CS311 Data Structures
Lecture 07—Priority Queue

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Queue
What operations does a queue support?

Priority: Number representing importance

- Convention lower is better priority
  
  *Bring back life form. Priority One. All other priorities rescinded.*

- Symmetric code if higher is better

Priority Queue (PQ): Supports 3 operations

- `void insert(T x, int p)`: Insert x with priority p
- `T findMin()`: Return the object with the best priority
- `void deleteMin()`: Remove the the object with the best priority
Explicit Priority

\texttt{insert(T x, int p)}

- Priority is explicitly \texttt{int p}
- Separate from data

Implicit Priority

\texttt{insert(Comparable\langle T \rangle x)}

- \texttt{x} "knows" its own priority
- Comparisons dictated by \texttt{x.compareTo(y)}

**Implicit** is simpler for discussion: only one thing (\texttt{x}) to draw

Explicit usually uses a wrapper node of sorts

class PQNode\langle T \rangle extends Comparable\langle PQNode\rangle{
    int priority;  T data;
    public int compareTo(PQNode that){
        return this.priority - that.priority;
    }

}
Exercise: Design a PQ

Discuss

- How would you design PriorityQueue class?
- What underlying data structures would you use?
- Discuss with a neighbor
- Give rough idea of implementation
- Make it as efficient as possible in Big-O sense

Must Implement

- Constructor
- `void insert(T x)`: Insert x, knows its own priority
- `T findMin()`: Return the object with the best priority
- `void deleteMin()`: Remove the object with the best priority
**Binary Heap: Sort of Sorted**

- Most common way to build a PQ is using a new-ish data structure, the **Binary Heap**.
- Looks similar to a Binary Search Tree but maintains a different property

**BST Property**
A Node must be bigger than its left children and smaller than its right children

**Binary Min-Heap Property**
A Node must be smaller than its children
Which of these is a min-heap and which is not?
Trees and Heaps in Arrays

- Mostly we have used trees of linked Nodes
- Can also put trees/heaps in an array

Root is at 1 (discuss root at 0 later)
- left(i) = 2*i
- right(i) = 2*i + 1
Balanced v. Unbalanced in Arrays

Find the array layout of these two trees

- Root is at 1
- left(i) = 2*i
- right(i) = 2*i + 1

Q: How big of array is required?
Balanced v. Unbalanced in Arrays

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48</td>
<td>17</td>
<td>89</td>
<td>3</td>
<td>25</td>
<td>63</td>
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Complete Trees

- Only "missing" nodes in their bottom row (level set)
- Nodes in bottom row are as far left as possible

Not Complete (Why?)

Complete

- Complete trees don’t waste space in arrays: no gaps
- Hard for general BSTs, easy for binary heaps...
PQ Ops with Binary Heaps

- Use an internal T array[] of queue contents
- Maintain min-heap order in array

Define
Tree-like ops for array[]

```
root() => 1
left(i) => i*2
right(i) => i*2 + 1
parent(i) => i / 2
```

T findMin()
Super easy
```
return array[root()];
```

insert(T x)
Ensure heap is a complete tree
- Insert at next array[size]
- Increment size
- Percolate new element up

deleteMin()
Ensure heap is a complete tree
- Decrement size
- Replace root with last data
- Percolate root down
Demos of Binary Heaps

Not allowed on exams, but good for studying

Min Heap from David Galles © Univ SanFran
  ▶ Visualize both heap and array version
  ▶ All ops supported

Max Heap from Steven Halim
  ▶ Good visuals
  ▶ No array
  ▶ Slow to load
// Binary Heap, 1-indexed
public class BinaryHeapPQ<T>{
    private T [] array;
    private int size;

    // Helpers
    static int root(){
        return 1;
    }
    static int left(int i){
        return i*2;
    }
    static int right(int i){
        return i*2+1;
    }
    static int parent(int i){
        return i / 2;
    }
    // Insert a data
    public void insert(T x){
        size++;
        ensureCapacity(size+1);
        array[size] = x;
        percolateUp(size);
    }
    // Remove the minimum element
    public void deleteMin(){
        array[root()] = array[size];
        array[size] = null;
        size--;
        percolateDown(root());
    }
}
void percolateUp(int xdx) {
    while(xdx!=root()){
        T x = array[xdx];
        T p = array[parent(xdx)];
        if(doCompare(x,p) < 0){
            array[xdx] = p;
            array[parent(xdx)] = x;
            xdx = parent(xdx);
        }
        else{ break; }
    }
}

void percolateDown(int xdx) {
    while(true){
        T x = array[xdx];
        int cdx = left(xdx);
        // Determine which child
        // if any to swap with
        if(cdx > size){ break; } // No left, bottom
        if(right(xdx) < size && // Right valid
            doCompare(array[right(xdx)], array[cdx]) < 0){
            cdx = right(xdx); // Right smaller
        }
        T child = array[cdx];
        if(doCompare(child,x) < 0){ // child smaller
            array[cdx] = x; // swap
            array[xdx] = child;
            xdx = cdx; // reset index
        }
        else{ break; }
    }
}
BinaryHeapPQ.java

- Code distribution today contains working heap
- `percolateUp()` and `percolateDown()` do most of the work
- Uses "root at index 1" convention

Text Book Binary Heap

- Weiss uses a different approach in percolate up/down
- Move a "hole" around rather than swapping
- Probably saves 1 comparison per loop iteration
- Have a look in `weiss/util/PriorityQueue.java`
Complexity of Binary Heap PQ methods?

T findMin();
void insert(T x); // x knows its priority
void deleteMin();

Give the complexity and justify for each
Efficiency of Binary Heap PQs

\texttt{findMin()} clearly $O(1)$
\texttt{deleteMin()} worst case height
\texttt{insert(x)} worst case height

Height of a \textbf{Complete Binary Tree} wrt number of nodes $N$?

- Guesses?
## Summary of Binary Heaps

<table>
<thead>
<tr>
<th>Op</th>
<th>Worst Case</th>
<th>Avg Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>findMin()</td>
<td>$O(1)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>insert(x)</td>
<td>$O(\log N)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>deleteMin()</td>
<td>$O(\log N)$</td>
<td>$O(\log N)$</td>
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- Notice: No `get(x)` method or `remove(x)` methods
- These would involve searching the whole binary heap/priority queue if they did existed: $O(N)$