

301AA - Advanced Programming

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AP-15: C++ Standard Template Library

Slides freely adapted from those of Antonio Cisternino

Introduction

- The C++ Standard Template Library (STL) has become part of C++ standard
- The main author of STL is Alexander Stepanov
- Developed in ~1992 but based on ideas of ~1970
- He chose C++ because of templates and no requirement of using OOP! 
- The library is somewhat unrelated with the rest of the standard library which is OO

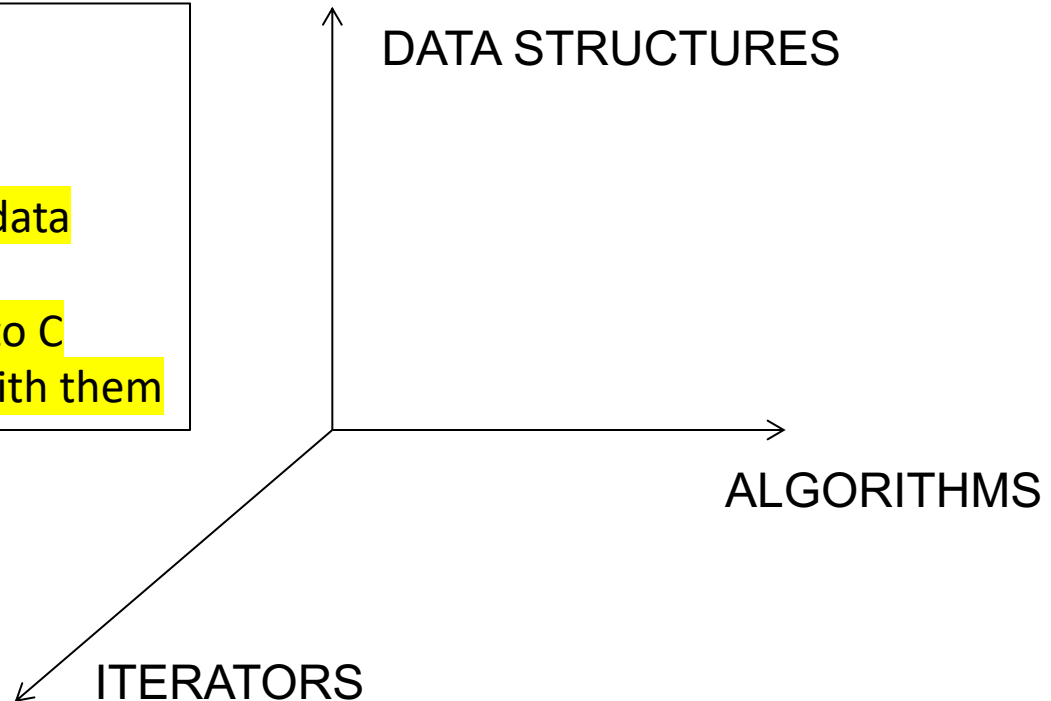
The Standard Template Library

- Goal: represent algorithms in as general form as possible without compromising efficiency
- Extensive use of **templates** and **overloading** 
- Only uses static binding (and inlining): **not object oriented, no dynamic binding** – very different from Java Collection Framework 
- Use of **iterators** for decoupling algorithms from containers
- Iterators are seen as **abstraction of pointers**
- Many generic abstractions
 - Polymorphic abstract types and operations
- Excellent example of generic programming
 - Generated code is very efficient


3D generic world

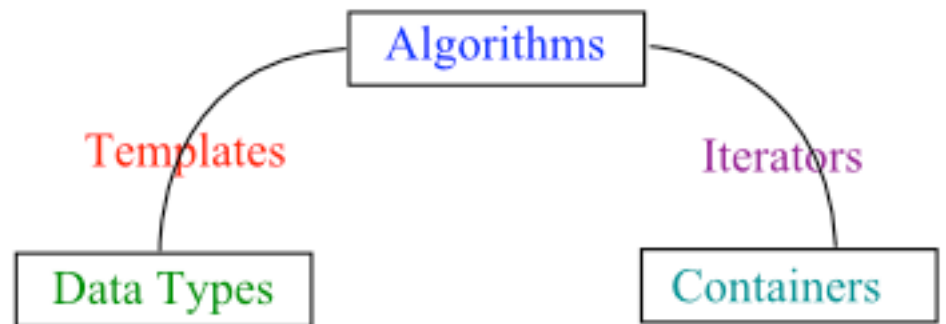
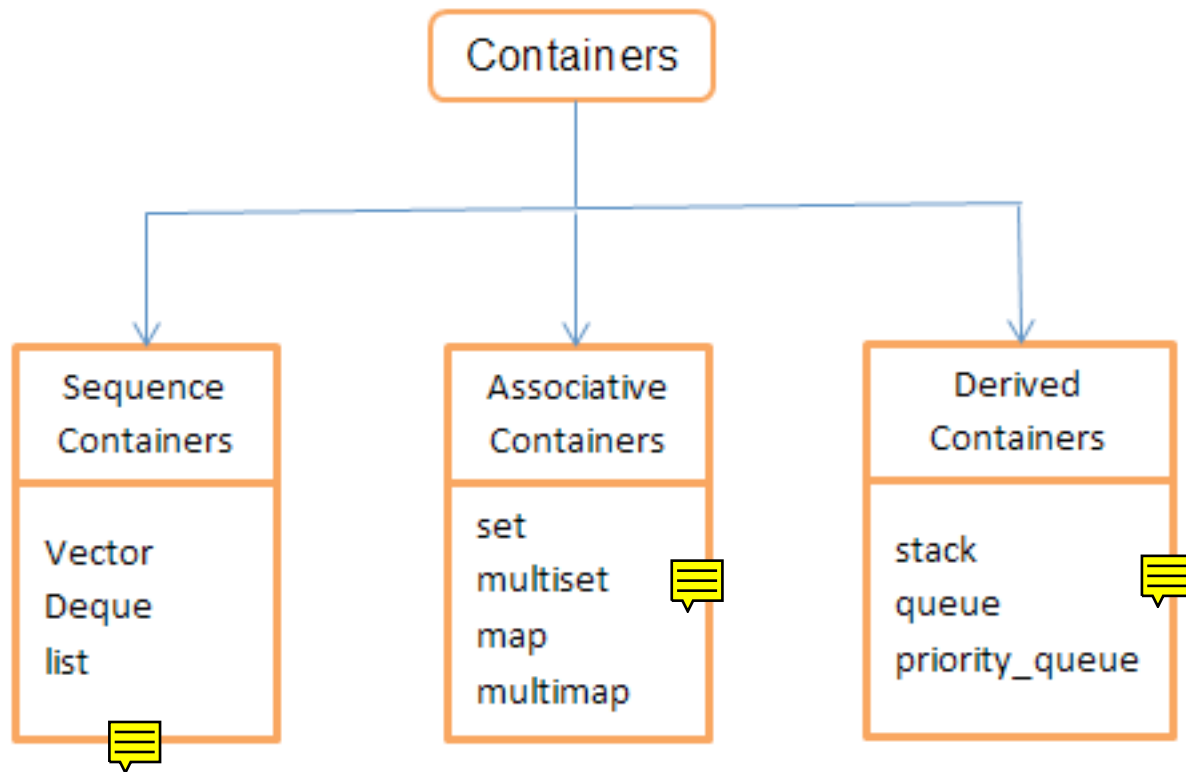
Stephanov observed three orthogonal dimensions in algorithms: iterators allow algorithms to iterate over data structures.

Iterators are very similar to C pointers and compatible with them




Main entities in STL


- **Container**: Collection of typed objects
 - Examples: array, vector, deque, list, set, map ...
- **Iterator**: Generalization of pointer or address. used to step through the elements of collections
 - forward_iterator, reverse_iterator, istream_iterator, ...
 - pointer arithmetic supported
- **Algorithm**: initialization, sorting, searching, and transforming of the contents of containers,
 - for_each, find, transform, sort
- **Adaptor**: Convert from one form to another
 - Example: produce iterator from updatable container; or stack from list
- **Function object**: Form of closure (class with "operator()" defined) 
 - plus, equal, logical_and
- **Allocator**: encapsulation of a memory pool
 - Example: GC memory, ref count memory, ...



1. **Templates**
make **algorithms** independent of the **data types**
2. **Iterators**
make **algorithms** independent of the **containers**

A digression: Iterators in Java

- Iterators are supported in the Java Collection Framework: interface **Iterator<T>**
- They exploit generics (as collections do)
- Iterators are usually defined as *nested classes* (*non-static private member classes*): each iterator instance is associated with an instance of the collection class 
- Collections equipped with iterators have to implement the **Iterable<T>** interface

```
class BinTree<T> implements Iterable<T> {  
    BinTree<T> left;  
    BinTree<T> right;  
    T val;  
    ...  
    // other methods: insert, delete, lookup, ...  
    public Iterator<T> iterator() {  
        return new TreeIterator(this);   
    }  
}
```

Iterators in Java (cont'd)

```
class BinTree<T> implements Iterable<T> {
    ...
    private class TreeIterator implements Iterator<T> {
        private Stack<BinTree<T>> s = new Stack<BinTree<T>>();
        TreeIterator(BinTree<T> n) {
            if (n.val != null) s.push(n);
        }
        public boolean hasNext() {
            return !s.empty();
        }
        public T next() {        //preorder traversal
            if (!hasNext()) throw new NoSuchElementException();
            BinTree<T> n = s.pop();
            if (n.right != null) s.push(n.right);
            if (n.left != null) s.push(n.left);
            return n.val;
        }
        public void remove() {
            throw new UnsupportedOperationException();
        }
    }
}
```


Iterators in Java (cont'd)

- Use of the iterator to print all the nodes of a BinTree:

```
for (Iterator<Integer> it = myBinTree.iterator();  
     it.hasNext(); )  
{   Integer i = it.next();  
    System.out.println(i);  
}
```

- Java provides (since Java 5.0) an *enhanced for* statement (*foreach*) which exploits iterators. The above loop can be written:





```
for (Integer i : myBinTree)  
    System.out.println(i);
```

- In the *enhanced for*, **myBinTree** must either be an array of integers, or it has to implement **Iterable<Integer>**
- The enhanced for on arrays is a **bounded iteration**. On an arbitrary iterator it depends on the way it is implemented.


Example of use: **Vector** and **Forward Iterator**

```
#include <iostream>
#include <vector>
using namespace std;
int main() {
    vector<int> vec; // create a vector to store int
    int i;
    // display the original size of vec
    cout << "vector size = " << vec.size() << endl;
    // push 5 values into the vector
    for(i = 0; i < 5; i++) {
        vec.push_back(i);
    }
    // display extended size of vec
    cout << "extended vector size = " << vec.size() << endl;
    // access 5 values from the vector
    for(i = 0; i < 5; i++) {
        cout << "value of vec [" << i << "] = " << vec[i] << endl;
    }
    // use iterator to access the values
    vector<int>::iterator v = vec.begin();
    while( v != vec.end()) {
        cout << "value of v = " << *v << endl;
        v++;
    }
    return 0;
}
```

Iterators and C++ namespaces!

- STL relies on C++ namespaces
- Containers expose a type named *iterator* in the container's namespace 
- Example: `std::vector<std::string>::iterator` 
- Each class implicitly introduces a new namespace 
- The *iterator* type name assumes its meaning depending on the context! 

Complexity of operations on containers

- It is *guaranteed* that inserting and erasing at the end of the vector takes *amortized* constant time whereas inserting and erasing in the middle takes linear time. 

<i>Container</i>	<i>insert/erase overhead at the beginning</i>	<i>in the middle</i>	<i>at the end</i>
Vector	linear	linear	amortized constant
List	constant	constant	constant
Deque	amortized constant	linear	amortized constant




Complexity of use of Iterators

- Consider the following code:

```
std::list<std::string> l;  
...  
quick_sort(l.begin(), l.end());
```

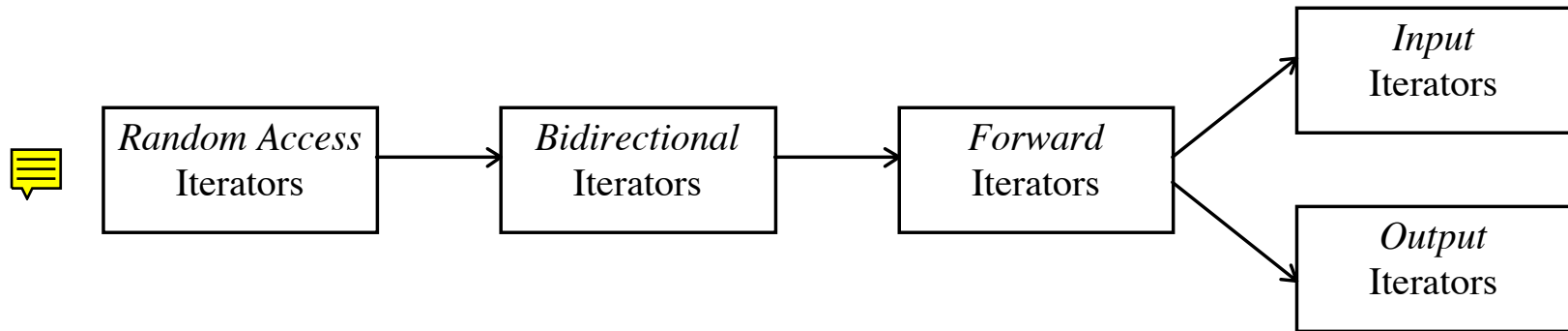
- This is not reasonable: `quick_sort` assumes random access to container's elements! 🗨
- How can we control complexity of algorithms and guarantee that code behaves as expected?

Classifying iterators

- The solution proposed by STL is assume that iterators implement all operations in **constant time** 
- Containers may support different iterators depending on their structure:
 - **Forward iterators**: only dereference (operator*), and pre/post-increment operators (operator++) 
 - **Bidirectional iterators**: like forward iterators with pre/post-decrement (operator--) 
 - **Random access iterators**: like bidirectional iterators but with integer sum ($p + n$) and difference ($p - q$)
- Iterators heavily rely on operator overloading provided by C++

Categories of iterators


- Five categories, with decreasing requirements



- Each category has only those functions defined that are realizable in **constant time**. [Efficiency concern of STL!]
- Not all iterators are defined for all categories: since **random access** takes **linear time** on lists, random access iterators **cannot be used with lists**.

<i>Container</i>	<i>Iterator Category</i>
vector	random access iterators
list	bidirectional iterators
deque	random access iterators

C++ operators and iterators

- **Forward iterators** provide for one-directional traversal of a sequence, expressed with ++:
 - Operator ==, !=, *, ++ 
- **Bidirectional iterators** provide for traversal in both directions, expressed with ++ and --:
 - Same operators as forward iterator
 - Operator --
- **Random access iterators** provide for bidirectional traversal, plus bidirectional “long jumps”:
 - Same operators as bidirectional iterator
 - Operator += *n* and -= *n* with *n* of type *int*
 - Addition and subtraction of an integer through operator + and operator –
 - Comparisons through operator <, operator >, operator <=, operator >=
- **Any C++ pointer type, T*, obeys all the laws of the random access iterator category.**

Iterator validity

- When a container is modified, iterators to it **can** become **invalid**: the result of operations on them is not defined
- Which iterators become invalid depends on the operation and on the container type

<i>Container</i>	<i>operation</i>	<i>iterator validity</i>
vector	inserting	reallocation necessary - all iterators get invalid
		no reallocation - all iterators before insert point remain valid
	erasing	all iterators after erase point get invalid
list	inserting	all iterators remain valid
	erasing	only iterators to erased elements get invalid
deque	inserting	all iterators get invalid
	erasing	all iterators get invalid

Limits of the model

- Iterators provide a linear view of a container
- Thus we can define only algorithms operating on single dimension containers
- If it is needed to access the organization of the container (i.e. to visit a tree in a custom fashion) the only way is to define a new iterator
- Nonetheless the model is expressive enough to define a large number of algorithms!

Under the hood...

- To really understand the philosophy behind STL it is necessary to dig into its implementation
- In particular it is useful to understand on which language mechanisms it is based upon:
 - Type aliases (typedefs)
 - Template functions and classes
 - Operator overloading
 - Namespaces

Iterators: small struct

- Iterators are implemented by containers
- Usually are implemented as struct (classes with only public members)
- An iterator implements a visit of the container
- An iterator retains inside information about the state of the visit (i.e. in a vector, the pointer to the current element and the number of remaining elements)
- The state may be complex in the case of non linear structures such as trees or graphs