# ECE36800 Programming Assignment 4

*Due Monday, March 29, 2021, 11:59pm*

This assignment covers learning objective 1: An understanding of basic data structures, including stacks, queues, and trees; learning objective 3: An ability to apply appropriate sorting and search algorithms for a given application.

You are required to implement a program to construct a height-balanced binary search tree (BST), starting from an empty tree, based on a sequence of insertion and deletion operations. You may have to perform rotation(s) to maintain the height-balanceness of the tree after each insertion or deletion. Note that height-balanceness is defined as we covered in the class. Given a node, its balance is the height of its left subtree minus the height of its right subtree. A tree is height-balanced when every node in the tree has a balance that is $-1$, 0, or 1. As in the class, we will define the height of a tree recursively. An empty tree has a height of $-1$. The height of a tree is 1 plus the maximum of the height of the left sub-tree and the height of the right sub-tree.

It is fine for you to use the code provided in the lecture notes for this assignment. However, you should re-organize the code. For example, you may want to write separate functions for clockwise rotation and counter-clockwise rotation, and the insertion function will call the appropriate rotation functions.

### Insertion

In the lecture notes, we do not allow duplicate keys in a tree. In this assignment, **we allow the insertion of a duplicate key**. In other words, the resulting height-balanced may have multiple nodes storing the same key value. Recall that insertion of a key requires you to search for a suitable location to insert a leaf node. To handle nodes storing the same key value, when you search for a leaf node location to insert the key, you should **always go left when you encounter a node storing the same key**. This requirement is imposed for the grading purpose of this assignment.

### Deletion

When you are asked to delete a key, the tree should stay intact if the key is currently not in the tree. There may be multiple nodes containing the key that you want to delete. You should delete the first such node that you encounter in the search process.

If the node you want to delete has two children, you should replace that node with its **immediate predecessor** (in an in-order traversal of the tree). Again, this requirement is imposed for the grading purpose of this assignment.

### Tree node structure

The tree node structure (`Tnode`) is defined in the file `hbt.h`.

```
typedef struct _Tnode {
   int key: 29, balance: 3;
   struct _Tnode *left;
   struct _Tnode *right;
} Tnode;
```

The `left` and `right` fields store the left and right child nodes of a `Tnode`, respectively.

An `int`, which has 32 bits, is used to store two bit fields: The bit field `key` uses 29 bits to store a signed integer value between `HBT_MIN` and `HBT_MAX` (inclusive), and the bit field `balance` uses 3 bits to store the difference in the height of the left sub-tree (`left`) and the height of the right sub-tree (`right`).

A 29-bit signed integer can be as large as $2^{28} - 1 = 268435455$ (= `HBT_MAX`) and as small as $-2^{28} = -268435456$ (= `HBT_MIN`). Both `HBT_MAX` and `HBT_MIN` are defined in `hbt.h` as follows:

```
#define HBT_MAX 268435455
#define HBT_MIN -268435456
```

A 3-bit (signed) field can be as large as $2^2 - 1 = 3$ and as small as $-4$. Therefore, the bit field `balance` can store the balance of a height-balanced tree properly. Moreover, it can also store an (in)balance of 2 or $-2$ at a node when the tree becomes temporarily unbalanced. A correctly implemented height-balanced tree insertion or deletion routine should not allow the balance of a node to go below $-2$ or above 2.

You should include this file in your other `.h` and `.c` files that you will develop for this assignment. This file will be provided when we compile your submission. You do not have to submit this file.

In your other `.h` and `.c`, you should not define other structures. No other user-defined structures are allowed in this assignment. If you have other user-defined structure(s) in your `.h` and/or `.c` files, your submission will not be graded.

### Deliverables

In this assignment, you are required to develop other include file(s) (in addition to the provided `hbt.h`) and source file(s), which can be compiled with the following command:

```
gcc -std=c99 -pedantic -Wvla -Wall -Wshadow -O3 *.c -o pa4
```

It is recommended that while you are developing your program, you use the "`-g`" flag instead of the "`-O3`" flag for compilation so that you can use a debugger if necessary.

There are two options that the executable `pa4` can accept. The `main` function should simply return `EXIT_FAILURE` if the argument count is incorrect or the options are invalid (see further details below).

### Option `"-b"`: Building a height-balanced BST

```
./pa4 -b operations_input_file tree_output_file
```

The option `"-b"` means that you are building a height-balanced BST (starting from an empty tree) based on the operations specified in `operations_input_file`.

### Input file format

The `operations_input_file` is an input file in `binary` format. Every operation is specifed by `(sizeof(int) + sizeof(char))` bytes, with the first `sizeof(int)` bytes being an `int` and the next `sizeof(char)` byte being a `char`.

The `int` is the key. **The value stored in an `int` is guaranteed to be in the range of `HBT_MIN` and `HBT_MAX` (inclusive).** In other words, the bit field `key` in a `Tnode` can always store the given `int` properly even though the bit field `key` has only 29 bits, whereas an `int` stored in a file has 32 bits.

If it is an insertion of the specified key, the `char` is an ASCII character `'i'`. If it is a deletion of the specified key, the `char` is an ASCII character `'d'`.

If there are $n$ keys to be inserted or deleted, the file size is $n \times$ (`sizeof(int)+sizeof(char)`) bytes.

**Output file format**

The `tree_output_file` is an output file in `binary` format. This file stores the **pre-order** traversal of the constructed height-balanced BST. Each `non-NULL` node is represented by an `int` and a `char`. The `int` is of course the key stored in the node. We cannot just write into a file 29 bits stored in the bit field `key`. So, we store the 29-bit `key` as an `int` in the output file.

The `char` is a binary pattern, with the least significant two bits capturing the types of branches that node has. At bit position 0 (the least significant bit position), a 0-bit means that the right branch of the node is `NULL`. A 1-bit means that the right branch of the node is a non-`NULL` node. At bit position 1 (the second least significant bit position), a 0-bit means that the left branch of the node is `NULL`. A 1-bit means that the left branch of the node is a non-`NULL`.

All other more significant bits in the `char` should be 0. Therefore, a numerical value of 2 or 3 (in decimal) for the binary pattern stored in the `char` means there is a left child. A numerical value of 1 or 3 (in decimal) means that there is a right child. A numerical value of 0 means that there are no child nodes.

**Output and return value of `main` function**

If the given input file can be opened, your program should attempt to build a height-balanced BST. If the given input file cannot be opened, the program should print the value -1 (using the format `"%d\n"`) to the `stdout` and return `EXIT_FAILURE`.

Now, suppose the given input file can be opened. If in the process of building the height-balanced BST, your program encounters a problem in the input file (wrong format, for example) or a failure in memory allocation, you should still write to the output file the tree that has been contructed so far. You should print the value 0 (using the format `"%d\n"`) to the `stdout` and return `EXIT_FAILURE`.

We will test your program with valid input files of reasonable sizes. Therefore, it is unlikely that you will have to print the value 0 to the `stdout`.

If you can successfully read the entire input file to build a tree, you should print the value 1 (using the format `"%d\n"`) to the `stdout` and return `EXIT_SUCCESS`; your program should return `EXIT_FAILURE` otherwise.

We are not asking you to check whether you can write to the output file. We will use the option `"-e"` to evaluate that.

**Option `"-e"`: Evaluating a height-balanced BST**

```
./pa4 -e tree_input_file
```

The option `"-e"` means that you are evaluating a tree specified in the `tree_input_file`.

The `tree_input_file` is actually of the same format as the output produced using the `"-b"` option. For the given `tree_input_file`, your program should print three integers to `stdout` using the format `"%d,%d,%d\n"`, where the first integer indicates the validity of the input file, the second integer indicates whether the tree is a BST, and the third integer indicates whether the tree is a height-balanced tree.

If the input file cannot be opened, the first integer should be -1. If it can be opened, but of the wrong format, the first integer should be 0. If it can be opened and is of the correct format, the first integer should be 1.

If the input file is a valid tree, the second and third integers are meaningful (otherwise, their values are not important). If the tree is a BST, the second integer is 1; otherwise, it is 0. If the tree is height-balanced, the third integer is 1; otherwise, it is 0.

The `main` function should return `EXIT_SUCCESS` only if the input file is valid (i.e., the first integer of the terminal output is 1); your program should return `EXIT_FAILURE` otherwise.

**Electronic Submission**

The project requires the submission (electronically) of the C-code (source and include files) through Brightspace. You should create and submit a zip file called `pa4.zip`, which contains the `.h` and `.c` files. Your zip file should not contain a folder.

```
zip pa4.zip *.c *.h
```

You should submit `pa4.zip` to Brightspace.

If you want to use a `Makefile` for your assignment, please include the `Makefile` in the zip file. In that case, you create the zip file as follows:

```
zip pa4.zip *.c *.h Makefile
```

If the zip file that you submit contains a `Makefile`, we use that file to make your executable (by typing "make pa4" at the command line to create the executable called pa4).

Again, the file `hbt.h` will be provided by us. You do not have to include the file in the zip file.

**Grading**

The assignment will be graded based on the two tasks performed by your program. The first task of constructing a height-balanced BST accounts for 70% and the second task of evaluating a height-balanced BST accounts for 30%.

It is important all the files that have been opened are closed and all the memory that have been allocated are freed before the program exits. Memory leaks or memory errors reported by `valgrind` will result in a 50-point penalty.

Be aware that we set a time-limit for each test case based on the size of the test case. If your program does not complete its execution before the time limit for a test case, it is deemed to have failed the test case.

As we are relying on some expected output printed to `stdout` for the evaluation of your submission, it is important that you do not use the stream `stdout` to printing other messages. If you are relying on printing for the purpose of debugging, please print to the stream `stderr`.

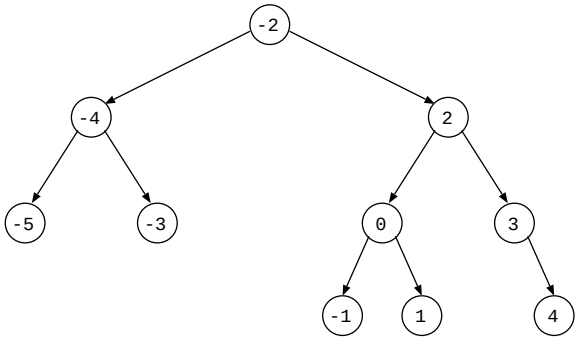
Moreover, we expect your program to print to `stdout` using the formats provided (one format for the `-b` option and one format for the `-e` option). If we cannot parse the output printed to `stdout` based on the formats provided in this assignment, your program is deemed to have failed the test case.

**What you are given**

You are given `hbt.h`, which defines the only structure you would use in this assignment.

Moreover, you are given 4 sample input files (ops0.b, ops1.b, ops2.b, ops3.b) and the corresponding output files for the trees constructed (tree0.b, tree1.b, tree2.b, and tree3.b).

The ops0.b file inserts 10 ascending keys -5, -4, ..., 3, 4. The following figure shows the corresponding height-balanced BST in tree0.b.




The files ops1.b and ops2.b contain the same insertion operations and a deletion operation: delete 2. In ops1.b, the "delete 2" operation occurs after the insertion of 2. Therefore, the final tree contains only 9 keys. In ops2.b, the "delete 2" operation occurs before the insertion of 2. Therefore, the tree2.b and tree0.b are the same.

While ops0.b, ops1.b, and ops2.b involve the insertion of distinct keys, ops3.b file involves the insertion and deletion of duplicate keys.

Besides these height-balanced BSTs, we also provide you three invalid height-balanced BSTs (invalidtree0.b, invalidtree1.b, and invalidtree2.b). For invalidtree0.b, it is neither a BST nor a height-balanced tree (the corresponding print out to the screen should be `1,0,0` when evaluated with the `"-e"` option). For invalidtree1.b, it is not a BST, but it is a height-balanced tree (the corresponding screen dump is `1,0,1`). For invalidtree2.b, it is a BST, but it is not a height-balanced tree (the corresponding screen dump is `1,1,0`).

To help you interpret these binary files, we also provide you the "equivalent" text files (ops0–3.txt, tree0–3.txt, and invalidtree0–2.txt).

For an operations input file, each (`int`) key is printed with `"%d"` format. The key is followed by a space, and then the (`char`) operation (`'i'` for insertion and `'d'` for deletion).

For a tree file, each (`int`) key is again printed with `"%d"` format. The key is followed by a space, and then char `'0'` (the node has no children), `'1'` (the node has a right child and it has no left child), `'2'` (the node has no right child and it has a left child), or `'3'` (the node has a right child and a left child).

**Suggestions**

You may want to write a program that allows you to convert from tree0.b to tree0.txt and a program that allows you to convert from ops0.b to ops0.txt (in fact, the two programs can be combined into one). Similarly, you may want to write a program that converts from tree0.txt (or ops0.txt) to tree0.b (or ops0.b). This way, you can easily create other examples (operations input files and tree files) to test your programs.

You should write the evaluation part first. This part allows you to test your construction part. (As a good practice, you think of how to evaluate/test your program before you write your program). There are two components of the evaluation (BST and height-balanceness), I recommend that you write the two components separately.

For the construction part, I suggest that you write the insertion routine (with rotations) first. However, try to write rotation operations as functions (that could be used by the deletion routine later on). Then, you write the deletion routine. It is easier to write the deletion as a recursive function because you may have to perform rotations all the way to the root node. A recursive routine makes it easier to keep track of all the nodes encountered in the process of searching for the deleted node. Otherwise, you should use a stack to keep track of the nodes encountered in the search process.

You should also write the deletion routine in such a way that the height-balancing part can be easily isolated such that if necessary, you could comment out the height-balancing part and the routine is simply doing a regular deletion of a key from a BST (without worrying about height-balancing). This could be helpful when it comes to debugging. Moreover, in the worst case scenario, you can also comment out this part and still have a somewhat functioning deletion routine in your final submission should you encounter problems in maintaining a height-balanced tree.

As you write the program, use the evaluation part to test your insertion and deletion routines.

**Bit fields**

A bit field in a `struct` can be accessed just like a regular field in a `struct`. Assume that we have a variable `Tnode nd`, we can access the bit field `key` in `nd` as `nd.key`. Similarly, assume that we have a variable `Tnode *nd_ptr` that stores the address of a `Tnode`, we can access the bit field `balance` as `nd_ptr->balance`.

However, there is a major distinction between a bit field in a `struct` and a "regular" field in a textttstruct. We cannot get the address of a bit field in a `struct`. For example, we cannot find the address of the bit field `key` or `balance` using the ampersand operator. Using the examples of `nd` and `nd_ptr` in the preceding paragraph, we **cannot** use `&(nd.key)` or `&(nd_ptr->balance)` to find the addresses of the corresponding bit fields.

Therefore, for this assignment, if you want to write the contents of `nd.key` into a file using `fwrite`, you would have to first assign the value to an `int` variable, and then use that variable to write to a file. Similarly, you also cannot use `fread` to read an `int` from a file into `nd_ptr->key` directly. You have to first read from a file into an `int` variable, and then assign the value to `nd_ptr->key`.

On the other hand, for a "regular" field such as `left` or `right`, we can find the addresses of the corresponding fields in a `Tnode` with the ampersand operator, e.g., `&(nd.left)` or `&(nd_ptr->right)`.