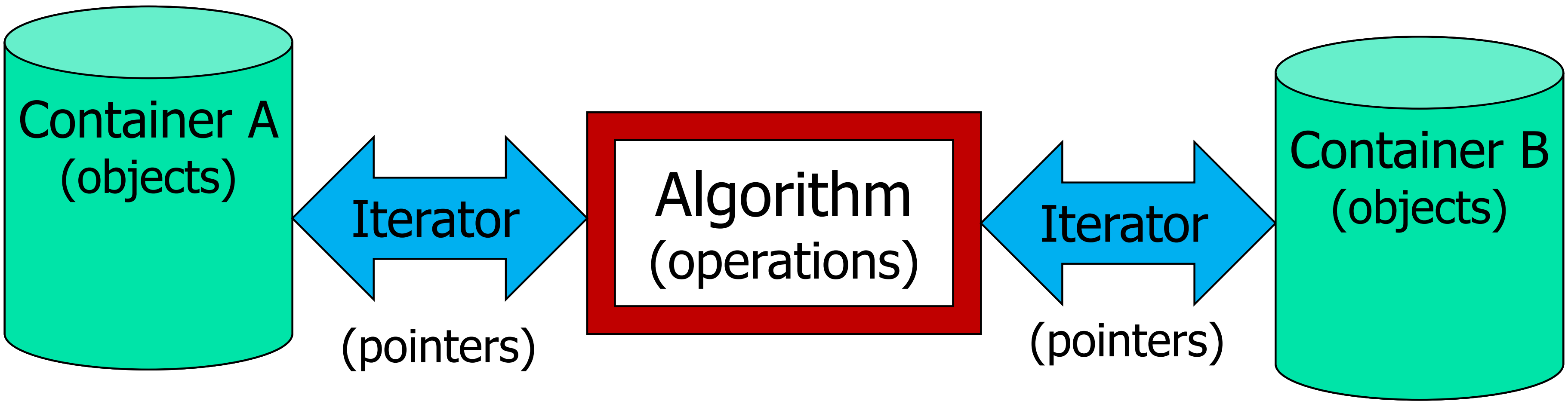
# C++ Standard Template Library (STL) and Algorithms

# Standard Library

- The Standard Library defines powerful, template-based, reusable components that implement many common data structures and algorithms used to process those data structures.

- The three key components of the Standard Library are containers (*templatized* data structures), iterators and algorithms.

# Containers, Iterators, Algorithms



# STL C++ Compilers

- To use most of the features in the examples in these slides you need c++11, so compile the code as:

  ```
  g++ -std=c++11 example1.cc
  ```

- Some STL features are supported only with C++14. To compile your program on the Linux server with that compiler version you need to do the following:
  - Type "`scl enable devtoolset-7 bash`" on the Linux prompt to enable the required version of the GNU Compiler.
  - Then compile your program by:
    ```
    g++ -std=c++14 myprogram.cpp
    ```

# Containers

- Containers are data structures capable of storing objects of *almost* any data type (there are some restrictions).
- Each container has associated member functions—a subset of these is defined in *all* containers.
- Container types are divided into four major categories—sequence containers, ordered associative containers, unordered associative containers, and container adapters.

# Containers (Cont'd)

- The *sequence containers* represent *linear* data structures, where data elements attached one after another, such as Arrays and Linked Lists.
- *Associative containers* are *nonlinear* data structures,where a data element could be connected to more than one elements, such as Trees and Graphs
  - Associative containers can store sets of values or key-value pairs.
- Stacks and Queues are typically constrained versions of sequence containers. For this reason, the Standard Library implements them as *container adapters* that enable a program to view a sequence container in a constrained manner.

# Sequence Containers

- **`array`** - Fixed size. Direct access to any element.
- **`deque`** - Rapid insertions and deletions at front or back. Direct access to any element.
- **`forward_list`** - Singly linked list, rapid insertion and deletion anywhere.
- **`list`** - Doubly linked list, rapid insertion and deletion anywhere.
- **`vector`** - Rapid insertions and deletions at back. Direct access to any element.

# Ordered Associative Containers

- These containers maintain keys in sorted order
- `set` - Rapid lookup, no duplicates allowed.
- `multiset` - Rapid lookup, duplicates allowed.
- `map` - One-to-one mapping, no duplicates allowed, rapid key-based lookup.
- `multimap` - One-to-many mapping, duplicates allowed, rapid key-based lookup.

# Container Adapters

- **`stack`** – Last-in, First-out (LIFO).
- **`queue`** – Fist-in, First-out (FIFO).
- **`priority_queue`** – Highest-priority element is always the first element out.

# Iterators

- Iterators, which have properties similar to those of *pointers*, are used to manipulate the container elements.

- Manipulating containers with iterators is convenient and provides tremendous expressive power when combined with Standard Library algorithms—in some cases, reducing many lines of code to a single statement.

# Algorithms

- Standard Library algorithms are function templates that perform such common data manipulations as *searching*, *sorting* and *comparing elements (or entire containers).*
- The Standard Library provides many algorithms. Most of them use iterators to access container elements.
- Each algorithm has *minimum requirements* for the types of iterators that can be used with it.
- A *container's* supported iterator type determines whether the container can be used with a specific algorithm.
  - Containers support specific iterator types, some more powerful than others.

# Common Containers’ Functions

- Many operations apply to all containers, and other operations apply to subsets of similar containers.
- The following slides describe the many functions that are commonly available in most Standard Library containers.
- Beyond these operations, each container typically provides a variety of other capabilities.
- Overloaded operators <, <=, >, >=, ==, and != perform element by element comparisons.

# Sample Functions (1 of 4)

- **`default constructor`** - A constructor that *initializes an empty container.* Normally, each container has several constructors that provide different ways to initialize the container.
- **`copy constructor`** - A constructor that initializes the container to be a *copy* of an existing container of the same type.
- **`move constructor`** - A move constructor moves the contents of an existing container into a new container of the same type - the old container no longer contains the data. This avoids the overhead of copying each element of the argument container.
- **`destructor`** - Destructor function for clean up after a container is no longer needed.
- **`empty`** - Returns true if there are *no* elements in the container; otherwise, returns false.
- **`insert`** - Inserts an item in the container.

# Sample Functions (2 of 4)

- **`operator=`** Copies, `c1 = c2`, or moves, `c1= std::move(c2)`, the elements of one container into another. For move operation, the old container no longer contains the data.
- **`Comparison operators`** – Comparison operators perform the appropriate comparison operation between the *lhs* and *rhs* containers. First sizes of the containers are compared, and if they match, the elements are compared sequentially and stop at the first mismatch. Comparison operators are:
  - `operator==`
  - `operator!=`
  - `operator<`
  - `operator<=`
  - `operator>`
  - `operator>=`

# Sample Functions (3 of 4)

- **`swap`** - Swaps the elements of two containers.
- **`size`** - Returns the number of elements currently in the container.
- **`capacity`** - Returns the allocated storage space for the container.
- **`max_size`** - Returns the maximum potential capacity the container could reach due to system or library implementation limitations.
- **`begin`** - Returns an iterator that refers to the *first element* of the container.
- **`end`** - Returns an iterator that refers to the *next position* after the end of the container.
- **`cbegin`** - Returns a constant iterator that refers to the container's *first element*.
- **`cend`** - Returns a constant iterator that refers to the *next position* after the end of the container.

# Sample Functions (4 of 4)

- **`rbegin`** - Returns a reverse iterator that refers to the *last element* of the container.
- **`rend`** - Returns a reverse iterator that refers to the *position before the first element* of the container.
- **`crbegin`** - Returns a constant reverse iterator that refers to the *last element* of the container.
- **`crend`** - Returns a constant reverse iterator that refers to the *position before the first element* of the container.
- **`erase`** - Removes *one or more* elements from the container.
- **`clear`** - Removes *all* elements from the container.

# `vector` Sequence Container

- Class template `vector` provides a data structure with *contiguous* memory locations.
- This enables efficient, direct access to any element of a vector via the subscript operator [], exactly as with a built-in array.
- Like class template `array`, template `vector` is most commonly used when the data in the container must be easily accessible via a subscript or will be sorted, and when the number of elements may need to <u>grow</u>.
- When a vector’s memory is exhausted, the `vector` *allocates* a larger built-in array, *copies* (or *moves*) the original elements into the new built-in array and *deallocates* the old built-in array.
- The following code illustrates several functions of the `vector` class template. You must include header `<vector>` to use class template vector.

# vector Example 1 (1 of 5)

```
// Standard Library vector class template.
#include <iostream>
#include <vector> // vector class-template definition
using namespace std;

int main() {
    vector<int> intVector; // create vector of ints

//size() returns the number of elements currently stored in the container.
    cout <<"The initial size of intVector is: "<< intVector.size();

//capacity() returns the number of elements that can be stored in the vector before the vector
//needs to dynamically resize itself to accommodate more elements
    cout << "\nThe initial capacity of intVector is: " <<
    intVector.capacity();
```

# vector Example 1 (2 of 5)

```
// function push_back() to add an element to the end of the vector.
// If an element is added to a full vector, the vector increases its size—some implementations
// have the vector double its capacity (though this could vary by compiler).
 intVector.push_back(2);
 intVector.push_back(3);
 intVector.push_back(4);

//call size and capacity to illustrate the new size and capacity of the vector
// after the three push_back operations.
 cout <<"\nThe size of intVector is: " << intVector.size();
 cout <<"\nThe capacity of intVector is: "<< intVector.capacity();
```

# vector Example 1 (3 of 5)

```
cout << "\nOutput vector using iterator notation: ";

//auto keyword tells the compiler to infer (determine) a variable's data type based
// on the variable's initializer value.
// vector member function cbegin() returns a const_iterator to the vector's first element.
// cend() member function returns a const_iterator indicating the location past
// the last element of the vector.
for (auto constIterator = intVector.cbegin();
    constIterator != intVector.cend(); ++constIterator) {
    cout << *constIterator << ' ';
}
```

# vector Example 1 (4 of 5)

```
 cout << "\nReversed contents of vector intVector: ";

// display vector in reverse order using const_reverse_iterator vector member functions crbegin()
// and crend() return const_reverse_iterators that represent the starting and ending
// points when iterating through a container in reverse.
 for (auto reverseIterator = intVector.crbegin();
      reverseIterator != intVector.crend(); ++reverseIterator) {
      cout << *reverseIterator << ' ';
 }
}
```

# vector Example 1 (5 of 5)

- Expected Output:

```
The initial size of intVector is: 0
The initial capacity of intVector is: 0
The size of intVector is: 3
The capacity of intVector is: 3
Output vector using iterator notation: 2 3 4
Reversed contents of vector intVector: 4 3 2
```

# `shrink_to_fit`

- You can ask a vector to return unneeded memory to the system by calling member function `shrink_to_fit`.
- This requests that the container reduce its capacity to the number of elements in the container.
- According to the C++ standard, implementations can ignore this request so that they can perform implementation-specific optimizations.

# vector Example 2 (1 of 5)

```
// Testing Standard Library vector class template element-manipulation functions.
#include <iostream>
#include <vector> // vector class-template definition
#include <algorithm> // for the copy algorithm
#include <iterator> // for the ostream_iterator iterator
#include <stdexcept> // for the out_of_range exception
using namespace std;

int main() {
//initializes a vector<int> with the vector constructor that receives a list initializer.
vector<int> values{ 1, 2, 3, 4, 5, 6 };

//initializes a vector<int> by two iterators as arguments with a copy of a range of elements from the
//vector values—in this case, the range from values.cbegin() up to, but not including, values.cend().
vector<int> intVector{ values.cbegin(), values.cend() };
```

# vector Example 2 (2 of 5)

```
//the ostream_iterator (defined in header <iterator>) to output the contents of the vector.
//The first argument to its constructor specifies the output stream, and
//the second argument is a string specifying the separator for the values output
ostream_iterator<int> output{ cout, " " };
cout << "Vector intVector contains: ";
//Standard Library algorithm copy (from header <algorithm>) to output the entire contents of
// intVector to the standard output. The algorithm copies each element in a range from the location
// specified by the iterator in its first argument and up to, but not including, the location specified by
// the iterator in its second argument.
// The elements are copied to the location specified by the iterator specified as the 3rd argument.
copy(intVector.cbegin(), intVector.cend(), output);

//Notice function front() returns a reference to the first element in the vector, while function begin()
// returns an iterator pointing to the first element in the vector. Same for functions back() and end()
cout << "\nFirst element of intVector: " << intVector.front()
<< "\nLast element of intVector: " << intVector.back();
```

# vector Example 2 (3 of 5)

```
//Using the subscript operator to access vector elements
intVector[0] = 7; // set first element to 7
//Function at() performs the same operation, but with bounds checking
intVector.at(2) = 10; // set element at position 2 to 10

// access out-of-range element
try { intVector.at(100) = 777;}
catch (out_of_range &outOfRange) { // out_of_range exception
 cout << "\n\nException: " << outOfRange.what();
}
// insert 22 as the 2nd element
intVector.insert(intVector.begin() + 1, 22);
cout << "\n\nContents of vector intVector after changes: ";
copy(intVector.cbegin(), intVector.cend(), output);
```

# vector Example 2 (4 of 5)

```
 intVector.erase(intVector.begin()); // erase first element
 cout << "\n\nVector intVector after erasing first element: ";
 copy(intVector.cbegin(), intVector.cend(), output);
// erase remaining elements
 intVector.erase(intVector.cbegin(), intVector.cend());
 cout << "\nAfter erasing all elements, vector intVector "
 << (intVector.empty() ? "is" : "is not") << " empty";
// insert elements from the vector values
intVector.insert(intVector.begin(),values.cbegin(),values.cend());
 cout << "\n\nContents of vector intVector before clear: ";
 copy(intVector.cbegin(), intVector.cend(), output);
 intVector.clear(); // empty intVector; clear calls erase to empty a collection
 cout << "\nAfter clear, vector intVector "
      << (intVector.empty() ? "is" : "is not") << " empty" << endl;
}
```

# vector Example 2 (5 of 5)

- Expected Output:

```
Vector intVector contains: 1 2 3 4 5 6
First element of intVector: 1
Last element of intVector: 6

Exception: invalid vector<T> subscript

Contents of vector intVector after changes: 7 22 2 10 4 5 6

Vector intVector after erasing first element: 22 2 10 4 5 6
After erasing all elements, vector intVector is empty

Contents of vector intVector before clear: 1 2 3 4 5 6
After clear, vector intVector is empty
```

# `list` Sequence Container

- The list *sequence container* (from header `<list>`) allows insertion and deletion operations at *any* location in the container.
- Class template `list` is implemented as a *doubly linked list* where very node in the list contains a pointer to the previous node in the list and to the next node in the list.
- This enables class template list to support *bidirectional iterators* that allow the container to be traversed both forward and backward.
- In addition to the common containers' functions, class template `list` provides nine other member functions including `splice`, `push_front`, `pop_front`, `remove`, `remove_if`, `unique`, `merge`, `reverse` and `sort`.
- Many of the functions presented in the previous `vector` examples can be used with class `list`.

# list Example (1 of 7)

```
// Standard library list class template.
#include <iostream>
#include <vector>
#include <list> // list class-template definition
#include <algorithm> // copy algorithm
#include <iterator> // ostream_iterator
using namespace std;

int main() {
list<int> values; // create list of ints
list<int> otherValues; // create list of ints
ostream_iterator<int> output{ cout, " " };
```

# list Example (2 of 7)

```
// insert items to the front and back of the “values” list
values.push_front(1); values.push_front(2);
values.push_back(4);  values.push_back(3);
cout << "values contains: ";
copy(values.cbegin(), values.cend(), output);
// function sort() arranges the elements in the list in ascending order.
values.sort();
cout << "\nvalues after sorting contains: ";
copy(values.cbegin(), values.cend(), output);
// insert elements from vector ints into list otherValues
vector<int> ints{ 2, 6, 4, 8 };
otherValues.insert(otherValues.begin(),
                   ints.cbegin(), ints.cend());
cout << "\nAfter insert, otherValues contains: ";
copy(otherValues.cbegin(), otherValues.cend(), output);
```

# list Example (3 of 7)

```
// remove elements of otherValues and insert them before the iterator position specified by the first
// argument (in this example at end of values)
values.splice(values.end(), otherValues);
cout << "\nAfter splice, values contains: ";
copy(values.cbegin(), values.cend(), output);
values.sort(); // sort values
cout << "\nAfter sort, values contains: ";
copy(values.cbegin(), values.cend(), output);
// Re-insert elements of ints into otherValues
otherValues.insert(otherValues.begin(),
                   ints.cbegin(), ints.cend());
otherValues.sort(); // sort the list
cout << "\nAfter insert and sort, otherValues contains: ";
copy(otherValues.cbegin(), otherValues.cend(), output);
```

# list Example (4 of 7)

```
//Use merge() to remove otherValues elements and insert into values in sorted order
values.merge(otherValues);
cout << "\nAfter merge:\n   values contains: ";
copy(values.cbegin(), values.cend(), output);
cout << "\n   otherValues contains: ";
copy(otherValues.cbegin(), otherValues.cend(), output);

values.pop_front(); // remove element from front
values.pop_back(); // remove element from back
cout << "\nAfter pop_front and pop_back:\n   values contains: ";
copy(values.cbegin(), values.cend(), output);

values.unique(); // remove duplicate elements (the list should be in sorted order)
cout << "\nAfter unique, values contains: ";
copy(values.cbegin(), values.cend(), output);
```

# list Example (5 of 7)

```
values.swap(otherValues); // swap elements of values and otherValues
cout << "\nAfter swap:\n   values contains: ";
copy(values.cbegin(), values.cend(), output);
cout << "\n   otherValues contains: ";
copy(otherValues.cbegin(), otherValues.cend(), output);

// replace contents of values with the specified elements of otherValues
values.assign(otherValues.cbegin(), otherValues.cend());
cout << "\nAfter assign, values contains: ";
copy(values.cbegin(), values.cend(), output);
```

# list Example (6 of 7)

```
// remove otherValues elements and insert into values in sorted order
 values.merge(otherValues);
 cout << "\nAfter merge, values contains: ";
 copy(values.cbegin(), values.cend(), output);

 values.remove(4); // remove all 4s
 cout << "\nAfter remove(4), values contains: ";
 copy(values.cbegin(), values.cend(), output);
}
```

# `list` Example (7 of 7)

- Expected Output:

```
values contains: 2 1 4 3
values after sorting contains: 1 2 3 4
After insert, otherValues contains: 2 6 4 8
After splice, values contains: 1 2 3 4 2 6 4 8
After sort, values contains: 1 2 2 3 4 4 6 8
After insert and sort, otherValues contains: 2 4 6 8
After merge:
   values contains: 1 2 2 2 3 4 4 4 6 6 8 8
   otherValues contains:
After pop_front and pop_back:
   values contains: 2 2 2 3 4 4 4 6 6 8
After unique, values contains: 2 3 4 6 8
After swap:
   values contains:
   otherValues contains: 2 3 4 6 8
After assign, values contains: 2 3 4 6 8
After merge, values contains: 2 2 3 3 4 4 6 6 8 8
After remove(4), values contains: 2 2 3 3 6 6 8 8
```

# `map` Associative Container

- The *map associative container* (from header `<map>`) performs fast storage and retrieval of *unique keys* and *associated values*.
- Duplicate keys are *not* allowed—a single value can be associated with each key.
- This is called a one-to-one mapping.
- For example, a company that uses unique employee numbers, such as 100, 200 and 300, might have a map that associates employee numbers with their telephone extensions—4321, 4115 and 5217, respectively.
- With a map you specify the key and get back the associated data quickly.
- Providing the key in a map's subscript operator [ ] locates the value associated with that key in the map.
- Insertions and deletions can be made *anywhere* in a map.
- If the order of the keys is not important, you can use unordered_map (header <unordered_map>) instead.

# map Example (1 of 4)

```
// Standard Library class map class template.
#include <iostream>
#include <map> // map class-template definition
using namespace std;

int main() {
//Create a map in which the key type is int, the type of a key's associated value is double and
// the elements are ordered in ascending order.
map<int, double, less<int>> pairs;
// function insert() to add a new key-value pair to pairs.
// make_pair() creates a key-value pair object in which first is the key (15) of type int and
// second is the value (2.7) of type double.
// Function make_pair() automatically uses the types that you specified for the keys and values in
// the pairs map's declaration.
pairs.insert(make_pair(15, 2.7));
```

# map Example (2 of 4)

```
// insert seven more value_type objects in pairs
pairs.insert(make_pair(30, 111.11));
pairs.insert(make_pair(5, 1010.1));
pairs.insert(make_pair(10, 22.22));
pairs.insert(make_pair(25, 33.333));
pairs.insert(make_pair(5, 77.54)); // duplicate ignored
pairs.insert(make_pair(20, 9.345));
pairs.insert(make_pair(15, 99.3)); // duplicate ignored

cout << "Map pairs contains:\nKey\tValue\n";
// use const_iterator to walk through elements of pairs.
// Notice in the output that the keys appear in ascending order.
for (auto mapItem : pairs) {
  cout << mapItem.first << '\t' << mapItem.second << '\n';
 }
```

# map Example (3 of 4)

```
//Use the subscript operator of class map. When the subscript is a key that is already in the map
// the operator returns a reference to the associated value.
pairs[25] = 9999.99; // use subscripting to change value for key 25
pairs[40] = 8765.43; // use subscripting to insert value for key 40

cout << "\nAfter subscript operations,"
       <<" pairs contains:\nKey\tValue\n";
// use const_iterator to walk through elements of pairs
 for (auto mapItem : pairs) {
   cout << mapItem.first << '\t' << mapItem.second << '\n';
  }
}
```

# map Example (4 of 4)

Expected Output:

```
Map pairs contains:
Key      Value
5        1010.1
10       22.22
15       2.7
20       9.345
25       33.333
30       111.11

After subscript operations, pairs contains:
Key      Value
5        1010.1
10       22.22
15       2.7
20       9.345
25       9999.99
30       111.11
40       8765.43
```

# Container Adapters

- The three container adapters are `stack`, `queue` and `priority_queue`.
- Container adapters are *regular containers*, because they do not provide the actual data-structure implementation in which elements can be stored and because adapters do *not* support iterators.
- The benefit of an *adapter class* is that an appropriate underlying data structure can be adapted as needed.
- All three *adapter classes* provide member functions `push` and `pop` that properly insert an element into each adapter data structure and properly remove an element from each adapter data structure.

# stack Adapter

- Class `stack` (from header `<stack>`) enables insertions into and deletions from the underlying container at one end called the *top*, so a stack is commonly referred to as a *last-in, first-out* (LIFO) data structure.
- The stack operations are:
  - `push` to insert an element at the *top* of the stack
  - `pop` to remove the top element of the stack
  - `top` to get a reference to the top element of the stack
  - `empty` to determine whether the stack is empty
  - `size` to get the number of elements in the stack

# stack Adapter Example (1 of 2)

```
// Standard Library stack adapter class.
#include <iostream>
#include <stack> // stack adapter definition
using namespace std;
int main() {
stack<int> intStack;
// push the values 0-9 onto each stack
cout << "Pushing onto intStack: ";
for (int i{ 0 }; i < 10; ++i) {
 intStack.push(i); // push element onto stack
 cout <<intStack.top()<<' '; // view (and display) top element without removing it
}
cout << "\nCurrently the stack "
<< (intStack.empty() ? "is" : "is not") << " empty";
cout << endl;
```

# stack Adapter Example (2 of 2)

```
// display and remove elements from each stack
 cout << "Popping from intStack: ";
 while (!intStack.empty()) {
  cout << intStack.top() << ' '; // view (and display) top element
  intStack.pop(); // function pop() removes top element but it does not return a value
 }
 cout << "\nCurrently the stack "
 << (intStack.empty() ? "is" : "is not") << " empty";
 cout << endl;
}
```

## Expected output:

```
Pushing onto intStack: 0 1 2 3 4 5 6 7 8 9
Currently the stack is not empty
Popping from intStack: 9 8 7 6 5 4 3 2 1 0
Currently the stack is empty
```

# queue Adapter

- Class `queue` (from header `<queue>`) enables insertions at the *back* of the underlying data structure and deletions from the *front*, so a queue is commonly referred to as a *first-in, first-out* (FIFO) data structure.
- The common queue operations are:
  - `push` to insert an element at the back of the queue
  - `pop` to remove the element at the front of the queue
  - `front` to get a reference to the first element in the queue
  - `back` to get a reference to the last element in the queue
  - `empty` to determine whether the queue is empty
  - `size` to get the number of elements in the queue

# queue Adapter Example

```
// Standard Library queue adapter class template.
#include <iostream>
#include <queue> // queue adapter definition
using namespace std;
int main() {
queue<double> dblQueue; // queue with doubles
 // push elements onto queue dblQueue
  dblQueue.push(3.2); dblQueue.push(9.8); dblQueue.push(5.4);
cout << "Popping from dblQueue: ";
 while (!dblQueue.empty()) {
   cout << dblQueue.front() << ' '; // view front element
   dblQueue.pop(); // remove element from queue
  }
}
```

Expected output:

```
Popping from dblQueue: 3.2 9.8 5.4
```

# priority_queue Adapter

- Class `priority_queue` (from header `<queue>`) provides functionality that enables *insertions* in *sorted order* into the underlying data structure and deletions from the *front* of the underlying data structure.

- When elements are added to a `priority_queue`, they're inserted in *priority order*, such that the highest-priority element (i.e., the *largest* value) will be the first element removed from the `priority_queue`.

# `priority_queue` Operations

- Function `push` inserts an element at the appropriate location based on *priority order* of the `priority_queue`
- `pop` removes the *highest-priority* element of the `priority_queue`
- `top` gets a reference to the *top* element of the `priority_queue`
- `empty` determines whether the `priority_queue` is *empty*
- `size` gets the number of elements in the `priority_queue`

# priority_queue Example

```
// Standard Library priority_queue adapter class.
#include <iostream>
#include <queue> // priority_queue adapter definition
using namespace std;
int main() {
priority_queue<double> prQueue; // create priority_queue
// push elements onto prQueue
prQueue.push(3.2); prQueue.push(9.8); prQueue.push(5.4);
cout << "Popping from prQueue: ";
// pop element from prQueue
 while (!prQueue.empty()) {
  cout << prQueue.top() << ' '; // view top element
  prQueue.pop(); // remove top element
 }
}
```

Expected output:

```
Popping from prQueue: 9.8 5.4 3.2
```

# C++ Standard Library Algorithms

- The C++ standard specifies over 90 algorithms—many overloaded with two or more versions.
- To learn about all these algorithms, visit:
  - http://en.cppreference.com/w/cpp/algorithm
- Various algorithms can receive a function pointer as an argument. Such algorithms use the pointer to call the function, typically with one or two container elements as arguments.
- With few exceptions, the Standard Library separates algorithms from containers—makes it much easier to add new algorithms and to use them with multiple containers.

# Algorithms, Containers, and Iterators

- The type of iterator a container supports determines which algorithms can be applied to the container.
  - For example, both vectors and arrays support random-access iterators.
  - All Standard Library algorithms can operate on vectors and those that do not modify a container’s size can also operate on arrays.
- Each Standard Library algorithm that takes iterator arguments requires those iterators to provide a minimum level of functionality.
  - If an algorithm requires a forward iterator, for example, that algorithm can operate on any container that supports *forward iterators*, *bidirectional iterators* or *random-access iterators*.

# Iterator Invalidation

- Iterators simply *point* to container elements, so it's possible for iterators to become *invalid* when certain container modifications occur.
  - *Example 1*: if you clear a vector, *all* of its elements are *destroyed* and hence any iterators that pointed to that vector's elements before clear was called, would now be *invalid*.
  - *Example 2*: Inserting an element into a vector, iterators from the insertion point to the end of the vector are invalidated.
  - *Example 3*: Inserting an element into a list, all iterators *remain valid*.
  - *Example 4*: Erasing from a container, iterators to the erased elements are invalidated. For a vector, iterators from the erased element to the end of the vector are invalidated.

# Algorithm `for_each`

- Use the `for_each` algorithm to call a function that performs a task once for each element of the array values.
- `for_each`'s first two arguments represent the range of elements to process. They are two iterators that point into the same container.
- The function specified by `for_each`'s third argument specifies the function to call with each element in the range.
- The function must have one parameter of the container's element type. `for_each` passes the current element's value as the function's argument, then the function performs a task using that value.
- If the function's parameter is a non-constant reference and the iterators passed to `for_each` refer to non-constant data, the function can modify the element.

# for_each Example (1 of 4)

```
// for_each Algorithm with regular functions
#include <iostream>
#include <vector>
#include <algorithm>
#include <iterator>
using namespace std;
//function timesTwo displays the element value multiplied by 2
void timesTwo(int i) {
       cout << i * 2 << " "; }
//function doubleElements modifies the value of an element by doubling it
void doubleElemtns(int & i) {
       i = i * 2;}
//function findSum adds the value of an element to a global variable sum
static int sum;
void findSum(int i){
       sum += i; }
```

# for_each Example (2 of 4)

```
int main() {
 vector<int> myVector{ 1, 2, 3, 4 }; // initialize myVector
 ostream_iterator<int> output{ cout, " " };

 cout << "myVector contains: ";
 copy(myVector.cbegin(), myVector.cend(), output);

 cout << "\nDisplay each element multiplied by two: ";
// output each element multiplied by two
 for_each(myVector.cbegin(), myVector.cend(), timesTwo);

// add each element to sum
 sum = 0;
 for_each(myVector.cbegin(), myVector.cend(), findSum);
 cout << "\nSum of myVector's elements is: " << sum << endl;
```

# for_each Example (3 of 4)

```
//replace each element with its double (the iterators passed has to be non-const)
 for_each(myVector.begin(), myVector.end(), doubleElemtns);
 cout << "\nmyVector contains (after doubling): ";
 copy(myVector.cbegin(), myVector.cend(), output);

// add each element to sum
 sum = 0;
 for_each(myVector.cbegin(), myVector.cend(), findSum);
 cout << "\nSum of myVector's elements is: " << sum << endl;

}
```

# for_each Example (4 of 4)

Expected output:

```
myVector contains: 1 2 3 4
Display each element multiplied by two: 2 4 6 8
Sum of myVector's elements is: 10

myVector contains (after doubling): 2 4 6 8
Sum of myVector's elements is: 20
```

# Lambda Expressions

- C++11's lambda expressions (or simply lambdas) enable you to define functions locally inside other functions and can use and manipulate the local variables of the enclosing function.

- Lambdas can be passed as a function pointer to an algorithm.

- The following example is modified version of the code in the previous example where the third argument in the for_each calls are lambda expressions.

# Lambda Expressions Example (1 of 4)

```
// for_each Algorithm with Lambda Expressions
#include <iostream>
#include <vector>
#include <algorithm> // algorithm definitions
#include <iterator>
using namespace std;

int main() {
 vector<int> myVector{ 1, 2, 3, 4 }; // initialize myVector
 ostream_iterator<int> output{ cout, " " };

 cout << "myVector contains: ";
 copy(myVector.cbegin(), myVector.cend(), output);
```

# Lambda Expressions Example (2 of 4)

```
// output each element multiplied by two
 cout << "\nDisplay each element multiplied by two: ";
//The empty lambda introducer ([]) indicates that the lambda does not use any of
//  main function's local variables.
//Specifying the parameter's type as auto enables the compiler to infer the parameter's type,
//  based on the context in which the lambda appears (int in this case)
 for_each(myVector.cbegin(), myVector.cend(),
              [](auto i) {cout << i * 2 << " "; });
// The lambda introducer [&sum] indicates that the lambda expression captures the local
// variable sum by reference (to modify it).
int sum = 0;
for_each(myVector.cbegin(), myVector.cend(),
              [&sum](auto i) {sum += i; });
cout << "\nSum of myVector's elements is: " << sum << endl;
```

# Lambda Expressions Example (3 of 4)

```
//replace each element with its double (the passed iterators have to be non-constants and
// the parameter is passed by reference).
 for_each(myVector.begin(), myVector.end(),
              [](auto &i) {i *= 2; });
 cout << "\nmyVector contains (after doubling): ";
 copy(myVector.cbegin(), myVector.cend(), output);

// add each element to sum
 sum = 0;  //to calculate new sum.
 for_each(myVector.cbegin(), myVector.cend(),
                     [&sum](auto i) {sum += i; });
 cout << "\nSum of myVector's elements is: " << sum << endl;
}
```

# Lambda Expressions Example (4 of 4)

Expected output:

```
myVector contains: 1 2 3 4
Display each element multiplied by two: 2 4 6 8
Sum of myVector's elements is: 10

myVector contains (after doubling): 2 4 6 8
Sum of myVector's elements is: 20
```

# Algorithm `fill` and `generate`

- Algorithms `fill` and `fill_n` set every element in a range of container elements to a specific value.
- Algorithms `generate` and `generate_n` use a *generator function* to create values for every element in a range of container elements.
- The *generator function* takes no arguments and returns a value that can be placed in an element of the container.

# fill and generate Example (1 of 3)

```
// Algorithms fill, fill_n, generate and generate_n.
#include <iostream>
#include <algorithm> // algorithm definitions
#include <array> // array class-template definition
#include <iterator> // ostream_iterator
using namespace std;

int main() {
 array<char, 10> myChars;
 char myLetter{'A'};
 ostream_iterator<char> output{ cout, " " };
// fill chars with Zs using non-constant forward iterators
 fill(myChars.begin(), myChars.end(), 'Z');
 cout << "myChars after filling with Zs:\n";
 copy(myChars.cbegin(), myChars.cend(), output);
```

# fill and generate Example (2 of 3)

```
// fill first five elements of chars with Ys
 fill_n(myChars.begin(), 5, 'Y');
 cout << "\n\nmyChars after filling five elements with Ys:\n";
 copy(myChars.cbegin(), myChars.cend(), output);

// generate values for all elements of myChars with A, B, C, …etc.
 generate(myChars.begin(), myChars.end(),
              [&myLetter]() { return myLetter++; });
 cout << "\n\nmyChars after generating its letters:\n";
 copy(myChars.cbegin(), myChars.cend(), output);
// generate values for first five elements of chars with the next letters
 generate_n(myChars.begin(), 5,
              [&myLetter]() { return myLetter++; });
 cout<<"\n\nmyChars after re-generating the first 5 elements:\n";
 copy(myChars.cbegin(), myChars.cend(), output);
}
```

# fill and generate Example (3 of 3)

Expected output:

```
myChars after filling with Zs:
Z Z Z Z Z Z Z Z Z Z

myChars after filling five elements with Ys:
Y Y Y Y Y Z Z Z Z Z

myChars after generating its letters:
A B C D E F G H I J

myChars after re-generating the first 5 elements:
K L M N O F G H I J
```

# Mathematical Algorithms

- The following example demonstrates several common mathematical algorithms, including
  - `count`
  - `count_if`
  - `min_element`
  - `max_element`
  - `minmax_element`
  - `accumulate`
  - `transform`

# Mathematical Algorithms Example (1 of 4)

```
// Mathematical algorithms of the Standard Library.
#include <iostream>
#include <algorithm> // algorithm definitions
#include <numeric> // accumulate is defined here
#include <vector>
#include <array>
#include <iterator>
using namespace std;

int main() {
 vector<int> a1{ 100, 2, 8, 1, 50, 3, 8, 8, 9, 10 };
 ostream_iterator<int> output{ cout, " " };
// count number of elements in a1 with value 8
 auto result = count(a1.cbegin(), a1.cend(), 8);
 cout << "\nNumber of elements matching 8: " << result;
```

# Mathematical Algorithms Example (2 of 4)

```
// count number of elements in a1 that are greater than 9
 result = count_if(a1.cbegin(), a1.cend(),
               [](auto x) {return x > 9; });
 cout << "\nNumber of elements greater than 9: " << result;
// min_element locates minimum element in a1.
// It returns an iterator located at the first smallest element, or a1.end() if the range is empty
 cout << "\n\nMinimum element in a1 is: "
  << *(min_element(a1.cbegin(), a1.cend()));
// locate maximum element in a1
 cout << "\nMaximum element in a1 is: "
  << *(max_element(a1.cbegin(), a1.cend()));
// locate minimum and maximum elements in a1
// If there are duplicate, the iterators are located at the first smallest and last largest values
 auto minAndMax = minmax_element(a1.cbegin(), a1.cend());
 cout << "\nThe minimum and maximum elements in a1 are "
 << *minAndMax.first << " and " << *minAndMax.second;
```

# Mathematical Algorithms Example (3 of 4)

```
// accumulate calculates the sum of elements in a1
// its third argument represents the initial value of the total
 cout << "\n\nThe total of the elements in a1 is: "
 << accumulate(a1.cbegin(), a1.cend(), 0);

 array<int, 10> cubes; // instantiate cubes
// transform calculates cube of each element in a1; place results in array cubes.
// Its third argument can equal the first but not constant (e.g., a1.begin()).
 transform(a1.cbegin(), a1.cend(), cubes.begin(),
       [](auto x) {return x * x * x; });
 cout << "\n\nThe cube of every integer in a1 is:\n";
 copy(cubes.cbegin(), cubes.cend(), output);
}
```

# Mathematical Algorithms Example (4 of 4)

Expected output:

```
Number of elements matching 8: 3
Number of elements greater than 9: 3

Minimum element in a1 is: 1
Maximum element in a1 is: 100
The minimum and maximum elements in a1 are 1 and 100

The total of the elements in a1 is: 199

The cube of every integer in a1 is:
1000000 8 512 1 125000 27 512 512 729 1000
```

# Searching and Sorting Algorithms

- The following example demonstrates some basic searching and sorting capabilities of the Standard Library, including:
  - `find`
  - `find_if`
  - `sort`
  - `binary_search`
  - `all_of`
  - `any_of`
  - `none_of`
  - `find_if_not`

# Searching and Sorting Algorithms Example (1 of 6)

```
// Standard Library search and sort algorithms.
#include <iostream>
#include <algorithm> // algorithm definitions
#include <array> // array class-template definition
#include <iterator>
using namespace std;

int main() {
 const size_t SIZE{ 10 };
 array<int, SIZE> A{ 10, 2, 17, 5, 16, 8, 13, 11, 20, 7 };
 ostream_iterator<int> output{ cout, " " };
// display the contents of A
 cout << "Array A contains: ";
 copy(A.cbegin(), A.cend(), output);
```

# Searching and Sorting Algorithms Example (2 of 6)

```
// locate first occurrence of 16 in A
 auto location = find(A.cbegin(), A.cend(), 16);
 if (location != A.cend()) { // found 16
   cout << "\n\nFound 16 at location " <<
              (location - A.cbegin());
 }
 else { cout << "\n\n16 not found";}

// create variable to store lambda for reuse later
 auto isGreaterThan10 = [](auto x) {return x > 10; };
// locate first occurrence of value greater than 10 in A
 location = find_if(A.cbegin(), A.cend(), isGreaterThan10);
 if (location != A.cend()) { // found value greater than 10
  cout << "\n\nThe first value greater than 10 is "
  << *location << "\nfound at location " <<(location-A.cbegin());
 }
```

# Searching and Sorting Algorithms Example (3 of 6)

```
  else { // value greater than 10 not found
    cout << "\n\nNo values greater than 10 were found";}
// sort elements of A. This algorithm requires its two iterator arguments to be random-access
// iterators. Can be used with Standard Library containers array, vector and deque
 sort(A.begin(), A.end());
 cout << "\n\nArray A after sort: ";
 copy(A.cbegin(), A.cend(), output);
// use binary_search to check whether 13 exists in A
 if (binary_search(A.cbegin(), A.cend(), 13)) {
      cout << "\n\n13 was found in A"; }
 else { cout << "\n\n13 was not found in A"; }
// use binary_search to check whether 100 exists in A
 if (binary_search(A.cbegin(), A.cend(), 100)) {
      cout << "\n100 was found in A"; }
 else { cout << "\n100 was not found in A"; }
```

# Searching and Sorting Algorithms Example (4 of 6)

```
// determine whether all of the elements of A are greater than 10
 if (all_of(A.cbegin(), A.cend(), isGreaterThan10)) {
   cout << "\n\nAll the elements in A are greater than 10";}
 else {
   cout << "\n\nSome elements in A are not greater than 10";}
// determine whether any of the elements of A are greater than 10
 if (any_of(A.cbegin(), A.cend(), isGreaterThan10)) {
  cout << "\n\nAt least one element in A is greater than 10";}
 else { cout << "\n\nNo element in A is greater than 10"; }
// determine whether none of the elements of a are greater than 10
 if (none_of(A.cbegin(), A.cend(), isGreaterThan10)) {
  cout << "\n\nNone of the elements in A are greater than 10";}
 else {
  cout << "\n\nSome of the elements in A are greater than 10";}
```

# Searching and Sorting Algorithms Example (5 of 6)

```
// locate first occurrence of value that's not greater than 10 in A
 location = find_if_not(A.cbegin(), A.cend(), isGreaterThan10);

if (location != A.cend()) { // found A value less than or equal to 10
   cout << "\n\nThe first value not greater than 10 is "
        << *location << "\nfound at location "
        << (location - A.cbegin());
 }
 else { // no values less than or equal to 10 were found
    cout << "\n\nOnly values greater than 10 were found";}
}
```

# Searching and Sorting Algorithms Example (6 of 6)

Expected output:

```
Array A contains: 10 2 17 5 16 8 13 11 20 7
Found 16 at location 4
The first value greater than 10 is 17
found at location 2
Array A after sort: 2 5 7 8 10 11 13 16 17 20
13 was found in A
100 was not found in A
Some elements in A are not greater than 10
At least one element in A is greater than 10
Some of the elements in A are greater than 10
The first value not greater than 10 is 2
found at location 0
```

# More Readings

- Chapters 15 and 16 in:

  P. Deitel and H. Deitel, "C++, How to Program", Pearson, 10th Edition.