Priority Queues and Binary Heaps (Part 1)

Binary heaps, types of heaps, and complexity analysis

Connor Baker

2019-04-02, Compiled on May 7, 2019 at 10:12am

Priority Queues and Binary Heaps (Part 1)

Review: Queues

- First in, first out (FIFO)
- Operations:
  - `getFront()`, `enqueue(T t)`, and `dequeue()`
  - `size()` and `isEmpty()`
- Applications
  - Simulate a process with FIFO ordering
  - Scheduling the queue in a CPU, disk, or printer
  - Buffer for file I/O, network communication, or other transmissions
- A lot of the time, tasks in a queue have priorities
  - Dequeue should remove or return the one with the best priority
- Common priority queue operations
  - `add(T t, int p)` and `enqueue(T t, int p)`: enqueue item `t` with priority `p`
  - `peek()` and `findMin()`: return the object with the best priority
    * Per convention, lower is better
    * Symmetric code if higher is better
  - `dequeue()` and `deleteMin()`: remove and return the object with the best priority

Priority Queue Implementation

Data Structure	`enqueue(T t)`	peek*	dequeue*	Notes
Unsorted List	$O(1)$	$O(n)$	$O(n)$	best priority can be any location
Sorted Array	$O(n)$	$O(1)$	$O(1)$	best priority at high index
Sorted Linked List	$O(n)$	$O(1)$	$O(1)$	best at head or tail
Multiple Queues	$O(1)$	$O(m)$	$O(m)$	-
Binary Search Tree	$O(\text{height})$	$O(\text{height})$	$O(\text{height})$	min at left-most

- *: assuming best priority
- n: the number of items in a queue
- m: the number of priority levels

Binary Heap

- A *binary heap* is a binary tree but *not* a binary search tree
- Differences:
  - Sort of sorted: each node is smaller than, or equal to, both its children
  - Must be a complete binary tree

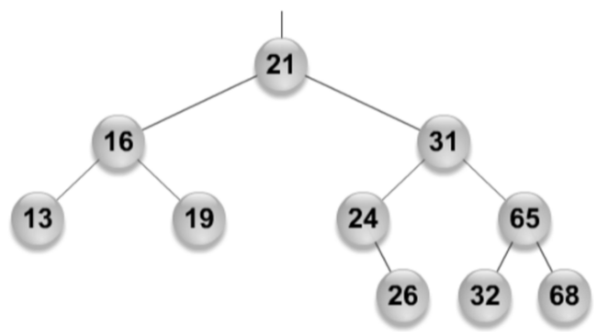

Figure 1: BST Example

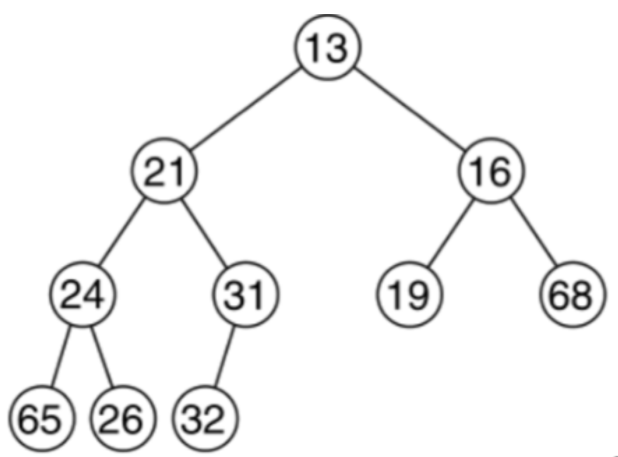

Figure 2: Binary Heap Example

Sorted Binary Heap Example

- The left binary tree is a heap, because it satisfies the Heap Order Property
- The right binary tree is not a heap because it does not satisfy the Heap Order Property – 6 is not less than its parent node, 21, yet it is the child of that node

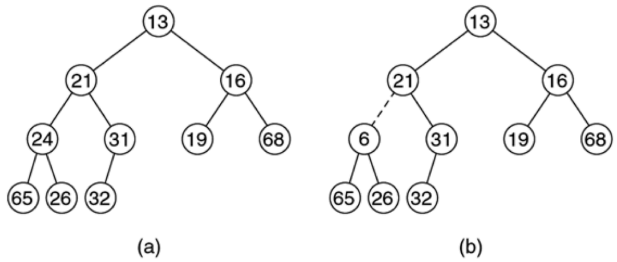

Figure 3: Sorted Binary Heap Example

Heap Order

- Max heap
  - The node is always larger than, or equal to, any of its descendants
- Min heap
  - The node is always smaller than, or equal to, any of its descendants
- Idea: we want to find the min, or max, quickly
  - Keep at the root of the tree
  - Recursive definition: every subtree should have the largest, or smallest, item at the root of the subtree

Binary Heap Examples

- The left tree is a max-heap, since the largest values are at the top
- The right ree is a min-heap, since the smallest values are at the top

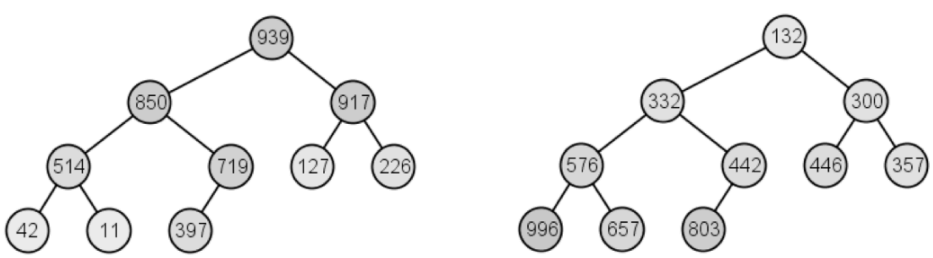

Figure 4: Examples

Complete Trees

- Could only be missing nodes in their bottom row
- Nodes in the bottom row are as far lest as possible

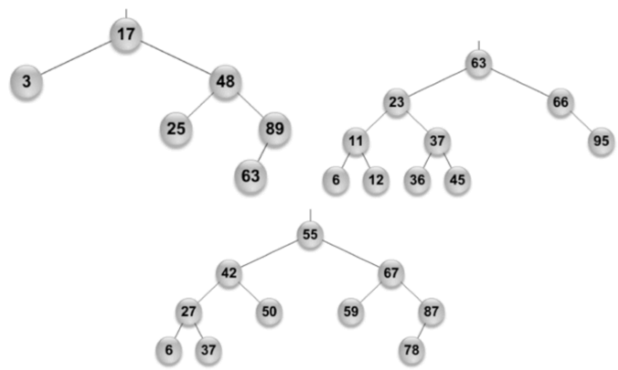

Figure 5: Incomplete Trees

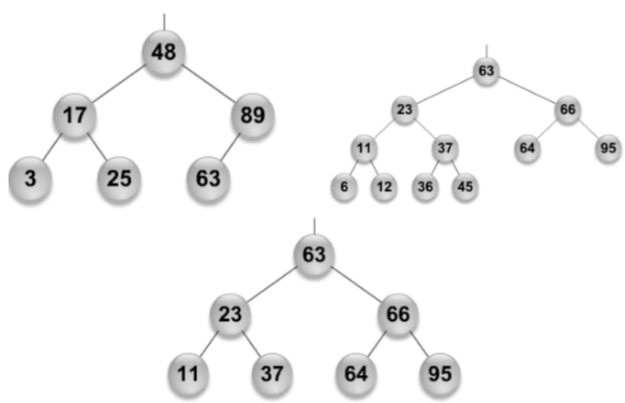

Figure 6: Complete Trees

Trees and Heaps in Arrays

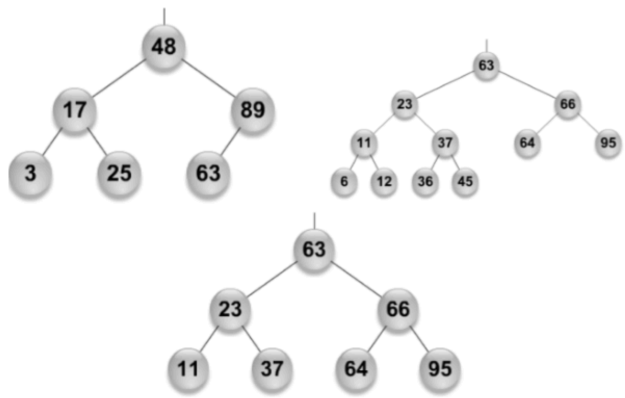

Figure 7: A complete binary tree and its array representation

- The root is at index 1
- Binary tree
  - `left(i)= 2 * i`
  - `right(i)= 2 * i + 1`
  - `parent(i)= i / 2`

Road Map

- Priority queue
  - `insert(T t),findMin(),deleteMin()`
- Heap
  - Complete binary tree
  - Heap order
    * Min heap
    * Max heap
  - Operations and complexity
    * Insert: percolate up
    * Delete: percolate down
- Heap sort

Priority Queue Operations with Binary Heaps

- Use an internal `T array[]` for queue contents
  - Maintain min-heap order in array
  - Make sure it is always a complete tree
- `T findMin()`
  - `return array[root()];`
- `insert(T t, int p)`
  - Insert at the end of the array, increment size
    * Might violate the min-heap order property
  - Fix by swimming the new element up (percolate up)
- `deleteMin()`
  - Simply removing the root will leave a hole
  - We can swap the last value and the root to fill the hole
    * `null` out the last value (which prevents loitering)
    * Decrement the size
    * The new root *might* not be minimal
  - Percolate the new root value down the tree
- Max heap follows the same ideas

Binary Heap Demo

- Starting from a min-heap like Example 2
  - Insert 50, 18, and 10
  - `deleteMin()`
- Starting form an empty max-heap
  - Insert 2, 3, 5, 3, and 9
  - `deleteMax()` five times

Operation Details

- Basic questions
  - With whom do we compare or swap?

    - When do we stop moving?

- Percolate up (bubble up)
    - Compare / swap with the parent
    - Halting condition: when we reach the top (the root) or no longer violate the heap order
- Percolate down (sink down)
    - Compare / swap with a child
    - Halting condition: when we reach the bottom (a leaf) or no longer violate the heap order

Weiss Code Example

```java
/**
 * Removes the smallest item in the priority queue.
 * @return the smallest item.
 * @throws NoSuchElementException if empty.
 */
public T remove() {
  T minItem = element();
  // Move the tail element to the root
  array[1] = array[currentSize--];
  // Sink the new root down to fix the heap order
  percolateDown(1);
}

 /**
  * Internal method to percolate down in the heap.
  * @param hole the index at which to percolate begins.
  */
private void percolateDown(int hole) {
  int child;
  T tmp = array[hole];
  // Decide which child to compare/swap
  for (; hole * 2 <= currentSize; hole = child) {
    child = hole * 2;
    if (child != currentSize && compare(array[child+1], array[child]) < 0) {
      child++;
    }
    // Keep swapping with children until parent-child comparison result is
    // satisfactory, or the bottom is reached
    if (compare(array[child], tmp) < 0) {
      array[hole] = array[child];
    } else {
      break;
```

```
        }
        array[hole] = tmp;
    }
}
```

Complexity Analysis

- `findMin()` is clearly $O(1)$
- What about `insert(T t)` and `deleteMin()`?
  - Percolation does most of the work
  - Worst case: $O(\text{height})$
    - Complete binary tree: $O(\log(n))$
- Note: no `get(T t)` or `remove(T t)`

Priority Queues Comparison

Data Structure	`enqueue(T t)`	peek*	dequeue*	Notes
Unsorted List	$O(1)$	$O(n)$	$O(n)$	best priority can be any location
Sorted Array	$O(n)$	$O(1)$	$O(1)$	best priority at high index
Sorted Linked List	$O(n)$	$O(1)$	$O(1)$	best at head or tail
Multiple Queues	$O(1)$	$O(m)$	$O(m)$	-
Binary Search Tree	$O(\text{height})$	$O(\text{height})$	$O(\text{height})$	min at left-most
Binary Heap	$O(\log(n))$	$O(1)$	$O(\log(n))$	best priority at root

- *: assuming best priority
- n: the number of items in a queue
- m: the number of priority levels