JVM - Priority Queue with $O(logn)$ removals

csd4366 - Orfeas Chatzipanagiotis

csd4149 - Konstantinos Anemozalis

Introduction

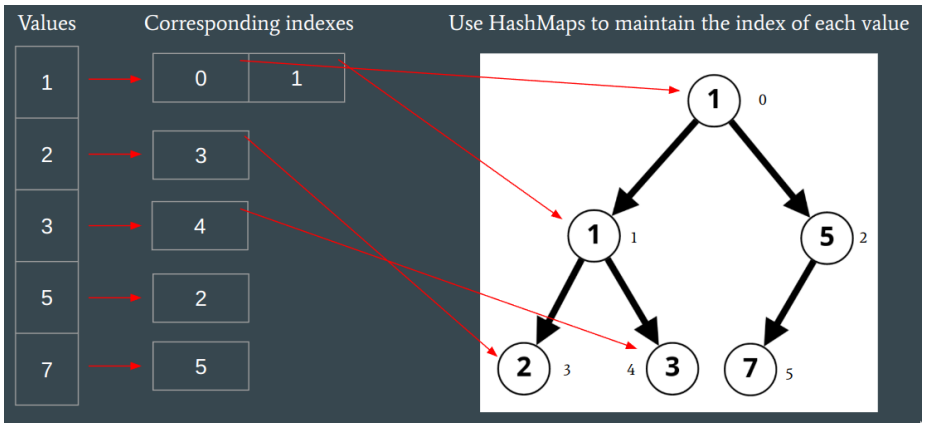
The priority queue is one of the most commonly used data structures in applications. Most modern languages have support for the priority queue data structure through their original libraries. Java provides a priority queue class with a original implementation that offers low space complexity as well as $O(1)$ access to the first element of the priority queue. However, one operation that is often very slow on priority queues is element removal. Removal has a $O(n)$ time complexity making it extremely inefficient for applications that remove elements very frequently. We introduced a new priority queue implementation that is optimized for fast removals using a hash map. The hash table is used along side the heap structure to maintain the indices of all the elements in the heap and support arbitrary element removals in $O(logn)$.

Original implementation

The priority queue implementation in the Java original library uses a heap structure, a one-dimensional array with size equal or greater to the number of elements in the priority queue. It also caches the first element to ensure $O(1)$ access.

Our implementation

Our implementation sacrifices $O(n)$ extra space to support $O(logn)$ removal time. This is achieved using a hash table that keeps track of all the indices a certain element is present on (it can be multiple). The picture below better envisions this concept:



Time complexity comparison

	Insert	Poll	Peek	Remove
Original impl.	$O(logn)$	$O(logn)$	$O(1)$	$O(n)$
Our impl.	$O(logn)$	$O(logn)$	$O(1)$	$O(logn)$

Limitations & Drawbacks

Despite improving the overall complexity of the removal times, our implementation has two main drawbacks:

1) It suffers from a high constant factor since it has to perform a lot of bookkeeping. Depending on the application the constant factor may become significant enough that our implementation performs worse than the original

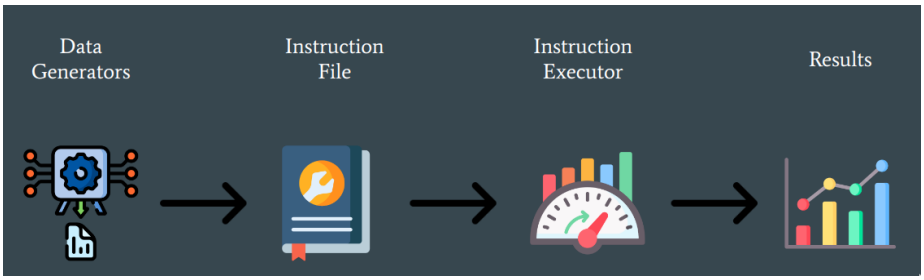
2) It has a much larger memory footprint in order to store the hash map

Validity

To validate the correctness of our implementation we stress tested it against a much simpler implementation (can be found under the `../src/stresstest` directory). Both implementations produced the same results which convinced us that no errors were made.

Benchmarking

We exhibited a series of benchmarks based on various test cases that we created. The test cases were created at random and contained different patterns in order to observe how our algorithm performs. Here is a picture that shows our benchmarking pipeline:



The data generator was a simple script that produced a list of instructions in the form of:

```
...
INSERT 5
REMOVE 1
INSERT 2
POLL   2
...
```

This list was then read by the instruction executor, the program we were experimenting on, and it performed these operations on a priority queue. The test suites were produced once in the beginning and then were tested on both our and original implementation.

Turning off garbage collection

Since our goal was to compare the time difference between the two implementations, we used the EpsilonGC, a special Garbage Collector that doesn't perform any collections. Thus we avoided any collections that would skew our results.

Environment

OS: `Ubuntu 23.04`

CPU: `AMD Ryzen 7 5800X 8-Core Processor`

RAM: `32GB`

JDK: `Openjdk 21-internal 2023-09-19`

JVM-args: `-Xms15G -Xmx15G -XX:+UnlockExperimentalVMOptions -XX:+UseEpsilonGC`

Generators

- ReverseRemoval - *original worst case scenario/our best case scenario*
  - This generator produces output that is the worst case scenario for the original implementation of the priority queue, and it is expected to run much faster in our implementation.
- Insert4Remove1

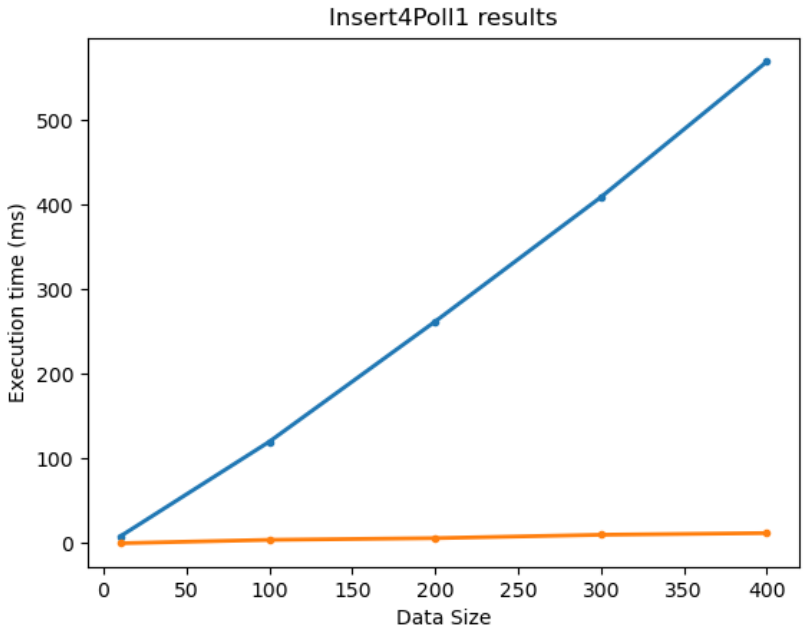
  - This generator inserts 4 elements, and removes 1 random that is already inside the priority queue.
- InsertRemoveRandom
  - This generator takes an integer parameter $p >= 1$
    - It produces remove operations with probability $P = 1/p$
    - It produces remove operations with probability $P = 1 - 1/p$
    - We run this generator with two different p values:
      - $p = 3$ - One remove operation per 3 operations
      - $p = 5$ - One remove operation per 5 operations (should be similar to the Insert4Remove1)
- Insert4Poll1 - *original best case scenario/our worst case scenario (doesn't use remove operations)*

Results

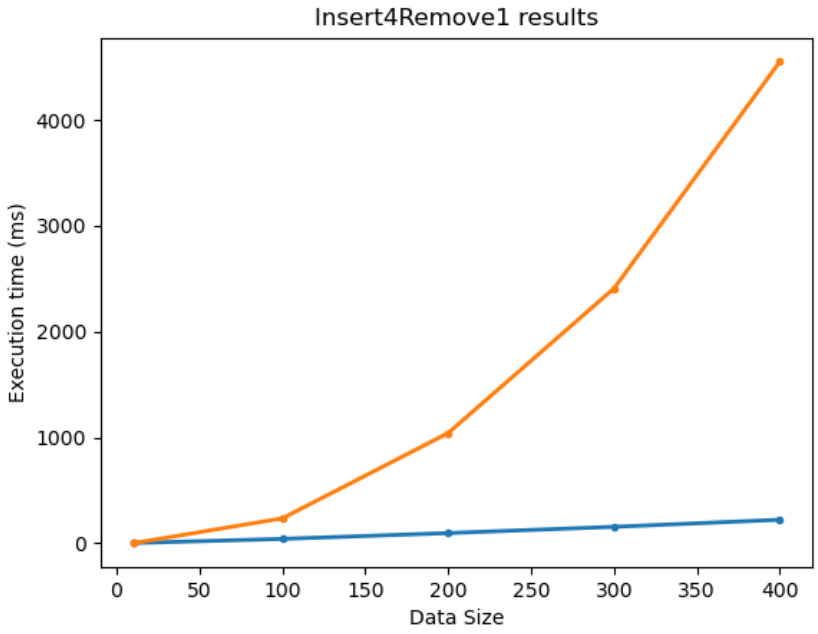
Blue line: our implementation

Orange line: original JVM implementation

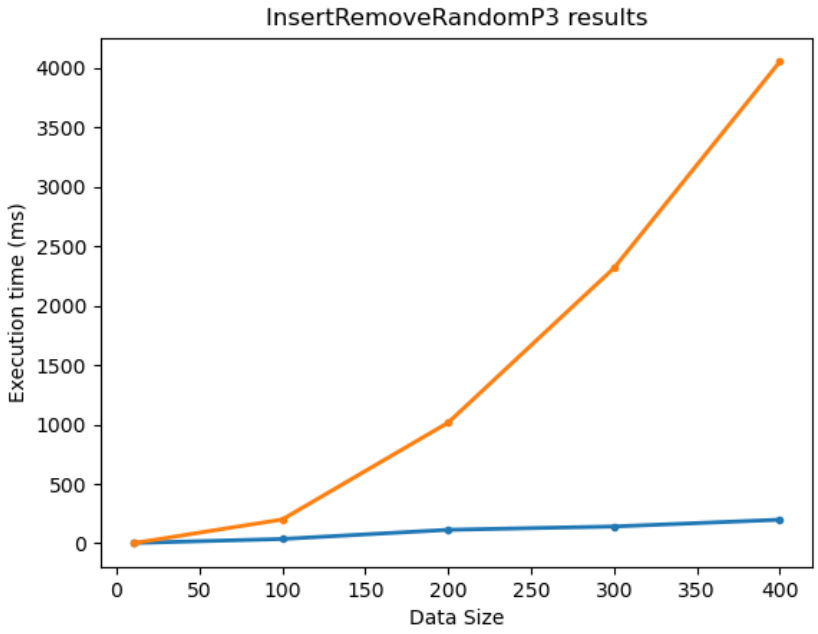
Insert4Poll1



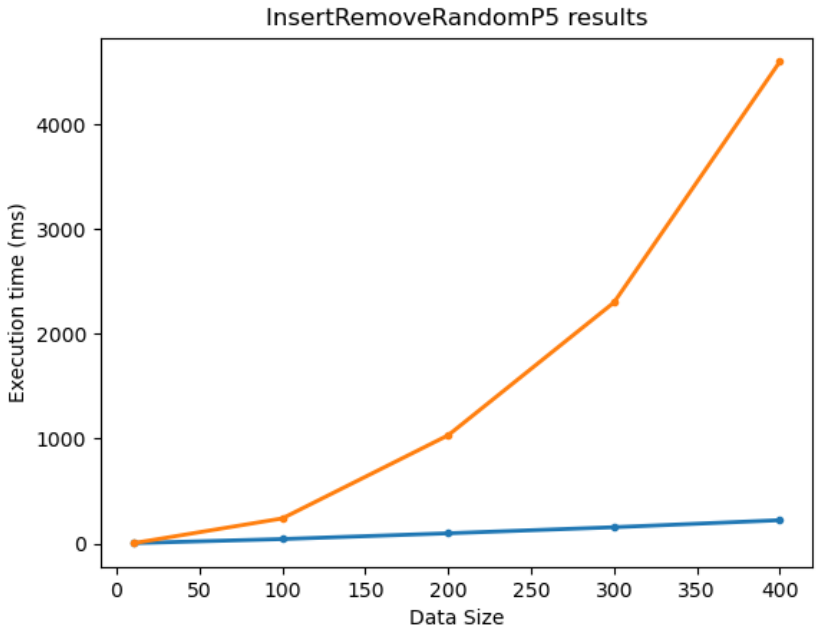
Insert4Remove1



InsertRemoveRandomP3



InsertRemoveRandomP5



Comments

The goal of the first test was to show how our implementation scales when there are no removal operations. As we can see as the data size grows, our implementation becomes slower at a linear rate. This is was something we expected since the overhead of bookkeeping and the constant factor of our algorithm has a significant toll on the overall performance.

The rest of the test cases, however, exhibit the opposite behaviour: the original implementation becomes quadratically slower, whereas our implementation maintains an almost linear rate.