

# Project 1

## Balanced binary

*Due: 7 September 2017*

You saw basic binary search trees in 162, and may remember that their weakness is that in the worst case they behave like linked lists, with many operations requiring  $O(n)$  time. The solution to this is to require that every operation maintain *balance* in the tree, and if carefully done you can guarantee add, search, and remove operations in  $O(\lg n)$  time even in the worst case. One data structure with such guarantees is the red-black tree, which we'll be covering in class over the next few days.

In this project, you'll complete the implementation of a balanced binary search tree.

### Objectives

In the course of this project, the successful student will:

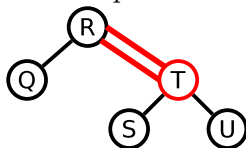
- read complex code written by someone else (me),
- read and write unit tests,
- perform a case analysis, i.e. exhaustively enumerate the logically-possible cases in a system, and
- manipulate link-based data structures using pointers/references.

### Prep work

Your starting point is a partial implementation that I have written. Start by creating a working directory for this project and copying my files into it; I've put them in `/home/shared/262/rbtree/`. There are implementations in both C++ and Java, and you may use either one. (If you were hoping to work in a different programming language, talk to me—I'm willing to help you port the code to another language, but it's probably more work than it's worth.)

The prep work mostly involves reading the existing code and becoming familiar with it. To give you some starting points on working with the code, I want you to perform the following tasks:

0. Read the readme! There's important instructions there on how to compile and run the code.
1. Fix the three compiler errors in the `RBTree` definition.
2. Fill in the `removeLeafRight` test case in the unit tests for `RBTree` to actually test that the code correctly removes leaves that are the right child of their parent node; compile it and run the tests to make sure it works. (Note that there are a few other cases that fail—`removeRotateThreeRight`, `removeRotateCase2`, and `removeMystery`. Don't worry about those yet.)
3. Compile the speed test, run it, and put its output into a file named `speed.txt`.
4. At the bottom of the readme file, add lines that show exactly what the `TreeDump` algorithm would output if it were given the following tree:<sup>1</sup>



You can either generate it by hand (after looking at the examples and seeing how `TreeDump` works) or write a small program to generate it.

This work is due Thursday **at 4pm**. You'll have a chance to ask questions about it in class on Thursday to clear up any last-minute issues, but if you haven't started it you won't have time to finish. When you're ready to hand it in, use the `handin` script as described at the end of this document.

You shouldn't have to edit either the `TreeDump` algorithms or their test cases, but you're encouraged to look at them—*especially* the test cases, which will help you understand what `TreeDump` is doing.

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<sup>1</sup>To make the red nodes more distinct and easier to see, I generally draw both the nodes and their inbound edges in red, and I draw the inbound edges as a double line. The double line is visible even when the red isn't (and is suggestive of what the ASCII diagrams will look like...).

## Design work

Now that you've gotten the general layout, it's time to dive in to the algorithmic work. This will focus in particular on three parts of the program:

1. Verifying BST and red-black conditions. In `isValidRBTree` and in `validateAndCountBlack`, there is code to verify correctness of a red-black tree. Describe the algorithm. What is it checking for? How does it work?
2. Adding values. The main tree-modifying work here is concentrated in `splitFour` and `maybeRotate`. Draw a “before” and “after” diagram for a scenario where `splitFour` would be called, and what that tree should look like after the call to `splitFour`. Then, noting that there are four distinct cases inside `maybeRotate`, draw “before” and “after” diagrams for each distinct case. Use concrete, actual values in your diagrams (i.e. don't just draw the nodes). Note that in one of the cases my code is buggy and in another it is absent; your “after” drawings will reflect what *should* happen in those cases, based on your understanding of 234 and red-black trees, not what the code currently does.
3. Removing values. The important tree manipulations when removing values from the tree all occur in `guaranteeRedLeaf`, which works to ensure that by the time we get down to the leaf node that will be removed, that leaf node is a red one (while preserving the red-black conditions along the way). This code distinguishes twelve different cases, although some of those cases require no work to be done. Again, draw diagrams to illustrate each case. Where no change is made, you can just say that, but for the cases where a tree manipulation occurs, draw an “after” diagram to illustrate it. You don't need to draw the entire red-black tree, just the portion relevant to the algorithm, but as before, make sure you use concrete values and indicate what value the algorithm is seeking to (eventually) delete. Cases 4 and 5 at the end are meant to be the mirror image of cases 2 and 3 respectively.

Write your design work on paper (or do it on your laptop, but paper's probably easier for this) and bring it to class; this work is due **at the start of class** on Tuesday the 29th. If you're really stuck on something, do your best, make a note of it, and move on; we'll be discussing this extensively in class. In fact, discussing this is the main topic of the day.

## Final version

A full-credit final version will be a complete, non-buggy, working implementation of a red-black tree TOGETHER WITH convincing proof that it is correct. The form that proof takes will be a complete, rounded-out set of test cases along with empirical speed tests comparing the red-black implementation with the naïve BST implementation.

Note that I am not able to spend a ton of time with your program (and in fact may not read it at all, and definitely won't do your debugging for you), so your documentation will need to tell me anything I need to know to run and test your program. I'll also be running your tests against buggy code I've written, and your code against a complete set of test cases that I've written—so you shouldn't go changing the public interface of anything. Having complete and correct documentation is an easy 25 points, but if your documentation omits important info or tells me the wrong thing, you'll get less than full credit there.

After prep work (15 points), design work (10 points), and documentation (25 points), there remain 100 points in the rubric, which will be awarded according to the table on the next page. Under each score, I show (for your convenience) the total cumulative points if you get that item plus *all* the previous points, and the letter grade this corresponds to. It is arranged roughly in the order I suggest you attempt them, with the earlier ones being easier or enlightening with respect to the later ones, but you can in general get points for the later ones (if they work) without getting the earlier ones.

BUT: if your code doesn't compile, or compiles but immediately crashes when it's run, you will get zero of these points. Don't let this happen to you!

Make good use of the case analysis you did in your design work to help you work through the rest of the implementation work—both in writing test cases and in understanding just what the implementation needs to be doing.

Score	Description
10 (60/D-)	Get all the prep work done, whether or not you got it working by the original deadline. Include <i>both</i> the speed test for the naïve BST <i>and</i> the one for the red-black implementation.
15 (75/D+)	Add test cases for the other three cases in <code>maybeRotate</code> (currently only <code>addRotateCase2</code> is tested). 5 each.
5 (80/D+)	Fix the bug in the implementation of addition case 3.
10 (90/C)	Do the implementation of addition case 4.
5 (95/C)	Fix the bug in <code>rotateThreeNodeRight</code> .
5 (100/C+)	Write the <code>removeRotateCase3</code> test case.
5 (105/B-)	Write the <code>removeRotateCase4</code> and <code>removeRotateCase5</code> test cases.
10 (115/B)	Add conditions to <code>guaranteeRedLeaf</code> to correctly identify cases 4 and 5 (which are the mirror images of cases 2 and 3).
10 (125/B+)	Implement deletion case 2.
10 (135/A)	Implement deletion cases 4 and 5.
5 (140/A)	In the <code>add</code> method of <code>RBTree</code> , there is an <code>if</code> statement involving the parent. It is algorithmically important, although its omission doesn't currently break any test cases. Figure out why it's there, and write an appropriately-named test case that would break if it were omitted or commented out.
5 (145/A)	In the <code>remove</code> method of <code>RBTree</code> , there is an <code>if</code> statement to specially handle the case where the root and both its children are all effectively 2-nodes (i.e. none of them have red children). Using only public methods ( <code>add</code> and <code>remove</code> ), construct a test case that confirms that this code works correctly.
5 (150/A+)	The <code>removeMystery</code> test case builds a scenario that, in the current implementation, fails. Debug the problem and fix it.

## Handing in

There is a script called `handin` installed on torvalds and all the Hardy House lab machines that you'll use to hand in your code (once for the prep work, and then again for the final handin). This course is `cmsc262`, and the assignment is `proj1` so you'll type something like

```
handin cmsc262 proj1 bbst/
```

if the directory with your work in it happened to be named `bbst`. Read the output of the `handin` script—it will tell you just which files it handed in, or give you a hopefully-helpful error message to help you fix the problem.

If you work on your own machine, that's fine, but when you copy the files into the lab systems, *make sure it compiles and runs and works correctly* before handing in. If a configuration difference between your machine and the lab means that it compiles on yours but not in the lab... then you have a program that doesn't compile or run, and you've lost a lot of points. Don't let this happen to you!

You can run the `handin` script as many times as you like; I only look at the latest-handed-in version. So, if you hand in and then realise you now understand a bug you created (and the deadline hasn't passed yet), fix it and resubmit for a higher score!