CMSC 341

Binary Search Trees
Binary Search Tree

A *Binary Search Tree* is a Binary Tree in which, at every node \( v \), the values stored in the left subtree of \( v \) are less than the value at \( v \) and the values stored in the right subtree are greater.

The elements in the BST must be comparable.

Duplicates are not allowed.
BST Implementation

The SearchTree ADT

- A *search tree* is a binary search tree which stores homogeneous elements with no duplicates.
- It is dynamic.
- The elements are ordered in the following ways
  - inorder -- as dictated by operator<
  - preorder, postorder, levelorder -- as dictated by the structure of the tree
- Each BST maintains a simple object, known as ITEM_NOT_FOUND, that is guaranteed to not be an element of the tree. ITEM_NOT_FOUND is provided to the constructor. (author’s code)
BinarySearchTree class

template <class Comparable>
class BinarySearchTree {
    public:
    BinarySearchTree(const Comparable& notFnd);
    BinarySearchTree (const BinarySearchTree& rhs);
    ~BinarySearchTree();

    const Comparable& findMin() const;
    const Comparable& findMax() const;
    const Comparable& find(const Comparable& x) const;
    bool isEmpty() const;
    void printTree() const;
    void makeEmpty();
    void insert (const Comparable& x);
    void remove (const Comparable& x);
    const BinarySearchTree &operator=(const
    BinarySearchTree& rhs);
BinarySearchTree class (cont)

private:
    BinaryNode<Comparable> *root;
    const Comparable ITEM_NOT_FOUND;
    const Comparable&
        elementAt(BinaryNode<Comparable> *t) const;
    void insert (const Comparable& x,
        BinaryNode<Comparable> *& t) const;
    void remove (const Comparable& x,
        BinaryNode<Comparable> *& t) const;
    BinaryNode<Comparable>*
        findMin(BinaryNode<Comparable>* t const;
    BinaryNode<Comparable>*
        findMax(BinaryNode<Comparable>* t) const;
    BinaryNode<Comparable>*
        find(const Comparable& x, BinaryNode<Comparable>* t) const;
    void makeEmpty(BinaryNode<Comparable> * & t) const;
    void printTree(BinaryNode<Comparable>* t) const;
    BinaryNode<Comparable>* clone(BinaryNode<Comparable>* t) const;
};
BinarySearchTree Implementation

template <class Comparable>
const Comparable &BinarySearchTree<Comparable> ::
find(const Comparable& x) const {
    return elementAt(find(x, root));
}

template <class Comparable>
const Comparable& BinarySearchTree<Comparable> ::
elementAt(BinaryNode<Comparable>* t) const {
    return t == NULL ? ITEM_NOT_FOUND : t->element;
}

template <class Comparable>
BinaryNode<Comparable>* BinarySearchTree<Comparable> ::
find(const Comparable& x, BinaryNode<Comparable>* t) const {
if (t == NULL) return NULL;
else if (x < t->element) return find(x, t->left);
else if (t->element < x) return find(x, t->right);
else return t; // Match
Performance of find

Searching in randomly built BST is $O(\lg n)$ on average

- but generally, a BST is not randomly built

Asymptotic performance is $O(\text{height})$ in all cases
Predecessor in BST

Predecessor of a node $v$ in a BST is the node that holds the data value that immediately precedes the data at $v$ in order.

Finding predecessor

– $v$ has a left subtree
  • then predecessor must be the largest value in the left subtree (the rightmost node in the left subtree)

– $v$ does not have a left subtree
  • predecessor is the first node on path back to root that does not have $v$ in its left subtree
Successor in BST

Successor of a node $v$ in a BST is the node that holds the data value that immediately follows the data at $v$ in order.

Finding Successor

- $v$ has right subtree
  - successor is smallest value in right subtree (the leftmost node in the right subtree)

- $v$ does not have right subtree
  - successor is first node on path back to root that does not have $v$ in its right subtree
The remove Operation

template <class Comparable>
void BinarySearchTree<Comparable>::
remove(const Comparable& x, BinaryNode<Comparable> * & t) const
{
    if (t == NULL)
        return;        // item not found, do nothing
    if (x < t->element)
        remove(x, t->left);
    else if (t->element < x)
        remove(x, t->right);
    else if (((t->left != NULL) && (t->right != NULL)) {  
        t->element = (findMin (t->right))->element;
        remove (t->element, t->right);
    } else {
        BinaryNode<Comparable> *oldNode = t;
        t = (t->left != NULL) ? t->left : t->right;
    delete oldNode;
}
The insert Operation

template <class Comparable>
void BinarySearchTree<Comparable>::
insert(const Comparable& x)   // public insert( )
{
    insert (x, root);          // calls private insert( )
}

template <class Comparable>
void BinarySearchTree<Comparable>::
insert(const Comparable& x, BinaryNode<Comparable>* &t ) const
{
    if (t == NULL)
        t = new BinaryNode<Comparable>(x, NULL, NULL);
    else if (x < t->element)
        insert (x, t->left);
    else if (t->element < x)
        insert (x, t->right);
    else
        ; // Duplicate; do nothing
}
Implementation of makeEmpty

template <class Comparable>
void BinarySearchTree<Comparable>::
makeEmpty() // public makeEmpty ()
{
    makeEmpty(root); // calls private makeEmpty ()
}

template <class Comparable>
void BinarySearchTree<Comparable>::
makeEmpty(BinaryNode<Comparable> *& t) const
{
    if (t != NULL) { // post order traversal
        makeEmpty (t->left);
        makeEmpty (t->right);
        delete t;
    }
    t = NULL;
}
Tree Iterators

Could provide separate iterators for each desired order

- `Iterator<T> *GetInorderIterator();`
- `Iterator<T> *GetPreorderIterator();`
- `Iterator<T> *GetPostorderIterator();`
- `Iterator<T> *GetLevelorderIterator();`
Tree Iterator Implementation
Approach 1: Store traversal in list (private data member). Return iterator for list.

```cpp
Iterator<T> BinaryTree::GetInorderIterator() {
    m_theList = new ArrayList<T>;
    FullListInorder(m_theList, getRoot());
    return m_theList->GetIterator();
}

void FillListInorder(ArrayList<T> *lst, Bnode<T> *node) {
    if (node == NULL) return;
    FillListInorder(lst, node->left);
    lst->Append(node->data);
    FillListInorder(lst, node->right);
}
```
Tree Iterators (cont)

Approach 2: store traversal in stack to mimic recursive traversal

template <class T>
class InOrderIterator
{
    private:
        Stack<BNode<T> > m_stack;

    public:
        InOrderIterator(BinaryTree<T> *t);
        bool hasNext()       // aka isPastEnd
            {return !m_stack.isEmpty(); } // aka advance()
Tree Iterators (cont’d)

template <class T>
InOrderIterator<T>::InOrderIterator(BinaryTree<T> *t)
{
    BNode<T> *v = t->getRoot();
    while (v != NULL) {
        m_stack.Push(v); // push root
        v = v->left;     // and all left descendants
    }
}
Tree Iterators (cont’d)

template <class T>
T InOrderIterator<T>::Next()
{
    Bnode<T> *top = m_stack.Top();
    m_stack.Pop();
    BNode<T> *v = top->right;
    while (v != NULL) {
        m_stack.Push(v);       // push right child
        v = v->left;           // and all left descendants
    }
    return top->element;
}