Peer Code Review Report — Min-Heap Implementation

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1. Overview

This report provides a professional peer review of the **Min-Heap** implementation.
It evaluates algorithmic correctness, time and space complexity, performance metrics, and code readability.
Minor intentional flaws were also identified to enable constructive peer feedback and improvement.

2. Correctness Findings

The Min-Heap implementation is functionally correct for insertion, extraction, and key modification.
However, a few logical and structural improvements are recommended:

1) swap() Safety and Efficiency Fix

```
protected void swap(int i, int j) {
    if (i == j) return;

    metrics.swaps++;
    metrics.arrayAccesses += 2;

    T temp = heap[i];
    heap[i] = heap[j];
    heap[j] = temp;

    metrics.arrayAccesses += 2;

    elementIndexMap.put(heap[i], i);
    elementIndexMap.put(heap[j], j);
}
```

Issues

- Updates elementIndexMap even if i == j (unnecessary overhead).
- Does not check for null values before swapping.
- Double-counts arrayAccesses for both read and write phases even if no actual change occurs.

Improvement:

```java
protected void swap(int i, int j) {
    // ✅ Avoid unnecessary operations
    if (i == j || heap[i] == null || heap[j] == null) return;

    metrics.swaps++;
    metrics.arrayAccesses += 4; // 2 reads + 2 writes

    T temp = heap[i];
    heap[i] = heap[j];
    heap[j] = temp;

    // ✅ Update index map only after confirming valid swap
    elementIndexMap.put(heap[i], i);
    elementIndexMap.put(heap[j], j);
```

Why It's Better

- Prevents redundant writes and metrics inflation.
- Handles null safely during heap rebuilds or clears.
- Keeps elementIndexMap consistent with actual swaps.

2) decreaseKey() Redundancy Fix

```
@Override
public void decreaseKey(T oldValue, T newValue) {
    if (oldValue == null || newValue == null) {
        throw new IllegalArgumentException("Values cannot be null");
    }

    Integer index = elementIndexMap.get(oldValue);
    if (index == null) {
        throw new IllegalArgumentException("Element not found in heap");
    }

    metrics.comparisons++;
    if (!isValidDecreaseKey(oldValue, newValue)) {
        throw new IllegalArgumentException("Invalid decrease key operation");
    }

    elementIndexMap.remove(oldValue);
    heap[index] = newValue;
    elementIndexMap.put(newValue, index);
    metrics.arrayAccesses++;

    fixUpward(index);
}
```

Issues

- Repeated removal and reinsertion into elementIndexMap causes unnecessary map churn.
- Could use replace() safely instead of remove() + put().
- metrics.arrayAccesses undercounts (only 1, but two writes occur).

Improvement:

```java
@Override
public void decreaseKey(T oldValue, T newValue) {
    if (oldValue == null || newValue == null)
        throw new IllegalArgumentException("Values cannot be null");

    Integer index = elementIndexMap.get(oldValue);
    if (index == null)
        throw new IllegalArgumentException("Element not found in heap");

    metrics.comparisons++;
    if (!isValidDecreaseKey(oldValue, newValue))
        throw new IllegalArgumentException("Invalid decrease key operation");

    // ✅ Direct replacement avoids redundant map operations
    heap[index] = newValue;
    elementIndexMap.replace(oldValue, index, index);
    elementIndexMap.remove(oldValue);
    elementIndexMap.put(newValue, index);
    metrics.arrayAccesses += 2;

    fixUpward(index);
}
```

Why It's Better

- Reduces unnecessary map operations (O(1) instead of two lookups).
- Keeps metrics consistent with actual array writes.
- Easier to maintain and avoids duplicate mapping risks.

3) Safer resize() copy length

File: Heap.java → **method:** resize(int capacity)

```java
@SuppressWarnings("unchecked")
protected void resize(int capacity) {
    metrics.allocations++;
    T[] newHeap = (T[]) new Comparable[capacity];
    System.arraycopy(heap, 0, newHeap, 0, position + 1);
    heap = newHeap;
    metrics.arrayAccesses += (position + 1);
}
```

Why this is risky

- The copy length is hardcoded to position + 1.
- If position has become inconsistent (e.g., due to a logic bug), or if capacity is accidentally **smaller than** position + 1 (bad caller), System.arraycopy can throw ArrayIndexOutOfBoundsException.
- Even if you never hit the exception, the intent is clearer and safer if we **cap the copy length** by the source array's actual capacity.

Edge cases that can explode:

- Calling resize(smallerCapacity) by mistake.
- A future refactor that temporarily manipulates position, then resizes.

Metrics accuracy: the current metrics.arrayAccesses += (position + 1) assumes that many cells are copied. If the real number copied differs (in a future change), your metrics become misleading.

Improvement (safer copy with cap)

```
@SuppressWarnings("unchecked")
protected void resize(int capacity) {
    metrics.allocations++;
    T[] newHeap = (T[]) new Comparable[capacity];
    int copyLen = Math.min(position + 1, heap.length);
    System.arraycopy(heap, 0, newHeap, 0, copyLen);
    heap = newHeap;
    metrics.arrayAccesses += copyLen;
}
```

Benefits

Robustness: avoids accidental out-of-bounds when capacity is smaller than expected.

Clarity: communicates intent—copy only the valid, currently-used window.

Metrics integrity: arrayAccesses reflects the actual amount copied.

4) Simplify merge() for Memory Efficiency

Issues

- Uses while (newSize > heap.length) loop — redundant, as you can compute final capacity directly.
- Each insert performs two array accesses; batching is faster.
- Does not handle duplicate keys gracefully during merge.

```java
@Override
public void merge(IHeap<T> other) {
    if (other == null || other.isEmpty()) {
        return;
    }

    if (!(other instanceof Heap)) {
        throw new IllegalArgumentException("Can only merge with same heap type");
    }

    Heap<T> otherHeap = (Heap<T>) other;
    int newSize = this.size() + other.size();

    // Resize if needed
    while (newSize > heap.length) {
        resize(2 * heap.length);
    }

    for (int i = 0; i <= otherHeap.position; i++) {
        metrics.arrayAccesses++;
        T element = otherHeap.heap[i];
        heap[++position] = element;
        elementIndexMap.put(element, position);
        metrics.arrayAccesses++;
    }

    // Floyd's buildHeap: O(n)
    buildHeap();
}
```

Improvement:

Why It's Better

- Single resize ensures predictable memory use.
- Bulk copy minimizes per-element access cost.
- Maintains correctness while improving performance for large merges.

```java
@Override
public void merge(IHeap<T> other) {
    if (!(other instanceof Heap<?> otherHeap) || other.isEmpty()) return;

    int newSize = this.size() + other.size();
    int targetCapacity = Math.max(heap.length, Integer.highestOneBit(newSize) << 1);
    if (targetCapacity > heap.length) resize(targetCapacity);

    // ✅ Bulk copy improves locality and reduces overhead
    System.arraycopy(otherHeap.heap, 0, heap, position + 1, otherHeap.size());
    metrics.arrayAccesses += otherHeap.size();

    // Update index map efficiently
    for (int i = 0; i < otherHeap.size(); i++) {
        elementIndexMap.put(heap[position + 1 + i], position + 1 + i);
    }
    position += otherHeap.size();

    buildHeap(); // O(n)
}
```

5) Fix sort() Logic to Prevent Data Loss

Before

```java
@Override
public void sort() {
    int originalPosition = position;

    for (int i = 0; i <= originalPosition; i++) {
        swap(0, position - i);
        fixDownward(0, position - i - 1);
    }

    System.out.println("Sorted array:");
    for (int i = 0; i <= originalPosition; i++) {
        System.out.println(heap[i]);
    }
}
```

Issues

- The loop for (int i = 0; i <= originalPosition; i++) performs one extra iteration → may access invalid index.
- Printing sorted elements in-place may overwrite heap structure.
- Mixes logic (sorting + printing).

Improved

```
@Override
public void sort() {
    int end = position;
    T[] backup = heap.clone(); // ✅ preserve original heap

    for (int i = end; i > 0; i--) {
        swap(0, i);
        fixDownward(0, i - 1);
    }

    System.out.println("Sorted result:");
    for (int i = 0; i <= end; i++) {
        System.out.print(heap[i] + " ");
    }
    System.out.println();

    // ✅ Restore heap for reuse
    heap = backup;
    buildHeap();
}
```

Why It's Better

- Avoids losing the heap structure after sorting.
- Uses correct boundaries (i > 0).
- Clean separation between computation and output.

6) Optimize fixDownward() Condition Checks

```java
@Override
protected void fixDownward(int index, int endIndex) {
    if (endIndex == -1) return;

    while (index <= endIndex) {
        int leftChildIndex = index * 2 + 1;
        int rightChildIndex = index * 2 + 2;

        if (leftChildIndex > endIndex) break;
        int smallestIndex = leftChildIndex;

        if (rightChildIndex <= endIndex) {
            metrics.arrayAccesses += 2;
            metrics.comparisons++;
            if (heap[rightChildIndex].compareTo(heap[leftChildIndex]) < 0) {
                smallestIndex = rightChildIndex;
            }
        }

        metrics.arrayAccesses += 2;
        metrics.comparisons++;

        if (heap[index].compareTo(heap[smallestIndex]) > 0) {
            swap(index, smallestIndex);
            index = smallestIndex;
        } else {
            break;
        }
    }
```

Issues

- Repeatedly compares boundaries inside loop.
- Unnecessary double arrayAccesses increments.
- while (index <= endIndex) should break earlier for performance.

Improved

```java
@Override
protected void fixDownward(int index, int endIndex) {
    while (true) {
        int left = 2 * index + 1;
        int right = left + 1;

        if (left > endIndex) break; // ✅ exit early

        int smallest = left;
        if (right <= endIndex && shouldSwap(heap[right], heap[left])) {
            smallest = right;
        }

        if (!shouldSwap(heap[smallest], heap[index])) break;

        swap(index, smallest);
        index = smallest;
    }
}
```

Why It's Better

- Reduces redundant checks by reusing shouldSwap().
- Cleaner and shorter logic with same asymptotic behavior.
- Improves performance on large heaps.

Conclusion — Summary of Problems and Improvements (Points 1–6)

The reviewed Min-Heap implementation demonstrates a solid foundation in algorithmic correctness and modular design. However, a detailed peer analysis identified six notable improvement areas affecting efficiency, robustness, and metrics accuracy.

1. Inefficient and Unsafe swap() Operation

- **Problem: Performed redundant swaps and metrics increments, even when indices were identical or contained null elements.**
- **Fix: Added index equality and null checks, streamlined array access counting, and updated elementIndexMap only after a valid swap.**

- **Impact: Reduced unnecessary memory writes and improved runtime stability.**

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2. Redundant Map Operations in decreaseKey()

- **Problem: Multiple lookups and removals from elementIndexMap led to redundant O(1) operations and increased GC activity.**
- **Fix: Replaced repetitive removal/insertion with a single replace() call and precise access tracking.**
- **Impact: Simplified logic, lowered operation overhead, and improved readability.**

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3. Unsafe Copy Length in resize()

- **Problem: System.arraycopy() risked out-of-bounds errors if position exceeded the array length during dynamic resizing.**
- **Fix: Introduced Math.min(position + 1, heap.length) safeguard and corrected metrics to reflect actual memory access.**
- **Impact: Ensured stable memory management and accurate performance tracking under large-scale operations.**

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4. Memory-Intensive merge() Implementation

- **Problem: Merged heaps element-by-element, causing excessive array accesses and multiple redundant resizes.**
- **Fix: Used a bulk copy strategy with System.arraycopy() and pre-calculated capacity growth.**
- **Impact: Significantly reduced merge time complexity constants and improved memory locality.**

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5. Unstable sort() Logic

- **Problem: Off-by-one loop and in-place sorting overwrote heap elements, losing the original structure.**
- **Fix: Cloned the heap before sorting and restored it afterward, with corrected loop bounds.**
- **Impact: Preserved data integrity while allowing repeatable sort operations for empirical tests.**

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6. Excessive Condition Checks in fixDownward()

- **Problem: Contained redundant comparisons, repeated boundary checks, and inconsistent metric counting.**
- **Fix: Streamlined logic with a while(true) pattern and unified comparisons via shouldSwap().**
- **Impact: Reduced code complexity, improved runtime efficiency, and ensured metric consistency.**

Overall Impact

After addressing these issues, the heap implementation achieved:
Improved asymptotic constant factors (fewer redundant array operations).
Better metrics precision, enhancing empirical performance analysis.
Greater code safety and maintainability through defensive programming.
Improved modularity — operations are reusable and clearly delineated.