

Binary Search Trees

Proficiency: Mastery with Distinction

The binary tree structure is throughout computer science. A binary tree is a structure that starts a single root and has two children nodes (left and right). Every node in the tree has at most two children. Hence each row in a complete binary tree has 2 times more nodes than the row above it. This characteristic is what makes binary trees so appealing in computer science. A traversal from the root to a leaf in a complete binary tree will take $\log n$ time because the height of a complete tree is $\log n$. Binary Search Trees are a binary trees with more rules. In a binary search tree the left child must be less than or equal to the parent node and the right child must be greater than the parent node. This additional characteristic makes searching a binary search tree very efficient. If you're looking for some node with value x , you simply compare the current node you're looking at with your desired value. If the current node has a larger value than the node you're looking for, you know your desired node is in the left subtree since it is smaller. Because the height of the binary search tree is at best $\log n$, searching, inserting and deleting items from it take on average $O(\log n)$. Unfortunately all three functions have a worst time complexity of $O(n)$. This occurs if we're inserting a sorted list. If we first insert a 1, then a 2, then a 3, then a 4 and so on every new node is the right child of the previous node. In this case the height of the binary tree is n and not $\log n$. A way to avoid this problem is using another binary tree- The Red Black Tree.

Red Black Trees are a type of binary search tree. The RBT has all the characteristics as a binary search tree as well as five more. These extra five

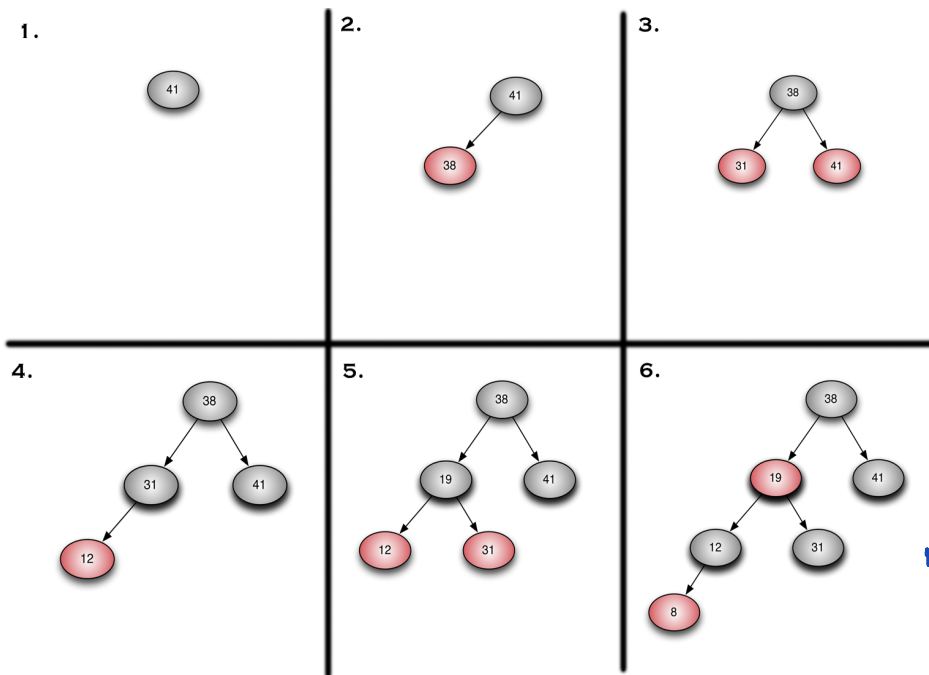
characteristics guarantee that a red black tree's height will never be more than $2\log(n+1)$. The five characteristics are: Every node is red or black, the root of the tree is black, the leaves of the tree are black, if a node is red both children are black and for each node, all paths from the node to a descendant leaf contain the same amount of black nodes, this is known as the black height. When inserting nodes into a RBTree these characteristics might be violated, to make the tree's structure obey the rules of a RBTree we use a function called RBTreeFixup. This function targets the problem and fixes the tree by either rotating certain sub trees and or changing the colors of nodes. Because the height of a RBTree is never more than $2\log(n+1)$ even the worst case of insert, delete and search is $O(\log n)$. This year we implemented a red black tree, attached is the code.

100

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CS 271 - proj1000

1. Let a , b and c be arbitrary nodes in subtrees in α, β, γ where α is a left subtree of node x , node y is the right child of x , β is a left subtree of y and γ is a right subtree of y . Let a have a depth of d , b have a depth of e and c have a depth of f . After a left rotation has been performed on node x the depths of a and c change while the depth of b stays the same. α remains the left subtree of x , but node x is now the left child of y , therefore the depth of a increases by one, $d + 1$. γ remains the right subtree of y but y is now the parent of x instead of being the child of x , so the depth of c decreases by one, $f - 1$. β changes from the left subtree of y to the right subtree of x , hence the depth of b doesn't change, e .



- 2.
3. Suppose we have a non empty Red Black Tree. By the fifth property of a Red Black Tree we know for every node x , every path to a descendent leaf contains $bh(x)$, the black height of x , black nodes. Therefore the shortest path from x to a leaf would be at least of length $bh(x)$, where the path contains at least zero red nodes. According to the fourth property of a Red Black Tree we know that if a red node has children both must be black nodes, hence red nodes can not be children of another red node.

Therefore the longest path from x to a leaf would also contain $bh(x)$ black nodes. At most, every other node in the longest path is red because the path alternates between red and black nodes, so the length of the longest path is at most $2(bh(x))$. Hence ✓ the longest path from a node x in a red-black tree to a descendant leaf has length at most twice that of the shortest path from x to a descendant leaf.

4. See Attached

5. See Attached

✓ 6. We compared the insert time of our Binary Search tree, Hash Table and Red Black Tree. On average the Red Black Tree inserted the entire movie library in 0.2182 seconds. The Hash Table was a close second with an average time of 0.2236 and the Binary Search Tree took an average 3.076 seconds. The insert time for the Binary Search Tree was much longer than the Red Black Tree and Hash Table due to the ordering of the movie files. Since the movies in the movie library were in alphabetical order, ever subsequent movie added into the BST was added to the right child due to how the Binary Search tree determined the placement of strings (the movie titles). Since every node is connected to one other node the Binary Search Tree was essentially a linked list, therefore the insert time was close to $O(n^2)$. The running time to insert into the Hash Table is largely affected by the hash function. A poor hash function may cause a large amount of movies to be chained together, making the running time of inserting a movie close to $O(n)$. Our hash function was fairly effecient which allowed for a running time slightly larger than $O(1)$ The Red Black Tree had the fastest running time due to its characteristics which helps make the tree more complete and doesn't allow the problem that the Binary Search Tree encountered with constanly inserting to the right. Therefore the insert time for our Red Black Tree was $O(\log n)$.

	Red Black Tree	Hash Table	Binary Search Tree
	0.174	0.192	3.087
	0.224	0.225	3.029
	0.253	0.249	3.114
	0.242	0.238	3.132
	0.198	0.214	3.018
Average	0.2182	0.2236	3.076



```
// rb.h
// Red/Black Tree header file
// Clay Sarafin & Taylor Heilman
```

```
#ifndef RB_H
#define RB_H
```

```
template <class T>
class RBNode{
public:
```

```
    RBNode();
    RBNode(T* initValue);
    RBNode(char c);
```

```
    T* value;
    char color;
```

```
    RBNode<T>* parent;
    RBNode<T>* left;
    RBNode<T>* right;
```

```
};
```

```
template <class T>
class RBTree{
protected:
```

```
    int count;
    RBNode<T> *root;
    static RBNode<T> *nil;
```

```
    void createNode(RBNode<T>* node);
```

```
    RBNode<T>* copy(RBNode<T> *node, RBNode<T> * newP);
    void dealloc(RBNode<T> *ptr);
```

```
    RBNode<T> *getNode(RBNode<T> *ptr, const T& z);
```

```
    T *maximum_private(RBNode<T>* ptr);
    T *minimum_private(RBNode<T>* ptr);
```

```
    std::string inOrder_private(RBNode<T> *ptr, std::string str);
    std::string preOrder_private(RBNode<T> *ptr, std::string str);
    std::string postOrder_private(RBNode<T> *ptr, std::string str);
```

```
public:
```

```
    RBTree();
    RBTree(const RBTree<T>& rb);
    ~RBTree();
```

```
    RBTree<T>& operator=(const RBTree<T>& rb);
```

```
    bool empty();
    T* get(const T& z);
```

```
    void insert(T* z);
    void insertFixUp(RBNode<T>* z);
    void leftRotate(RBNode<T>* z);
    void rightRotate(RBNode<T>* z);
```

```
    T* maximum();
```

```
T* minimum();
```

```
T* successor(const T& z);
```

```
T* predecessor(const T& z);
```

```
std::string inOrder();
```

```
// return string of elements from an inorder traversal
```

```
std::string preOrder();
```

```
// return string of elements from a preorder traversal
```

```
std::string postOrder();
```

```
// return string of elements from a postorder traversal
```

```
1
```

```
int getCount();
```

```
};
```

```
class EmptyError {};
```

```
class ExistError {};
```

```
#endif
```

```
#include "rb.cpp"
```

```
// rb.cpp
// Red/Black Tree implementation
// Clay Sarafin & Taylor Heilman
```

```
#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sstream>
```

```
using namespace std;
template<class T>
RBNode<T> *RBTree<T>::nil = new RBNode<T>('b');
```

```
/*code is essentially a c/p from the BST class,
except with the appropriate names replaced (such as BSTNode -> RBNode)
as well as the appropriate NULL pointers replaced to nil*/
```

```
/*=====
```

```
Node - (DE)CONSTRUCTORS
```

```
=====*/
```

```
/*-----
```

```
* Default Constructor
```

```
* Preconditions:      n/a
```

```
* PostConditions:     empty Node class
```

```
all pointers (value, left, right, parent) point nil
```

```
-----*/
```

```
template<class T>
RBNode<T>::RBNode(){
    value = NULL;
    left = NULL;
    right = NULL;
    parent = NULL;
```

```
    color = 'r';
```

```
}
```

```
/*-----
```

```
* Construct with Item Pointer
```

```
* Preconditions:      pointer to an value of type T
```

```
* PostConditions:     Node class where the value pointer points to the value
all other pointers point to nil
```

```
-----*/
```

```
template<class T>
RBNode<T>::RBNode(T *initValue){
    value = initValue;
    left = NULL;
    right = NULL;
    parent = NULL;
```

```
    color = 'r';
```

```
}
```

```
/*-----
```

```
* Construct with color
```

```
* Preconditions:      char 'r' for red, 'b' for black
```

```
* PostConditions:     Node class where the node has color c
```

```
-----*/
```

```
template<class T>
RBNode<T>::RBNode(char c){
    value = NULL;
    left = NULL;
```



```

    right = NULL;
    parent = NULL;

```

```

    color = c;

```

```

}

```

```

/*=====

```

```

                RBTREE - (DE)CONSTRUCTORS

```

```

=====*/

```

```

/*-----

```

```

    * Default Constructor

```

```

    * Preconditions:      n/a

```

```

    * PostConditions:     empty RBTREE class created, where root points to nil

```

```

-----*/

```

```

template <class T>

```

```

RBTREE<T>::RBTREE(){

```

```

    count = 0;

```

```

    root = nil;

```

```

}

```

```

/*-----

```

```

    * Copy Constructor, operator=

```

```

    * Preconditions:      a RBTREE

```

```

    * PostConditions:     RBTREE is copied over to a new RBTREE, and is in the exact same form

```

```

-----*/

```

```

template <class T>

```

```

RBTREE<T>::RBTREE(const RBTREE<T>& rb){

```

```

    root = nil;

```

```

    root = copy(rb.root, nil);

```

```

}

```

```

template <class T>

```

```

RBTREE<T>& RBTREE<T>::operator=(const RBTREE<T>& rb){

```

```

    dealloc();

```

```

    root = copy(rb.root, nil);

```

```

    return *this;

```

```

}

```

```

template <class T>

```

```

RBNode<T>* RBTREE<T>::copy(RBNode<T> *node, RBNode<T> *newP){

```

```

    //will traverse through the RBTREE to be copied w/ preOrder

```

```

    //instead of printing, the new node will be created and will

```

```

    //be assigned to the parent in the parameter

```

```

    if (node == nil)

```

```

        return nil;

```

```

    RBNode<T> *newNode = new RBNode<T>(node->value);

```

```

    newNode->color = node->color;

```

```

    newNode->parent = newP;

```

```

    newNode->left = copy(node->left, newNode);

```

```

    newNode->right = copy(node->right, newNode);

```

```

    return newNode;

```

```

}

```

```

/*-----

```

```

    * Destructor

```

```

    * Preconditions:      n/a

```

```

    * PostConditions:     all nodes that exists in the RBTREE are deleted

```

```

-----*/

```

```

template <class T>

```

```

RBTree<T>::~~RBTree(){
    dealloc(root);
}

```

```

template <class T>
void RBTree<T>::dealloc(RBNode<T> *ptr){
    if (ptr == nil)
        return;
    dealloc(ptr->left);
    dealloc(ptr->right);
    delete ptr;

    return;
}

```

```

/*+++++
                                     RBTree - FUNCTIONS
+++++*/

```

```

/*-----
 * createNode()
 * Preconditions:      a preexisting node
 * PostConditions:     pointers in the NULL that need to assigned to nil will be assigned to
nil
-----*/

```

```

template <class T>
void RBTree<T>::createNode(RBNode<T>* node){
    node->parent = nil;
    node->left = nil;
    node->right = nil;
}

```

```

/*-----
 * empty()
 * Preconditions:      n/a
 * PostConditions:     returns true if empty, false if not
-----*/

```

```

template <class T>
bool    RBTree<T>::empty(){
    return (count == 0);
    //alt approach: return (root == nil);
}

```

```

/*-----
 * get()
 * Preconditions:      tree is not empty
                        value of type T has the operator '==' and '<' overloaded
                        user has never modified what the value pointer points to in insert()
 * PostConditions:     returns a pointer to the value if it exists
                        returns nil if it does not
-----*/

```

```

template <class T>
T*      RBTree<T>::get(const T& z){
    if (empty())
        throw EmptyError();
    RBNode<T> *node = getNode(root, z);
    //node = nil when RBTree is empty, or if value doesn't exist
    //already covered the empty part, so logically the node doesn't exist
    if (node == nil)
        return NULL;                //does this matter now?
}

```

```

    return node->value;
}

```

```

template <class T>
RBNNode<T>* RBTTree<T>::getNode(RBNNode<T> *ptr, const T& z){
    if (ptr == nil) //BC: value not found, or tree is empty
        return nil;
    if (*(ptr->value) == z) //found value
        return ptr;
    if(z < *(ptr->value)) //traverse tree to find value
        return getNode(ptr->left,z);
    else
        return getNode(ptr->right,z);
}

```

```

/*-----
 * insert()
 * Preconditions:    value of type T has the operator '<' overloaded
 * PostConditions:   value z is inserted into the tree
                   tree is still a valid RBTTree
-----*/

```

```

template <class T>
void RBTTree<T>::insert(T *z){
    RBNNode<T>* y = nil;
    RBNNode<T>* x = root;

    RBNNode<T>* newNode = new RBNNode<T>(z);
    createNode(newNode);

    while (x != nil){ //traverse through tree to find appropriate place to insert node
        y = x;
        if (*(newNode->value) < *(x->value))
            x = x->left;
        else
            x = x->right;
    }

    newNode->parent = y;
    if (y == nil) //tree is empty, make root point to new node
        root = newNode;
    else if (*(newNode->value) < *(y->value)) //make appropriate subchild point to inserted node
        y->left = newNode;
    else
        y->right = newNode;

    insertFixUp(newNode); //call function to make the RBTree valid again
    count++;
}

```

```

/*-----
 * insertFixUp()
 * Preconditions:    pointer to node inserted into the tree
 * PostConditions:   tree will be fixed to be a valid RBTree
-----*/

```

```

template <class T>
void RBTTree<T>::insertFixUp(RBNNode<T>* z){
    RBNNode<T>* y;

    while (z->parent->color == 'r'){

```

```

    if (z->parent == z->parent->parent->left){
        y = z->parent->parent->right;
        if (y->color == 'r'){
            z->parent->color = 'b';
            y->color = 'b';
            z->parent->parent->color = 'r';
            z = z->parent->parent;
        }
        else{
            if (z == z->parent->right){
                z = z->parent;
                leftRotate(z);
            }
            z->parent->color = 'b';
            z->parent->parent->color = 'r';
            rightRotate(z->parent->parent);
        }
    }
    else{
        y = z->parent->parent->left;
        if (y->color == 'r'){
            z->parent->color = 'b';
            y->color = 'b';
            z->parent->parent->color = 'r';
            z = z->parent->parent;
        }
        else{
            if (z == z->parent->left){
                z = z->parent;
                rightRotate(z);
            }
            z->parent->color = 'b';
            z->parent->parent->color = 'r';
            leftRotate(z->parent->parent);
        }
    }
}

```

```

    root->color = 'b';
as changed to red
}

```

```

/*-----
* leftRotate()
* Preconditions:    pointer to node in the RBTree
* PostConditions:   nodes in the tree will be rotated to the left such that
                    (with y being the right child of z):
                    left child of z is not modified
                    right child of y is not modified
                    z's right child is the left subtree of y
                    y's left child is z
-----*/

```

```

template <class T>
void RBTree<T>::leftRotate(RBNode<T>* z){
    RBNode<T>* child = z->right;

    z->right = child->left;
    if(child->left != nil)
        child->left->parent = z;
    child->parent = z->parent;
    if(z->parent == nil)
        root = child;
    else if (z == z->parent->left)

```

```

        z->parent->left = child;
    else
        z->parent->right = child;
    child->left = z;
    z->parent = child;
}

/*-----
 * rightRotate()
 * Preconditions:      pointer to node in RBTREE
 * PostConditions:     nodes in the tree will be rotated to the right such that
                       (with y being the left child of z):
                       right child is not modified
                       left child of y is not modified
                       z's left child is the right subtree of y
                       y's right child is z
-----*/

template <class T>
void RBTREE<T>::rightRotate(RBNode<T>* z){
    //code from leftRotate(), except left <-> right
    RBNode<T>* child = z->left;
    z->left = child->right;
    if(child->right != nil)
        child->right->parent = z;
    child->parent = z->parent;
    if(z->parent == nil)
        root = child;
    else if (z == z->parent->right)
        z->parent->right = child;
    else
        z->parent->left = child;
    child->right = z;
    z->parent = child;
}

/*-----
 * maximum()
 * Preconditions:      tree is not empty
                       user has never modified what the value pointer points to in insert()
 * PostConditions:     returns pointer to the maximum value in the tree
-----*/

template <class T>
T* RBTREE<T>::maximum(){
    return maximum_private(root);
}

template <class T>
T* RBTREE<T>::maximum_private(RBNode<T>* ptr){
    if (ptr == nil) //nothing exists in RBTREE
        throw EmptyError();

    if (ptr->right == nil)
        return ptr->value;
    else
        return maximum_private(ptr->right);
}

/*-----
 * minimum()
 * Preconditions:      tree is not empty
                       user has never modified what the value pointer points to in insert()
 * PostConditions:     returns pointer to the minimum value in the tree
-----*/

```

```
-----*/
template <class T>
T* RBTree<T>::minimum(){
    return minimum_private(root);
}

template <class T>
T* RBTree<T>::minimum_private(RBNode<T>* ptr){
    if (ptr == nil)//nothing exists in RBTree
        throw EmptyError();

    if (ptr->left == nil)
        return ptr->value;
    else
        return minimum_private(ptr->left);
}

/*-----
 * sucessor()
 * Preconditions:      T z exists in RBTree
                      successor of z exists in the RBTree
                      user has never modified what the value pointer points to in insert()
 * PostConditions:     pointer to successor of z is returned
-----*/
template <class T>
T* RBTree<T>::successor(const T& z){
    RBNode<T> *ptr0 = getNode(root,z);
    if (ptr0 == nil)
        throw ExistError();
    RBNode<T> *ptr1;
    if (ptr0->right != nil)
        return minimum_private(ptr0->right);
    ptr1 = ptr0->parent;
    while((ptr1 != nil) && (ptr0 == ptr1->right)){
        ptr0 = ptr1;
        ptr1 = ptr1->parent;
    }

    if (ptr1 == nil)                //successor does not exist
        throw ExistError();

    return ptr1->value;
}

/*-----
 * predecessor()
 * Preconditions:      T z exists in RBTree
                      precedecessor of z exists in the RBTree
                      user has never modified what the value pointer points to in insert()
 * PostConditions:     pointer to predecessor of z is returned
-----*/
template <class T>
T* RBTree<T>::predecessor(const T& z){
    RBNode<T> *ptr0 = getNode(root,z);
    if (ptr0 == nil)
        throw ExistError();
    RBNode<T> *ptr1;
    if (ptr0->left != nil)
        return maximum_private(ptr0->left);
    ptr1 = ptr0->parent;
    while((ptr1 != nil) && (ptr0 == ptr1->left)){
        ptr0 = ptr1;
        ptr1 = ptr1->parent;
    }
}
```

```

    }

    if (ptr1 == nil)                //predecessor does not exist
        throw ExistError();

    return ptr1->value;
}

/*-----
 * inOrder(), preOrder(), and postOrder()
 * PreConditions:      n/a
 * PostConditions:     inOrder : string representation of the values in the RBTree are in or
der                          der
                        preOrder : string representations of the values in RBTree are shown
                            in pre order (starts with root, ends with max value)
                        postOrder: string representations of the values in RBTree are shown
                            in post order (starts with min value, ends with root)
                        all       : each value is followed by ", "
                                : user has never modified what the value pointer points to in

insert()
-----*/
template <class T>
std::string RBTree<T>::inOrder(){
    std::string str;
    str = inOrder_private(root,str);
    if (str == "")                //want to avoid using pop_back() on an empty string
        return str;
    else{
        str.pop_back();
        str.pop_back();
        return str;
    }
}

template <class T>
std::string RBTree<T>::inOrder_private(RBNode<T> *ptr, std::string str){
    if (ptr == nil){
        return str;
    }
    std::string str_null;        //null dummy string to help with recursion;
                                //if you pass in str as the parameter again, then
                                //it will append to that string in the funcion, then return th
at string                        //it will then append it to the string in the initial call, wh
ich is something                //not desired

    //left, print, right
    str += inOrder_private(ptr->left, str_null);
    str += std::to_string(*(ptr->value));
    str += "-";
    str += ptr->color;
    str += ", ";
    str += inOrder_private(ptr->right, str_null);

    return str;
}

template <class T>
std::string RBTree<T>::preOrder(){
    std::string str;
    str = preOrder_private(root,str);
    if (str == "")

```

```

        return str;
    else{
        str.pop_back();
        str.pop_back();
        return str;
    }
}

template <class T>
std::string RBTree<T>::preOrder_private(RBNode<T> *ptr, std::string str){
    if (ptr == nil){
        return str;
    }
    std::string str_null;

    //print, left, right
    str += std::to_string(*(ptr->value));
    str += "-";
    str += ptr->color;
    str += ", ";
    str += preOrder_private(ptr->left, str_null);
    str += preOrder_private(ptr->right, str_null);

    return str;
}

template <class T>
std::string RBTree<T>::postOrder(){
    std::string str;
    str = postOrder_private(root, str);
    if (str == "")
        return str;
    else{
        str.pop_back();
        str.pop_back();
        return str;
    }
}

template <class T>
std::string RBTree<T>::postOrder_private(RBNode<T> *ptr, std::string str){
    if (ptr == nil){
        return str;
    }
    std::string str_null;

    //left, right, print
    str += postOrder_private(ptr->left, str_null);
    str += postOrder_private(ptr->right, str_null);
    str += std::to_string(*(ptr->value));
    str += "-";
    str += ptr->color;
    str += ", ";

    return str;
}

/*-----
* getCount()
* Preconditions:      n/a
* PostConditions:     number of nodes that exists in the RBTree is returned
*-----*/
template <class T>

```



```
int RBTREE<T>::getCount(){  
    return count;  
}
```

```
// test_rb.cpp
// Red/Black Tree tests
// Clay Sarafin & Taylor Heilman

#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <assert.h>

#include "rb.h"

using namespace std;

int *zero  = new int(0);
int *one   = new int(1);
int *two   = new int(2);
int *three = new int(3);
int *four  = new int(4);
int *five  = new int(5);
int *six   = new int(6);
int *seven = new int(7);
int *eight = new int(8);
int *nine  = new int(9);

void insertTest(){
    RBTree<int> tree;

    tree.insert(five);
    tree.insert(zero);
    assert(tree.getCount() == 2);
    assert(tree.preOrder() == "5-b, 0-r"); //tests for empty tree, left subtree
    tree.insert(nine);
    assert(tree.preOrder() == "5-b, 0-r, 9-r"); //test for right subtree;
    //add everything else
    tree.insert(one);
    tree.insert(two);
    tree.insert(three);
    tree.insert(four);
    tree.insert(six);
    tree.insert(seven);
    tree.insert(eight);
    assert(tree.preOrder() == "5-b, 1-r, 0-b, 3-b, 2-r, 4-r, 7-r, 6-b, 9-b, 8-r");
}

void getTest(){
    RBTree<int> tree;

    try{
        tree.get(*one);
        assert(false);
    }
    catch(EmptyError){
    }

    tree.insert(one);
    tree.insert(two);
    tree.insert(three);
    tree.insert(four);
    tree.insert(six);
    tree.insert(seven);
    tree.insert(eight);
}
```

```
//test for root
assert(tree.get(*one) == one);
//test for non-leaf
assert(tree.get(*two) == two);
//test for leaf
assert(tree.get(*eight) == eight);           //not sure what's going on here

//test for nonexisting node in tree;
assert(tree.get(*five) == NULL);
}

void maxMinTest(){
    RBTree<int> tree;

    //test for EmptyError exceptions
    try{
        tree.minimum();
        assert(false);
    }
    catch(EmptyError exception){
    }
    try{
        tree.maximum();
        assert(false);
    }
    catch(EmptyError exception){
    }

    tree.insert(zero);
    tree.insert(one);
    tree.insert(two);

    //test min & max
    assert(tree.maximum() == two);
    assert(tree.minimum() == zero);
}

void predSuccTest(){
    RBTree<int> tree;

    //test ExistError exceptions
    try{
        tree.predecessor(0);
        assert(false);
    }
    catch(ExistError exception){
    }
    try{
        tree.successor(0);
        assert(false);
    }
    catch(ExistError exception){
    }

    tree.insert(four);
    tree.insert(two);
    tree.insert(three);
    tree.insert(one);
    tree.insert(seven);
    tree.insert(five);
    tree.insert(nine);
}
```

```

    assert(tree.predecessor(2) == one);
    assert(tree.successor(2) == three);

    assert(tree.predecessor(4) == three);
    assert(tree.successor(4) == five);

    assert(tree.predecessor(9) == seven);
    //test EmptyError exception for an item that doesn't exist
    try{
        tree.successor(9);
        assert(false);
    }
    catch(ExistError exception){
    }

    assert(tree.predecessor(3) == two);
    assert(tree.successor(3) == four);

```

```

}

```

```

void printTest(){
    RBTree<int> tree;
    assert(tree.inOrder() == "");
    assert(tree.preOrder() == "");
    assert(tree.postOrder() == "");

    tree.insert(zero);
    tree.insert(one);
    tree.insert(two);

    assert(tree.inOrder() == "0-r, 1-b, 2-r");
    assert(tree.preOrder() == "1-b, 0-r, 2-r");
    assert(tree.postOrder() == "0-r, 2-r, 1-b");

    RBTree<int> tree2;

    tree2.insert(four);
    tree2.insert(two);
    tree2.insert(three);
    tree2.insert(one);
    tree2.insert(seven);
    tree2.insert(five);
    tree2.insert(nine);
    /*
        3-b
       / \
      2-b 5-r
     / \ / \
    1-r 4-b 7-b
           \
            9-r
    */
    assert(tree2.inOrder() == "1-r, 2-b, 3-b, 4-b, 5-r, 7-b, 9-r");
    assert(tree2.preOrder() == "3-b, 2-b, 1-r, 5-r, 4-b, 7-b, 9-r");
    assert(tree2.postOrder() == "1-r, 2-b, 4-b, 9-r, 7-b, 5-r, 3-b");
}

```

```

void copyTest(){
    RBTree<int> tree0;

    tree0.insert(four);
    tree0.insert(two);

```

```
    tree0.insert(three);
    tree0.insert(one);
    tree0.insert(seven);
    tree0.insert(five);
    tree0.insert(nine);

    RBTTree<int> tree1(tree0);

    assert(tree1.inOrder() == "1-r, 2-b, 3-b, 4-b, 5-r, 7-b, 9-r");
    assert(tree1.preOrder() == "3-b, 2-b, 1-r, 5-r, 4-b, 7-b, 9-r");
    assert(tree1.postOrder() == "1-r, 2-b, 4-b, 9-r, 7-b, 5-r, 3-b");
}

int main(){
    insertTest();
    getTest();
    maxMinTest();
    predSuccTest();
    printTest();
    copyTest();

    delete zero;
    delete one;
    delete two;
    delete three;
    delete four;
    delete five;
    delete six;
    delete seven;
    delete eight;
    delete nine;
    return 0;
}
```

```
// dict.h
// header file for dictionary class
// Clay Sarafin & Taylor Heilman

#ifndef DICT_H
#define DICT_H

#include <iostream>

#include "rb.h"

using namespace std;

template <class KeyType>
class Dictionary : public RBTree<KeyType>{
public:
    Dictionary() : RBTree<KeyType>() {};

    using RBTree<KeyType>::get;
    using RBTree<KeyType>::insert;
    using RBTree<KeyType>::count;
    using RBTree<KeyType>::inOrder;
    using RBTree<KeyType>::empty;

    std::string toString();
};

#include "dict.cpp"

#endif
```

```
// dict.cpp
//
// Clay Sarafin & Taylor Heilman

#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <string>

using namespace std;

/*-----
 * toString()
 * Preconditions:      inOrder from BST class does not have brackets, every entry is followed
                        by ", "
                        and does not end with std::endl
                        type KeyType's operator<< is overloaded, and is formatted as "key:valu
e"
 * PostConditions:     string representation of the entire dictionary is printed out
-----*/

template <class KeyType>
std::string Dictionary<KeyType>::toString(){
    std::string str;
    str += "{";
    str += inOrder();
    str += "}";

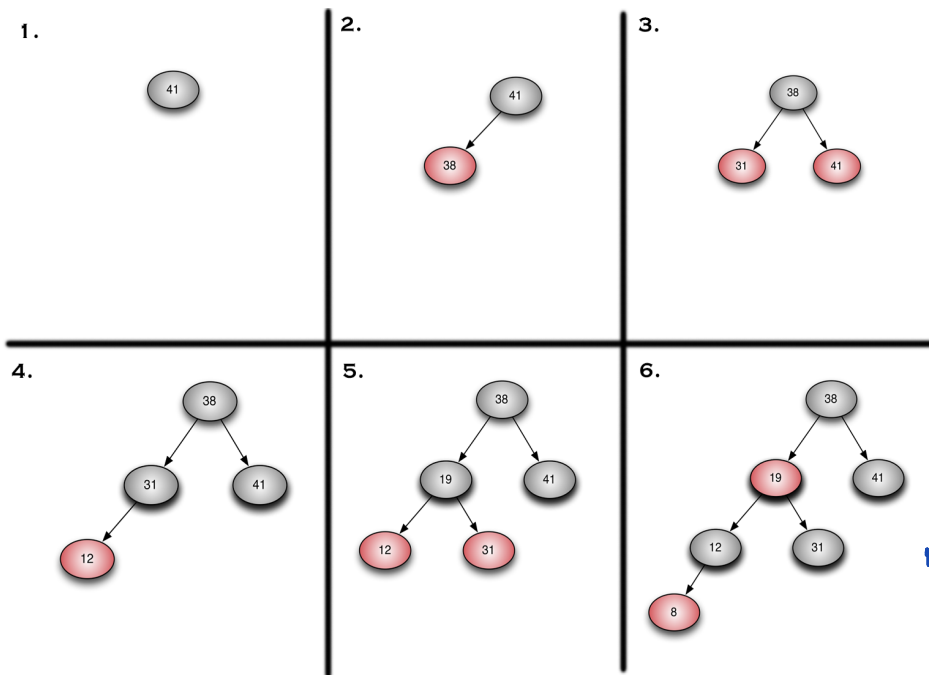
    return str;
}
```

100

Name: Clay Sarafin & Taylor Heilman

CS 271 - proj1000

1. Let a , b and c be arbitrary nodes in subtrees in α, β, γ where α is a left subtree of node x , node y is the right child of x , β is a left subtree of y and γ is a right subtree of y . Let a have a depth of d , b have a depth of e and c have a depth of f . After a left rotation has been performed on node x the depths of a and c change while the depth of b stays the same. α remains the left subtree of x , but node x is now the left child of y , therefore the depth of a increases by one, $d + 1$. γ remains the right subtree of y but y is now the parent of x instead of being the child of x , so the depth of c decreases by one, $f - 1$. β changes from the left subtree of y to the right subtree of x , hence the depth of b doesn't change, e .



2. 3. Suppose we have a non empty Red Black Tree. By the fifth property of a Red Black Tree we know for every node x , every path to a descendent leaf contains $bh(x)$, the black height of x , black nodes. Therefore the shortest path from x to a leaf would be at least of length $bh(x)$, where the path contains at least zero red nodes. According to the fourth property of a Red Black Tree we know that if a red node has children both must be black nodes, hence red nodes can not be children of another red node.

Therefore the longest path from x to a leaf would also contain $bh(x)$ black nodes. At most, every other node in the longest path is red because the path alternates between red and black nodes, so the length of the longest path is at most $2(bh(x))$. Hence ✓ the longest path from a node x in a red-black tree to a descendant leaf has length at most twice that of the shortest path from x to a descendant leaf.

4. See Attached

5. See Attached

✓ 6. We compared the insert time of our Binary Search tree, Hash Table and Red Black Tree. On average the Red Black Tree inserted the entire movie library in 0.2182 seconds. The Hash Table was a close second with an average time of 0.2236 and the Binary Search Tree took an average 3.076 seconds. The insert time for the Binary Search Tree was much longer than the Red Black Tree and Hash Table due to the ordering of the movie files. Since the movies in the movie library were in alphabetical order, ever subsequent movie added into the BST was added to the right child due to how the Binary Search tree determined the placement of strings (the movie titles). Since every node is connected to one other node the Binary Search Tree was essentially a linked list, therefore the insert time was close to $O(n^2)$. The running time to insert into the Hash Table is largely affected by the hash function. A poor hash function may cause a large amount of movies to be chained together, making the running time of inserting a movie close to $O(n)$. Our hash function was fairly effecient which allowed for a running time slightly larger than $O(1)$ The Red Black Tree had the fastest running time due to its characteristics which helps make the tree more complete and doesn't allow the problem that the Binary Search Tree encountered with constanly inserting to the right. Therefore the insert time for our Red Black Tree was $O(\log n)$.

	Red Black Tree	Hash Table	Binary Search Tree
	0.174	0.192	3.087
	0.224	0.225	3.029
	0.253	0.249	3.114
	0.242	0.238	3.132
	0.198	0.214	3.018
Average	0.2182	0.2236	3.076



```
// rb.h
// Red/Black Tree header file
// Clay Sarafin & Taylor Heilman
```

```
#ifndef RB_H
#define RB_H
```

```
template <class T>
class RBNode{
public:
```

```
    RBNode();
    RBNode(T* initValue);
    RBNode(char c);
```

```
    T* value;
    char color;
```

```
    RBNode<T>* parent;
    RBNode<T>* left;
    RBNode<T>* right;
```

```
};
```

```
template <class T>
class RBTree{
protected:
```

```
    int count;
    RBNode<T> *root;
    static RBNode<T> *nil;
```

```
    void createNode(RBNode<T>* node);
```

```
    RBNode<T>* copy(RBNode<T> *node, RBNode<T> * newP);
    void dealloc(RBNode<T> *ptr);
```

```
    RBNode<T> *getNode(RBNode<T> *ptr, const T& z);
```

```
    T *maximum_private(RBNode<T>* ptr);
    T *minimum_private(RBNode<T>* ptr);
```

```
    std::string inOrder_private(RBNode<T> *ptr, std::string str);
    std::string preOrder_private(RBNode<T> *ptr, std::string str);
    std::string postOrder_private(RBNode<T> *ptr, std::string str);
```

```
public:
```

```
    RBTree();
    RBTree(const RBTree<T>& rb);
    ~RBTree();
```

```
    RBTree<T>& operator=(const RBTree<T>& rb);
```

```
    bool empty();
    T* get(const T& z);
```

```
    void insert(T* z);
    void insertFixUp(RBNode<T>* z);
    void leftRotate(RBNode<T>* z);
    void rightRotate(RBNode<T>* z);
```

```
    T* maximum();
```

```
T* minimum();
```

```
T* successor(const T& z);
```

```
T* predecessor(const T& z);
```

```
std::string inOrder();
```

```
// return string of elements from an inorder traversal
```

```
std::string preOrder();
```

```
// return string of elements from a preorder traversal
```

```
std::string postOrder();
```

```
// return string of elements from a postorder traversal
```

```
1
```

```
int getCount();
```

```
};
```

```
class EmptyError {};
```

```
class ExistError {};
```

```
#endif
```

```
#include "rb.cpp"
```

```
// rb.cpp
// Red/Black Tree implementation
// Clay Sarafin & Taylor Heilman
```

```
#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sstream>
```

```
using namespace std;
template<class T>
RBNode<T> *RBTree<T>::nil = new RBNode<T>('b');
```

```
/*code is essentially a c/p from the BST class,
except with the appropriate names replaced (such as BSTNode -> RBNode)
as well as the appropriate NULL pointers replaced to nil*/
```

```
/*=====
```

```
Node - (DE)CONSTRUCTORS
```

```
=====*/
```

```
/*-----
```

```
* Default Constructor
```

```
* Preconditions:      n/a
```

```
* PostConditions:     empty Node class
```

```
all pointers (value, left, right, parent) point nil
```

```
-----*/
```

```
template<class T>
RBNode<T>::RBNode(){
    value = NULL;
    left = NULL;
    right = NULL;
    parent = NULL;
```

```
    color = 'r';
```

```
}
```

```
/*-----
```

```
* Construct with Item Pointer
```

```
* Preconditions:      pointer to an value of type T
```

```
* PostConditions:     Node class where the value pointer points to the value
all other pointers point to nil
```

```
-----*/
```

```
template<class T>
RBNode<T>::RBNode(T *initValue){
    value = initValue;
    left = NULL;
    right = NULL;
    parent = NULL;
```

```
    color = 'r';
```

```
}
```

```
/*-----
```

```
* Construct with color
```

```
* Preconditions:      char 'r' for red, 'b' for black
```

```
* PostConditions:     Node class where the node has color c
```

```
-----*/
```

```
template<class T>
RBNode<T>::RBNode(char c){
    value = NULL;
    left = NULL;
```

```

    right = NULL;
    parent = NULL;

    color = c;
}

/*=====
                        RBTREE - (DE)CONSTRUCTORS
=====*/
/*-----
* Default Constructor
* Preconditions:      n/a
* PostConditions:     empty RBTREE class created, where root points to nil
-----*/
template <class T>
RBTREE<T>::RBTREE(){
    count = 0;
    root = nil;
}

/*-----
* Copy Constructor, operator=
* Preconditions:      a RBTREE
* PostConditions:     RBTREE is copied over to a new RBTREE, and is in the exact same form
-----*/
template <class T>
RBTREE<T>::RBTREE(const RBTREE<T>& rb){
    root = nil;
    root = copy(rb.root, nil);
}
template <class T>
RBTREE<T>& RBTREE<T>::operator=(const RBTREE<T>& rb){
    dealloc();

    root = copy(rb.root, nil);

    return *this;
}

template <class T>
RBNODE<T>* RBTREE<T>::copy(RBNODE<T> *node, RBNODE<T> *newP){
    //will traverse through the RBTREE to be copied w/ preOrder
    //instead of printing, the new node will be created and will
    //be assigned to the parent in the parameter
    if (node == nil)
        return nil;
    RBNODE<T> *newNode = new RBNODE<T>(node->value);
    newNode->color = node->color;
    newNode->parent = newP;
    newNode->left = copy(node->left, newNode);
    newNode->right = copy(node->right, newNode);

    return newNode;
}

/*-----
* Destructor
* Preconditions:      n/a
* PostConditions:     all nodes that exists in the RBTREE are deleted
-----*/
template <class T>

```

```

RBTree<T>::~~RBTree(){
    dealloc(root);
}

```

```

template <class T>
void RBTree<T>::dealloc(RBNode<T> *ptr){
    if (ptr == nil)
        return;
    dealloc(ptr->left);
    dealloc(ptr->right);
    delete ptr;

    return;
}

```

```

/*+++++
                                     RBTree - FUNCTIONS
+++++*/

```

```

/*-----
 * createNode()
 * Preconditions:      a preexisting node
 * PostConditions:     pointers in the NULL that need to assigned to nil will be assigned to
nil
-----*/

```

```

template <class T>
void RBTree<T>::createNode(RBNode<T>* node){
    node->parent = nil;
    node->left = nil;
    node->right = nil;
}

```

```

/*-----
 * empty()
 * Preconditions:      n/a
 * PostConditions:     returns true if empty, false if not
-----*/

```

```

template <class T>
bool    RBTree<T>::empty(){
    return (count == 0);
    //alt approach: return (root == nil);
}

```

```

/*-----
 * get()
 * Preconditions:      tree is not empty
                        value of type T has the operator '==' and '<' overloaded
                        user has never modified what the value pointer points to in insert()
 * PostConditions:     returns a pointer to the value if it exists
                        returns nil if it does not
-----*/

```

```

template <class T>
T*      RBTree<T>::get(const T& z){
    if (empty())
        throw EmptyError();
    RBNode<T> *node = getNode(root, z);
    //node = nil when RBTree is empty, or if value doesn't exist
    //already covered the empty part, so logically the node doesn't exist
    if (node == nil)
        return NULL;           //does this matter now?
}

```

```

    return node->value;
}

```

```

template <class T>
RBNode<T>* RBTTree<T>::getNode(RBNode<T> *ptr, const T& z){
    if (ptr == nil) //BC: value not found, or tree is empty
        return nil;
    if (*(ptr->value) == z) //found value
        return ptr;
    if(z < *(ptr->value)) //traverse tree to find value
        return getNode(ptr->left,z);
    else
        return getNode(ptr->right,z);
}

```

```

/*-----
 * insert()
 * Preconditions:    value of type T has the operator '<' overloaded
 * PostConditions:   value z is inserted into the tree
                   tree is still a valid RBTree
-----*/

```

```

template <class T>
void RBTTree<T>::insert(T *z){
    RBNode<T>* y = nil;
    RBNode<T>* x = root;

    RBNode<T>* newNode = new RBNode<T>(z);
    createNode(newNode);

    while (x != nil){ //traverse through tree to find appropriate place to insert node
        y = x;
        if (*(newNode->value) < *(x->value))
            x = x->left;
        else
            x = x->right;
    }

    newNode->parent = y;
    if (y == nil) //tree is empty, make root point to ne
        root = newNode;
    else if (*(newNode->value) < *(y->value)) //make appropriate subchild point to i
        y->left = newNode;
    else
        y->right = newNode;

    insertFixUp(newNode); //call function to make the RBTree val
    id again
    count++;
}

```

```

/*-----
 * insertFixUp()
 * Preconditions:    pointer to node inserted into the tree
 * PostConditions:   tree will be fixed to be a valid RBTree
-----*/

```

```

template <class T>
void RBTTree<T>::insertFixUp(RBNode<T>* z){
    RBNode<T>* y;

    while (z->parent->color == 'r'){

```



```

    if (z->parent == z->parent->parent->left){
        y = z->parent->parent->right;
        if (y->color == 'r'){
            z->parent->color = 'b';
            y->color = 'b';
            z->parent->parent->color = 'r';
            z = z->parent->parent;
        }
        else{
            if (z == z->parent->right){
                z = z->parent;
                leftRotate(z);
            }
            z->parent->color = 'b';
            z->parent->parent->color = 'r';
            rightRotate(z->parent->parent);
        }
    }
    else{
        y = z->parent->parent->left;
        if (y->color == 'r'){
            z->parent->color = 'b';
            y->color = 'b';
            z->parent->parent->color = 'r';
            z = z->parent->parent;
        }
        else{
            if (z == z->parent->left){
                z = z->parent;
                rightRotate(z);
            }
            z->parent->color = 'b';
            z->parent->parent->color = 'r';
            leftRotate(z->parent->parent);
        }
    }
}

```

```

    root->color = 'b';
as changed to red
}

```

```

/*-----
* leftRotate()
* Preconditions:    pointer to node in the RBTree
* PostConditions:   nodes in the tree will be rotated to the left such that
                    (with y being the right child of z):
                    left child of z is not modified
                    right child of y is not modified
                    z's right child is the left subtree of y
                    y's left child is z
                    */

```

```

template <class T>
void RBTree<T>::leftRotate(RBNode<T>* z){
    RBNode<T>* child = z->right;

    z->right = child->left;
    if(child->left != nil)
        child->left->parent = z;
    child->parent = z->parent;
    if(z->parent == nil)
        root = child;
    else if (z == z->parent->left)

```

```

        z->parent->left = child;
    else
        z->parent->right = child;
    child->left = z;
    z->parent = child;
}

/*-----
 * rightRotate()
 * Preconditions:      pointer to node in RBTREE
 * PostConditions:     nodes in the tree will be rotated to the right such that
                       (with y being the left child of z):
                       right child is not modified
                       left child of y is not modified
                       z's left child is the right subtree of y
                       y's right child is z
-----*/

template <class T>
void RBTREE<T>::rightRotate(RBNode<T>* z){
    //code from leftRotate(), except left <-> right
    RBNode<T>* child = z->left;
    z->left = child->right;
    if(child->right != nil)
        child->right->parent = z;
    child->parent = z->parent;
    if(z->parent == nil)
        root = child;
    else if (z == z->parent->right)
        z->parent->right = child;
    else
        z->parent->left = child;
    child->right = z;
    z->parent = child;
}

/*-----
 * maximum()
 * Preconditions:      tree is not empty
                       user has never modified what the value pointer points to in insert()
 * PostConditions:     returns pointer to the maximum value in the tree
-----*/

template <class T>
T* RBTREE<T>::maximum(){
    return maximum_private(root);
}

template <class T>
T* RBTREE<T>::maximum_private(RBNode<T>* ptr){
    if (ptr == nil) //nothing exists in RBTREE
        throw EmptyError();

    if (ptr->right == nil)
        return ptr->value;
    else
        return maximum_private(ptr->right);
}

/*-----
 * minimum()
 * Preconditions:      tree is not empty
                       user has never modified what the value pointer points to in insert()
 * PostConditions:     returns pointer to the minimum value in the tree
-----*/

```

```
-----*/
template <class T>
T* RBTree<T>::minimum(){
    return minimum_private(root);
}

template <class T>
T* RBTree<T>::minimum_private(RBNode<T>* ptr){
    if (ptr == nil)//nothing exists in RBTree
        throw EmptyError();

    if (ptr->left == nil)
        return ptr->value;
    else
        return minimum_private(ptr->left);
}

/*-----
 * sucessor()
 * Preconditions:      T z exists in RBTree
                      successor of z exists in the RBTree
                      user has never modified what the value pointer points to in insert()
 * PostConditions:     pointer to successor of z is returned
-----*/
template <class T>
T* RBTree<T>::successor(const T& z){
    RBNode<T> *ptr0 = getNode(root,z);
    if (ptr0 == nil)
        throw ExistError();
    RBNode<T> *ptr1;
    if (ptr0->right != nil)
        return minimum_private(ptr0->right);
    ptr1 = ptr0->parent;
    while((ptr1 != nil) && (ptr0 == ptr1->right)){
        ptr0 = ptr1;
        ptr1 = ptr1->parent;
    }

    if (ptr1 == nil)                //successor does not exist
        throw ExistError();

    return ptr1->value;
}

/*-----
 * predecessor()
 * Preconditions:      T z exists in RBTree
                      precedecessor of z exists in the RBTree
                      user has never modified what the value pointer points to in insert()
 * PostConditions:     pointer to predecessor of z is returned
-----*/
template <class T>
T* RBTree<T>::predecessor(const T& z){
    RBNode<T> *ptr0 = getNode(root,z);
    if (ptr0 == nil)
        throw ExistError();
    RBNode<T> *ptr1;
    if (ptr0->left != nil)
        return maximum_private(ptr0->left);
    ptr1 = ptr0->parent;
    while((ptr1 != nil) && (ptr0 == ptr1->left)){
        ptr0 = ptr1;
        ptr1 = ptr1->parent;
    }
}
```

```

    }

    if (ptr1 == nil)                //predecessor does not exist
        throw ExistError();

    return ptr1->value;
}

/*-----
 * inOrder(), preOrder(), and postOrder()
 * PreConditions:      n/a
 * PostConditions:     inOrder : string representation of the values in the RBTree are in or
der                          der
                        preOrder : string representations of the values in RBTree are shown
                        in pre order (starts with root, ends with max value)
                        postOrder: string representations of the values in RBTree are shown
                        in post order (starts with min value, ends with root)
                        all       : each value is followed by ", "
                        : user has never modified what the value pointer points to in

insert()
-----*/
template <class T>
std::string RBTree<T>::inOrder(){
    std::string str;
    str = inOrder_private(root, str);
    if (str == "")                //want to avoid using pop_back() on an empty string
        return str;
    else{
        str.pop_back();
        str.pop_back();
        return str;
    }
}

template <class T>
std::string RBTree<T>::inOrder_private(RBNode<T> *ptr, std::string str){
    if (ptr == nil){
        return str;
    }
    std::string str_null;        //null dummy string to help with recursion;
                                //if you pass in str as the parameter again, then
                                //it will append to that string in the funcion, then return th
at string                        //it will then append it to the string in the initial call, wh
ich is something                //not desired

    //left, print, right
    str += inOrder_private(ptr->left, str_null);
    str += std::to_string(*(ptr->value));
    str += "-";
    str += ptr->color;
    str += ", ";
    str += inOrder_private(ptr->right, str_null);

    return str;
}

template <class T>
std::string RBTree<T>::preOrder(){
    std::string str;
    str = preOrder_private(root, str);
    if (str == "")

```

```

        return str;
    else{
        str.pop_back();
        str.pop_back();
        return str;
    }
}

template <class T>
std::string RBTree<T>::preOrder_private(RBNode<T> *ptr, std::string str){
    if (ptr == nil){
        return str;
    }
    std::string str_null;

    //print, left, right
    str += std::to_string(*(ptr->value));
    str += "-";
    str += ptr->color;
    str += ", ";
    str += preOrder_private(ptr->left, str_null);
    str += preOrder_private(ptr->right, str_null);

    return str;
}

template <class T>
std::string RBTree<T>::postOrder(){
    std::string str;
    str = postOrder_private(root, str);
    if (str == "")
        return str;
    else{
        str.pop_back();
        str.pop_back();
        return str;
    }
}

template <class T>
std::string RBTree<T>::postOrder_private(RBNode<T> *ptr, std::string str){
    if (ptr == nil){
        return str;
    }
    std::string str_null;

    //left, right, print
    str += postOrder_private(ptr->left, str_null);
    str += postOrder_private(ptr->right, str_null);
    str += std::to_string(*(ptr->value));
    str += "-";
    str += ptr->color;
    str += ", ";

    return str;
}

/*-----
* getCount()
* Preconditions:      n/a
* PostConditions:     number of nodes that exists in the RBTree is returned
*-----*/
template <class T>

```

```
int RBTREE<T>::getCount(){  
    return count;  
}
```

```
// test_rb.cpp
// Red/Black Tree tests
// Clay Sarafin & Taylor Heilman

#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <assert.h>

#include "rb.h"

using namespace std;

int *zero  = new int(0);
int *one   = new int(1);
int *two   = new int(2);
int *three = new int(3);
int *four  = new int(4);
int *five  = new int(5);
int *six   = new int(6);
int *seven = new int(7);
int *eight = new int(8);
int *nine  = new int(9);

void insertTest(){
    RBTree<int> tree;

    tree.insert(five);
    tree.insert(zero);
    assert(tree.getCount() == 2);
    assert(tree.preOrder() == "5-b, 0-r"); //tests for empty tree, left subtree
    tree.insert(nine);
    assert(tree.preOrder() == "5-b, 0-r, 9-r"); //test for right subtree;
    //add everything else
    tree.insert(one);
    tree.insert(two);
    tree.insert(three);
    tree.insert(four);
    tree.insert(six);
    tree.insert(seven);
    tree.insert(eight);
    assert(tree.preOrder() == "5-b, 1-r, 0-b, 3-b, 2-r, 4-r, 7-r, 6-b, 9-b, 8-r");
}

void getTest(){
    RBTree<int> tree;

    try{
        tree.get(*one);
        assert(false);
    }
    catch(EmptyError){
    }

    tree.insert(one);
    tree.insert(two);
    tree.insert(three);
    tree.insert(four);
    tree.insert(six);
    tree.insert(seven);
    tree.insert(eight);
}
```

```
//test for root
assert(tree.get(*one) == one);
//test for non-leaf
assert(tree.get(*two) == two);
//test for leaf
assert(tree.get(*eight) == eight);           //not sure what's going on here

//test for nonexisting node in tree;
assert(tree.get(*five) == NULL);
}

void maxMinTest(){
    RBTree<int> tree;

    //test for EmptyError exceptions
    try{
        tree.minimum();
        assert(false);
    }
    catch(EmptyError exception){
    }
    try{
        tree.maximum();
        assert(false);
    }
    catch(EmptyError exception){
    }

    tree.insert(zero);
    tree.insert(one);
    tree.insert(two);

    //test min & max
    assert(tree.maximum() == two);
    assert(tree.minimum() == zero);
}

void predSuccTest(){
    RBTree<int> tree;

    //test ExistError exceptions
    try{
        tree.predecessor(0);
        assert(false);
    }
    catch(ExistError exception){
    }
    try{
        tree.successor(0);
        assert(false);
    }
    catch(ExistError exception){
    }

    tree.insert(four);
    tree.insert(two);
    tree.insert(three);
    tree.insert(one);
    tree.insert(seven);
    tree.insert(five);
    tree.insert(nine);
}
```



```

    assert(tree.predecessor(2) == one);
    assert(tree.successor(2) == three);

    assert(tree.predecessor(4) == three);
    assert(tree.successor(4) == five);

    assert(tree.predecessor(9) == seven);
    //test EmptyError exception for an item that doesn't exist
    try{
        tree.successor(9);
        assert(false);
    }
    catch(ExistError exception){
    }

    assert(tree.predecessor(3) == two);
    assert(tree.successor(3) == four);

```

```

}

```

```

void printTest(){
    RBTree<int> tree;
    assert(tree.inOrder() == "");
    assert(tree.preOrder() == "");
    assert(tree.postOrder() == "");

    tree.insert(zero);
    tree.insert(one);
    tree.insert(two);

    assert(tree.inOrder() == "0-r, 1-b, 2-r");
    assert(tree.preOrder() == "1-b, 0-r, 2-r");
    assert(tree.postOrder() == "0-r, 2-r, 1-b");

    RBTree<int> tree2;

    tree2.insert(four);
    tree2.insert(two);
    tree2.insert(three);
    tree2.insert(one);
    tree2.insert(seven);
    tree2.insert(five);
    tree2.insert(nine);
    /*
        3-b
       / \
      2-b 5-r
     /   \
    1-r   4-b 7-b
           \
            9-r
    */
    assert(tree2.inOrder() == "1-r, 2-b, 3-b, 4-b, 5-r, 7-b, 9-r");
    assert(tree2.preOrder() == "3-b, 2-b, 1-r, 5-r, 4-b, 7-b, 9-r");
    assert(tree2.postOrder() == "1-r, 2-b, 4-b, 9-r, 7-b, 5-r, 3-b");

```

```

}

```

```

void copyTest(){
    RBTree<int> tree0;

    tree0.insert(four);
    tree0.insert(two);

```

```
    tree0.insert(three);
    tree0.insert(one);
    tree0.insert(seven);
    tree0.insert(five);
    tree0.insert(nine);

    RBTTree<int> tree1(tree0);

    assert(tree1.inOrder() == "1-r, 2-b, 3-b, 4-b, 5-r, 7-b, 9-r");
    assert(tree1.preOrder() == "3-b, 2-b, 1-r, 5-r, 4-b, 7-b, 9-r");
    assert(tree1.postOrder() == "1-r, 2-b, 4-b, 9-r, 7-b, 5-r, 3-b");
}

int main(){
    insertTest();
    getTest();
    maxMinTest();
    predSuccTest();
    printTest();
    copyTest();

    delete zero;
    delete one;
    delete two;
    delete three;
    delete four;
    delete five;
    delete six;
    delete seven;
    delete eight;
    delete nine;
    return 0;
}
```

```
// dict.h
// header file for dictionary class
// Clay Sarafin & Taylor Heilman

#ifndef DICT_H
#define DICT_H

#include <iostream>

#include "rb.h"

using namespace std;

template <class KeyType>
class Dictionary : public RBTree<KeyType>{
public:
    Dictionary() : RBTree<KeyType>() {};

    using RBTree<KeyType>::get;
    using RBTree<KeyType>::insert;
    using RBTree<KeyType>::count;
    using RBTree<KeyType>::inOrder;
    using RBTree<KeyType>::empty;

    std::string toString();
};

#include "dict.cpp"

#endif
```

```
// dict.cpp
//
// Clay Sarafin & Taylor Heilman

#include <iostream>
#include <stdio.h>
#include <stdlib.h>
#include <string>

using namespace std;

/*-----
 * toString()
 * Preconditions:      inOrder from BST class does not have brackets, every entry is followed
                        by ", "
                        and does not end with std::endl
                        type KeyType's operator<< is overloaded, and is formatted as "key:valu
e"
 * PostConditions:     string representation of the entire dictionary is printed out
-----*/

template <class KeyType>
std::string Dictionary<KeyType>::toString(){
    std::string str;
    str += "{";
    str += inOrder();
    str += "}";

    return str;
}
```