Announcements:
- Prof. Thompson’s office hours are canceled for Tuesday Mar. 1

Review from Lecture 9
- Finish Recursion Introduction

Today’s Class
- Quick review of iterators
- Implementation of iterators in our homemade Vec class (from Lecture 8)
- const and reference on return values
- Building our own basic linked lists:
  - Stepping through a list
  - Push back
  - ... & even more in the next couple lectures!

10.1 Review: Iterators and Iterator Operations
- An iterator type is defined by each STL container class. For example:
  ```cpp
  std::vector<double>::iterator v_itr;
  std::list<std::string>::iterator l_itr;
  std::string::iterator s_itr;
  ```
- An iterator is assigned to a specific location in a container. For example:
  ```cpp
  v_itr = vec.begin() + i; // i-th location in a vector
  l_itr = lst.begin(); // first entry in a list
  s_itr = str.begin(); // first char of a string
  ```
  Note: We can add an integer to vector and string iterators, but not to list iterators.
- The contents of the specific entry referred to by an iterator are accessed using the * dereference operator:
  In the first and third lines, *v_itr and *l_itr are l-values. In the second, *s_itr is an r-value.
  ```cpp
  *v_itr = 3.14;
  cout << *s_itr << endl;
  *l_itr = "Hello";
  ```
- Stepping through a container, either forward and backward, is done using increment (++) and decrement (--) operators:
  ```cpp
  ++itr; itr++; --itr; itr--;
  ```
  These operations move the iterator to the next and previous locations in the vector, list, or string. The operations do not change the contents of container!
- Finally, we can change the container that a specific iterator is attached to as long as the types match. Thus, if v and w are both std::vector<double>, then the code:
  ```cpp
  v_itr = v.begin();
  *v_itr = 3.14; // changes 1st entry in v
  v_itr = w.begin() + 2;
  *v_itr = 2.78; // changes 3rd entry in w
  ```
  works fine because v_itr is a std::vector<double>::iterator, but if a is a std::vector<std::string> then
  ```cpp
  v_itr = a.begin();
  ```
  is a syntax error because of a type clash!
10.2 Additional Iterator Operations for Vector (& String) Iterators

- Initialization at a random spot in the vector:
  \[ v\_itr = v\_.begin() + i; \]

  Jumping around inside the vector through addition and subtraction of location counts:
  \[ v\_itr = v\_itr + 5; \]

  moves p 5 locations further in the vector. These operations are constant time, \( O(1) \) for vectors.

- These operations are not allowed for list iterators (and most other iterators, for that matter) because of the way the corresponding containers are built. These operations would be linear time, \( O(n) \), for lists, where \( n \) is the number of slots jumped forward/backward. Thus, they are not provided by STL for lists.

- Students are often confused by the difference between iterators and indices for vectors. Consider the following declarations:
  
  ```
  std::vector<double> a(10, 2.5);
  std::vector<double>::iterator p = a.begin() + 5;
  unsigned int i=5;
  ```

- Iterator \( p \) refers to location 5 in vector \( a \). The value stored there is directly accessed through the \( * \) operator:
  
  ```
  *p = 6.0;
  cout << *p << endl;
  ```

  The above code has changed the contents of vector \( a \). Here’s the equivalent code using subscripting:
  
  ```
  a[i] = 6.0;
  cout << a[i] << endl;
  ```

- Here’s another common confusion:

  ```
  std::list<int> lst;
  lst.push_back(100); lst.push_back(200); lst.push_back(300);
  lst.push_back(400); lst.push_back(500);
  std::list<int>::iterator itr,itr2,itr3;
  itr = lst.begin(); // itr is pointing at the 100
  ++itr; // itr is now pointing at 200
  *itr += 1; // 200 becomes 201
  // itr += 1; // does not compile! you can't advance a list iterator like this
  itr3 = --itr; // itr is now pointing at 300, itr3 is also pointing at 300
  // dangerous: decrementing the begin iterator is "undefined behavior"
  //  (similarly, incrementing the end iterator is also undefined)
  //  it may seem to work, but break later on this machine or on another machine!
  itr = lst.begin();
  itr--; // dangerous! -- undefined behavior
  itr++;
  assert (*itr == 100); // might seem ok... but rewrite the code to avoid this!
  ```

10.3 STL List: Erase & Insert (review)

- The `erase` member function (for STL `vector` and STL `list`) takes in a single argument, an iterator pointing at an element in the container. It removes that item, and the function returns an iterator pointing at the element after the removed item.

- Similarly, there is an `insert` function for STL `vector` and STL `list` that takes in 2 arguments, an iterator and a new element, and adds that element immediately before the item pointed to by the iterator. The function returns an iterator pointing at the newly added element.

- Even though the `erase` and `insert` functions have the same syntax for vector and for list, the vector versions are \( O(n) \), whereas the list versions are \( O(1) \).

- Iterators positioned on an STL `vector`, at or after the point of an `erase` operation, are invalidated. Iterators positioned anywhere on an STL `vector may be invalid after an insert (or push_back or resize) operation.

- Iterators attached to an STL `list` are not invalidated after an `insert` or `erase` (except iterators attached to the erased element!) or `push_back/push_front`. 
10.4 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. (See http://www.cs.rpi.edu/~thompw4/CSCI-1200/Spring2016/lec_7_notes.cpp).

10.5 Implementing Vec<T> Iterators

- Let’s add iterators to our Vec<T> class declaration from Lecture 8:

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! We’ll see how STL list iterators work in a later lecture.

- 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. We don’t need to write any additional functions for iterators, since we get all of the necessary behavior from the underlying pointer implementation.

- The erase function requires a bit more attention. We’ve implemented a version of this function in the previous lecture. 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.
10.6 References and Return Values

- A reference is an alias for another variable. For example:

```cpp
string a = "Tommy";
string b = a; // a new string is created using the string copy constructor
string& c = a; // c is an alias/reference to the string object a
b[1] = 'i';
cout << a << " " << b << " " << c << endl; // outputs: Tommy Timmy Tommy
```

The reference variable c refers to the same string as variable a. Therefore, when we change c, we change a.

- Exactly the same thing occurs with reference parameters to functions and the return values of functions. Let’s look at the Student class from Lecture 4 again:

```cpp
class Student {
public:
    const string& first_name() const { return first_name_; }
    const string& last_name() const { return last_name_; }
private:
    string first_name_; 
    string last_name_; 
};
```

- In the main function we had a vector of students:

```cpp
vector<Student> students;
```

Based on our discussion of references above and looking at the class declaration, what if we wrote the following. Would the code then be changing the internal contents of the i-th Student object?

```cpp
string & fname = students[i].first_name();
fname[1] = 'i'
```

- The answer is NO! The Student class member function first_name returns a const reference. The compiler will complain that the above code is attempting to assign a const reference to a non-const reference variable.

- If we instead wrote the following, then compiler would complain that you are trying to change a const object.

```cpp
const string & fname = students[i].first_name();
fname[1] = 'i'
```

- Hence in both cases the Student class would be “safe” from attempts at external modification.

- However, the author of the Student class would get into trouble if the member function return type was only a reference, and not a const reference. Then external users could access and change the internal contents of an object! This is a bad idea in most cases.

10.7 Working towards our own version of the STL list

- Our discussion of how the STL list<T> is implemented has been intuitive: it is a “chain” of objects.

- Now we will study the underlying mechanism — linked lists.

- This will allow us to build custom classes that mimic the STL list class, and add extensions and new features (more in the next couple lectures!).

10.8 Objects with Pointers, Linking Objects Together

- The two fundamental mechanisms of linked lists are:
  - creating objects with pointers as one of the member variables, and
  - making these pointers point to other objects of the same type.

- These mechanisms are illustrated in the following program:
template <class T>
class Node {
  public:
    T value;
    Node* ptr;
};

int main() {
  Node<int>* ll;  // ll is a pointer to a (non-existent) Node
  ll = new Node<int>;  // Create a Node and assign its memory address to ll
  ll->value = 6;  // This is the same as (*ll).value = 6;
  ll->ptr = NULL;  // NULL == 0, which indicates a "null" pointer

  Node<int>* q = new Node<int>;
  q->value = 8;
  q->ptr = NULL;

  // set ll's ptr member variable to
  // point to the same thing as variable q
  ll->ptr = q;

  cout << "1st value: " << ll->value << "\n"
       << "2nd value: " << ll->ptr->value << endl;
}

10.9 Definition: A Linked List
- The definition is recursive: A linked list is either:
  - Empty, or
  - Contains a node storing a value and a pointer to a linked list.
- The first node in the linked list is called the head node and the pointer to this node is called the head pointer. The pointer’s value will be stored in a variable called head.

10.10 Visualizing Linked Lists
- The head pointer variable is drawn with its own box. It is an individual variable. It is important to have a separate pointer to the first node, since the “first” node may change.
- The objects (nodes) that have been dynamically allocated and stored in the linked lists are shown as boxes, with arrows drawn to represent pointers.
  - Note that this is a conceptual view only. The memory locations could be anywhere, and the actual values of the memory addresses aren’t usually meaningful.
- The last node MUST have NULL for its pointer value — you will have all sorts of trouble if you don’t ensure this!
- You should make a habit of drawing pictures of linked lists to figure out how to do the operations.

10.11 Basic Mechanisms: Stepping Through the List
- We’d like to write a function to determine if a particular value, stored in x, is also in the list.
- We can access the entire contents of the list, one step at a time, by starting just from the head pointer.
  - We will need a separate, local pointer variable to point to nodes in the list as we access them.
  - We will need a loop to step through the linked list (using the pointer variable) and a check on each value.
10.12 Exercise: Write is_there

```cpp
template <class T> bool is_there(Node<T>* head, const T& x) {
```

10.13 Basic Mechanisms: Pushing on the Back

- Goal: place a new node at the end of the list.
- We must step to the end of the linked list, remembering the pointer to the last node.
  - This is an $O(n)$ operation and is a major drawback to the ordinary linked-list data structure we are discussing now. We will correct this drawback by creating a slightly more complicated linking structure in our next lecture.
- We must create a new node and attach it to the end.
- We must remember to update the head pointer variable’s value if the linked list is initially empty.
  - Hence, in writing the function, we must pass the pointer variable by reference.

10.14 Exercise: Write push_front

```cpp
template <class T> void push_front( Node<T>* & head, T const& value ) {
```

- If the input linked list chain contains $n$ elements, what is the order notation of the implementation of push_front?

10.15 Exercise: Write push_back

```cpp
template <class T> void push_back( Node<T>* & head, T const& value ) {
```

- If the input linked list chain contains $n$ elements, what is the order notation of this implementation of push_back?

10.16 Next time... Can we get better performance out of linked lists? Yes!