Review from Lecture 8
- Designing our own container classes
- Dynamically allocated memory in classes
- Copy constructors, assignment operators, and destructors
- Templated classes, Implementation of the DS Vec class, mimicking the STL vector class

Today
- Another vector operation: pop_back
- Erasing items from vectors is inefficient!
- Iterators and iterator operations
- STL lists are a different sequential container class.
- Returning references to member variables from member functions
- Vec iterator implementation

Optional Reading: Ford & Topp Ch 6; Koenig & Moo, Sections 5.1-5.5

9.1 Review: Constructors, Assignment Operator, and Destructor
From an old test: Match up the line of code with the function that is called. Each letter is used exactly once.

```
Foo f1; a) assignment operator
Foo* f2; b) destructor
f2 = new Foo(f1); c) copy constructor
f1 = *f2; d) default constructor
delete f2; e) none of the above
```

9.2 Another STL vector operation: pop_back
- We have seen how push_back adds a value to the end of a vector, increasing the size of the vector by 1. There is a corresponding function called pop_back, which removes the last item in a vector, reducing the size by 1.
- There are also vector functions called front and back which denote (and thereby provide access to) the first and last item in the vector, allowing them to be changed. For example:

```
vector<int> a(5,1); // a has 5 values, all 1
a.pop_back(); // a now has 4 values
a.front() = 3; // equivalent to the statement, a[0] = 3;
a.back() = -2; // equivalent to the statement, a[a.size()-1] = -2;
```
#include <algorithm>
#include <iostream>
#include <string>
#include <vector>

using namespace std;

void erase_from_vector(unsigned int i, vector<string>& v) {
    assert(i < v.size());
    v.erase(v.begin() + i);
}

// Enroll a student if there is room and the student is not already in course or on waiting list.
void enroll_student(const string& id, unsigned int max_students, vector<string>& enrolled, vector<string>& waiting) {
    // Check to see if the student is already enrolled.
    bool found = false;
    unsigned int loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
            return;
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
            return;
        }
    }
    // If the course isn’t full, add the student.
    if (enrolled.size() < max_students) {
        enrolled.push_back(id);
        cout << "Student " << id << " added."
    }
    // If not, add the student to the waiting list.
    else {
        cout << "Student " << id << " has been added to the waiting list."
    }
}

// Remove a student from the course or from the waiting list. If removing the student from the
// course opens up a slot, then the first person on the waiting list is placed in the course.
void remove_student(const string& id, unsigned int max_students, vector<string>& enrolled, vector<string>& waiting) {
    // Check to see if the student is on the course list.
    bool found = false;
    unsigned int loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << waiting[loc] << " added to the course from the waiting list."
        }
    }
    // Check to see if the student is on the waiting list.
    found = false;
    loc = 0;
    while (!found && loc < waiting.size()) {
        if (found) ++loc;
        if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
        } else if (id == enrolled[loc]) {
            // Remove from the course.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        }
    }
    // Check to see if the student is on the waiting list.
    // If not, add the student to the waiting list.
    if (!found && loc < waiting.size()) {
        waiting.push_back(id);
        cout << "Student " << id << " has been added to the waiting list."
    }
    // Check to see if the student is on the course list.
    found = false;
    loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << waiting[loc] << " added to the course from the waiting list."
        }
    }
    // Check to see if the student is on the waiting list.
    found = false;
    loc = 0;
    while (!found && loc < waiting.size()) {
        if (found) ++loc;
        if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
        } else if (id == enrolled[loc]) {
            // Remove from the course.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        }
    }
    // Check to see if the student is on the course list.
    found = false;
    loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << waiting[loc] << " added to the course from the waiting list."
        }
    }
    // Check to see if the student is on the waiting list.
    found = false;
    loc = 0;
    while (!found && loc < waiting.size()) {
        if (found) ++loc;
        if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
        } else if (id == enrolled[loc]) {
            // Remove from the course.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        }
    }
    // Check to see if the student is on the course list.
    found = false;
    loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << waiting[loc] << " added to the course from the waiting list."
        }
    }
    // Check to see if the student is on the waiting list.
    found = false;
    loc = 0;
    while (!found && loc < waiting.size()) {
        if (found) ++loc;
        if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
        } else if (id == enrolled[loc]) {
            // Remove from the course.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        }
    }
    // Check to see if the student is on the course list.
    found = false;
    loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << waiting[loc] << " added to the course from the waiting list."
        }
    }
    // Check to see if the student is on the waiting list.
    found = false;
    loc = 0;
    while (!found && loc < waiting.size()) {
        if (found) ++loc;
        if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
        } else if (id == enrolled[loc]) {
            // Remove from the course.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        }
    }
    // Check to see if the student is on the course list.
    found = false;
    loc = 0;
    while (!found && loc < enrolled.size()) {
        if (found) ++loc;
        if (id == enrolled[loc]) {
            // Remove the student and see if a student can be taken from the waiting list.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        } else if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << waiting[loc] << " added to the course from the waiting list."
        }
    }
    // Check to see if the student is on the waiting list.
    found = false;
    loc = 0;
    while (!found && loc < waiting.size()) {
        if (found) ++loc;
        if (id == waiting[loc]) {
            // Remove from the waiting list.
            erase_from_vector(loc, waiting);
            cout << "Student " << id << " removed from the waiting list."
        } else if (id == enrolled[loc]) {
            // Remove from the course.
            erase_from_vector(loc, enrolled);
            cout << "Student " << id << " removed from the course."
        }
    }
}

int main() {
    // Read in the maximum number of students in the course
    unsigned int max_students;
    cout << "Enter the maximum number of students allowed: \n";
    cin >> max_students;
    // Initialize the vectors
    vector<string> enrolled; vector<string> waiting;
    // Invariant:
    // (1) enrolled contains the students already in the course,
    // (2) waiting contains students who will be admitted (in the order of request) if a spot opens up
    // (3) enrolled.size() <= max_students,
    // (4) if the course is not filled (enrolled.size() != max_students) then waiting is empty
do {
    // check (part of) the invariant
    assert (enrolled.size() <= max_students);    assert (enrolled.size() == max_students || waiting.size() == 0);
    cout << "Options:
    1. To enroll a student type 0
    2. To remove a student type 1
    3. To end type 2
    Type option == ";
    int option;
    if (!(cin >> option)) {
        cout << "Illegal input.  Good-bye.\n";
        return 0;
    } else if (option == 2) {
        // break by breaking out of the loop.
        cout << "Invalid option. Try again.\n";
    } else if (option == 0) {
        // option is 0 or 1
        string id;
        cout << "Enter student id: ";
        cin >> id;
        if (!cin >> id) {
            cout << "Invalid input. Try again.\n";
            return 0;
        }
        enroll_student(id, max_students, enrolled, waiting);
    } else if (option == 1) {    // option is 0 or 1
        enroll_student(id, max_students, enrolled, waiting);
    }    remove_student(id, max_students, enrolled, waiting);
    } while (true);
    // some nice output
    sort(enrolled.begin(), enrolled.end());
    cout << "At the end of the enrollment period, the following students are in the class:\n"
    for (unsigned int i=0; i<enrolled.size(); ++i) { cout << enrolled[i] << endl;  }
    for (unsigned int j=0; j<waiting.size(); ++j) { cout << waiting[j] << endl;  }
    return 0;
}
9.3 Motivating Example: Course Enrollment and Waiting List

- This program maintains the class list and the waiting list for a single course. The program is structured to handle interactive input. Error checking ensures that the input is valid.
- Vectors store the enrolled students and the waiting students. The main work is done in the two functions `enroll_student` and `remove_student`.
- The invariant on the loop in the main function determines how these functions must behave.

9.4 Exercises

1. Write `erase_from_vector`. This function removes the value at index location `i` from a vector of strings. The size of the vector should be reduced by one when the function is finished.

   ```cpp
   // Remove the value at index location i from a vector of strings. The
   // size of the vector should be reduced by one when the function is finished.
   void erase_from_vector(unsigned int i, vector<string>& v) {
   }
   ```

2. Give an order notation estimate of the cost of `erase_from_vector`, `pop_back`, and `push_back`.

9.5 What To Do About the Expense of Erasing From a Vector?

- When items are continually being inserted and removed, vectors are not a good choice for the container.
- Instead we need a different sequential container, called a `list`.
  - This has a “linked” structure that makes the cost of erasing independent of the size.
- We will move toward a list-based implementation of the program in two steps:
  - Rewriting our `classlist_vec.cpp` code in terms of `iterator` operations.
  - Replacing vectors with lists

9.6 Iterators

- Here’s the definition (from Koenig & Moo). An iterator:
  - identifies a container and a specific element stored in the container,
  - lets us examine (and change, except for const iterators) the value stored at that element of the container,
  - provides operations for moving (the iterators) between elements in the container,
  - restricts the available operations in ways that correspond to what the container can handle efficiently.
- As we will see, iterators for different container classes have many operations in common. This often makes the switch between containers fairly straightforward from the programmer’s viewpoint.
- Iterators in many ways are generalizations of pointers: many operators / operations defined for pointers are defined for iterators. You should use this to guide your beginning understanding and use of iterators.

9.7 Iterator Declarations and Operations

- Iterator types are declared by the container class. For example,

  ```cpp
  vector<string>::iterator p;
  vector<string>::const_iterator q;
  ```

  defines two (uninitialized) iterator variables.
- The `dereference operator` is used to access the value stored at an element of the container. The code:

  ```cpp
  p = enrolled.begin();
  *p = "012312";
  ```

  changes the first entry in the `enrolled` vector.
The dereference operator is combined with dot operator for accessing the member variables and member functions of elements stored in containers. Here’s an example using the `Student` class and `students` vector from Lecture 4:

```cpp
vector<Student>::iterator i = students.begin();
(*i).compute_averages(0.45);
```

Notes:
- This operation would be illegal if `i` had been defined as a `const_iterator` because `compute_averages` is a non-const member function.
- The parentheses on the `*i` are required (because of operator precedence).

There is a “syntactic sugar” for the combination of the dereference operator and the dot operator, which is exactly equivalent:

```cpp
vector<StudentRec>::iterator i = students.begin();
i->compute_averages(0.45);
```

Just like pointers, iterators can be incremented and decremented using the `++` and `--` operators to move to the next or previous element of any container.

Iterators can be compared using the `==` and `!=` operators.

Iterators can be assigned, just like any other variable.

Vector iterators have several additional operations:
- Integer values may be added to them or subtracted from them. This leads to statements like
  ```cpp
  enrolled.erase(enrolled.begin() + 5);
  ```
- Vector iterators may be compared using operators like `<`, `<=`, etc.
- For most containers (other than vectors), these “random access” iterator operations are not legal and therefore prevented by the compiler. The reasons will become clear as we look at their implementations.

#### 9.8 Exercise: Revising the Class List Program to Use Iterators

Now let’s modify the class list program to use iterators. First rewrite the `erase_from_vector` to use iterators.

```cpp
void erase_from_vector(vector<string>::iterator itr, vector<string>& v) {
    // Implementation...
}
```

Note: the STL `vector` class has a function that does just this... called `erase`!

Now, edit the rest of the file to remove all use of the vector subscripting operator.

#### 9.9 A New Datatype: The `list` Standard Library Container Class

- Lists are our second standard-library container class. (Vectors were the first.) Both lists & vectors store sequential data that can shrink or grow.

- However, the use of memory is fundamentally different. Vectors are formed as a single contiguous array-like block of memory. Lists are formed as a sequentially linked structure instead.

```plaintext
array/vector:          list:

<table>
<thead>
<tr>
<th>7</th>
<th>5</th>
<th>8</th>
<th>1</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
```

```plaintext
<table>
<thead>
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<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
```

<table>
<thead>
<tr>
<th>7 ——— 5 ——— 8 ——— 1 ——— 9</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>0 ——— 1 ——— 2 ——— 3 ——— 4</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>7 ——— 5 ——— 8 ——— 1 ——— 9</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>0 ——— 1 ——— 2 ——— 3 ——— 4</th>
</tr>
</thead>
</table>
• Although the interface (functions called) of lists and vectors and their iterators are quite similar, their implementations are VERY different. Clues to these differences can be seen in the operations that are NOT in common, such as:
  
  - STL vectors / arrays allow “random-access” / indexing / [] subscripting. We can immediately jump to an arbitrary location within the vector / array.
  
  - STL lists have no subscripting operation (we can’t use [] to access data). The only way to get to the middle of a list is to follow pointers one link at a time.
  
  - Lists have push_front and pop_front functions in addition to the push_back and pop_back functions of vectors.
  
  - erase and insert in the middle of the STL list is very efficient, independent of the size of the list. Both are implemented by rearranging pointers between the small blocks of memory. (We’ll see this when we discuss the implementation details next week).
  
  - We can’t use the same STL sort function we used for vector; we must use a special sort function defined by the STL list type.

```cpp
std::vector<int> my_vec;
std::list<int> my_lst;
// ... put some data in my_vec & my_lst
std::sort(my_vec.begin(),my_vec.end(),optional_compare_function);
my_lst.sort(optional_compare_function);
```

Note: STL list sort member function is just as efficient, $O(n \log n)$, and will also take the same optional compare function as STL vector.

- Several operations invalidate the values of vector iterators, but not list iterators:
  
  - * erase invalidates all iterators after the point of erasure in vectors;
  
  - * push_back and resize invalidate ALL iterators in a vector

The value of any associated vector iterator must be re-assigned / re-initialized after these operations.

### 9.10 Exercise: Revising the Class List Program to Use Lists (& Iterators)

Now let’s further modify the program to use lists instead of vectors. Because we’ve already switched to iterators, this change will be relatively easy. And now the program will be more efficient!

#### 9.11 Erase & Iterators

- STL lists and vectors each have a special member function called erase. In particular, given list of ints s, consider the example:

```cpp
std::list<int>::iterator p = s.begin();
++p;
std::list<int>::iterator q = s.erase(p);
```

- After the code above is executed:
  
  - The integer stored in the second entry of the list has been removed.
  
  - The size of the list has shrunk by one.
  
  - The iterator p does not refer to a valid entry.
  
  - The iterator q refers to the item that was the third entry and is now the second.

```
?   7   8   1   9
p    5   9 
q
```

- To reuse the iterator p and make it a valid entry, you will often see the code written:

```cpp
std::list<int>::iterator p = s.begin();
++p;
p = s.erase(p);
```
• Even though the erase function has the same syntax for vectors and for list, the vector version is $O(n)$, whereas the list version is $O(1)$.

9.12 Insert

• Similarly, there is an insert function for STL lists that takes an iterator and a value and adds a link in the chain with the new value immediately before the item pointed to by the iterator.

• The call returns an iterator that points to the newly added element. Variants on the basic insert function are also defined.

9.13 Exercise: Using STL list Erase & Insert

Write a function that takes an STL list of integers, lst, and an integer, x. The function should 1) remove all negative numbers from the list, 2) verify that the remaining elements in the list are sorted in increasing order, and 3) insert x into the list such that the order is maintained.

9.14 Implementing Vec<T> Iterators

• Let’s add iterators to our Vec<T> class declaration from last lecture:

```cpp
public:
    // TYPEDEFS
    typedef T* iterator;
    typedef const T* const_iterator;

    // MODIFIERS
    iterator erase(iterator p);

    // ITERATOR OPERATIONS
    iterator begin() { return m_data; }
    const_iterator begin() const { return m_data; }
    iterator end() { return m_data + m_size; }
    const_iterator end() const { return m_data + m_size; }
```

• First, remember that typedef statements create custom, alternate names for existing types. 

Vec<int>::iterator is an iterator type defined by the Vec<int> class. It is just a T *(an int *). Thus, internal to the declarations and member functions, T* and iterator may be used interchangeably.

• Because the underlying implementation of Vec uses an array, and because pointers are the “iterator”s of arrays, the implementation of vector iterators is quite simple. Note: the implementation of iterators for other STL containers is more involved!

• Thus, begin() returns a pointer to the first slot in the m_data array. And end() returns a pointer to the “slot” just beyond the last legal element in the m_data array (as prescribed in the STL standard).

• Furthermore, dereferencing a Vec<T>::iterator (dereferencing a pointer to type T) correctly returns one of the objects in the m_data array, an object with type T.

• And similarly, the ++, --, <, ==, !=, >, etc. operators on pointers automatically apply to Vec iterators.

• The erase function requires a bit more attention. We’ve implemented the core of this function above. The STL standard further specifies that the return value of erase is an iterator pointing to the new location of the element just after the one that was deleted.

• Finally, note that after a push_back or erase or resize call some or all iterators referring to elements in that vector may be invalidated. Why? You must take care when designing your program logic to avoid invalid iterator bugs!