CIS 121—Data Structures and Algorithms with Java—Spring 2018

Homework 9—Hashing and Tries

Due: Monday, April 9 by 11:59 PM on Gradescope Only (no Canvas)

2 Required Problems (75 points), Quantitative Analysis (15 points), and Style and Tests (10 points)

DO NOT modify methods, method headers, or variables that were already provided to you.
DO NOT add public or protected methods.
DO introduce helper methods that are *package-private* (i.e., do not have a privacy modifier) as you deem necessary.

Submission (to Gradescope)

5 Files to Submit: `HashMap.java`, `HashMapTest.java`, `TrieMap.java`, `TrieMapTest.java`, `QuantitativeAnalysis.pdf` *(please do not submit any extra files, and no Canvas ☺)*

For all of your source files **DO NOT** place any in a package, and ensure that no file has a package declaration e.g. `package src;`. When you submit, be sure that all files are located at the root level i.e. do not submit a folder that contains the source files. The easiest way to do this is to drag the files individually onto Gradescope.

Important: Be sure that your own test cases pass and do not stall. Otherwise, your submission will not be processed correctly.

Important: Do not wait until the last minute to try submitting. You are responsible for ensuring your submission goes through by the deadline.

You have unlimited submissions for this homework. Upon submission, our infrastructure will compile your code and run some basic test cases against the interface. These are here to test that your code compiles (i.e. you didn't forget to add a class etc.) when we run real tests. They should not be used to test your own codes correctness since the functionality they test is very very basic.

Autograder Failures/Error Messages Upon Submission:

If you receive an error message with a message to contact the course staff, please check the following before posting on Piazza or going to office hours for help:

1. Did you submit ALL the required files listed above? This includes checking that you submitted `.java` files and not `.class` files.
2. Check the files you submitted to Gradescope. Do the names of the files appear as `folder/filename.java`? If so, please drag the files individually so that they appear only as `filename.java`. Do not submit a zip of files contained inside a folder.
3. Are you in the default package? That means checking the top of all files to make sure there is no statement like `package src;` Remove all these statements and resubmit.
4. Are you getting a **Jacoco Error**? This means you are failing one of your own test cases, or one of your test cases is running in an infinite loop. Try fixing the test case you are failing, and if you can't fix it by the deadline then just remove it and resubmit.

Motivation

`java.util.HashMap`: A Rite of Passage

We have used hash-based data structures throughout this class on various programming assignments, and we have proven certain properties about them in lecture and recitation. The time has now come to embark on a rite of passage that every budding computer scientist must take. It is time to implement a hash table.

But seriously, too many people go around blissfully using this magical all-operations-expected-$O(1)$ data structure unaware of how it works, how to get the most out of it, and when something else might be better. In this homework, to ensure you aren't that person, you will implement a production-grade hash map which will conform to the Java `Map` interface. We provide a `BaseAbstractMap` which your implementation should extend from, which reduces the work for a few complex `Map` methods. Before you get started, take a look at the `java.util.Map` interface to familiarize yourself with the API.

Tree? Trie?

A *prefix trie*[1] is an ordered tree data structure, which stores string keys by storing characters in nodes. The "prefix" part of the name comes from the fact that common prefixes between keys share the same path from the root in the trie. For a naïve trie, is a fair amount of overhead, since every character lives in its own node. One example of an optimization that addresses this object overhead issue is a PATRICIA trie, in which each nodes are compressed into its parent when appropriate in order to optimize space and memory usage. Unfortunately, you will not be implementing PATRICIA tries for this assignment.

Part Zero: `Set up` (0 points)

Important: Historically, many students have experienced issues setting up `jamm.jar` and `TestHarness.java`. Please ensure that you can get this up and running as soon as possible, since it's required for the conceptual questions below. You **can**, however, do the programming part of this homework without this step.

When you first import the project into your workspace, you may see some error messages associated with the `TestHarness.java` file. Here is a few setup you need to follow:

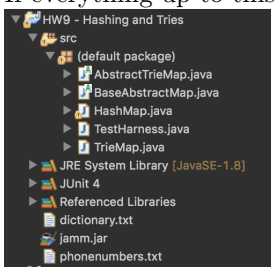
We've provided a test harness in `TestHarness.java` that records execution duration and memory usage of both map implementations. The harness tests two datasets, `dictionary.txt` (350,000 words) and `phonenumbers.txt` (8,000 phone numbers, all of the form (215)-898-xxxx, encoded as letters and thus starting with "cbfiji"). You might need to move these files to the root of your project (not in the `src` folder) to avoid `FileNotFoundExceptions`. Before you do run the harness, you should take a look at each dataset and form a hypothesis on the CPU times and memory usages of each implementation on each dataset; the results might surprise you!

There are a couple steps to set this up.

0. Download `jamm.jar` from the hw page under "extra files".
1. Make sure the `jamm.jar` file is in the **root** (the folder you will click delete on if you want this whole project gone) of your project (not the `src` folder). Also, make sure the `dictionary.txt` and `phonenumbers.txt` files are at the root.
2. Right click on your project and go to Build Path →Configure Build Path →Libraries →Add JARs. Select `jamm.jar` from the file selector drop down and hit "Okay".

[1] The term "trie" comes from re**trie**val.

If everything up to this point was done correctly, you should see something like this:



3. Right-click on `TestHarness.java` and go to Run As →Run Configurations. In Java Application, under the "arguments" tab, add the string `-javaagent:jamm.jar` to the VM arguments field, then Apply and Run.

4. Now, run `TestHarness.java`. It will report the CPU time and memory usage of your implementation! If it run successfully, and give zeros for your memory usage (since you haven't implement any methods), you are good to go! (You will use this part again in Part Three). If you receive an error, restart Eclipse and try it again.

Note: If you are using OS X, you may receive the following error in the console: `Class JavaLaunchHelper is implemented in both /Library/Java/JavaVirtualMachines/jdk1.8.0_102.jdk/Contents/Home/bin/java and /Library/Java/JavaVirtualMachines/jdk1.8.0_102.jdk/Contents/Home/jre/lib/libinstrument.dylib. One of the two will be used. Which one is undefined.` This is fine, as the test harness will still run as long as everything else is set up properly.

Part One: `HashMap` (35 points)

Files to submit: `HashMap.java`, `HashMapTest.java`

Recall the method of chaining, discussed in lecture and in recitation. A hash table first hashes an `Object`'s hash code into a bucket index appropriate for the length of the backing array. Each bucket is a linked list of map entries that can be added to, modified in place, or removed from. **Note that when you add an element to a bucket, you should add the element to the front of the bucket** (i.e., the head of the linked list).

We have provided a fair bit of skeleton code for you, namely the constructors, the table buckets, and the hashing methods. You need to worry about the following eight method stubs:

1. `get(K key)`
2. `containsKey(K key)`
3. `put(K key, V value)`
4. `resize(int newCapacity)`
5. `remove(K key)`
6. `containsValue(V value)`
7. `clear()`
8. `entryIterator()`

Each method stub contains further instructions. **It is critical that you read *both* the Javadoc comments *and* the implementation comments for each method.** They contain necessary information on both the external and internal behavior of these methods.

It is also critical that you understand the provided code and methods. You will want to pay special attention to the `threshold` and `loadFactor` variables, the `hash(int h, int length)` method, and the `Entry` inner class. Your solution will explicitly invoke these entities.

The trickiest part of this implementation will be managing pointers when resizing. It might help to draw out some examples before you begin coding this part! Additionally, you should make sure you are correctly handling null keys and null values (for example, null keys should be hashed to index zero). Be careful to explicitly handle and test those, and don't be afraid to repeat some code if you want to explicitly isolate the null cases.

Part Two: `TrieMap` (40 points)

Files to submit: `TrieMap.java`, `TrieMapTest.java`

This should be a straightforward "standard" trie implementation, as described in the lecture notes. We have provided a skeleton for you in the form of a nested class `Node` and a few helper methods, and we've left you to worry about the following method stubs:

1. `put(CharSequence key, V value)`
2. `get(CharSequence key)`
3. `containsKey(CharSequence key)`
4. `containsValue(V value)`
5. `remove(CharSequence key)`
6. `clear()`

Each method stub contains further instructions. **It is critical that you read *both* the Javadoc specification (best done by using Eclipse to read the spec) *and* the implementation comments for each method.** They contain necessary information on behavior of these methods, hints on how to go about implementing them, and important explanations of differences from the `HashMap` implementation.

The trickiest part of this implementation will be correct removal of keys. You might find it helpful to work out examples of each method on paper before going forward with your implementation.

Note that unlike in your HashMap implementation, your TrieMap should not support `null` keys or values. The empty string is still valid as a key, however.

Kudos problem: Lazy iterator (No points)

Implement the `entryIterator()` method to return the entries in lexicographic order with respect to the keys. You must write this as a true lazy iterator—an implementation that simply dumps all the elements into a collection and retrieves an iterator from the collection will be awarded no points. The iterator only stores enough state to do its job. Constraints:

- The running time must be linear in the number of elements in the trie.
- The space usage must be proportional to the height of the trie.

If this last constraint about space usage is too difficult, you can ignore that constraint for half kudos.

Part Three: `Quantitative Analysis` (15 points)

Files to submit: `QuantitativeAnalysis.pdf`
Please answer the following questions in a LaTeX typeset document. You will submit this along with your programming files to Gradescope (no Canvas for this one).

Note: You must have followed the setup instructions for `TestHarness.java` and `jamm.jar` in Part Zero to be able to answer these questions.

Important: You must provide the actual program output for question 1, and actual numbers for question 5. If you do not, you will receive no credit for this section.

1. After finish your implementation of the HashMap and TrieMap, click run on TestHarness.java.
   Note: this will take a few minutes to run on your computer. We recommend that you take a brief walk outdoors in the meantime, or sword-fight a friend.

   Now please copy and paste the output of `TestHarness.java` as an answer to this question, and place it inside of a verbatim environment.

2. For `dictionary.txt`, which implementation had a better running time? Which implementation had better space usage? What about for `phonenumbers.txt`? Was this what you were expecting? Why or why not?

3. It was mentioned in lecture that tries are more space-efficient than hash tables due to the fact that they compress common prefixes. Did your implementation reflect this for `dictionary.txt`? What about for `phonenumbers.txt`? If so, why? If not, what could you potentially do to improve the memory consumption of your `TrieMap`?

4. Based on your answer to 3, does Big-Oh notation tell us anything about the *actual* running time or space usage of an algorithm on a data set? Why or why not? What might an implication of this be for software development?

5. Add a call to `initChildren()` to the end of the `Node` constructor in `TrieMap.java`, then re-run the test harness, and consider the results for `TrieMap` and `dictionary.txt`. The difference here is that now we initialize the children array as soon as the node is constructed, instead of waiting until we actually add a child (the "lazy" way). How much memory, both absolutely and relatively, does the lazy initialization save us? (*Give actual numbers.*) Would you say the lazy initialization is a worthwhile optimization?

Again, as a reminder: you must provide the actual program output for question 1, and actual numbers for question 5. If you do not, you will receive no credit for this section.

Style & Tests (10 points)

The above parts together are worth a total of 90 points. The remaining 10 points are awarded for code style, documentation and sensible tests. Style is worth 5 of the 10 points, and you will be graded according to the 121 style guide.

On this assignment in particular, focus on the behaviors that are specific to one implementation or the other. Especially consider edge cases, exceptions, and null keys and values. As always, use multiple methods instead of cramming a bunch of asserts into a single test method, and be sure to demonstrate that you've

considered "bad" inputs, exceptions, etc. Your test cases will be autograded for code coverage, and are worth 5 of the 10 points. You will have to thoroughly test your code to get full points! This includes testing any additional helper methods you have written. **Note**: you will not be able to write JUnit test cases for any private methods. Instead, make them package-private by leaving off any privacy modifier.

Mocking `hashCode()`

When writing unit tests for your `HashMap`, you may find it useful to force collisions between `Objects` that you are inserting in the map. Since your implementation will require the use of Java's `hashCode()` method, you will have to override this method when testing your chaining.

Suppose you want to force a collision between two objects in your unit test. You can do the following:

```
@Test
public void testCollision() {
    Object obj1 = new Object() {
        @Override
        int hashCode() {
            return 5;
        }
    };

    Object obj2 = new Object() {
        @Override
        int hashCode() {
            return 5;
        }
    };

    map.put(obj1, "foo");
    map.put(obj2, "bar");
    //...
}
```

An alternative, more clean approach would be to create a class where you can set the `hashCode` at construction:

```
static class MockHashObject {
    private final int hashCode;

    public MockHashObject(int hashCode) {
        this.hashCode = hashCode;
    }

    @Override
    int hashCode() {
        return hashCode;
    }
}
```

Either of these approaches works for testing your chaining.