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 in our discussion.

Note that each subtree of a BST is also a BST.
A BST of integers

Describe the values which might appear in the subtrees labeled A, B, C, and D
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
BST Implementation

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

        const Comparable & findMin( ) const;
        const Comparable & findMax( ) const;
        bool contains( const Comparable & x ) const;
        bool isEmpty( ) const;
        void printTree( ) const;

        void makeEmpty( );
        void insert( const Comparable & x );
        void remove( const Comparable & x );
BST Implementation (2)

```
const BinarySearchTree &
    operator=( const BinarySearchTree & rhs );

private:
    struct BinaryNode
    {
        Comparable element;
        BinaryNode *left;
        BinaryNode *right;

        BinaryNode( const Comparable & theElement,
                    BinaryNode *lt, BinaryNode *rt )
            : element( theElement ), left( lt ), right( rt )
            { } };
```
BST Implementation (3)

// private data
  BinaryNode *root;

// private recursive functions
void insert( const Comparable & x, BinaryNode * & t ) const;
void remove( const Comparable & x, BinaryNode * & t ) const;
BinaryNode * findMin( BinaryNode *t ) const;
BinaryNode * findMax( BinaryNode *t ) const;
bool contains( const Comparable & x, BinaryNode *t ) const;
void makeEmpty( BinaryNode * & t );
void printTree( BinaryNode *t ) const;
BinaryNode * clone( BinaryNode *t ) const;
};
BST “contains” method

// Returns true if x is found (contained) in the tree.
bool contains( const Comparable & x ) const
{
    return contains( x, root );
}

// Internal (private) method to test if an item is in a subtree.
// x is item to search for.
// t is the node that roots the subtree.
bool contains( const Comparable & x, BinaryNode *t ) const
{
    if( t == NULL )
        return false;
    else if( x < t->element )
        return contains( x, t->left );
    else if( t->element < x )
        return contains( x, t->right );
    else
        return true;    // Match
Performance of "contains"

Searching in randomly built BST is $O(lg n)$ on average — but generally, a BST is not randomly built.

Asymptotic performance is $O($height$)$ in all cases.
The insert Operation

// Internal method to insert into a subtree.
// x is the item to insert.
// t is the node that roots the subtree.
// Set the new root of the subtree.

void insert( const Comparable & x, BinaryNode * & t )
{
    if( t == NULL )
        t = new BinaryNode( 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
}
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

// Internal (private) method to remove from a subtree.
// x is the item to remove.
// t is the node that roots the subtree.
// Set the new root of the subtree.
void remove( const Comparable & x, BinaryNode * & t )
{
    if( t == NULL )
        return; // x 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 ) // two children
        {
            t->element = findMin( t->right )->element;
            remove( t->element, t->right );
        }
    else // zero or one child
        {
            BinaryNode *oldNode = t;
            t = ( t->left != NULL ) ? t->left : t->right;
            delete oldNode;
        }
}
Implementation of makeEmpty

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

template <typename 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;
}
Implementation of Assignment Operator

// operator= makes a deep copy via cloning
const BinarySearchTree & operator=( const BinarySearchTree & rhs )
{
    if( this != &rhs )
    {
        makeEmpty(); // free LHS nodes first
        root = clone( rhs.root ); // make a copy of rhs
    }
    return *this;
}

//Internal method to clone subtree -- note the recursion
BinaryNode * clone( BinaryNode * t ) const
{
    if( t == NULL )
        return NULL;
    return new BinaryNode( t->element, clone(t->left), clone(t->right) );
}
Performance of BST methods

What is the asymptotic performance of each of the BST methods?

<table>
<thead>
<tr>
<th></th>
<th>Best Case</th>
<th>Worst Case</th>
<th>Average Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>contains</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>insert</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remove</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>findMin/Max</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>makeEmpty</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>assignment</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Building a BST

Given an array/vector of elements, what is the performance (best/worst/average) of building a BST from scratch?
Tree Iterators

As we know there are several ways to traverse through a BST. For the user to do so, we must supply different kind of iterators. The iterator type defines how the elements are traversed.

- InOrderIterator<T> *InOrderBegin( );
- PerOrderIterator<T> *PreOrderBegin( );
- PostOrderIterator<T> *PostOrderBegin( );
- LevelOrderIterator<T> *LevelOrderBegin( );
Using Tree Iterator

main ( )
{
    BST<int> tree;

    // store some ints into the tree
    BST<int>::InOrderIterator<int> itr = tree.InOrderBegin( );
    while ( itr != tree.InOrderEnd( ) )
    {
        int x = *itr;

        // do something with x

        ++itr;
    }
}
BST begin( ) and end( )

// BST InOrderBegin( ) to create an InOrderIterator
template <typename T>
InOrderIterator<T> BST<T>::InOrderBegin( )
{
    return InOrderIterator( m_root );
}

// BST InOrderEnd( ) to signal "end" of the tree
template <typename T>
InOrderIterator<T> BST<T>::InOrderBegin( )
{
    return InOrderIterator( NULL );
}
// An InOrderIterator that uses a list to store
// the complete in-order traversal
template < typename T >
class InOrderIterator
{
    public:
        InOrderIterator( );
        InOrderIterator operator++ ( );
        T operator* ( ) const;
        bool operator != (const InOrderIterator& rhs) const;
    private:
        InOrderIterator( BinaryNode<T> * root);
        typename List<T>::iterator m_listIter;
        List<T> m_theList;
};
// InOrderIterator constructor
// if root == NULL, an empty list is created
template <typename T>
InOrderIterator<T>::InOrderIterator( BinaryNode<T> * root )
{
    FillListInorder( m_theList, root );
    m_listIter = m_theList.begin( );
}

// constructor helper function
template <typename T>
void FillListInorder( List<T>& list, BinaryNode<T> *node)
{
    if (node == NULL) return;
    FillListInorder( list, node->left );
    list.push_back( node->data );
    FillListInorder( list, node->right );
}
List-based InOrderIterator Operators
Call List Iterator operators

template <typename T>
T InOrderIterator<T>::operator++ ( )
{
    ++m_listIter;
}

template <typename T>
T InOrderIterator<T>::operator* ( ) const
{
    return *m_listIter;
}

template <typename T>
bool InOrderIterator<T>::operator!=(const InOrderIterator& rhs) const
{
    return m_ListIter != rhs.m_listIter;
}
InOrderIterator Class with a Stack

// An InOrderIterator that uses a stack to mimic recursive traversal
// InOrderEnd() creates a stack containing only a NULL point
// InOrderBegin() pushes a NULL onto the stack so that iterators
// can be compared

template < typename T >
class InOrderIterator
{

public:
   InOrderIterator( );
   InOrderIterator operator++ ( );
   T operator* ( ) const;
   bool operator== (const InOrderIterator& rhs) const;

private:
   InOrderIterator( BinaryNode<T>* root );
   Stack<BinaryNode<T> * > m_theStack;
}

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Stack-Based InOrderIterator Constructor

template< typename T >  // default constructor
InOrderIterator<T>::InOrderIterator ( )
{
    m_theStack.Push(NULL);
}

// if t is null, an empty stack is created
template <typename T>
InOrderIterator<T>::InOrderIterator( BinaryNode<T> *t )
{
    // push a NULL as "end" of traversal
    m_theStack.Push( NULL );

    BinaryNode *v = t;   // root
    while (v != NULL) {
        m_theStack.Push(v); // push root
        v = v->left;        // and all left descendants
    }
}
Stack-Based InOrderIterator Operators

template <typename T>
InOrderIterator<T> InOrderIterator<T>::operator++( )
{
    if (m_theStack.IsEmpty( ) || m_theStack.Top() == NULL)
        throw StackException( );

    BinaryNode *v = (m_theStack.Top( ))->right;
    m_theStack.Pop();
    while ( v != NULL )
    {
        m_theStack.Push( v ); // push right child
        v = v->left;         // and all left descendants
    }
    return *this;
}
// operator* -- return data from node on top of stack
template< typename T >
T InOrderIterator<T>::operator*() const
{
    if (m_theStack.IsEmpty())
        throw StackException();
    return (m_theStack.Top())->element;
}

// operator ==
template< typename T >
bool InOrderIterator<T>::operator==(const InOrderIterator& rhs) const
{
    return m_theStack.Top() == rhs.m_theStack.Top();
}
More Recursive Binary (Search) Tree Functions

- `bool isBST ( BinaryNode<T> *t )` returns true if the Binary tree is a BST

- `const T& findMin( BinaryNode<T> *t )` returns the minimum value in a BST

- `int CountFullNodes ( BinaryNode<T> *t )` returns the number of full nodes (those with 2 children) in a binary tree

- `int CountLeaves( BinaryNode<T> *t )` counts the number of leaves in a Binary Tree