.

- Typical declaration:

  `set<T> s;`

- `T` must support a comparison function with strict weak ordering
  - i.e., anti-reflexive, anti-symmetric, transitive.
  - Default is operator<
  - Can use a user-defined class, but you must ensure that there is a "reasonable" operator< defined or provide an ordering *functor* to the set constructor.

Sets do not allow duplicate elements.

- If you try to `insert` an element that is already present in the `set`, the `set` is unchanged. Return value is a `pair <iterator,bool>`.
  - The `second` of the `pair` indicates whether the insertion was successful.
  - The `first` of the `pair` is the position of the new/existing element.

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```
// Example with user defined class and operator<
#include <algorithm>
#include <set>
#include <iostream>
#include <string>

using namespace std;

class Student {
  public:
    Student (string name, int sNum, double gpa);
    string getName() const;
    int getSNum() const;
    double getGPA() const;
  private:
    string name_;
    int sNum_;
    double gpa_;
};

Student::Student(string name, int sNum, double gpa) :
      name_{name}, sNum_{sNum}, gpa_{gpa} {}
string Student::getName() const {return name_;}
int Student::getSNum() const {return sNum_;}
double Student::getGPA() const {return gpa_;}

bool operator== (const Student& s1, const Student& s2) {
    return (s1.getSNum() == s2.getSNum()) &&
           (s1.getName() == s2.getName()) &&
           (s1.getGPA() == s2.getGPA());
}
```

```
bool operator< (const Student& s1, const Student& s2) {
    return s1.getSNum() < s2.getSNum();
}

ostream& operator<< (ostream &os, const Student& s) {
    os << s.getName() << " " << s.getSNum()
    << " " << s.getGPA();
    return os;
}

int main () {
    Student* pJohn = new Student{ “John Smith”, 666, 3.7 };
    Student* pMary = new Student{ “Mary Jones”, 345, 3.4 };
    Student* pPeter = new Student{ “Peter Piper”, 345, 3.1 }; // Same SNum as Mary

    set<Student> s;
    s.insert(*pJohn);
    s.insert(*pMary);
    s.insert(*pPeter);

    // Will print in numeric order of sNum
    for (auto i=s.begin(); i!=s.end();i++){
        cout << i << endl;
    }
    if ( s.find(*pPeter) != s.end() )
        cout << "Found it with set's find()!" << endl;
    if ( find(s.begin(), s.end(), *pPeter ) != s.end() )
        cout << "Found it with STL algorithm find()" << endl;
}
```


Equality vs. Equivalence

Equivalence

The container search methods (e.g., `find`, `count`, `lower_bound`, ...) will use the following test for equality for elements in ordered associate containers *even if you have your own definition of* `operator==`.

```
if ( !(a<b) && !(b<a) )
```

Equality

Whereas the STL algorithms `find`, `count`, `remove_if` compare elements using `operator==`.

map<key,T>

A map maps a key to a (unique) value.

- Typical declaration:

  `map<T1, T2> m;`

- `T1` is the *key field type*; it must support a comparison function with strict weak ordering
  - i.e., anti-reflexive, anti-symmetric, transitive.
  - Default is operator<.
  - Can use a user-defined class, but you must ensure that there is a “reasonable” operator< defined or provide an ordering functor to the map constructor.
- `T2` is the *value field*; can be anything that is copyable and assignable.

Querying Map for Element

Intuitive method (lookup via indexing) will insert the key if it is not already present:

```
if ( words [ "bach" ] == 0 )
    // bach not present
```

Alternatively, can use map's find() operation to return an iterator pointing the queried key/value pair.

```
map<string, int>::iterator  it;

it = words.find( "bach" );
if ( it == words.end( ) )
    // bach not present
```

end() is iterator value that points beyond the last element in a collection

```cpp
#include <iostream>
#include <string>
#include <cassert>
#include <map>
using namespace std;

// Examples adapted from Josuttis
int main () {
    map<string,string> dict;

    dict["car"] = "voiture";
    dict["hello"] = "bonjour";
    dict["apple"] = "pomme";

    cout << "Printing simple dictionary" << endl;

    for ( auto i: dict ){
        cout << i.first << ":\t" << i.second << endl;
    }
```



```cpp
// Examples adapted from Josuttis

    multimap<string,string> mdict;

    mdict.insert(make_pair ("car", "voiture"));
    mdict.insert(make_pair ("car", "auto"));
    mdict.insert(make_pair ("car", "wagon"));
    mdict.insert(make_pair ("hello", "bonjour"));
    mdict.insert(make_pair ("apple", "pomme"));

    cout << "\nPrinting all defs of \"car\"" << endl;

    for (multimap<string,string>::const_iterator
         i=mdict.lower_bound("car");
         i!=mdict.upper_bound("car"); i++) {

        cout << (*i).first << ":    " << (*i).second << endl;
    }
}
```


How are they Implemented?

`[multi]set` and `[multi]map` are usually implemented as a red-black tree (see CS240).

- This is a binary search tree that keeps itself reasonably balanced by doing a little bit of work on insert/delete.
- Red-black trees guarantee that lookup/insert/delete are all O(log N) worst case, which is what the C++ standard requires .
- Optimized search methods (e.g., `find`, `count`, `lower_bound`, `upper_bound`) .

Because the containers are automatically sorted, you cannot change the value of an element directly (because doing so might compromise the order of elements).

- There are no operations for direct element access.
- To modify an element, you must remove the old element and insert the new value.

(C++11) Unsorted Associative Containers

They are:

`unordered_[multi]set`

`unordered_[multi]map`

They are pretty much the same as the sorted versions except:

- They're not sorted. 😊
- They're implemented using hash tables, so they are O(1) for insert/lookup/remove.
- They do provide iterators that will traverse all of the elements in the container, just not in any "interesting" order.

The C++ Standard Template Library (STL)

The STL is a major component of the C++ Standard Library; it is a large collection of general-purpose generic classes, functions, and iterators:

1. Generic containers that take the element type as a parameter.
   - e.g., `vector, list, deque, set, stack, queue, …`

2. Different kinds of iterators that can navigate through the containers.

3. Algorithms that (via iterators) perform an interesting operation on a range of elements.
   - e.g., `sort, random_shuffle, transform, find`

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STL Iterators

The iterator is a fundamental *design pattern*.

- It represents an abstract way of walking through all elements of some interesting data structure.
- You start at the beginning, advance one element at a time, until you reach the end.

In its simplest form, we are given:

- A pointer to the first element in the collection.
- A pointer to just beyond the last element; reaching this element is the stopping criterion for the iteration.
- A way of advancing to the next element (e.g., `operator++, operator--`).

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STL Containers Provide Iterators

If `c` is a `vector, deque, list, set, map`, etc. then

- `c.begin()/c.cbegin()` returns a pointer to the first element
- `c.end()/c.cend()` returns a pointer to just beyond the last element
- `operator++` is defined to advance to the next element

Example

```
vector<string>::const_iterator    vi = v.begin();
map<int,string>::iterator         mi = mymap.begin();
list<Figure*>::reverse_iterator   li = scene.rbegin();
```

This is the type!

- The iterator types are *nested* types, defined inside the respective container classes, who understand what "++" should mean!

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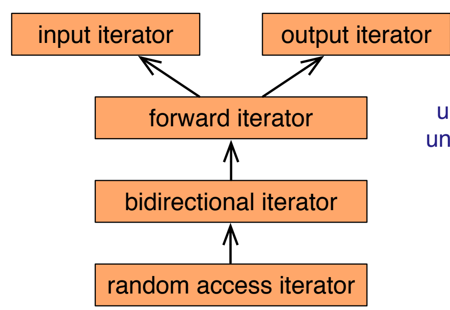
Kinds of Iterators

Iterator categories are hierarchical, with lower level categories adding constraints to more general categories.



istream, ostream

unordered_set, unordered_multiset, unordered_map, unordered_multimap

list, set, multiset, map, multimap

vector, deque

Why should you care??

Input and Output Iterators

Input iterators are read-only iterators where each iterated location may be read only once.

Output iterators are write-only iterators where each iterated location may be written only once.

Operators: ++, * (can be `const`), ==, != (for comparing iterators)

Mostly used to iterate over streams.

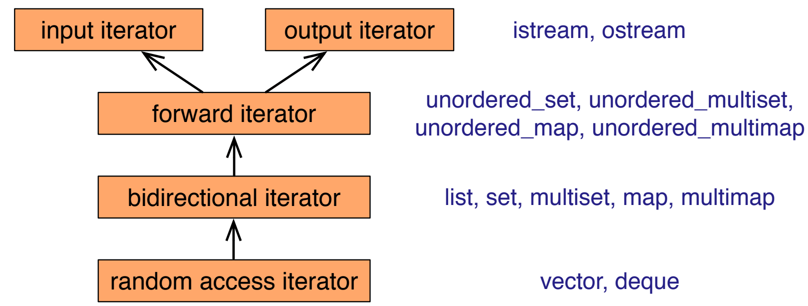
```
#include <iostream>
#include <iterator>
...
copy ( istream_iterator<char> (cin),    // input stream
       istream_iterator<char> (),       // end-of-stream
       ostream_iterator<char> (cout) )  // output stream
```


Other Kinds of Iterators

Forward iterators can read and write to the same location repeatedly.

Bidirectional iterators can iterate backwards (−−) and forwards (++).

Random access iterators : can iterate backwards (−−) and forwards (++), access any element ([ ]), iterator arithmetic (+, −, +=, −=).



Insert Iterators (Inserters)

Iterator that inserts elements into its container:

- back_inserter: uses container's `push_back()`
- front_inserter: uses container's `push_front()`
- inserter: uses container's `insert()`

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


   istream_iterator< string > is (cin);
   istream_iterator< string > eof;    // end sentinel
   vector< string > text;
   copy ( is, eof, back_inserter( text ));
```


Concluding Remarks

Iterators are a great example of both information hiding and polymorphism.

- Simple, natural, uniform interface for accessing all containers or data structures.
- Can create iterators (STL-derived or homespun) for our own data structures.
- STL iterators are compatible with C pointers, so we can use STL algorithms with legacy C data structures.