C and C++

8. Standard Template Library (STL)

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Alexander Stepanov, designer of the Standard Template Library says:

“STL was designed with four fundamental ideas in mind:

▶ Abstractness
▶ Efficiency
▶ Von Neumann computational model
▶ Value semantics”

It’s an example of generic programming; in other words reusable or “widely adaptable, but still efficient” code
Advantages of generic programming

- Traditional container libraries place algorithms as member functions of classes
  - Consider, for example, "test".substring(1,2); in Java
- So if you have $m$ container types and $n$ algorithms, that’s $nm$ pieces of code to write, test and document
- Also, a programmer may have to copy values between container types to execute an algorithm
- The STL does not make algorithms member functions of classes, but uses meta programming to allow programmers to link containers and algorithms in a more flexible way
- This means the library writer only has to produce $n + m$ pieces of code
- The STL, unsurprisingly, uses templates to do this
Plugging together storage and algorithms

Basic idea:

- define useful data storage components, called **containers**, to store a set of objects
- define a generic set of access methods, called **iterators**, to manipulate the values stored in containers of any type
- define a set of **algorithms** which use containers for storage, but only access data held in them through iterators

The time and space complexity of containers and algorithms is specified in the STL standard
A simple example

```cpp
#include <iostream>
#include <vector>  //vector<T> template
#include <numeric>  //required for accumulate

int main() {
    int i[] = {1,2,3,4,5};
    std::vector<int> vi(&i[0],&i[5]);

    std::vector<int>::iterator viter;

    for(viter=vi.begin(); viter < vi.end(); ++viter)
        std::cout << *viter << std::endl;

    std::cout << accumulate(vi.begin(),vi.end(),0) << std::endl;
}
```
Containers

- The STL uses containers to store collections of objects.
- Each container allows the programmer to store multiple objects of the same type.
- Containers differ in a variety of ways:
  - memory efficiency
  - access time to arbitrary elements
  - arbitrary insertion cost
  - append and prepend cost
  - deletion cost
  - ...
Containers

- Container examples for storing sequences:
  - `vector<T>`
  - `deque<T>`
  - `list<T>`

- Container examples for storing associations:
  - `set<Key>`
  - `multiset<Key>`
  - `map<Key,T>`
  - `multimap<Key, T>`
Using containers

```cpp
#include <string>
#include <map>
#include <iostream>

int main() {

    std::map<std::string,std::pair<int,int> > born_award;

    born_award["Perlis"] = std::pair<int,int>(1922,1966);
    born_award["Wilkes"] = std::pair<int,int>(1913,1967);
    born_award["Hamming"] = std::pair<int,int>(1915,1968);
    //Turing Award winners (from Wikipedia)

    std::cout << born_award["Wilkes"].first << std::endl;

    return 0;
}
```
**std::string**

- Built-in arrays and the `std::string` hold elements and can be considered as containers in most cases.
- You can’t call `.begin()` on an array however!
- Strings are designed to interact well with C char arrays.
- String assignments, like containers, have value semantics:

```cpp
#include <iostream>
#include <string>

int main() {
    char s[] = "A string ";
    std::string str1 = s, str2 = str1;

    str1[0] = ’a’, str2[0] = ’B’;
    std::cout << s << str1 << str2 << std::endl;
    return 0;
}
```
Iterators

- Containers support **iterators**, which allow access to values stored in a container
- Iterators have similar semantics to pointers
  - A compiler may represent an iterator as a pointer at run-time
- There are a number of different types of iterator
- Each container supports a subset of possible iterator operations
- Containers have a concept of a **beginning** and **end**
### Iterator types

<table>
<thead>
<tr>
<th>Iterator type</th>
<th>Supported operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>== != ++ *(read only)</td>
</tr>
<tr>
<td>Output</td>
<td>== != ++ *(write only)</td>
</tr>
<tr>
<td>Forward</td>
<td>== != ++ *</td>
</tr>
<tr>
<td>Bidirectional</td>
<td>== != ++ * --</td>
</tr>
<tr>
<td>Random Access</td>
<td>== != ++ * -- + - += -= &lt; &gt; &lt;= &gt;=</td>
</tr>
</tbody>
</table>

- Notice that, with the exception of input and output iterators, the relationship is hierarchical.
- Whilst iterators are organised logically in a hierarchy, they do not do so formally through inheritance!
- There are also const iterators which prohibit writing to ref’d objects.
Adaptors

- An adaptor modifies the interface of another component
- For example, the reverse_iterator modifies the behaviour of an iterator

```cpp
#include <vector>
#include <iostream>

int main() {
    int i[] = {1, 3, 2, 2, 3, 5};
    std::vector<int> v(&i[0], &i[6]);

    for (std::vector<int>::reverse_iterator i = v.rbegin(); i != v.rend(); ++i)
        std::cout << *i << std::endl;

    return 0;
}
```
Generic algorithms

- Generic algorithms make use of iterators to access data in a container.
- This means an algorithm need only be written once, yet it can function on containers of many different types.
- When implementing an algorithm, the library writer tries to use the most restrictive form of iterator, where practical.
- Some algorithms (e.g. `sort`) cannot be written efficiently using anything other than random access iterators.
- Other algorithms (e.g. `find`) can be written efficiently using only input iterators.
- Lesson: use common sense when deciding what types of iterator to support.
- Lesson: if a container type doesn’t support the algorithm you want, you are probably using the wrong container type!
Algorithm example

- Algorithms usually take a `start` and `finish` iterator and assume the valid range is `start` to `finish-1`; if this isn’t true the result is undefined.

Here is an example routine `search` to find the first element of a storage container which contains the value `element`:

```cpp
//search: similar to std::find
template<class I,class T> I search(I start, I finish, T element) {
    while (*start != element && start != finish)
        ++start;
    return start;
}
```
#include "example23.hh"

#include "example23a.cc"

int main() {
    char s[] = "The quick brown fox jumps over the lazy dog";
    std::cout << search(&s[0],&s[strlen(s)],'d') << std::endl;

    int i[] = {1,2,3,4,5};
    std::vector<int> v(&i[0],&i[5]);
    std::cout << search(v.begin(),v.end(),3)-v.begin() << std::endl;

    std::list<int> l(&i[0],&i[5]);
    std::cout << (search(l.begin(),l.end(),4)!=l.end()) << std::endl;

    return 0;
}
Heterogeneity of iterators

```cpp
#include "example24.hh"

int main() {
    char one[] = {1,2,3,4,5};
    int two[] = {0,2,4,6,8};
    std::list<int> l (&two[0],&two[5]);
    std::deque<long> d(10);

    std::merge(&one[0],&one[5],l.begin(),l.end(),d.begin());

    for(std::deque<long>::iterator i=d.begin(); i!=d.end(); ++i)
        std::cout << *i << " ";
    std::cout << std::endl;

    return 0;
}
```
Function objects

- C++ allows the function call "( )" to be overloaded
- This is useful if we want to pass functions as parameters in the STL
- More flexible than function pointers, since we can store per-instance object state inside the function
- Example:

```cpp
1 struct binaccum {
2     int operator()(int x, int y) const {return 2*x + y;}
3 }
```
Higher-order functions in C++

- In ML we can write: \( \text{foldl (fn (y,x) => 2*x+y) 0 [1,1,0]}; \)
- Or in Python: \( \text{reduce(lambda x,y: 2*x+y, [1,1,0])} \)
- Or in C++:

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

#include "example27a.cc"

int main() { // equivalent to foldl
    bool binary[] = {true,true,false};
    std::cout<< std::accumulate(&binary[0],&binary[3],0,binaccum())
             << std::endl; // output: 6
    return 0;
}
```
Higher-order functions in C++

By using reverse iterators, we can also get foldr:

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

#include "example27a.cc"

int main() { //equivalent to foldr

  bool binary[] = {true,true,false};
  std::vector<bool> v(&binary[0],&binary[3]);

  std::cout << std::accumulate(v.rbegin(),v.rend(),0,binaccum());
  std::cout << std::endl; //output: 3

  return 0;
}
```