Chapter 19

Standard Template Library

Learning Objectives

- Iterators
  - Constant and mutable iterators
  - Reverse iterators
- Containers
  - Sequential containers
  - Container adapters stack and queue
  - Associative Containers set and map
- Generic Algorithms
  - Big-O notation
  - Sequence, set, and sorting algorithms

Introduction

- Recall stack and queue data structures
  - We created our own
  - Large collection of standard data structures exists
  - Make sense to have standard portable implementations of them!
- Standard Template Library (STL)
  - Includes libraries for all such data structures
    - Like container classes: stacks and queues

Iterators

- Recall: generalization of a pointer
  - Typically even implemented with pointer!
- "Abstraction" of iterators
  - Designed to hide details of implementation
  - Provide uniform interface across different container classes
- Each container class has "own" iterator type
  - Similar to how each data type has own pointer type

Manipulating Iterators

- Recall using overloaded operators:
  - ++, --, ==, !=
  - *
    - So if p is an iterator variable, *p gives access to data pointed to by p
- Vector template class
  - Has all above overloads
  - Also has members begin() and end()

```
c.begin();  //Returns iterator for 1st item in c
c.end();    //Returns "test" value for end
```

Cycling with Iterators

- Recall cycling ability:

```
for (p=c.begin();p!=c.end();p++)
    process *p//*p is current data item
```

- Big picture so far…
- Keep in mind:
  - Each container type in STL has own iterator types
    - Even though they're all used similarly

Display 19.1
Iterators Used with a Vector (1 of 2)

```
1       //Program to demonstrate STL iterators.
2       #include <iostream>
3       #include <vector>
4       using std::cout;
5       using std::endl;
6       using std::vector;

7       int main( )
8       {
9           vector<int> container;

10          for (int i = 1; i <= 4; i++)
11              container.push_back(i);

12          cout << "Here is what is in the container:\n";
13          vector<int>::iterator p;
14          for (p = container.begin( ); p != container.end( ); p++)
15              cout << *p << " ";
16          cout << endl;

17          cout << "Setting entries to 0:\n";
18          for (p = container.begin( ); p != container.end( ); p++)
19               *p = 0;
```

Display 19.1
Iterators Used with a Vector (2 of 2)

```
20          cout << "Container now contains:\n";
21          for (p = container.begin( ); p !=
                    container.end( ); p++)
22              cout << *p << " ";
23          cout << endl;

24          return 0;
25      }
```

SAMPLE DIALOGUE

Here is what is in the container:
1 2 3 4
Setting entries to 0:
Container now contains:
0 0 0 0

Vector Iterator Types

- Iterators for vectors of ints are of type:
  `std::vector<int>::iterator`
- Iterators for lists of ints are of type:
  `std::list<int>::iterator`
- Vector is in std namespace, so need:
  `using std::vector<int>::iterator;`

Kinds of Iterators

- Different containers → different iterators
- Vector iterators
  - Most "general" form
  - All operations work with vector iterators
  - Vector container great for iterator examples

Random Access:
Display 19.2 Bidirectional and Random-Access Iterator Use

```
 7  int main( )
 8  {
 9      vector<char> container;

10      container.push_back('A');
11      container.push_back('B');
12      container.push_back('C');
13      container.push_back('D');

14      for (int i = 0; i < 4; i++)
15          cout << "container[" << i << "] == "
16               << container[i] << endl;

17      vector<char>::iterator p = container.begin( );
18      cout << "The third entry is " << container[2] << endl;
19      cout << "The third entry is " << p[2] << endl;
20      cout << "The third entry is " << *(p + 2) << endl;

21      cout << "Back to container[0].\n";
22      p = container.begin( );
23      cout << "which has value " << *p << endl;

24      cout << "Two steps forward and one step back:\n";
25      p++;
26      cout << *p << endl;
```

Three different notations for the same thing

This notation is specialized to vectors and arrays.

These two work for any random-access iterator.

Iterator Classifications

- Forward iterators:
  - ++ works on iterator
- Bidirectional iterators:
  - Both ++ and – work on iterator
- Random-access iterators:
  - ++, --, and random access all work with iterator
- These are "kinds" of iterators, not types!

Constant and Mutable Iterators

- Dereferencing operator's behavior dictates
- Constant iterator:
  - * produces read-only version of element
  - Can use *p to assign to variable or output, but cannot change element in container
    - E.g., *p = <anything>; is illegal
- Mutable iterator:
  - *p can be assigned value
  - Changes corresponding element in container
  - i.e.: *p returns an lvalue

Reverse Iterators

- To cycle elements in reverse order
  - Requires container with bidirectional iterators
- Might consider:

```
iterator p;
for (p=container.end();p!=container.begin(); p--)
    cout << *p << " " ;
```

  - But recall: end() is just "sentinel", begin() not!
  - Might work on some systems, but not most

Reverse Iterators Correct

- To correctly cycle elements in reverse order:

```
reverse_iterator rp;
for (rp=container.rbegin();rp!=container.rend(); rp++)
    cout << *rp << " " ;
```

- rbegin()
  - Returns iterator at last element
- rend()
  - Returns sentinel "end" marker

Compiler Problems

- Some compilers problematic with iterator declarations
- Consider our usage:

```
using std::vector<char>::iterator;
…
iterator p;
```

- Alternatively:

```
std::vector<char>::iterator p;
```

- And others…
  - Try various forms if compiler problematic

Auto

- The C++11 **auto** keyword can make your code much more readable when it comes to templates and iterators.
- Instead of

```
vector<int>::iterator p = v.begin();
```

- We can do the same thing much more compactly with auto

```
auto p = v.begin();
```

Containers

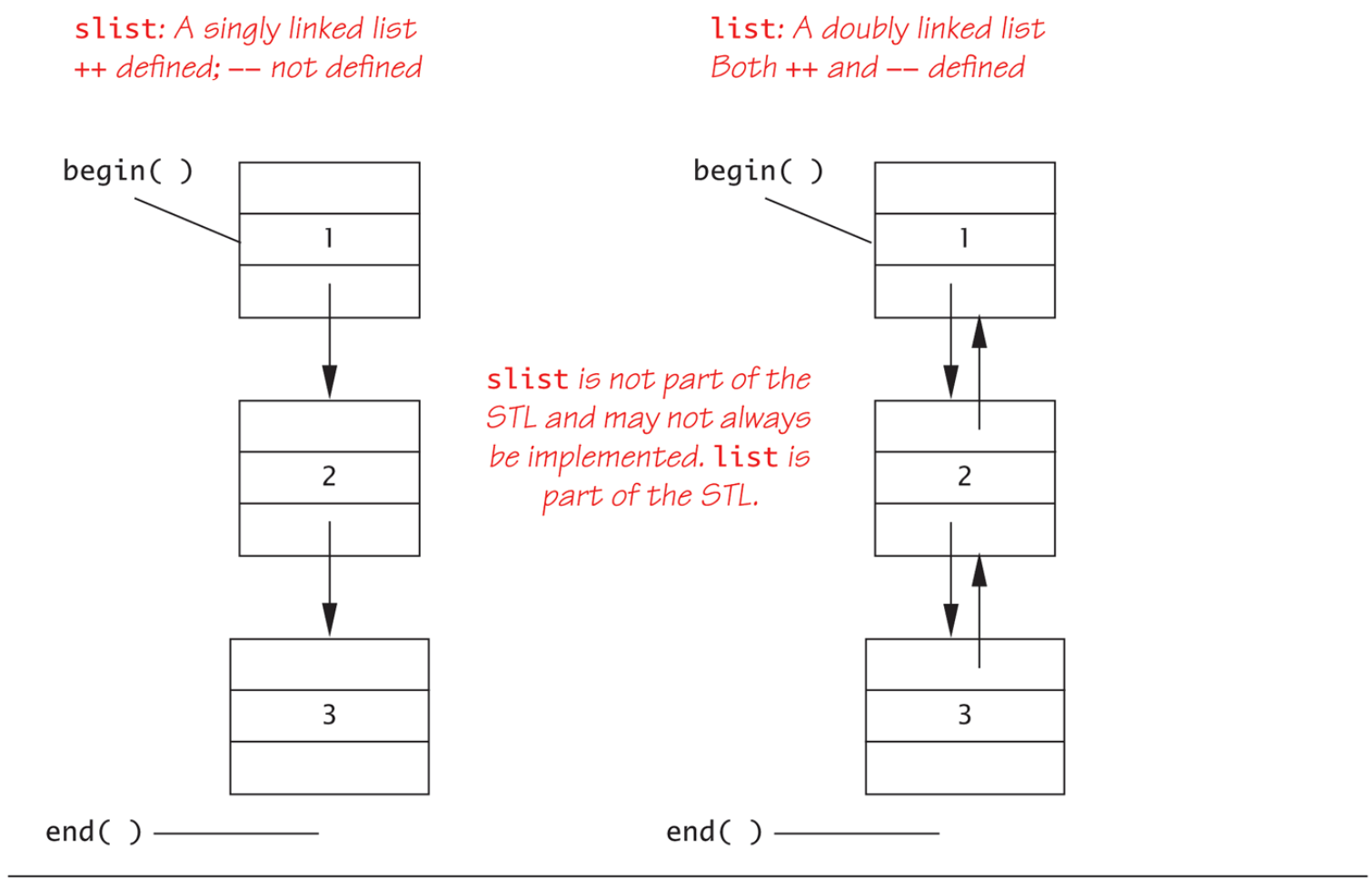
- Container classes in STL
  - Different kinds of data structures
  - Like lists, queues, stacks
- Each is template class with parameter for particular data type to be stored
  - e.g., Lists of ints, doubles or myClass types
- Each has own iterators
  - One might have bidirectional, another might just have forward iterators
- But all operators and members have same meaning

Sequential Containers

- Arranges list data
  - 1st element, next element, … to last element
- Linked list is sequential container
  - Earlier linked lists were "singly linked lists"
    - One link per node
- STL has no "singly linked list"
  - Only "doubly linked list": template class *list*

Display 19.4 Two Kinds of Lists

Display 19.4 Two Kinds of Lists



Display 19.5
Using the list Template Class(1 of 2)

```
1       //Program to demonstrate the STL template class list.
2       #include <iostream>
3       #include <list>
4       using std::cout;
5       using std::endl;
6       using std::list;

7       int main( )
8       {
9           list<int> listObject;

10          for (int i = 1; i <= 3; i++)
11              listObject.push_back(i);

12          cout << "List contains:\n";
13          list<int>::iterator iter;
14          for (iter = listObject.begin( ); iter != listObject.end( );
                 iter++)
15              cout << *iter << " ";
16          cout << endl;
```

Display 19.5
Using the list Template Class(2 of 2)

```
17          cout << "Setting all entries to 0:\n";
18          for (iter = listObject.begin( ); iter != listObject.end( );
                        iter++)
19              *iter = 0;

20          cout << "List now contains:\n";
21          for (iter = listObject.begin( ); iter != listObject.end( );
                        iter++)
22              cout << *iter << " ";
23          cout << endl;

24          return 0;
25      }
```

```
SAMPLE DIALOGUE
List contains:
1 2 3
Setting all entries to 0:
List now contains:
0 0 0
```

Container Adapters stack and queue

- Container adapters are template classes
  - Implemented "on top of" other classes
- Example:
  stack template class by default implemented on top of *deque* template class
  - Buried in stack's implementation is deque where all data resides
- Others:
  queue, priority_queue

Specifying Container Adapters

- Adapter template classes have "default" containers underneath
  - But can specify different underlying container
  - Examples:
    stack template class → any sequence container
    priority_queue → default is vector, could be others
- Implementing Example:

```
stack<int, vector<int> >
```

Note space between > >

  - Makes vector underlying container for stack

Associative Containers

- Associative container: simple database
- Store data
  - Each data item has key
- Example:
  data: employee's record as struct
  key: employee's SSN
  - Items retrieved based on key

set Template Class

- Simplest container possible
- Stores elements without repetition
- 1st insertion places element in set
- Each element is own key
- Capabilities:
  - Add elements
  - Delete elements
  - Ask if element is in set

More set Template Class

- Designed to be efficient
  - Stores values in sorted order
  - Can specify order:

```
set<T, Ordering> s;
```

    - Ordering is well-behaved ordering relation that returns bool
    - None specified: use < relational operator

Program Using the set Template Class (1 of 2)

```
1       //Program to demonstrate use of the set template class.
2       #include <iostream>
3       #include <set>
4       using std::cout;
5       using std::endl;
6       using std::set;

7       int main( )
8       {
9           set<char> s;

10          s.insert('A');
11          s.insert('D');
12          s.insert('D');
13          s.insert('C');
14          s.insert('C');
15          s.insert('B');

16          cout << "The set contains:\n";
17          set<char>::const_iterator p;
18          for (p = s.begin( ); p != s.end( ); p++)
19          cout << *p << " ";
20          cout << endl;
```

Program Using the set Template Class (2 of 2)

```
21          cout << "Set contains 'C': ";
22          if (s.find('C')==s.end( ))
23             cout << " no " << endl;
24          else
26             cout << " yes " << endl;

27             cout << "Removing C.\n";
28             s.erase('C');
29             for (p = s.begin( ); p != s.end( ); p++)
30             cout << *p << " ";
31             cout << endl;

32          cout << "Set contains 'C': ";
33          if (s.find('C')==s.end( ))
34              cout << " no " << endl;
35          else
36              cout << " yes " << endl;

37             return 0;
38       }
```

```
SAMPLE DIALOGUE

The set contains:
A B C D
Set contains 'C':  yes
Removing C.
A B D
Set contains 'C':  no
```

Map Template Class

- A function given as set of ordered pairs
  - For each value first, at most one value second in map
- Example map declaration:

```
map<string, int> numberMap;
```

- Can use [ ] notation to access the map
  - For both storage and retrieval
- Stores in sorted order, like set
  - Second value can have no ordering impact

Program Using the map Template Class (1 of 3)

```
1       //Program to demonstrate use of the map template class.
 2      #include <iostream>
 3      #include <map>
 4      #include <string>
 5      using std::cout;
 6      using std::endl;
 7      using std::map;
 8      using std::string;

 9      int main( )
10      {
11          map<string, string> planets;

12          planets["Mercury"] = "Hot planet";
13          planets["Venus"] = "Atmosphere of sulfuric acid";
14          planets["Earth"] = "Home";
15          planets["Mars"] = "The Red Planet";
16          planets["Jupiter"] = "Largest planet in our solar system";
17          planets["Saturn"] = "Has rings";
18          planets["Uranus"] = "Tilts on its side";
19          planets["Neptune"] = "1500 mile per hour winds";
20          planets["Pluto"] = "Dwarf planet";
```

Program Using the map Template Class (2 of 3)

```
21          cout << "Entry for Mercury - " << planets["Mercury"]
22               << endl << endl;

23          if (planets.find("Mercury") != planets.end())
24              cout << "Mercury is in the map." << endl;
25          if (planets.find("Ceres") == planets.end())
26              cout << "Ceres is not in the map." << endl << endl;

27          cout << "Iterating through all planets: " << endl;
28          map<string, string>::const_iterator iter;
29          for (iter = planets.begin(); iter != planets.end(); iter++)
30          {
31              cout << iter->first << " - " << iter->second << endl;
32          }

The iterator will output the map in order sorted by the key.
In this case the output will be listed alphabetically by planet.

33          return 0;
34      }
```

Program Using the map Template Class (3 of 3)

```
SAMPLE DIALOGUE

Entry for Mercury - Hot planet

Mercury is in the map.
Ceres is not in the map.

Iterating through all planets:
Earth - Home
Jupiter - Largest planet in our solar system
Mars - The Red Planet
Mercury - Hot planet
Neptune - 1500 mile per hour winds
Pluto - Dwarf planet
Saturn - Has rings
Uranus - Tilts on its side
Venus - Atmosphere of sulfuric acid
```

Use Initialization, Ranged For, and auto with Containers

- C++11's ranged for, auto, and initialization features make it easier to work with Containers
- Consider:

```
map<int, string> personIDs = {{1,"Walt"},{2,"Kenrick"}};
set<string> colors = {"red","green","blue"};
```

- We can easily iterate through each with:

```
for (auto p : personIDs)
        cout << p.first << " " << p.second << endl;
for (auto p : colors)
        cout << p << " ";
```

Efficiency

- STL designed with efficiency as important consideration
  - Strives to be optimally efficient
- Example: set, map elements stored in sorted order for fast searches
- Template class member functions:
  - Guaranteed maximum running time
  - Called "Big-O" notation, an "efficiency"-rating

Generic Algorithms

- Basic template functions
- Recall algorithm definition:
  - Set of instructions for performing a task
  - Can be represented in any language
  - Typically thought of in "pseudocode"
  - Considered "abstraction" of code
    - Gives important details, but not find code details
- STL's algorithms in template functions:
  - Certain details provided only
    - Therefore considered "generic algorithms"

Running Times

- How fast is program?
  - "Seconds"?
  - Consider: large input? .. small input?
- Produce "table"
  - Based on input size
  - Table called "function" in math
    - With arguments and return values!
  - Argument is input size:
    T(10), T(10,000), …
- Function T is called "running time"

Table for Running Time Function:
Display 19.15 Some Values of a Running Time Function

Some Values of a Running Time Function

INPUT SIZE	RUNNING TIME
10 numbers	2 seconds
100 numbers	2.1 seconds
1,000 numbers	10 seconds
10,000 numbers	2.5 minutes

Consider Sorting Program

- Faster on smaller input set?
  - Perhaps
  - Might depend on "state" of set
    - "Mostly" sorted already?
- Consider worst-case running time
  - T(N) is time taken by "hardest" list
    - List that takes longest to sort

Counting Operations

- T(N) given by formula, such as:
  T(N) = 5N + 5
  - "On inputs of size N program runs for 5N + 5 time units"
- Must be "computer-independent"
  - Doesn’t matter how "fast" computers are
  - Can’t count "time"
  - Instead count "operations"

Counting Operations Example

```
int I = 0;
bool found = false;
while (( I < N) && !found)
      if (a[I] == target)
          found = true;
      else
          I++;
```

- 5 operations per loop iteration:
  <, &&, !, [ ], ==, ++
- After N iterations, final three: <, &&, !
- So: 6N+5 operations when target not found

Big-O Notation

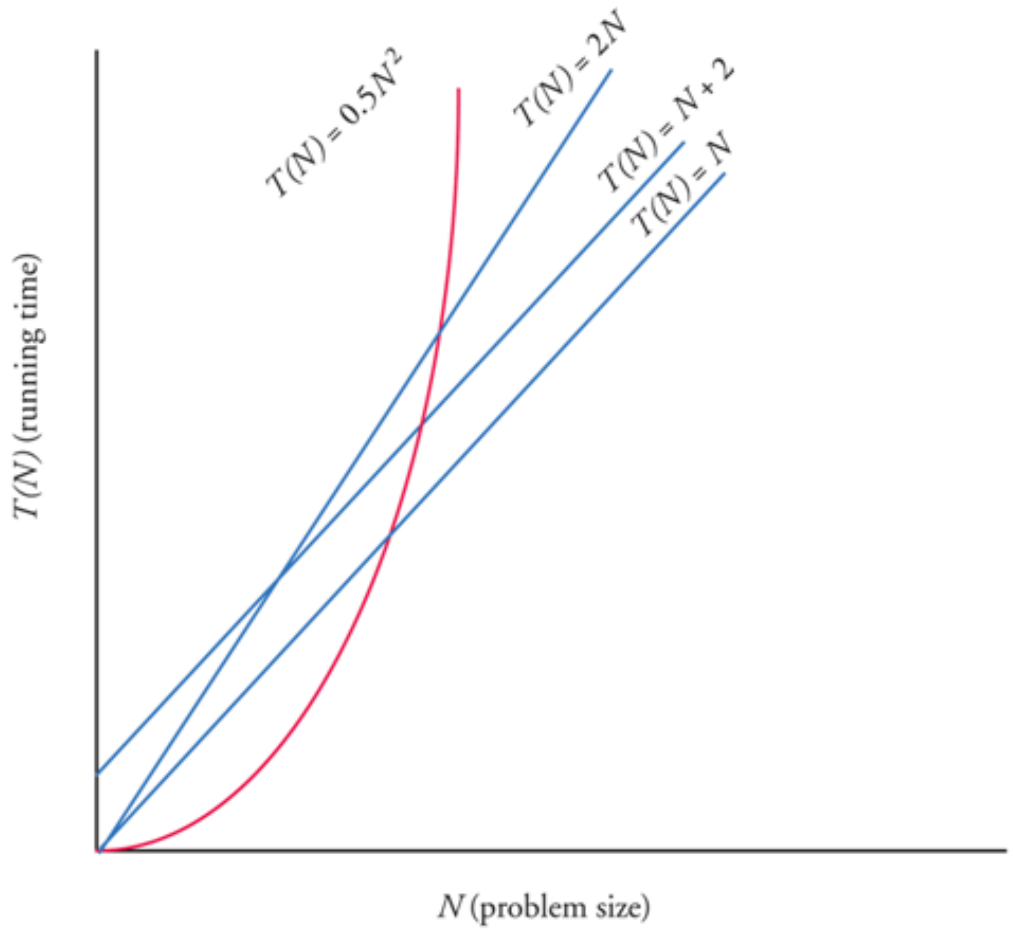
- Recall: 6N+5 operations in "worst-case"
- Expressed in "Big-O" notation
  - Some constant "c" factor where c(6N+5) is actual running time
    - c different on different systems
  - We say code runs in time O(6N+5)
  - But typically only consider "highest term"
    - Term with highest exponent
  - O(N) here

Big-O Terminology

- Linear running time:
  - O(N)—directly proportional to input size N
- Quadratic running time:
  - $O(N^2)$
- Logarithmic running time:
  - O(log N)
    - Typically "log base 2"
    - Very fast algorithms!

Display 19.16
Comparison of Running Times

Comparison of Running Times



Container Access Running Times

- O(1) - constant operation always:
  - Vector inserts to front or back
  - deque inserts
  - list inserts
- O(N)
  - Insert or delete of arbitrary element in vector or deque (N is number of elements)
- O(log N)
  - set or map finding

Sorting Algorithms

- STL contains two template functions:
  1. sort range of elements
  2. merge two sorted ranges of elements
- Guaranteed running time O(N log N)
  - No sort can be faster
  - Function guarantees fastest possible sort

Summary 1

- Iterator is "generalization" of a pointer
  - Used to move through elements of container
- Container classes with iterators have:
  - Member functions end() and begin() to assist cycling
- Main kinds of iterators:
  - Forward, bi-directional, random-access
- Given constant iterator p, *p is read-only version of element

Summary 2

- Given mutable iterator p → *p can be assigned value
- Bidirectional container has reverse iterators allowing reverse cycling
- Main STL containers: list, vector, deque
  - stack, queue: container adapter classes
- set, map, multiset, multimap containers store in sorted order
- STL implements generic algorithms
  - Provide maximum running time guarantees