Abstract Priority Queue

Source: `AbstractPriorityQueue.java`

```
public abstract class AbstractPriorityQueue<T extends Comparable<T>> {
    protected Comparator<T> comparator;

    public AbstractPriorityQueue(Comparator<T> comparator) {
        this.comparator = comparator;
    }
```

- Class types: `class` vs. `abstract class` vs. `interface`.
- Generics: `<T extends Comparable<T>>`.
- Interface in generics: `Comparable`.
- Member types: `private` vs. `package` vs. `protected` vs. `public`.
- Constructor: `this`.

```
    /**
     * Adds a comparable key to this queue.
     * @param key the comparable key.
     */
    abstract public void add(T key);

    /**
     * Removes the key with the highest priority if exists.
     * @return the key with the highest priority if exists; otherwise, {@code null}.
     */
    abstract public T remove();

    /** @return the size of this queue. */
    abstract public int size();

    /** @return {@code true} if the queue is empty; otherwise, {@code false}. */
    public boolean isEmpty() {
        return size() == 0;
    }
```

- Abstract methods: `add()`, `remove()`, `size()`.
- Regular method in abstract class: `isEmpty()`.
- Javadoc.

Lazy Priority Queue

Source: `LazyPriorityQueue.java`

```
public class LazyPriorityQueue<T extends Comparable<T>> extends AbstractPriorityQueue<T> {
    private List<T> keys;

    public LazyPriorityQueue(Comparator<T> comparator) {
        super(comparator);
        keys = new ArrayList<>();
    }

    public LazyPriorityQueue() {
        this(Comparator.naturalOrder());
    }
```

- Class inheritance: `extends AbstractPriorityQueue<T>`.
- Constructors: default vs. parameters, `this` vs. `super`.

```java
    /**
     * Adds a key to the back of the list.
     * @param key the comparable key.
     */
    @Override
    public void add(T key) { keys.add(key); }

    /**
     * Finds the key with the highest priority, and removes it from the list.
     * @return the key with the highest priority if exists; otherwise, {@code null}.
     */
    @Override
    public T remove() {
        if (isEmpty()) return null;
        T max = Collections.max(keys, comparator);
        keys.remove(max);
        return max;
    }

    @Override
    public int size() { return keys.size(); }
```

- Annotation: `@Override`.
- Edge case handling: `remove()`.
- Base API: `Collections.max()`.
- Complexity: `add()`, `remove()`.

Eager Priority Queue

Source: `EagerPriorityQueue.java`

```
    /**
     * Adds a key to the list according to the priority.
     * @param key the comparable key.
     */
    @Override
    public void add(T key) {
        int index = Collections.binarySearch(keys, key, comparator);
        if (index < 0) index = -(index + 1);
        keys.add(index, key);
    }

    /**
     * Remove the last key in the list.
     * @return the key with the highest priority if exists; otherwise, {@code null}.
     */
    @Override
    public T remove() {
        return isEmpty() ? null : keys.remove(keys.size() - 1);
    }
```

- Base API: `Collections.binarySearch()`.
- Ternary conditional operator: `condition ? :`.
- Complexity: `add()`, `remove()`.

Binary Heap

What is a heap?

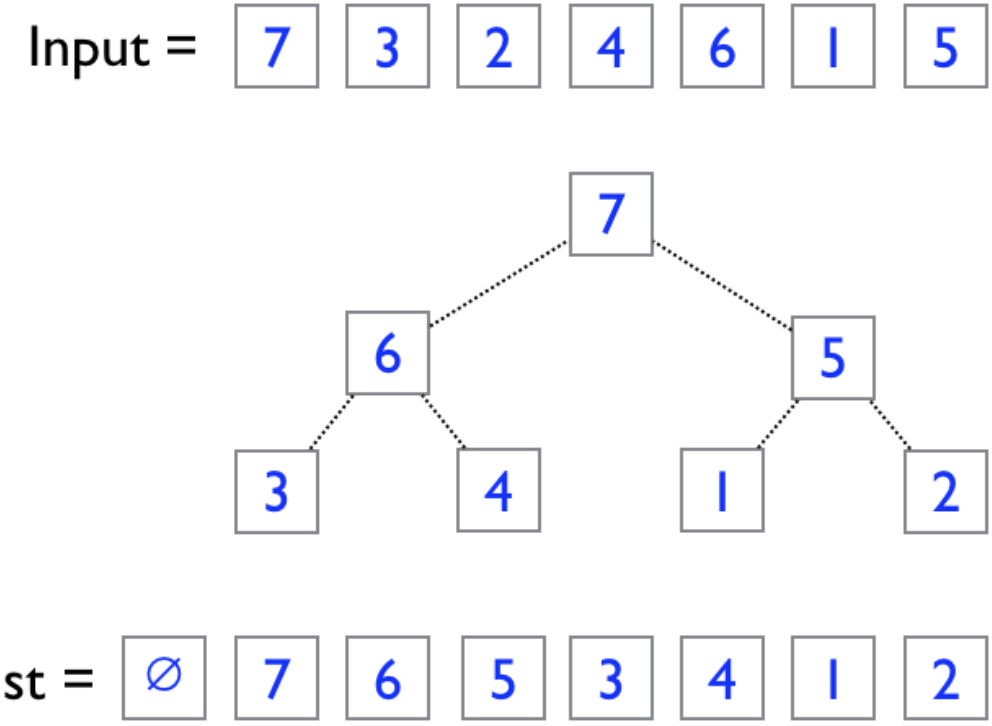
- A tree where each node has a higher (or equal) priority than its children.
- The tree must be balanced at all time.
- What is a binary heap?

Operations

- Add: swim.
- Remove: sink.
- Both operations can be done in $O(\log n)$.

Representation

- Binary heap can be represented by a list.
- Index of the parent: $k/2$.
- Index of the children: $k * 2$ and $(k * 2) + 1$.



Source: `BinaryHeap.java`

```
public class BinaryHeap<T extends Comparable<T>> extends AbstractPriorityQueue<T> {
    private List<T> keys;

    public BinaryHeap(Comparator<T> comparator) {
        super(comparator);
        keys = new ArrayList<>();
        keys.add(null);    // initialize the first item as null
    }

    public BinaryHeap() {
        this(Comparator.naturalOrder());
    }

    @Override
    public int size() {
        return keys.size() - 1;
    }
```

- Handle the `null` key at the front.

```java
    @Override
    public void add(T key) {
        keys.add(key);
        swim(size());
    }

    private void swim(int k) {
        while (1 < k && comparator.compare(keys.get(k / 2), keys.get(k)) < 0) {
            Collections.swap(keys, k / 2, k);
            k /= 2;
        }
    }
```

- Add each key to the end of the list and swim.
- `comparator.compare()` : compare itself to its parent.
- Base API: `Collections.swap()` .

```java
@Override
public T remove() {
    if (isEmpty()) return null;
    Collections.swap(keys, 1, size());
    T max = keys.remove(size());
    sink(1);
    return max;
}

private void sink(int k) {
    for (int i = k * 2; i <= size(); k = i, i *= 2) {
        if (i < size() && comparator.compare(keys.get(i), keys.get(i + 1)) < 0) i++;
        if (comparator.compare(keys.get(k), keys.get(i)) >= 0) break;
        Collections.swap(keys, k, i);
    }
}
```

- Replace the root with the last key in the list and sink.
- Compare two children.
- Compare itself to the greater child.

Unit Tests

Source: `PriorityQueueTest.java`

```java
/**
 * @param q a priority queue.
 * @param c a comparator used for sorting.
 * @param keys a list of comparable keys.
 */
private <T extends Comparable<T>>void testAccuracy(AbstractPriorityQueue<T> q, Comparator<T> c, List<T> keys) {
    keys.forEach(q::add);
    keys.sort(c);
    keys.forEach(key -> assertEquals(key, q.remove()));
}

@Test
public void testAccuracy() {
    List<Integer> keys = List.of(4, 1, 3, 2, 5, 6, 8, 3, 4, 7, 5, 9, 7);
    Comparator<Integer> natural = Comparator.naturalOrder();
    Comparator<Integer> reverse = Comparator.reverseOrder();

    testAccuracy(new LazyPriorityQueue<>(), reverse, new ArrayList<>(keys));
    testAccuracy(new EagerPriorityQueue<>(), reverse, new ArrayList<>(keys));
    testAccuracy(new BinaryHeap<>(), reverse, new ArrayList<>(keys));

    testAccuracy(new LazyPriorityQueue<Integer>(reverse), natural, new ArrayList<>(keys));
    testAccuracy(new EagerPriorityQueue<Integer>(reverse), natural, new ArrayList<>(keys));
    testAccuracy(new BinaryHeap<Integer>(reverse), natural, new ArrayList<>(keys));
}
```

- Generics on method.
- Lambda expression: `Iterable.forEach()`.
- Annotation: `@Test`.

Benchmarks

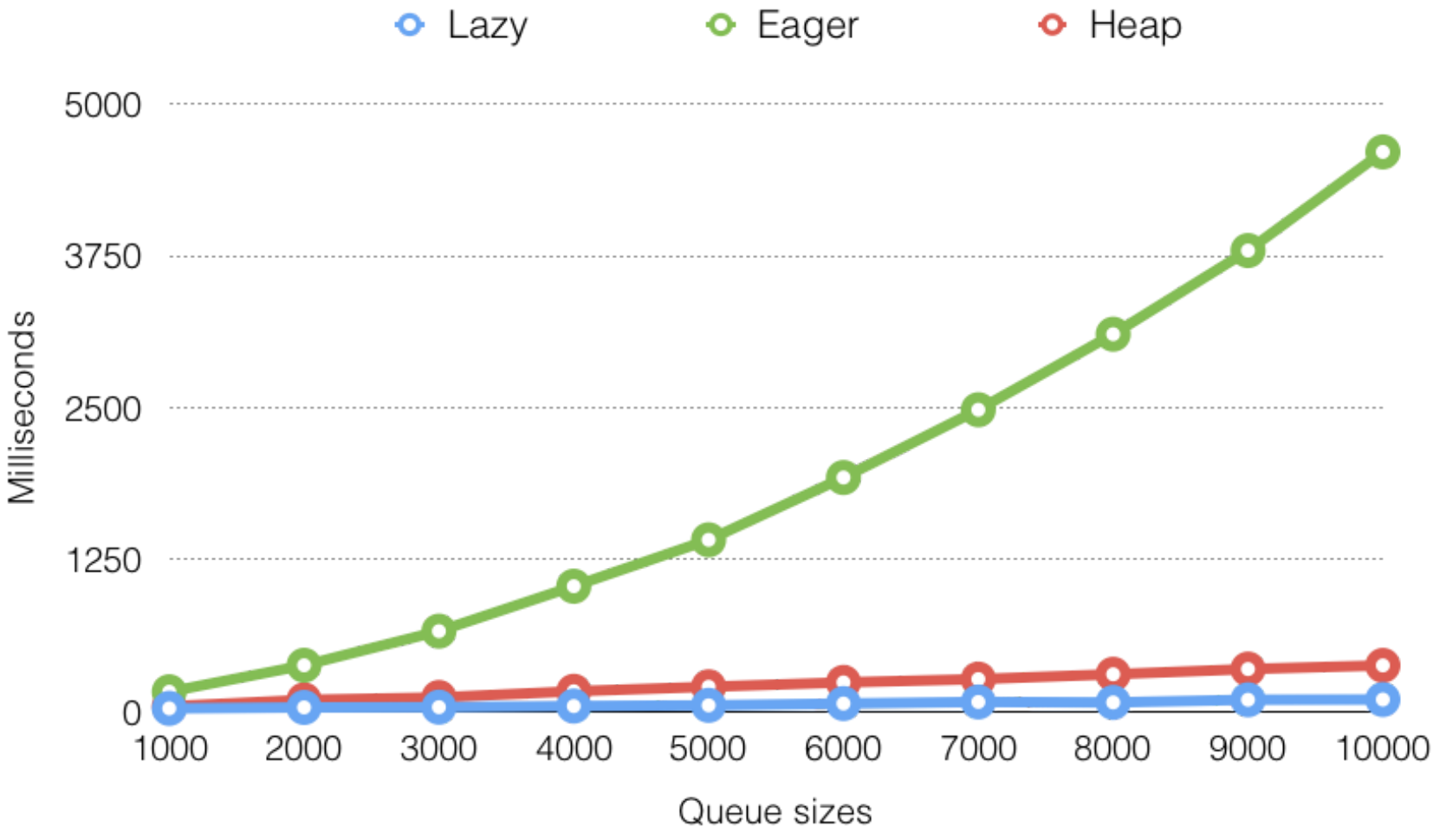
```
private class Time {
    long add;
    long remove;
}

private void addRuntime(AbstractPriorityQueue<Integer> q, Time t, int[] keys) {
    long st, et;

    // runtime for q.add()
    st = System.currentTimeMillis();
    Arrays.stream(keys).forEach(q::add);
    et = System.currentTimeMillis();
    t.add += et - st;

    // runtime for q.remove()
    st = System.currentTimeMillis();
    while (!q.isEmpty()) q.remove();
    et = System.currentTimeMillis();
    t.remove += et - st;
}
```

- Class type: `private class`.
- Base API: `System.currentTimeMillis()`.
- Lambda expression: `Arrays.stream()`.

```java
private Time[] benchmark(AbstractPriorityQueue<Integer>[] qs, int iter, int size) {
    Time[] ts = Stream.generate(Time::new).limit(qs.length).toArray(Time[]::new);
    Random rand = new Random();

    for (int i = 0; i < iter; i++) {
        int[] keys = Utils.getRandomIntArray(rand, size);

        for (int j = 0; j < qs.length; j++)
            addRuntime(qs[j], ts[j], keys);
    }

    return ts;
}

private void testSpeed(AbstractPriorityQueue<Integer>... qs) {
    for (int size = 1000; size <= 10000; size += 1000) {
        // JVM warmup
        benchmark(qs, 10, size);
        // benchmark all priority queues with the same keys
        Time[] times = benchmark(qs, 1000, size);
    }
}

@Test
public void testSpeed() {
    testSpeed(new LazyPriorityQueue<>(), new EagerPriorityQueue<>(), new BinaryHeap<>());
}
```

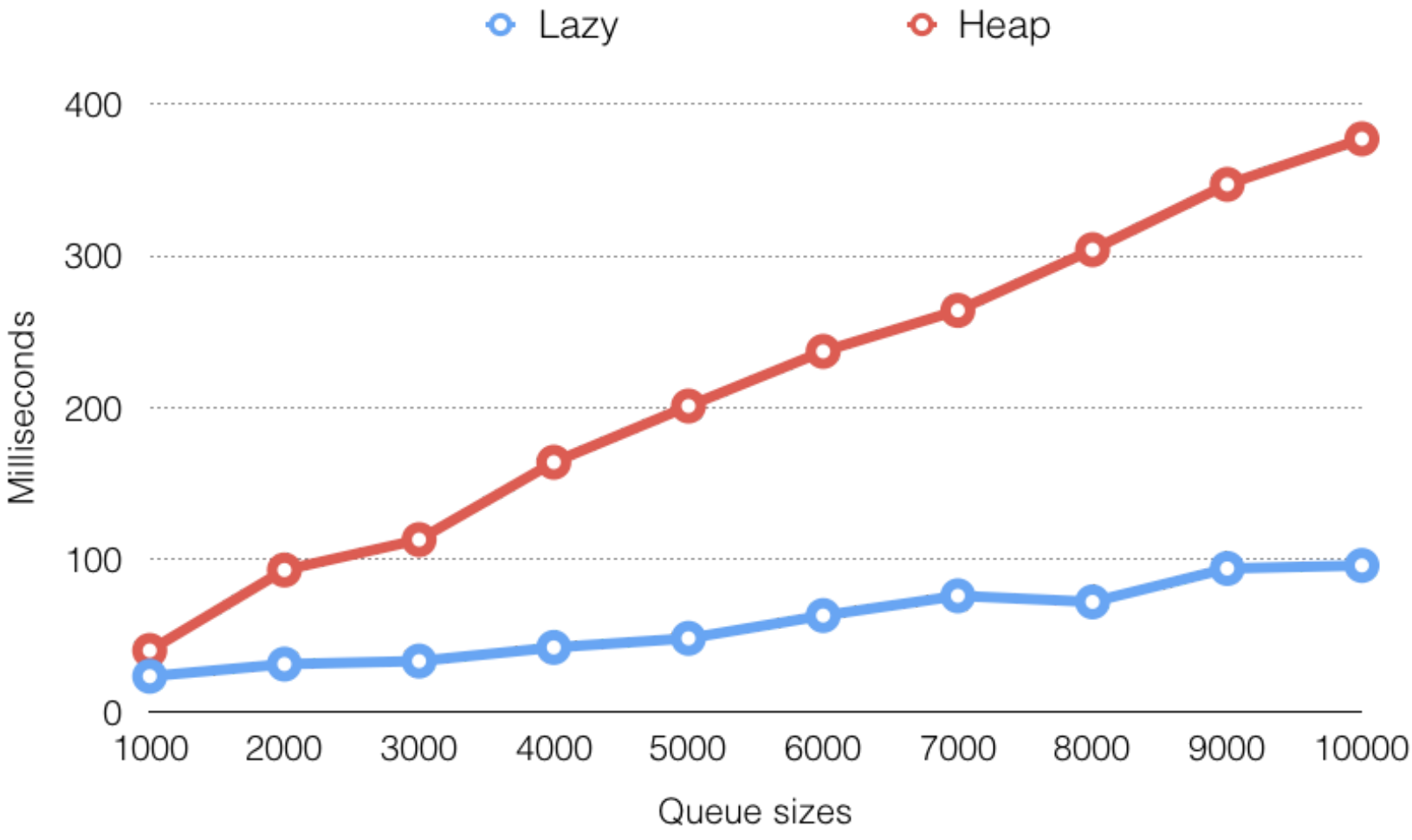
- Variable Arguments: `AbstractPriorityQueue<Integer>... qs`.
- Lambda expression: `Stream.generate().limit().toArray()`.

Benchmark - Add



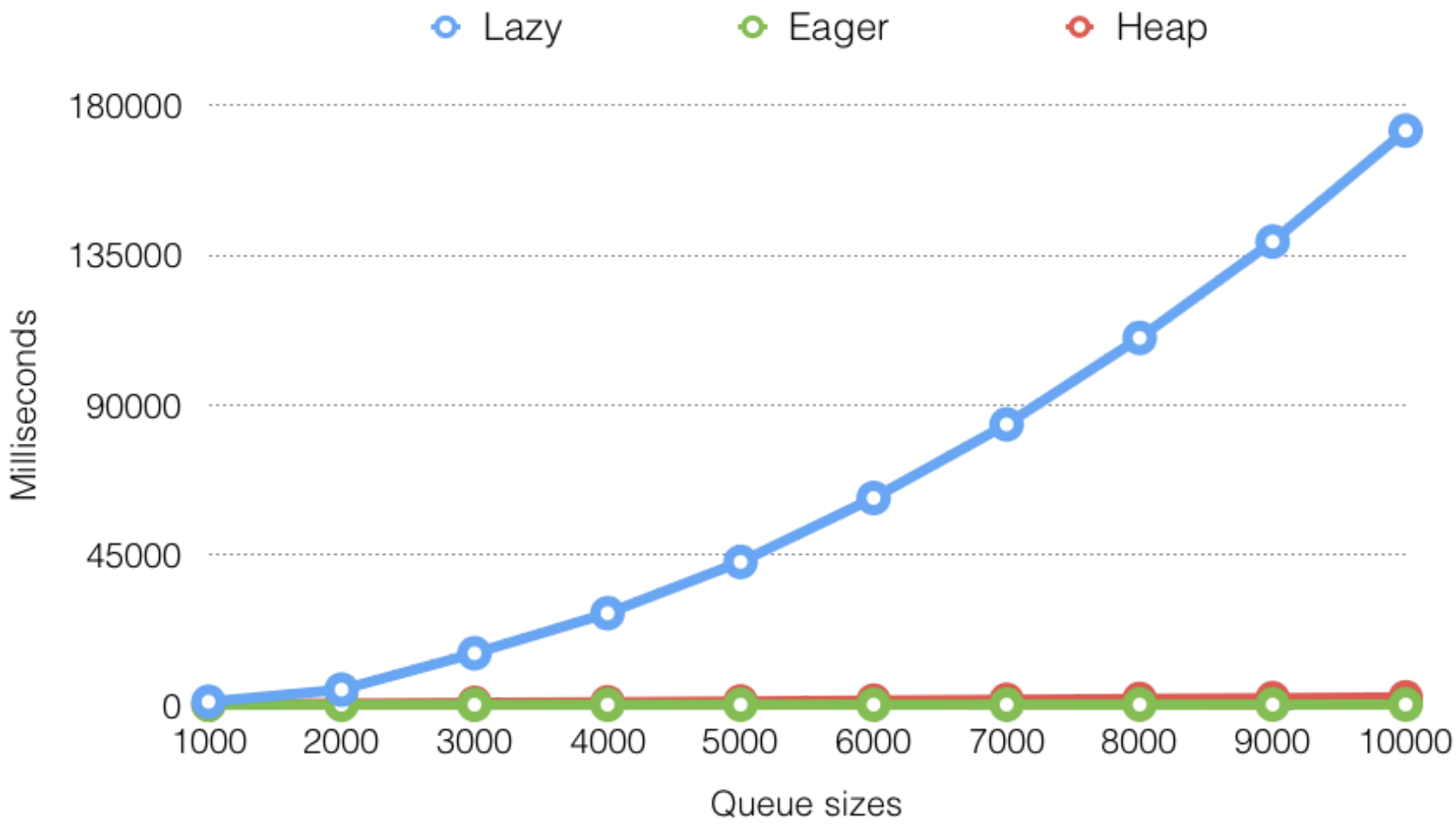
- Lazy: $O(1)$ vs. Eager: $O(\log n)$? vs. Heap: $O(\log n)$.

Benchmark - Add



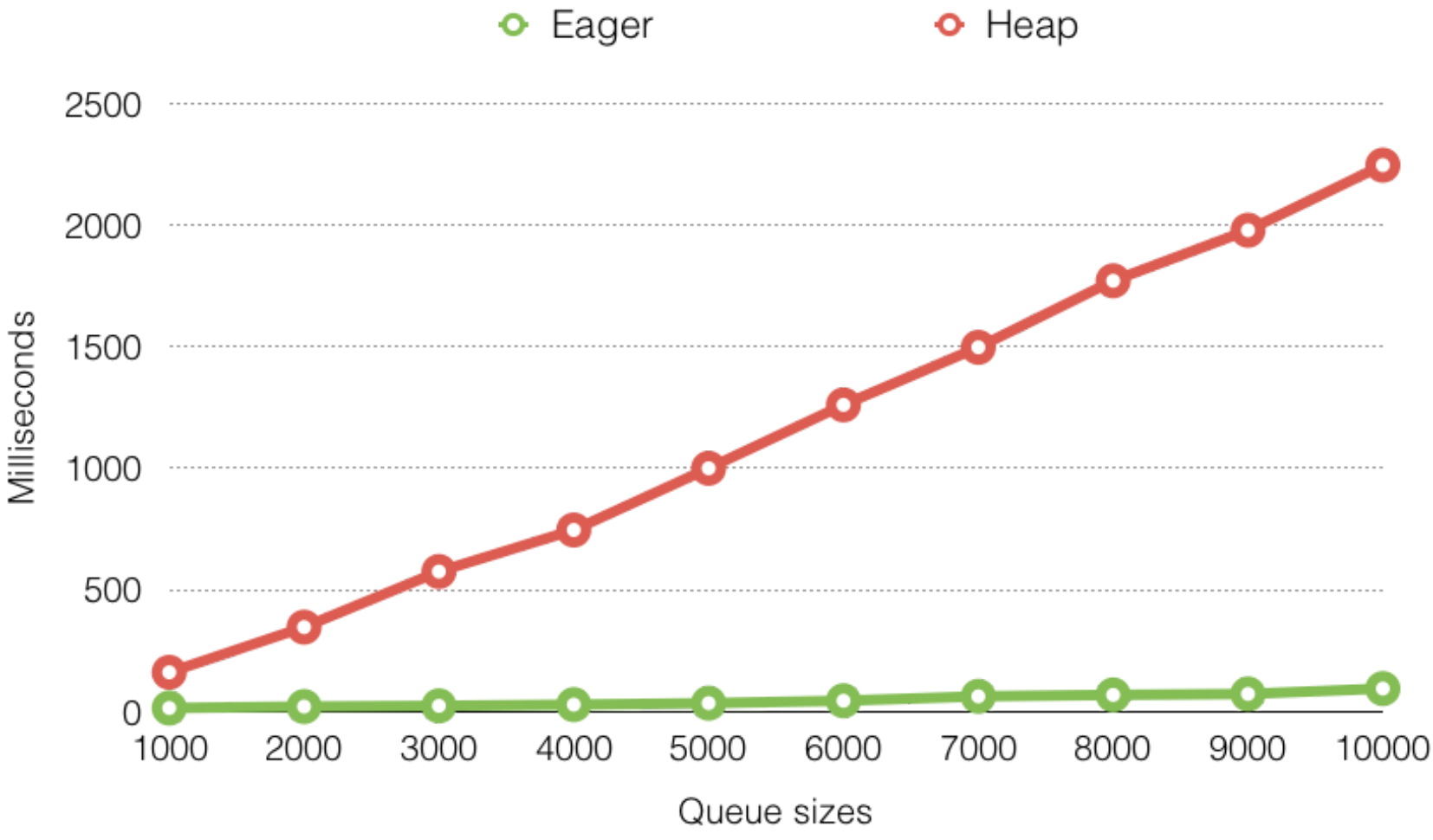
- Lazy: $O(1)$ vs. Heap: $O(\log n)$.

Benchmark - Remove



- Lazy: $O(n)$, Eager: $O(1)$, Heap: $O(\log n)$.

Benchmark - Remove



- Eager: $O(1)$, Heap: $O(\log n)$.

References

- Priority queue.
- Binary heap.
- JUnit
- Java Base API:
  - Comparable.
  - Collections: `max()`, `swap()`, `binarySearch()`.
  - Iterable: `forEach()`.
  - Arrays: `forEach()`.
  - Stream: `generate()`, `limit()`, `toArray()`.
- Java Annotation:
  - @Override.
  - @Test.