# CSE373: Data Structures & Algorithms

# Lecture 6: Priority Queues

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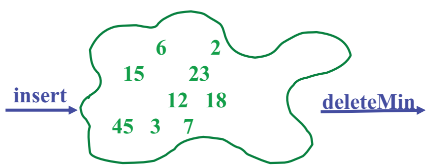
## *A new ADT: Priority Queue*

- Textbook Chapter 6
  - Nice to see a new and surprising data structure
- A **priority queue** holds *compare-able data*
  - Like dictionaries and unlike stacks and queues, need to *compare items*
    - Given *x* and *y*, is *x* less than, equal to, or greater than *y*
    - Meaning of the ordering can depend on your data
    - Many data structures require this: dictionaries, sorting
  - Integers are comparable, so will use them in examples
    - But the priority queue ADT is much more general
    - Typically two fields, the *priority* and the *data*



## *Priorities*

- Each item has a "priority"
  - The *lesser* item is the one with the *greater* priority
  - So "priority 1" is more important than "priority 4"
  - (Just a convention, think "first is best")
- Operations:
  - **`insert`**
  - **`deleteMin`**
  - **`is_empty`**




- Key property: **`deleteMin`** *returns* and *deletes* the item with greatest priority (lowest priority value)
  - Can resolve ties arbitrarily



## *Example*

**`insert`** *x1* with priority *5*
**`insert`** *x2* with priority *3*
**`insert`** *x3* with priority *4*
*a* = **`deleteMin // x2`**
*b* = **`deleteMin // x3`**
**`insert`** *x4* with priority *2*
**`insert`** *x5* with priority *6*
c = **`deleteMin // x4`**
d = **`deleteMin // x1`**

- Analogy: **`insert`** is like **`enqueue`**, **`deleteMin`** is like **`dequeue`**
  - But the whole point is to use priorities instead of FIFO



## *Applications*

Like all good ADTs, the priority queue arises often
  - Sometimes blatant, sometimes less obvious

- Run multiple programs in the operating system
  - "critical" before "interactive" before "compute-intensive"
  - Maybe let users set priority level
- Treat hospital patients in order of severity (or triage)
- Select print jobs in order of decreasing length?
- Forward network packets in order of urgency
- Select most frequent symbols for data compression (cf. CSE143)
- Sort (first **`insert`** all, then repeatedly **`deleteMin`**)
  - Much like Homework 1 uses a stack to implement reverse



## *More applications*

- "Greedy" algorithms
  - May see an example when we study graphs in a few weeks
- Discrete event simulation (system simulation, virtual worlds, …)
  - Each event *e* happens at some time *t*, updating system state and generating new events *e1*, …, *en* at times *t+t1*, …, *t+tn*
  - Naïve approach: advance "clock" by 1 unit at a time and process any events that happen then
  - Better:
    - *Pending events* in a priority queue (priority = event time)
    - Repeatedly: **`deleteMin`** and then **`insert`** new events
    - Effectively "set clock ahead to next event"

## Finding a good data structure

- Will show an efficient, non-obvious data structure
  - But first let's analyze some "obvious" ideas for *n* data items
  - All times worst-case; assume arrays "have room"

| *data* | *insert algorithm / time* | *deleteMin algorithm / time* |
|---|---|---|
| unsorted array | | |
| unsorted linked list | | |
| sorted circular array | | |
| sorted linked list | | |
| binary search tree | | |
| AVL tree | | |



## Need a good data structure!

- Will show an efficient, non-obvious data structure for this ADT
  - But first let's analyze some "obvious" ideas for *n* data items
  - All times worst-case; assume arrays "have room"

| *data* | *insert algorithm / time* | | *deleteMin algorithm / time* | |
|---|---|---|---|---|
| unsorted array | add at end | $O(1)$ | search | $O(n)$ |
| unsorted linked list | add at front | $O(1)$ | search | $O(n)$ |
| sorted circular array | search / shift | $O(n)$ | move front | $O(1)$ |
| sorted linked list | put in right place | $O(n)$ | remove at front | $O(1)$ |
| binary search tree | put in right place | $O(n)$ | leftmost | $O(n)$ |
| AVL tree | put in right place | $O(\log n)$ | leftmost | $O(\log n)$ |



## More on possibilities

- *If* priorities are random, binary search tree will likely do better
  - $O(\log n)$ **`insert`** and $O(\log n)$ **`deleteMin`** on *average*
- One more idea: if priorities are 0, 1, …, *k* can use array of lists
  - **`insert`**: add to front of list at **`arr[priority]`**, $O(1)$
  - **`deleteMin`**: remove from lowest non-empty list $O(k)$
- We are about to see a data structure called a "binary heap"
  - $O(\log n)$ **`insert`** and $O(\log n)$ **`deleteMin`** *worst-case*
    - Possible because we don't support unneeded operations; no need to maintain a full sort
  - *Very* good constant factors
  - *If* items arrive in random order, then **`insert`** is $O(1)$ on *average*

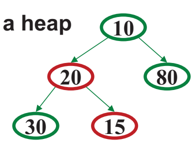


## Our data structure

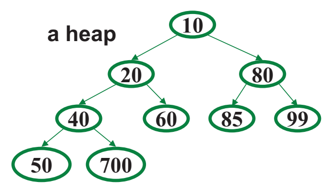
A *binary min-heap* (or just *binary heap* or just *heap*) is:

- Structure property: A *complete* binary tree
- Heap property: The priority of every (non-root) node is greater than the priority of its parent
  - ***Not*** a binary search tree

**not a heap**




**a heap**



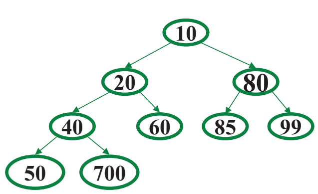

So:

- Where is the highest-priority item?
- What is the height of a heap with *n* items?



## Operations: basic idea

- **`findMin`**: return **`root.data`**
- **`deleteMin`**:
  1. **`answer = root.data`**
  2. Move right-most node in last row to root to restore structure property
  3. "Percolate down" to restore heap property
- **`insert:`**
  1. Put new node in next position on bottom row to restore structure property
  2. "Percolate up" to restore heap property



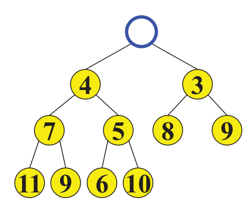

*Overall strategy:*

- *Preserve structure property*
- *Break and restore heap property*



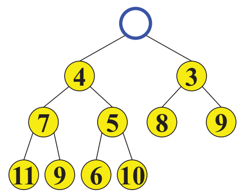
## DeleteMin

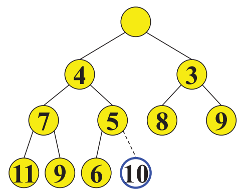
1. Delete (and later return) value at root node



## 2. Restore the Structure Property

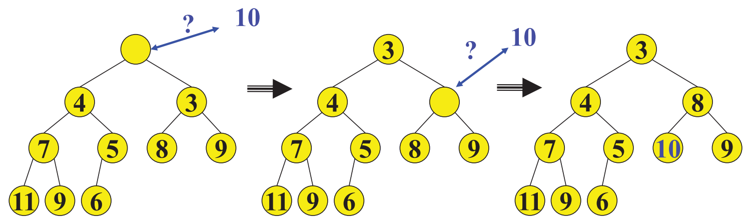
- We now have a “hole” at the root
  - Need to fill the hole with another value
- When we are done, the tree will have one less node and must still be complete







## 3. Restore the Heap Property



Percolate down:
- Keep comparing with both children
- Swap with lesser child and go down one level
- Done if both children are ≥ item or reached a leaf node

Why is this correct? What is the run time?



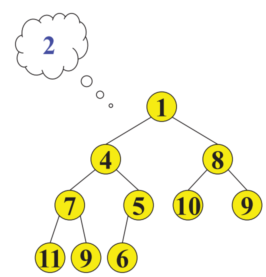
## DeleteMin: Run Time Analysis

- Run time is *O*(height of heap)
- A heap is a complete binary tree
- Height of a complete binary tree of *n* nodes?
  - height = $\lfloor \log_2(n) \rfloor$
- Run time of **`deleteMin`** is $O(\log n)$



## Insert

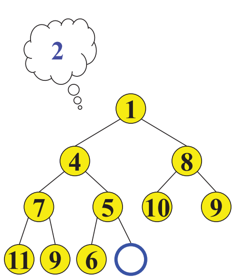
- Add a value to the tree
- Afterwards, structure and heap properties must still be correct





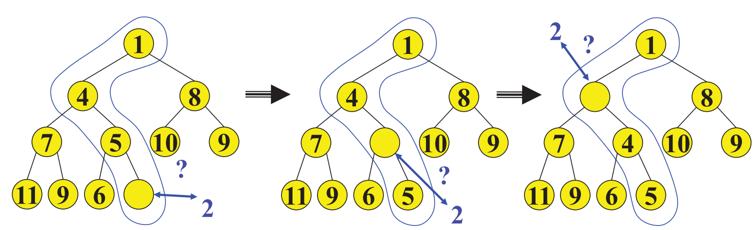
## Insert: Maintain the Structure Property

- There is only one valid tree shape after we add one more node
- So put our new data there and then focus on restoring the heap property





## Maintain the heap property



Percolate up:
- Put new data in new location
- If parent larger, swap with parent, and continue
- Done if parent ≤ item or reached root

Why is this correct? What is the run time?

# *Insert: Run Time Analysis*

- Like **`deleteMin`**, worst-case time proportional to tree height
  - *O*(**`log`** *n*)
- But… **`deleteMin`** needs the “last used” complete-tree position and **`insert`** needs the “next to use” complete-tree position
  - If “keep a reference to there” then **`insert`** and **`deleteMin`** have to adjust that reference: *O*(**`log`** *n*) in worst case
  - Could calculate how to find it in *O*(**`log`** *n*) from the root given the size of the heap
    - But it’s not easy
    - And then **`insert`** is always *O*(**`log`** *n*), promised *O*(1) on average (assuming random arrival of items)
- There’s a “trick”: don’t represent complete trees with explicit edges!