301AA - Advanced Programming

Lecturer: Andrea Corradini

andrea@di.unipi.it

http://pages.di.unipi.it/corradini/

AP-16: 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 Stephanov
- 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
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

```java
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:

```java
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:

```java
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.
#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;
}
Example: using algorithm *inner_product*

```cpp
#include <iostream>
#include <numeric>

int main() {
    int A1[] = {1, 2, 3};
    int A2[] = {4, 1, -2};
    const int N1 = sizeof(A1) / sizeof(A1[0]);

    std::cout << inner_product(A1, A1 + N1, A2, 0) << std::endl;
    return 0;
}
```

It will print 0:

```
0 = 0 + 1 * 4 + 2 * 1 + 3 * -2
```

Start of A1

End of A1

Start of A2

The signature:

```
template< class InputIt1, class InputIt2, class T >
T inner_product( InputIt1 first1, InputIt1 last1,
                  InputIt2 first2, T value );
```
With strings?

• We have strings in two vectors: labels and values to display
• Can we exploit inner product algorithm?
• It would be enough to use string concatenation with a tab instead of ‘*’ and with a new line instead of ‘+’
• Note that overloading of ‘+’ and ‘*’ operators for strings make no sense: we don't want just string cat and we may interfere with already defined overloads
• Fortunately there is another version of inner_product that allows specifying function objects to use instead of ‘*’ and ‘+’
inner_product: more general definition

template<class InputIt1, class InputIt2, class T, 
   class BinaryOperation1, class BinaryOperation2>
T inner_product( InputIt1 first1, InputIt1 last1, 
   InputIt2 first2, T init, BinaryOperation1 op1, 
   BinaryOperation2 op2 );

• Ordered map/reduce
• Initializes result to \textit{init}
• For each \(i_1\) in \([first1, \ last1)\), 
  and \(i_2 = first2 + (i_1 - first1)\) 
  updates result as follows:
  \[
  \text{result} = \text{op1}(\text{result}, \text{op2}(\*i_1, \*i_2))
  \]
• Let us show the generality of such algorithm
#include <iostream>
#include <numeric>
#include <string.h>

struct Cat {
    const char* sep;
    Cat(const char* s) : sep(s) {}
    char* operator()(const char* t, const char* s) {
        char* ret = new char[strlen(t) + strlen(sep) + strlen(s) + 1];
        strcpy(ret, t);
        strcat(ret, sep);
        strcat(ret, s);
        return ret;
    };
};

int main() {
    char *A1[] = { "Name", "Organization", "Country" };
    char *A2[] = { "Antonio Cisternino", "Università di Pisa", "Italy" };
    const int N1 = sizeof(A1) / sizeof(A1[0]);

    std::cout << inner_product(A1, A1 + N1, A2, "", Cat("\n"), Cat("\t")) << std::endl;
    return 0;
}
...and with C++ std::string

```cpp
#include <iostream>
#include <numeric>
#include <string.h>
#include <string>
#include <vector>

struct CatS {
    std::string sep;
    CatS(std::string s) : sep(s) {} 
    std::string operator()(std::string t, std::string s) { return t + sep + s; }
};

int main() {
    std::vector<std::string> s, v;
    s.push_back(std::string("Hello")); s.push_back(std::string("Antonio"));
    v.push_back(std::string("World")); v.push_back(std::string("Cisternino"));

    std::vector<std::string>::const_iterator A1 = s.begin(), A2 = v.begin();
    int N1 = s.size();
    std::cout << inner_product(A1, A1 + N1, A2, std::string(""), CatS(std::string("\n")),
                              CatS(std::string("\t"))) << std::endl;
    return 0;
}
```

Much easier than before

Using vector<T> instead of arrays

A1 and A2 now are iterators to vector<string>
The three calls

\[
\text{std::cout} \ll \text{inner_product}(A1, A1 + N1, A2, 0) \\
\ll \text{std::endl};
\]

\[
\text{std::cout} \ll \\
\quad \text{inner_product}(A1, A1 + N1, A2, "", \\
\quad \text{Cat("
"), Cat("\t")}) \ll \text{std::endl};
\]

\[
\text{std::cout} \ll \\
\quad \text{inner_product}(A1, A1 + N1, A2, \\
\quad \text{std::string(""), CatS(std::string("\n")), \\
\quad \text{CatS(std::string("\t"))}) \ll \text{std::endl};
\]
The same syntax…

• Though we have used different data types and containers the invocation of *inner_product* has been essentially the same

• And we are not using inheritance…

• How is this possible? On what language mechanisms do rely STL?

• What really are iterators? Why can be interchanged with pointers?

• STL seems to be really effective and generic but what happens to the code generated?
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.

<table>
<thead>
<tr>
<th>Container</th>
<th>insert/erase overhead at the beginning</th>
<th>in the middle</th>
<th>at the end</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector</td>
<td>linear</td>
<td>linear</td>
<td>amortized constant</td>
</tr>
<tr>
<td>List</td>
<td>constant</td>
<td>constant</td>
<td>constant</td>
</tr>
<tr>
<td>Deque</td>
<td>amortized constant</td>
<td>linear</td>
<td>amortized constant</td>
</tr>
</tbody>
</table>
Complexity of use of Iterators

• Consider the following code:

```cpp
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 to 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++)
  – **Input and Output iterators**: like forward iterators but with possible issues in dereferencing the iterator (due to I/O operations)
  – **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**.

<table>
<thead>
<tr>
<th>Container</th>
<th>Iterator Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>vector</td>
<td>random access iterators</td>
</tr>
<tr>
<td>list</td>
<td>bidirectional iterators</td>
</tr>
<tr>
<td>deque</td>
<td>random access iterators</td>
</tr>
</tbody>
</table>
C++ operators and iterators

- **Forward iterators** provide for one-directional traversal of a sequence, expressed with ++:
  - Operator ==, !, *, ++
- **Input iterators and output iterators** are like forward iterators but do not guarantee these properties of forward iterators:
  - That an input or output iterator can be saved and used to start advancing from the position it holds a second time
  - That it is possible to assign to the object obtained by applying * to an input iterator
  - That it is possible to read from the object obtained by applying * to an output iterator
  - That it is possible to test two output iterators for equality or inequality (== and != may not be defined)
- **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

<table>
<thead>
<tr>
<th>Container</th>
<th>operation</th>
<th>iterator validity</th>
</tr>
</thead>
<tbody>
<tr>
<td>vector</td>
<td>inserting</td>
<td>reallocation necessary - all iterators get invalid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no reallocation - all iterators before insert point remain valid</td>
</tr>
<tr>
<td></td>
<td>erasing</td>
<td>all iterators after erasee point get invalid</td>
</tr>
<tr>
<td>list</td>
<td>inserting</td>
<td>all iterators remain valid</td>
</tr>
<tr>
<td></td>
<td>erasing</td>
<td>only iterators to erased elements get invalid</td>
</tr>
<tr>
<td>deque</td>
<td>inserting</td>
<td>all iterators get invalid</td>
</tr>
<tr>
<td></td>
<td>erasing</td>
<td>all iterators get invalid</td>
</tr>
</tbody>
</table>
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 the 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 graphs
A simple forward iterator for vectors

template <class T>
struct v_iterator {
    T *v;
    int sz;
    v_iterator(T* v, int sz) : v(v), sz(sz) {}
    // != implicitly defined
    bool operator==(v_iterator& p) { return v == p->v; }
    T operator*() { return *v; }
    v_iterator& operator++() { // Pre-increment
        if (sz) ++v, --sz; else v = NULL;
        return *this;
    }
    v_iterator operator++(int) { // Post-increment!
        v_iterator ret = *this;
        ++(*this); // call pre-increment
        return ret;
    }
};
Where is used `v_iterator`?

template <class T>
class vector {
private:
    T v[];
    int sz;
    struct v_iterator { ... };  
public:
    typedef v_iterator iterator;
    typedef v_iterator const const_iterator;
    typedef T element;

    iterator begin() { return v_iterator(v, sz); } 
    iterator end() { return v_iterator(NULL, 0); } 
};
Inheritance? No thanks!

• STL relies on typedefs combined with namespaces to implement genericity
• The programmer always refers to `container::iterator` to know the type of the iterator
• *There is no relation among iterators for different containers!*
• The reason for this is **PERFORMANCE**
• Without inheritance types are resolved at compile time and the compiler may produce better code!
• This is an extreme position: sacrificing inheritance may lead to lower expressivity and lack of type-checking
• STL relies only on coding conventions: when the programmer uses a wrong iterator the compiler complains of a bug in the library!
Inlining

• STL relies also on the compiler
• C++ standard has the notion of inlining which is a form of semantic macros
• A method invocation is type-checked then it is replaced by the method body
• Inline methods should be available in header files and can be labelled inline or defined within class definition
• Inlining isn't always used: the compiler tends to inline methods with small bodies and without iteration
• The compiler is able to determine types at compile time and usually does inlining of function objects
Memory management

- STL abstracts from the specific memory model used by a concept named **allocators**.
- All the information about the memory model is encapsulated in the **Allocator** class.
- Each container is parametrized by such an **allocator** to let the implementation be unchanged when switching memory models.

```cpp
template <class T,
          template <class U> class Allocator = allocator>
class vector {
    ... }
```

- The second template argument is a default argument that uses the pre-defined allocator "allocator" (implementing **STL's own memory management strategies**), when no other allocator is specified by the user.
Potential problems

• The main problem with STL is error checking
• Almost all facilities of the compiler fail with STL resulting in lengthy error messages that ends with error within the library
• The generative approach taken by C++ compiler also leads to possible code bloat
• Code bloat can be a problem if the working set of a process becomes too large!