Lab 08: HashMap

FAQ

The FAQ for this lab can be found here.

Introduction

The lab intro slides can be found here.

In this lab, you'll work on `MyHashMap`, a hashtable-based implementation of the `Map61B` interface. This will be very similar to Lab 07, except this time we're building a `HashMap` rather than a `TreeMap`.

Please use the usual `git` commands to pull the skeleton. If you are experiencing a merge conflict, refer to the special `git pull` commands listed on the Lab06 spec.

After you've completed your implementation, you'll compare the performance of your implementation to a list-based Map implementation `ULLMap` as well as the built-in Java `HashMap` class (which also uses a hash table). We'll also compare the performance of `MyHashMap` when it uses different data structures to be the buckets.

MyHashMap

Overview

We've created a class `MyHashMap` in `MyHashMap.java`, with very minimal starter code. Your goal is to implement all of the methods in the `Map61B` interface from which `MyHashMap` inherits, *except* `remove`, `keySet` and `iterator` (optional for Lab 08). For these, feel free to throw an `UnsupportedOperationException`.

Note that your code will not compile until you implement all the methods of `Map61B`. You can implement methods one at a time by writing the method signatures of all the required methods, but throwing `UnsupportedOperationException`s for the implementations until you get around to actually writing them.

Refresher Animation

The following is a quick animation of how a hash table works. `N` refers to the number of items in the hash table, and `M` refers to the number of buckets.

We use an object's `hashCode` modulo'd by the number of buckets to determine which bucket the object (represented by a shape) falls into. When the load factor is reached, we multiply the number of buckets by the resizing factor and rehash all of the items, modulo-ing them by the new number of buckets.

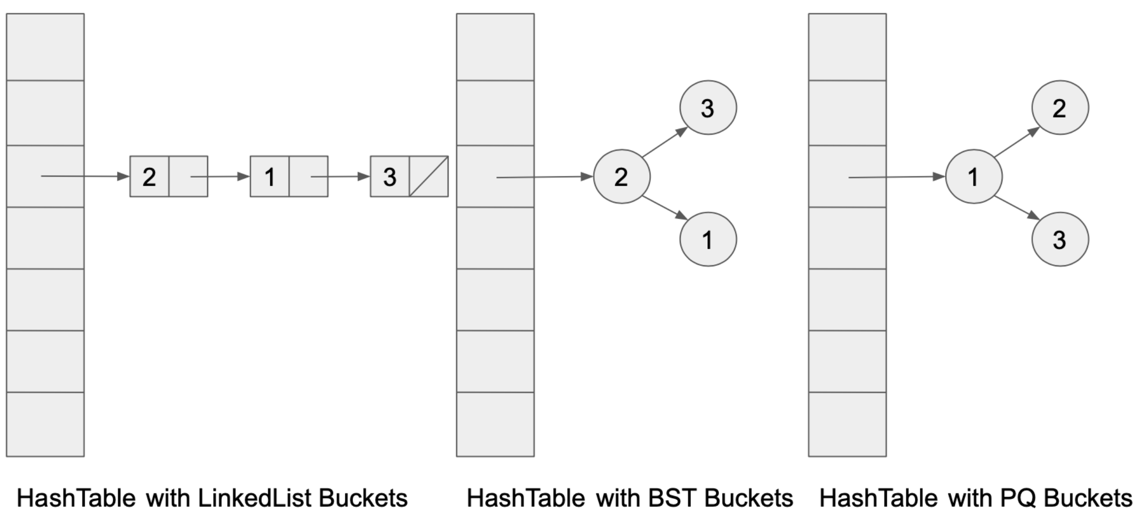
Credits to Meshan Khosla for this animation!

Refresher Video

If you need a more in-depth explanation of how hash tables work, the following video will prove useful.

Skeleton Code

You might recall from lecture that when we build a hash table, we can choose a number of different data structures to be the buckets. The classic approach is to choose a `LinkedList`. But we can also choose `ArrayList`s, `TreeSet`s, or even other crazier data structures like `PriorityQueue`s or even other `HashSet`s!



During this lab, we will try out hash tables with different data structures for each of the buckets, and see empirically if there is an asymptotic difference between using different data structures as hash table buckets.

For this lab, we will be trying out `LinkedList`, `ArrayList`, `HashSet`, `Stack`, and `ArrayDeque` (unfortunately, no `TreeSet` or `PriorityQueue` like the diagram above shows due to excessive boilerplate, though you're welcome to try it if you'd like). That's a lot of classes!

You can imagine that if we implemented `MyHashMap` without much care, it would take a lot of effort with Find + Replace to be able to change out the bucket type with a different bucket type. For example, if we wanted to change all our `ArrayList` buckets to `LinkedList` buckets, we would have to Find + Replace for all occurrences of `ArrayList` and replace that with `LinkedList`. This is not ideal - for example, we may have a non-bucket component that relies on some `ArrayList` methods. We wouldn't want to ruin our code by changing that to a `LinkedList`!

The purpose of the starter code is to have an easier way to try out different bucket types with `MyHashMap`. It accomplishes this through polymorphism and inheritance, which we learned about earlier this semester. It also makes use of **factory methods and classes**, which are utility code used to create objects. This is a common pattern when working with more advanced code, though the details are out-of-scope for 61B.

`MyHashMap` implements the `Map61B` interface through use of a hash table. In the starter code, we give the instance variable `private Collection<Node>[] buckets`, which is the underlying data structure of the hash table. Let's unpack what this code means:

- `buckets` is a `private` variable in the `MyHashMap` class.
- It is an array (or table) of `Collection<Node>` objects, where each `Collection` of `Node`s represents a single bucket in the hash table
- `Node` is a private helper class we give that stores a single key-value mapping. The starter code for this class should be straightforward to understand, and should not require any modification.

- `java.util.Collection` is an interface which most data structures inherit from, and it represents a group of objects. The `Collection` interface supports methods such as `add`, `remove`, and `iterator`. Many data structures in `java.util` implement `Collection`, including `ArrayList`, `LinkedList`, `TreeSet`, `HashSet`, `PriorityQueue`, and many others. Note that because these data structures implement `Collection`, we can assign them to a variable of static type `Collection` with polymorphism.

- Therefore, our array of `Collection<Node>` objects can be instantated by many different types of data structures, e.g. `LinkedList<Node>` or `ArrayList<Node>`. **Make sure your buckets generalize to any Collection!** See the below warning for how to do this.
- When creating a new `Collection<Node>[]` to store in our `buckets` variable, be aware that in Java, you cannot create an array of parameterized type. `Collection<Node>` is a parameterized type, because we parameterize the `Collection` class with the `Node` class. Therefore, Java disallows `new Collection<Node>[size]`, for any given `size`. To get around this, you should instead create a `new Collection[size]`, where `size` is the desired size. The elements of a `Collection[]` can be a collection of any type, like a `Collection<Integer>` or a `Collection<Node>`. For our purposes, we will only add elements of type `Collection<Node>` to our `Collection[]`.

The mechanism by which different implementations of the hash table implement different buckets is through a factory method `protected Collection<Node> createBucket()`, which simply returns a `Collection`. For `MyHashMap.java`, you can choose any data structure you'd like. For example, if you choose `LinkedList`, the body of `createBucket` would simply be:

```
protected Collection<Node> createBucket() {
        return new LinkedList<>();
}
```

Instead of creating new bucket data structures with the `new` operator, you must use the `createBucket` method instead. This might seem useless at first, but it allows our factory classes to override the `createBucket` method in order to provide different data structures as each of the buckets.

In `MyHashMap`, you can just have this method return a new `LinkedList` or `ArrayList`.

Implementation Requirements

You should implement the following constructors:

```
public MyHashMap();
public MyHashMap(int initialCapacity);
public MyHashMap(int initialCapacity, double loadFactor);
```

Some additional requirements for `MyHashMap` are below:

- Your hash map should initially have a number of buckets equal to `initialCapacity`. You should increase the size of your `MyHashMap` when the load factor exceeds the maximum `loadFactor` threshold. Recall that the current **load factor** can be computed as `loadFactor = N/M`, where `N` is the number of elements in the map and `M` is the number of buckets. The load factor represents the amount of elements per bucket, on average. If `initialCapacity` and `loadFactor` aren't given, you should set defaults `initialCapacity = 16` and `loadFactor = 0.75` (as Java's built-in HashMap does).
- You should handle collisions with separate chaining. You should not use any libraries other than the bucket classes, `Collection`, `Iterator`, `Set`, and `HashSet`. For more detail on how you should implement separate chaining, see the **Skeleton Code** section above.
- Because we use a `Collection<Node>[]` for our `buckets`, when implementing `MyHashMap`, you are restricted to using methods that are specified by the `Collection` interface. When you are searching for a `Node` in a `Collection`, simply iterate over the `Collection`, and find the `Node` whose `key` is `.equal()` to the desired key.
- If the same key is inserted more than once, the value should be updated each time (i.e., no `Node`s should be added). You can assume `null` keys will never be inserted.
- When resizing, make sure to multiplicatively (geometrically) resize, not additively (arithmetically) resize. You are **not** required to resize down.
- `MyHashMap` operations should all be constant amortized time, assuming that the `hashCode` of any objects inserted spread things out

nicely (recall: every `Object` in Java has its own `hashCode()` method).

Note: `hashCode()` can return a *negative value*! Java's modulo operator `%` will return a negative value for negative inputs, but we need to send items to a bucket in the range $[0, M)$. There are a myriad of ways to handle this:

1. (Recommended) You can use `Math.floorMod()` in place of `%` for the modulo operation. This has a non-negative range of values, similar to Python's modulo.
2. If the resulting value after the `%` operation is negative, you can add the size of the array to it.
3. You can use the `Math.abs()` function to convert the negative value to a positive value. Note that $|x| \bmod m$, $|x \bmod m|$, and $x \bmod m$ **are not equivalent in general**! We're just using the modulo operation here to make sure we have a valid index. We don't necessarily care too much about the exact bucket the item goes into, because a good hash function should spread things out nicely over positive and negative numbers.
4. Option (3) but with a bitmask (don't worry if you don't know what this means). This is out-of-scope for 61B, but some of the resources do this, which is why we've put it here.

Task: Complete the `MyHashMap` class according to the specifications in `Map61B` and the guidelines above.

Testing

You can test your implementation using `TestMyHashMap.java`. Some of the tests are quite tricky and do weird stuff we haven't learned in 61B. The comments will prove useful to see what the tests are actually doing.

If you've correctly implemented generic `Collection` buckets, you should also be passing the tests in `TestMyHashMapBuckets.java`. The `TestMyHashMapBuckets.java` file simply calls methods in `TestMyHashMap.java` for each of the different map subclasses that implement a different bucket data structure. Make sure you've correctly implemented `MyHashMap` using the factory methods provided (i.e., `createBucket`) for `TestHashMapBuckets.java` to pass.

If you choose to implement the additional `remove`, `keySet`, and `iterator` methods, we provide some tests in `TestHashMapExtra.java`.

Resources

You may find the following resources useful

- Lecture slides:
    - hashing 1
    - hashing 2
    - inheritance
    - subtype polymorphism

The following may contain antiquated code or use unfamiliar techniques, but should still be useful:

- HashMap code from pages 136 and 137 of Data Structures Into Java, from our course references page
- Chapter 3.4 of our optional textbook
- HashTable code from our optional textbook
- `ULLMap.java` (provided), a working unordered linked list based `Map61B` implementation

Speed Testing

There are two interactive speed tests provided in `InsertRandomSpeedTest.java` and `InsertInOrderSpeedTest.java`. Do not attempt to run these tests before you've completed `MyHashMap`. Once you're ready, you can run the tests in IntelliJ.

The `InsertRandomSpeedTest` class performs tests on element-insertion speed of your `MyHashMap`, **ULLMap** (provided), and Java's built-in **HashMap**. It works by asking the user for an input size `N`, then generates `N` Strings of length `10` and inserts them into the maps as `<String, Integer>` pairs.

Try it out and see how your data structure scales with `N` compared to the naive and industrial-strength implementations. Record your results in the provided file named `src/results.txt`. There is no standard format required for your results, and there is no required number of data points. We expect you to write at least sentence or two with your observations, though.

Now try running `InsertInOrderSpeedTest`, which behaves similarly to `InsertRandomSpeedTest`, except this time the `String`s in `<String, Integer>` key-value pairs are inserted in lexicographically-increasing order. Note that unlike Lab 7, your code should be in the rough ballpark of Java's built in solution – say, within a factor of 10 or so. What this tells us is that state-of-the-art `HashMaps` are relatively easy to implement compared to state-of-the-art `TreeMaps`. When would it be better to use a `BSTMap`/`TreeMap` instead of a `HashMap`? Discuss this with your labmates, and add your answer to `results.txt`.

Different Bucket Types

If you've correctly implemented generic `Collection` buckets, most of the work is done! We can directly compare the different data structures used to implement buckets. We provide `speed/BucketsSpeedTest.java`, which is an interactive test that queries the user for an integer `L` for the length of string to use on subsequent operations. Then, in a loop, it queries the user for an integer `N`, and runs a speed test on your `MyHashMap` using different types of buckets.

Try it out and compare how the different implementations scale with `N`. Discuss your results with your labmates, and record your responses in `results.txt`.

You might notice that our implementation using `HashSet`s as buckets searches for a `Node` by iterating over the entire data structure. But we know hash tables support more efficient lookups than that. Would our hash table speed up asymptotically if we were able to use a constant-time search over the `HashSet`? You do not need to implement anything new here, just discuss with your labmates, and record your ideas in `results.txt`.

Task: Run the above speed tests in the `speed` directory and record your results in `results.txt`.

Deliverables and Scoring

The lab is out of 256 points. There is one hidden test on Gradescope (that checks your `results.txt`). The rest of the tests are local. If you pass all the local tests and fill out the `results.txt` file sufficiently, you will get full credit on Gradescope.

Each of the following is worth $\frac{256}{11}$ points and corresponds to a unit test:

- Generics
- `clear`
- `containsKey`
- `get`
- `size`
- `put`
- Functionality
- Resizing
- Edge cases
- Buckets (all of `TestMyHashMapBuckets`)
- `results.txt` (not tested locally)

Submission

Just as you did for the previous assignments, add, commit, then push your Lab 08 code to GitHub. Then, submit to Gradescope to test your code. If you need a refresher, check out the instructions in the Lab 1 spec and the Assignment Workflow Guide.

Optional Exercises

These will not be graded, but you can still receive feedback with the given tests.

Implement the methods `remove(K key)` and `remove(K key, V value)`, in your `MyHashMap` class. For an extra challenge, implement `keySet()` and `iterator()` without using a second instance variable to store the set of keys.

For `remove`, you should return `null` if the argument key does not exist in the `MyHashMap`. Otherwise, delete the key-value pair (key, value) and return the associated value.

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