CSCI-1200 Data Structures — Spring 2023
Lecture 10 — Vector Iterators & Linked Lists

Review from Lecture 9

- Explored a program to maintain a class enrollment list and an associated waiting list.
- Unfortunately, erasing items from the front or middle of vectors is inefficient.
- Iterators can be used to access elements of a vector
- Iterators and iterator operations (increment, decrement, erase, & insert)
- STL's `list` class
- Differences between indices and iterators, differences between STL `list` and STL `vector`.

Today's Class

- Finishing up Lecture 9 (and Lecture 7!)
- Quick review of iterators
- Implementation of iterators in our homemade `Vec` class (from Lecture 7)
- `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:

```
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:

```
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.

```
*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:

```
++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:

```
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

```
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!  can't advance list iterator like this

itr = lst.end();  // itr is pointing "one past the last legal value" of lst
itr--;            // itr is now pointing at 500;
itr2 = itr--;     // itr is now pointing at 400, itr2 is still pointing at 500
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!
itr++;
assert (*itr == 100);  // might seem ok...  but rewrite the code to avoid this!
```

10.3 References and Return Values

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

  ```
  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
  c[1] = 'a';
  cout << a << " " << b << " " << c << endl;    // outputs:  Tammy Timmy Tammy
  ```

  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:

```
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:

  ```
  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?

  ```
  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.

  ```
  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.

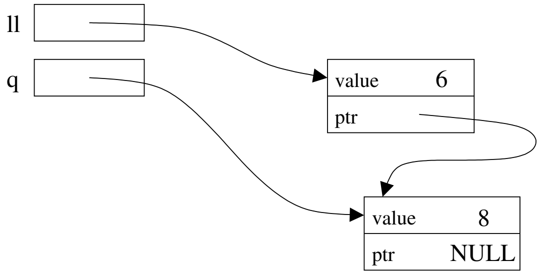
10.4 Working towards *our own* version of the STL `list`

- 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!).

10.5 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:

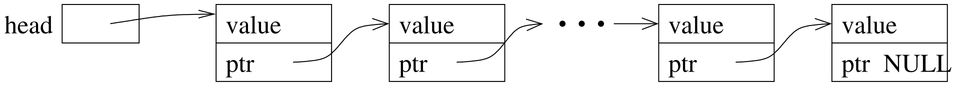
```
template <class T>
class Node {
public:
  T value;
  Node* ptr;
};

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;
}
```



10.6 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`.

10.7 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.

10.8 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.

10.9 Exercise: Write `is_there`

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

- If the input linked list chain contains n elements, what is the order notation of `is_there`?

10.10 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**.

10.11 Exercise: Write `push_front`

```
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`?

10.12 Exercise: Write `push_back`

```
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`?

10.13 Inserting a Node into a Singly-Linked List

- With a singly-linked list, we'll need a pointer to the node *before* the spot where we wish to insert the new item.
- If `p` is a pointer to this node, and `x` holds the value to be inserted, then the following code will do the insertion. Draw a picture to illustrate what is happening.

```
Node<T> * q = new Node<T>; //  create a new node
q -> value = x;            //  store x in this node
q -> next = p -> next;     //  make its successor be the current successor of p
p -> next = q;             //  make p's successor be this new node
```

- Note: This code will not work if you want to insert `x` in a new node at the *front* of the linked list. Why not?

10.14 Removing a Node from a Singly-Linked List

- The remove operation itself requires a pointer to the node *before* the node to be removed.
- Suppose `p` points to a node that should be removed from a linked list, `q` points to the node before `p`, and `head` points to the first node in the linked list. Note: Removing the first node is an important special case.
- Write code to remove `p`, making sure that if `p` points to the first node that `head` points to what was the second node and now is the first after `p` is removed. Draw a picture of each scenario.

10.15 Exercise: Singly-Linked List Copy

Write a *recursive* function to copy all nodes in a linked list to form an new linked list of nodes with identical structure and values. Here's the function prototype:

```
template <class T> void CopyAll(Node<T>* old_head,  Node<T>*& new_head) {
```

10.16 Exercise: Singly-Linked List Remove All

Write a *recursive* function to delete all nodes in a linked list. Here's the function prototype:

```
template <class T> void RemoveAll(Node<T>*& head) {
```

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