Review from Lectures 15

- Maps containing more complicated values.
  Example: index mapping words to the text line numbers on which they appear.
- Maps whose keys are class objects.
  Example: maintaining student records.
- Summary discussion of when to use maps.

Today’s Lecture

- STL set container class (like STL map without the pairs)
- Binary Trees and Binary Search Trees
- Definition & basic operations
- Implementation of cs2set class using binary search trees
- Note: Lots more tree stuff in CSCI 2300 Data Structures & Algorithms (DSA)!

16.1 Standard Library Sets

- STL sets are ordered containers storing unique “keys”. An ordering relation on the keys, which defaults to operator<, is necessary. Because STL sets are ordered, they are technically not traditional mathematical sets.
- Sets are like maps except they have only keys, there are no associated values. Like maps, the keys are constant. This means you can’t change a key while it is in the set. You must remove it, change it, and then reinsert it.
- Access to items in sets is extremely fast! $O(\log n)$, just like maps.
- Like other containers, sets have the usual constructors as well as the size member function.

16.2 Set iterators

- Set iterators, similar to map iterators, are bidirectional: they allow you to step forward (++) and backward (--) through the set. Sets provide begin() and end() iterators to delimit the bounds of the set.
- Set iterators refer to const keys (as opposed to the pairs referred to by map iterators). For example, the following code outputs all strings in the set words:

```cpp
for (set<string>::iterator p = words.begin(); p!= words.end(); ++p)
    cout << *p << endl;
```

16.3 Set insert, erase, and find

- There are two different versions of the insert member function. The first version inserts the entry into the set and returns a pair. The first component of the returned pair refers to the location in the set containing the entry. The second component is true if the entry wasn’t already in the set and therefore was inserted. It is false otherwise. The second version also inserts the key if it is not already there. The iterator pos is a “hint” as to where to put it. This makes the insert faster if the hint is good.

```cpp
pair<iterator,bool> set<Key>::insert(const Key& entry);
iterator set<Key>::insert(iterator pos, const Key& entry);
```

- There are three versions of erase. The first erase returns the number of entries removed (either 0 or 1). The second and third erase functions are just like the corresponding erase functions for maps. Note that the erase functions do not return iterators. This is different from the vector and list erase functions.

```cpp
size_type set<Key>::erase(const Key& x);
void set<Key>::erase(iterator p);
void set<Key>::erase(iterator first, iterator last);
```

- The find function returns the end iterator if the key is not in the set:

```cpp
const_iterator set<Key>::find(const Key& x) const;
```
16.4 Overview: Lists vs. Trees vs. Graphs

- Trees create a hierarchical organization of data, rather than the linear organization in linked lists (and arrays and vectors).
- Binary search trees are the mechanism underlying maps & sets (and multimaps & multisets).
- Mathematically speaking: A graph is a set of vertices connected by edges. And a tree is a special graph that has no cycles. The edges that connect nodes in trees and graphs may be directed or undirected.
  
  - For HW8 you will be building a graph with bi-directional edges to represent train service between cities.

16.5 Definition: Binary Trees

- A binary tree (strictly speaking, a “rooted binary tree”) is either empty or is a node that has pointers to two binary trees.
- Here’s a picture of a binary tree storing integer values. In this figure, each large box indicates a tree node, with the top rectangle representing the value stored and the two lower boxes representing pointers. Pointers that are null are shown with a slash through the box.
- The topmost node in the tree is called the root.
- The pointers from each node are called left and right. The nodes they point to are referred to as that node’s (left and right) children.
- The (sub)trees pointed to by the left and right pointers at any node are called the left subtree and right subtree of that node.
- A node where both children pointers are null is called a leaf node.
- A node’s parent is the unique node that points to it. Only the root has no parent.

16.6 Definition: Binary Search Trees

- A binary search tree is a binary tree where at each node of the tree, the value stored at the node is
  
  - greater than or equal to all values stored in the left subtree, and
  - less than or equal to all values stored in the right subtree.
- Here is a picture of a binary search tree storing string values.

16.7 Definition: Balanced Trees

- The number of nodes on each subtree of each node in a “balanced” tree is approximately the same. In order to be an exactly balanced binary tree, what must be true about the number of nodes in the tree?
- In order to claim the performance advantages of trees, we must assume and ensure that our data structure remains approximately balanced. (You’ll see much more of this in DSA!)
16.8 Exercise

Consider the following values:

4.5, 9.8, 3.5, 13.6, 19.2, 7.4, 11.7

1. Draw a binary tree with these values that is NOT a binary search tree.

2. Draw two different binary search trees with these values. Important note: This shows that the binary search tree structure for a given set of values is not unique!

3. How many exactly balanced binary search trees exist with these numbers? How many exactly balanced binary trees exist with these numbers?

16.9 The Tree Node Class

Here is the class definition for nodes in the tree. We will use this for the tree manipulation code we write.

```cpp
template <class T>
class TreeNode {
    public:
    TreeNode() : left(NULL), right(NULL) {}  
    TreeNode(const T& init) : value(init), left(NULL), right(NULL) {}  
    T value;
    TreeNode* left;
    TreeNode* right;
};
```

Sometimes a 3rd pointer — to the parent TreeNode — is added.

16.10 In-order Traversal

- One of the fundamental tree operations is “traversing” the nodes in the tree and doing something at each node. The “doing something”, which is often just printing, is referred to generically as “visiting” the node.

- There are three general orders in which binary trees are traversed: pre-order, in-order and post-order.

- These are usually written recursively, and the code for the three functions looks amazingly similar.

- Here’s the code for an in-order traversal to print the contents of a tree:

```cpp
void print_in_order(ostream& ostr, const TreeNode<T>* p) {
    if (p) {
        print_in_order(ostr, p->left);
        ostr << p->value << \n;
        print_in_order(ostr, p->right);
    }
}
```

- How would you modify this code to perform pre-order and post-order traversals?
16.11 Exercises

1. Write a templated function to find the smallest value stored in a binary search tree whose root node is pointed to by \( p \).

2. Write a function to count the number of odd numbers stored in a binary tree (not necessarily a binary search tree) of integers. The function should accept a \( \text{TreeNode<int>} \) pointer as its sole argument and return an integer. Hint: think recursively!

16.12 cs2set and Binary Search Tree Implementation

- A partial implementation of a set using a binary search tree is in the code attached. We will continue to study this implementation in the next lecture & lab.
- The increment and decrement operations for iterators have been omitted from this implementation. Next lecture we will discuss a couple strategies for adding these operations.
- We will use this as the basis both for understanding an initial selection of tree algorithms and for thinking about how standard library sets really work.

16.13 cs2set: Class Overview

- There is an auxiliary \( \text{TreeNode} \) class, and a \( \text{tree_iterator} \) class. The classes are templated.
- The only member variables of the \( \text{cs2set} \) class are the root and the size (number of tree nodes).
- The iterator class is declared internally, and is effectively a wrapper on the TreeNode pointers.
  - Note that \( \text{operator*} \) returns a const reference because the keys can’t change.
  - As just discussed the increment and decrement operators are missing.
- The main public member functions just call a private (and often recursive) member function (passing the root node) that does all of the work.
- Because the class stores and manages dynamically allocated memory, a copy constructor, \( \text{operator=} \), and destructor must be provided.

16.14 Exercises

1. Provide the implementation of the member function \( \text{cs2set<T>::begin} \). This is essentially the problem of finding the node in the tree that stores the smallest value.

2. Write a recursive version of the function \( \text{find} \).
// Partial implementation of binary-tree based set class similar to std::set.
// The iterator increment & decrement operations have been omitted.
#ifndef cs2set_h_
#define cs2set_h_
#include <iostream>
#include <utility>

// -------------------------------------------------------------------
// TREE NODE CLASS
template <class T>
class TreeNode {
public:
    TreeNode() : left(NULL), right(NULL) {} 
    TreeNode(const T& init) : value(init), left(NULL), right(NULL) {
        T value; 
        TreeNode* left; 
        TreeNode* right; 
    };

    template <class T> class cs2set;

// -------------------------------------------------------------------
// TREE NODE ITERATOR CLASS
template <class T>
class tree_iterator {
public:
    tree_iterator() : ptr_(NULL) {} 
    tree_iterator(TreeNode<T>* p) : ptr_(p) {} 
    tree_iterator(const tree_iterator& old) : ptr_(old.ptr_) {} 
    "tree_iterator() {} 
    tree_iterator& operator=(const tree_iterator& old) { ptr_ = old.ptr_; return *this; } 
    // operator* gives constant access to the value at the pointer 
    const T& operator*() const { return ptr_->value; } 
    // comparisions operators are straightforward 
    friend bool operator==(const tree_iterator& l, const tree_iterator& r) { return l.ptr_ == r.ptr_; } 
    friend bool operator!=(const tree_iterator& l, const tree_iterator& r) { return l.ptr_ != r.ptr_; } 
    // increment & decrement will be discussed in Lecture 17 and Lab 11

private:
    // representation 
    TreeNode<T>* ptr_; 
};

// -------------------------------------------------------------------
// CS2 SET CLASS
template <class T>
class cs2set {
public:
    cs2set() : root_(NULL), size_(0) {} 
    cs2set(const cs2set<T>& old) : size_(old.size_) {
        root_ = this->copy_tree(old.root_); 
    } 
    ~cs2set() { this->destroy_tree(root_); root_ = NULL; } 
    cs2set& operator=(const cs2set<T>& old) {
        if (old != *this) {
            this->destroy_tree(root_); 
            root_ = this->copy_tree(old.root_); 
            size_ = old.size_; 
        }
        return *this;
    }

typedef tree_iterator<T> iterator;

int size() const { return size_; } 
bool operator==(const cs2set<T>& old) const { return (old.root_ == this->root_); }
// FIND, INSERT & ERASE
iterator find(const T& key_value) { return find(key_value, root_); }
std::pair< iterator, bool > insert(T const& key_value) { return insert(key_value, root_); }
int erase(T const& key_value) { return erase(key_value, root_); }

// OUTPUT & PRINTING
friend std::ostream& operator<< (std::ostream& ostr, const cs2set<T>& s) {
    s.print_in_order(ostr, s.root_);
    return ostr;
}
void print_as_sideways_tree(std::ostream& ostr) const { print_as_sideways_tree(ostr, root_, 0); }

// ITERATORS
iterator begin() const {
    // Implemented in Lecture 16
}
iterator end() const { return iterator(NULL); }

private:
    // REPRESENTATION
    TreeNode<T>* root_;
    int size_;

    // PRIVATE HELPER FUNCTIONS
    TreeNode<T>* copy_tree(TreeNode<T>* old_root) { /* Implemented in Lab 10 */ }
    void destroy_tree(TreeNode<T>* p) { /* Implemented in Lecture 17 */ }

    iterator find(const T& key_value, TreeNode<T>* p) {
        // Implemented in Lecture 16
    }

    std::pair<iterator, bool> insert(const T& key_value, TreeNode<T>*& p) { /* Discussed in Lecture 17 */ }
    int erase(T const& key_value, TreeNode<T>* &p) { /* Implemented in Lecture 17 */ }

    void print_in_order(std::ostream& ostr, const TreeNode<T>* p) const {
        // Discussed in Lecture 16
        if (p) {
            print_in_order(ostr, p->left);
            ostr << p->value << "\n";
            print_in_order(ostr, p->right);
        }
    }
    void print_as_sideways_tree(std::ostream& ostr, const TreeNode<T>* p, int depth) const {
        /* Discussed in Lecture 17 */
    }
};

#endif