

# **COMMONWEALTH OF AUSTRALIA**

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# Data structures and Algorithms

## Lecture 5: Priority Queues [GT 5]

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# Priority Queue ADT

Special type of ADT map to store a collection of key-value items where we can only remove smallest key:

- **insert**(k, v): insert item with key **k** and value **v**
- **remove\_min**(): remove and return the item with smallest key
- **min**(): return item with smallest key
- **size**(): return how many items are stored
- **is\_empty**(): test if queue is empty

We can also have a max version of this min version, but we cannot use both versions at once.

# Example

A sequence of priority queue methods:

Method	Return value	Priority queue
insert(5,A)		{(5,A)}
insert(9,C)		{(5,A),(9,C)}
insert(3,B)		{(3,B),(5,A),(9,C)}
min()	(3,B)	{(3,B),(5,A),(9,C)}
remove_min()	(3,B)	{(5,A),(9,C)}
insert(7,D)		{(5,A),(7,D),(9,C)}
remove_min()	(5,A)	{(7,D),(9,C)}
remove_min()	(7,D)	{(9,C)}
remove_min()	(9,C)	{}
is_empty()	true	{}

# Application: Stock Matching Engines

At the heart of modern stock trading systems are highly reliable systems known as **matching engines**, which match the stock trades of buyers and sellers.

Buyers post bids to buy a number of shares of a given stock at or below a specified price

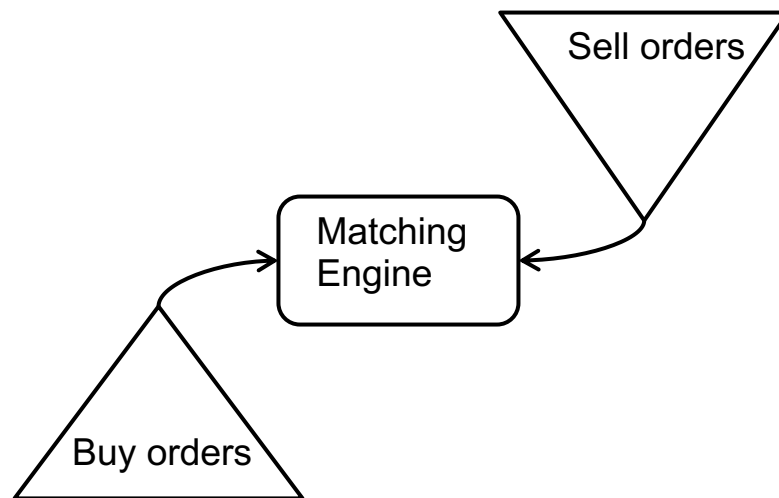
Sellers post offers (asks) to sell a number of shares of a given stock at or above a specified price.

STOCK: EXAMPLE.COM					
Buy Orders			Sell Orders		
Shares	Price	Time	Shares	Price	Time
1000	4.05	20 s	500	4.06	13 s
100	4.05	6 s	2000	4.07	46 s
2100	4.03	20 s	400	4.07	22 s
1000	4.02	3 s	3000	4.10	54 s
2500	4.01	81 s	500	4.12	2 s
			3000	4.20	58 s
			800	4.25	33 s
			100	4.50	92 s

# Application: Stock Matching Engines

Buy and sell orders are organized according to a **price-time priority**, where price has highest priority and time is used to break ties

When a new order is entered, the matching engine determines if a trade can be immediately executed and if so, then it performs the appropriate matches according to price-time priority.



STOCK: EXAMPLE.COM					
Buy Orders			Sell Orders		
Shares	Price	Time	Shares	Price	Time
1000	4.05	20 s	500	4.06	13 s
100	4.05	6 s	2000	4.07	46 s
2100	4.03	20 s	400	4.07	22 s
1000	4.02	3 s	3000	4.10	54 s
2500	4.01	81 s	500	4.12	2 s
			3000	4.20	58 s
			800	4.25	33 s
			100	4.50	92 s

# Application: Stock Matching Engines

A matching engine can be implemented with two **priority queues**, one for buy orders and one for sell orders.

This data structure performs element removals based on priorities assigned to elements when they are inserted.

```
while True:
    bid ← buy_orders.remove_max()
    ask ← sell_orders.remove_min()
    if bid.price ≥ ask.price then
        carry out trade (bid, ask)
    else
        buy_orders.insert(bid)
        sell_orders.insert(ask)
```

STOCK: EXAMPLE.COM					
Buy Orders			Sell Orders		
Shares	Price	Time	Shares	Price	Time
1000	4.05	20 s	500	4.06	13 s
100	4.05	6 s	2000	4.07	46 s
2100	4.03	20 s	400	4.07	22 s
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2500	4.01	81 s	500	4.12	2 s
			3000	4.20	58 s
			800	4.25	33 s
			100	4.50	92 s

# Sequence-based Priority Queue

## Unsorted list implementation



- **insert** in  $O(1)$  time since we can insert the item at the beginning or end of the sequence
- **remove\_min** and **min** in  $O(n)$  time since we have to traverse the entire list to find the smallest key

## Sorted list implementation



- **insert** in  $O(n)$  time since we have to find the place where to insert the item
- **remove\_min** and **min** in  $O(1)$  time since the smallest key is at the beginning

Method	Unsorted List	Sorted List
size, isEmpty	$O(1)$	$O(1)$
insert	$O(1)$	$O(n)$
min, removeMin	$O(n)$	$O(1)$



# Priority Queue Sorting

We can use a priority queue to sort a list of keys:

1. iteratively insert keys into an empty priority queue
2. iteratively **remove\_min** to get the keys in sorted order

Complexity analysis:

- **n** insert operations
- **n** remove\_min operations

Either sequence-based  
implementation take  **$O(n^2)$**

```
def priority_queue_sorting(A):  
    pq ← new priority queue  
    n ← size(A)  
    for i in [0:n] do  
        pq.insert(A[i])  
    for i in [0:n] do  
        A[i] = pq.remove_min()
```

Method	Unsorted List	Sorted List
size, isEmpty	$O(1)$	$O(1)$
insert	$O(1)$	$O(n)$
min, removeMin	$O(n)$	$O(1)$

# Selection-Sort

Variant of pq-sort using unsorted sequence implementation:

1. inserting elements with  $n$  insert operations takes  $O(n)$  time
2. removing elements with  $n$  remove\_min operations takes  $O(n^2)$

Can be done in place  
(no need for extra space)

Top level loop invariant:

- $A[0, i)$  is sorted
- $A[i, n)$  is the priority queue  
and all  $\geq A[i-1]$

```
def selection_sort(A):  
    n ← size(A)  
    for i in [0:n] do  
        # find s ≥ i minimizing A[s]  
        s ← i  
        for j in [i:n] do  
            if A[j] < A[s] then  
                s ← j  
        # swap A[i] and A[s]  
        A[i], A[s] ← A[s], A[i]
```

# Selection-Sort Example

i	A	s
0	2, 4, 8, <u>2</u> , 5, 3, 9	3
1	2, <u>4</u> , 8, 7, 5, <u>3</u> , 9	5
2	2, 3, <u>8</u> , 7, 5, <u>4</u> , 9	5
3	2, 3, 4, <u>2</u> , <u>5</u> , 8, 9	4
4	2, 3, 4, 5, <u>2</u> , 8, 9	4
5	2, 3, 4, 5, 7, <u>8</u> , 9	5
6	2, 3, 4, 5, 7, 8, <u>9</u>	6

```
def selection_sort(A):
    n ← size(A)
    for i in [0:n] do
        # find s ≥ i minimizing A[s]
        s ← i
        for j in [i:n] do
            if A[j] < A[s] then
                s ← j
        # swap A[i] and A[s]
        A[i], A[s] ← A[s], A[i]
```

# Insertion-Sort

Variant of pq-sort using sorted sequence implementation:

1. inserting elements with  $n$  insert operations takes  $O(n^2)$  time
2. removing elements with  $n$  remove\_min operations takes  $O(n)$

Can be done in place  
(no need for extra space)

Top level loop invariant:

- $A[0, i)$  is the priority queue  
(and thus sorted)
- $A[i, n)$  is yet-to-be-inserted

```
def insertion_sort(A):  
    n ← size(A)  
    for i in [1:n] do  
        x ← A[i]  
        # move forward entries > x  
        j ← i  
        while j > 0 and x < A[j-1] do  
            A[j] ← A[j-1]  
            j ← j - 1  
        # if j>0 ⇒ x ≥ A[j-1]  
        # if j<i ⇒ x < A[j+1]  
        A[j] ← x
```

# Insertion-Sort Example

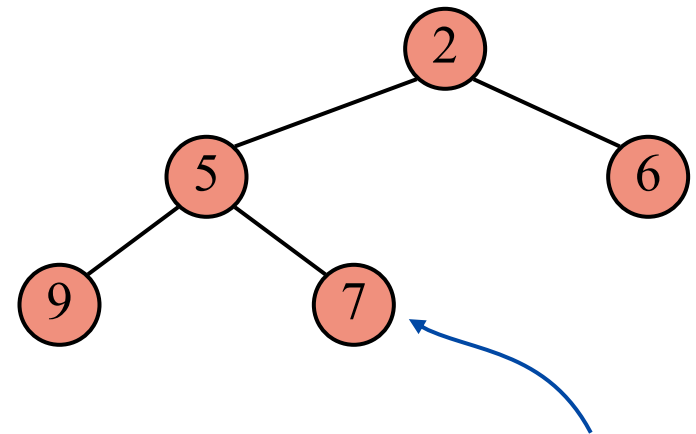
i	A	i
1	Z, <u>4</u> , 8, 2, 5, 3, 9	0
2	4, 7, <u>8</u> , 2, 5, 3, 9	2
3	<u>4</u> , 7, 8, <u>2</u> , 5, 3, 9	0
4	2, 4, Z, 8, <u>5</u> , 3, 9	2
5	2, <u>4</u> , 5, 7, 8, <u>3</u> , 9	1
6	2, 3, 4, 5, 7, 8, <u>2</u>	6

```
def insertion_sort(A):  
    n ← size(A)  
    for i in [1:n] do  
        x ← A[i]  
        # move forward entries > x  
        j ← i  
        while j > 0 and x < A[j-1] do  
            A[j] ← A[j-1]  
            j ← j - 1  
        # if j>0 ⇒ x ≥ A[j-1]  
        # if j<i ⇒ x < A[j+1]  
        A[j] ← x
```

# Heap data structure (min-heap)

A **heap** is a binary tree storing (key, value) items at its nodes, satisfying the following properties:

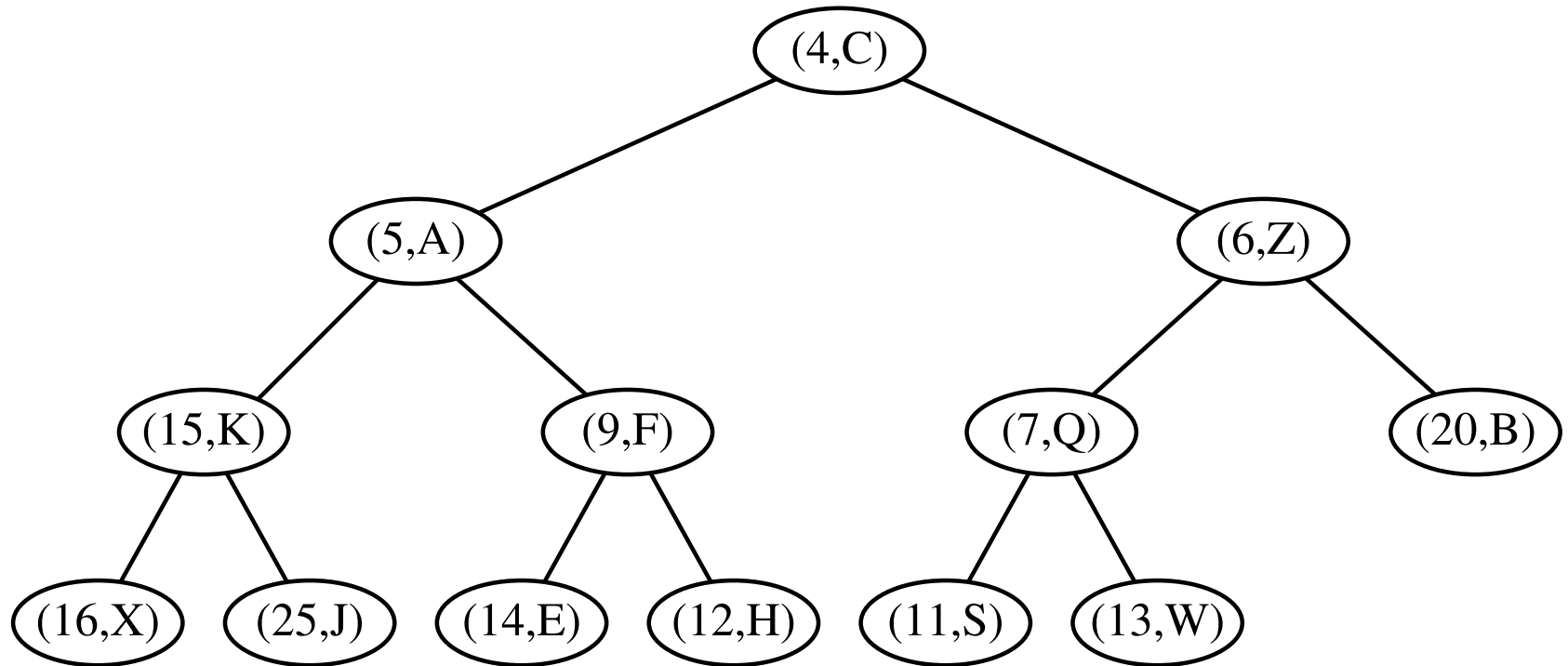
1. **Heap-Order:** for every node  $m \neq \text{root}$ ,  
 $\text{key}(m) \geq \text{key}(\text{parent}(m))$



2. **Complete Binary Tree:** let  $h$  be the height
  - every level  $i < h$  is full (i.e., there are  $2^i$  nodes)
  - remaining nodes take leftmost positions of level  $h$

The **last node** is the rightmost node of maximum depth

# Example

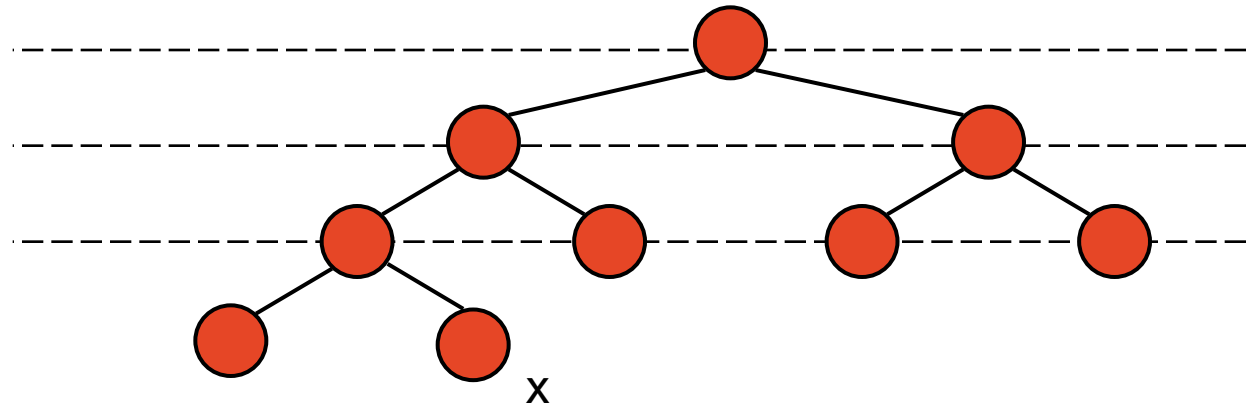


# Minimum of a Heap

**Fact:** The root always holds the smallest key in the heap

**Proof:**

- Suppose the minimum key is at some internal node  $x$
- Because of the heap property, as we move up the tree, the keys can only get smaller (assuming repeats, otherwise contradiction)
- If  $x$  is not the root, then its parent must also hold a smallest key
- Keep going until we reach the root



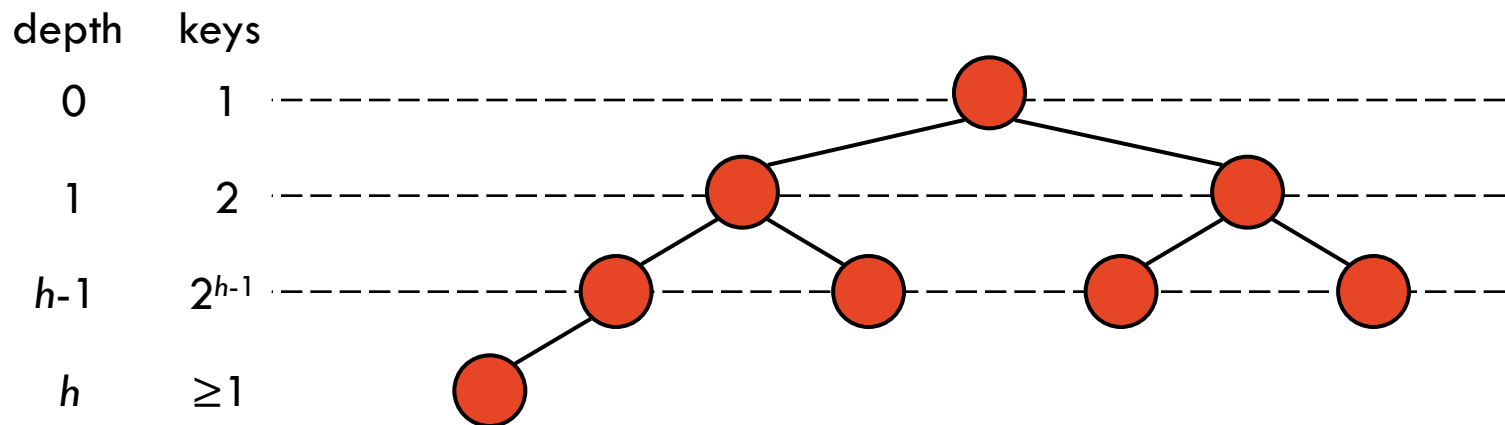


# Height of a Heap

**Fact:** A heap storing  $n$  keys has height  $\log n$

**Proof:**

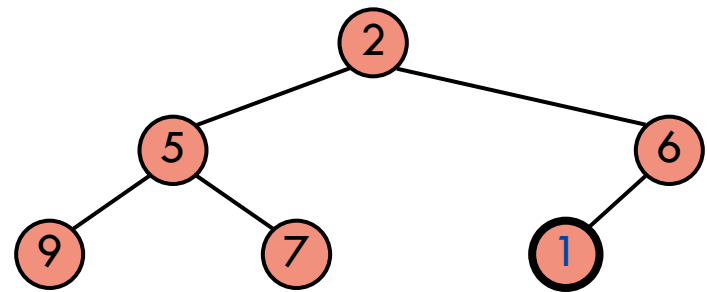
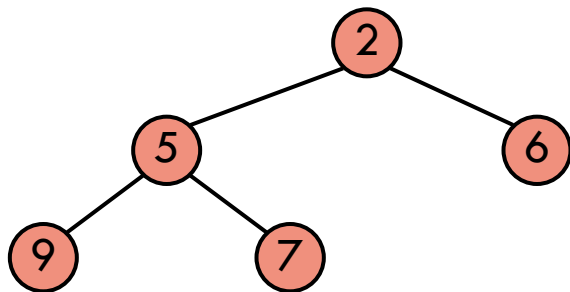
- Let  $h$  be the height of a heap storing  $n$  keys
- Since there are  $2^i$  keys at depth  $i = 0, \dots, h - 1$  and at least one key at depth  $h$ , we have  $n \geq 1 + 2 + 4 + \dots + 2^{h-1} + 1$
- Thus,  $n \geq 2^h$ , applying  $\log_2$  on both sides,  $\log_2 n \geq h$



# Insertion into a Heap

- Create a new node with given key
- Find location for new node
- Restore the heap-order property

insert(1)



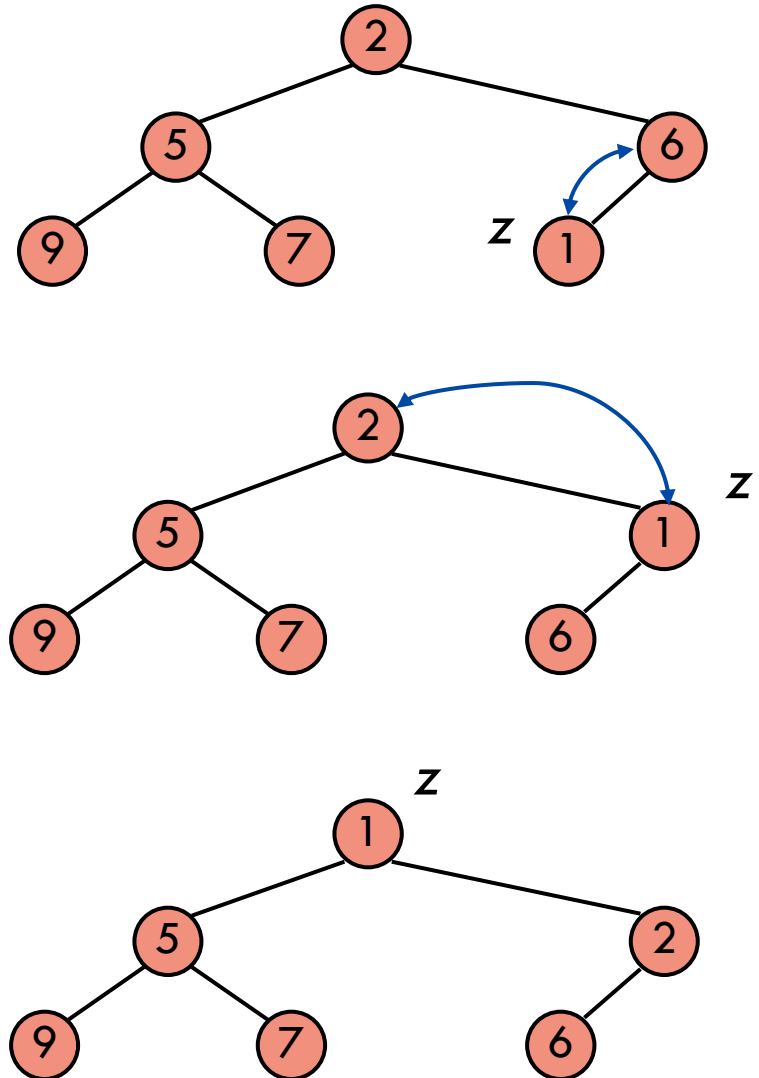
# Upheap

Restore heap-order property by swapping keys along upward path from insertion point

```
def up_heap(z):  
    while z  $\neq$  root and  
        key(parent(z)) > key(z) do  
        swap key of z and parent(z)  
        z  $\leftarrow$  parent(z)
```

Correctness: after swapping the subtree rooted at **z** has the property

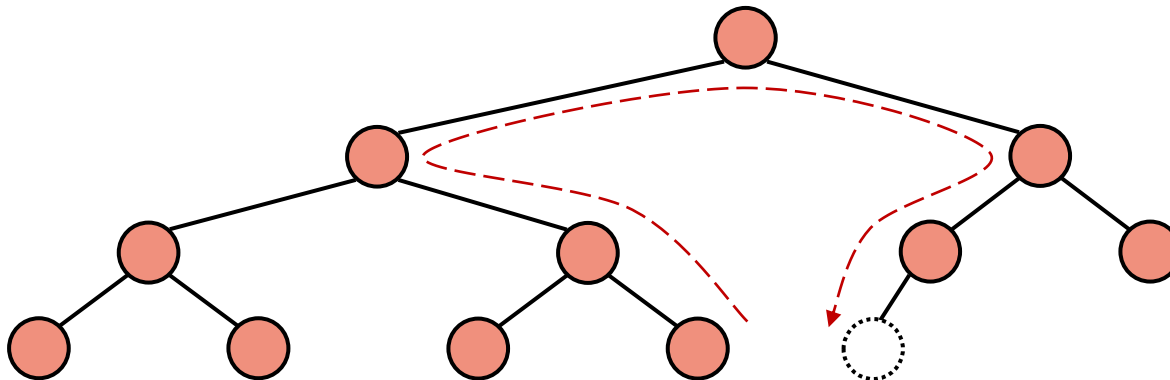
Complexity:  $O(\log n)$  time because the height of the heap is  $\log n$



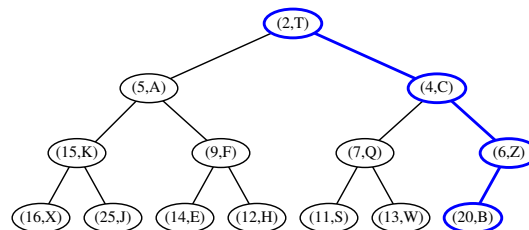
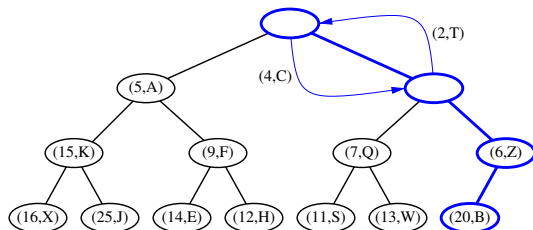
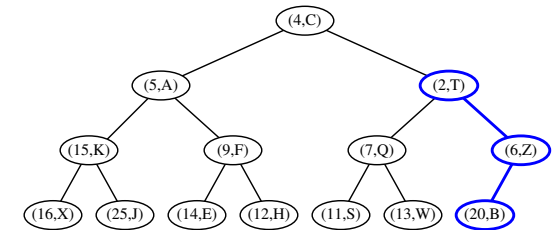
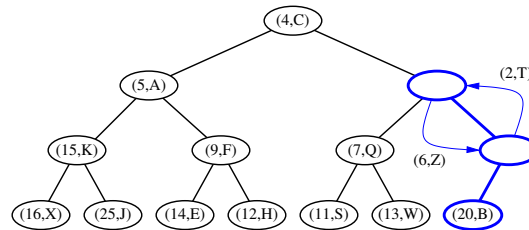
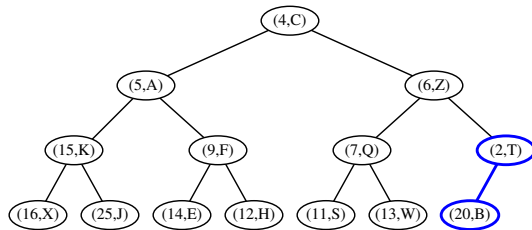
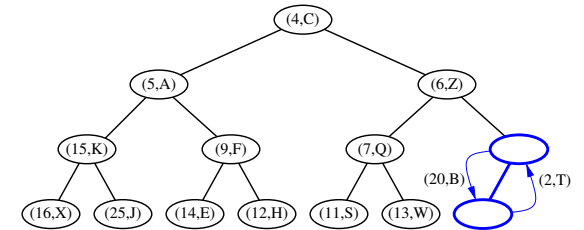
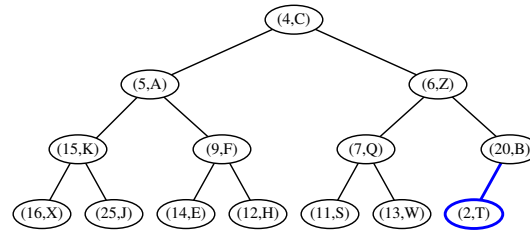
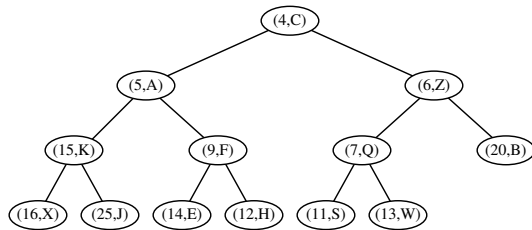
# Finding the position for insertion

- start from the last node
- go up until a left child or the root is reached
- if we reach the root then need to open a new level
- otherwise, go to the sibling (right child of parent)
- go down left until a leaf is reached

Complexity of this search is  $O(\log n)$  because the height is  $\log n$ .  
Thus, overall complexity of insertion is  $O(\log n)$  time



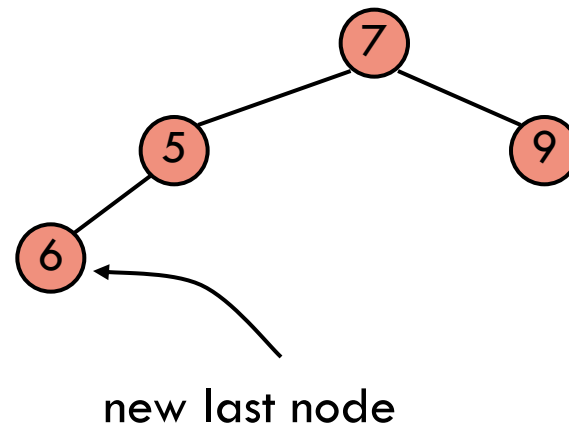
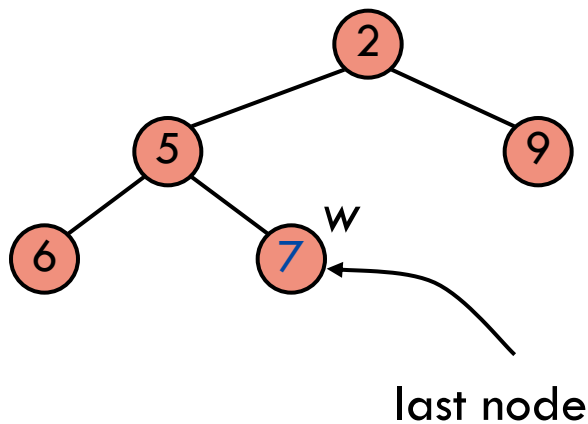
# Example insertion



# Removal from a Heap

- Replace the root key with the key of the last node  $w$
- Delete  $w$
- Restore the heap-order property

`remove_min()`



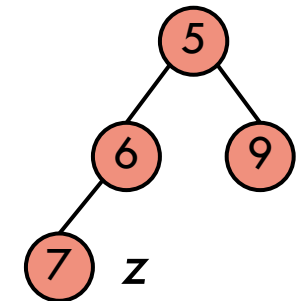
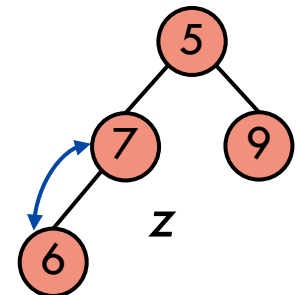
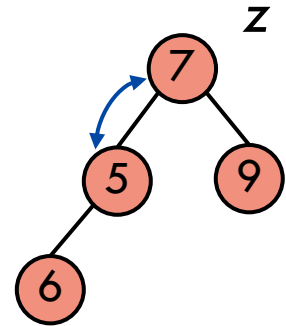
# Downheap

Restore heap-order property by swapping keys along downward path from the root

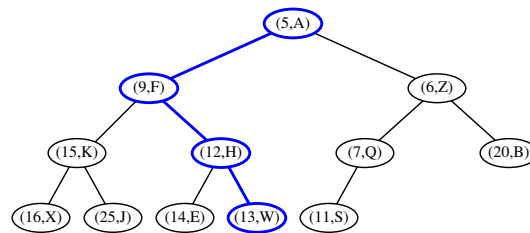
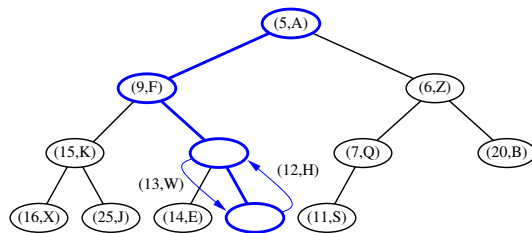
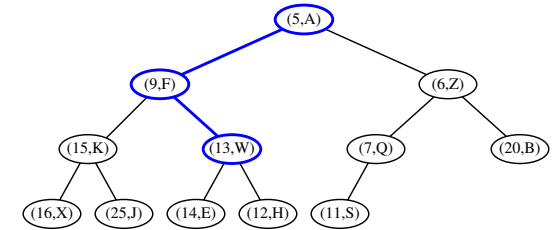
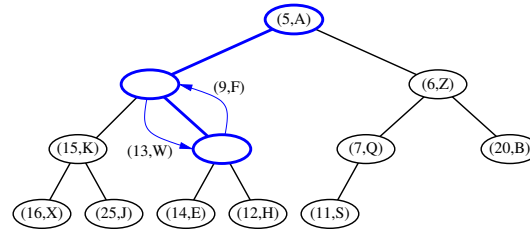
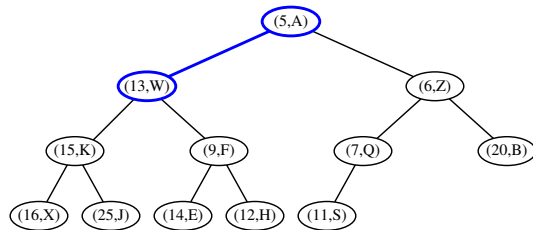
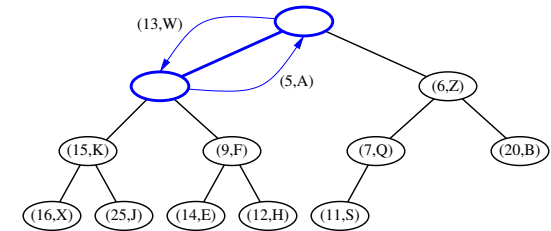
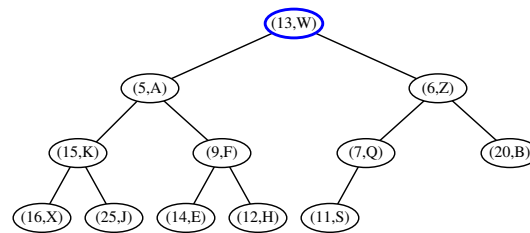
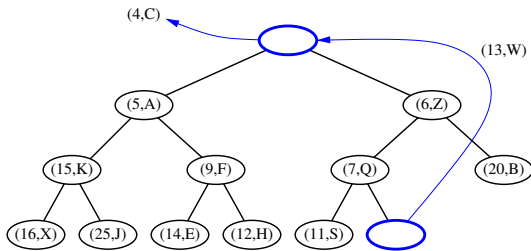
```
def down_heap(z):  
    while z has child with  
        key(child) < key(z) do  
        x ← child of z with smallest key  
        swap keys of x and z  
        z ← x
```

Correctness: after swap **z** heap-order property is restored up to level of **z**

Complexity:  $O(\log n)$  time because the height of the heap is  $\log n$



# Example removal

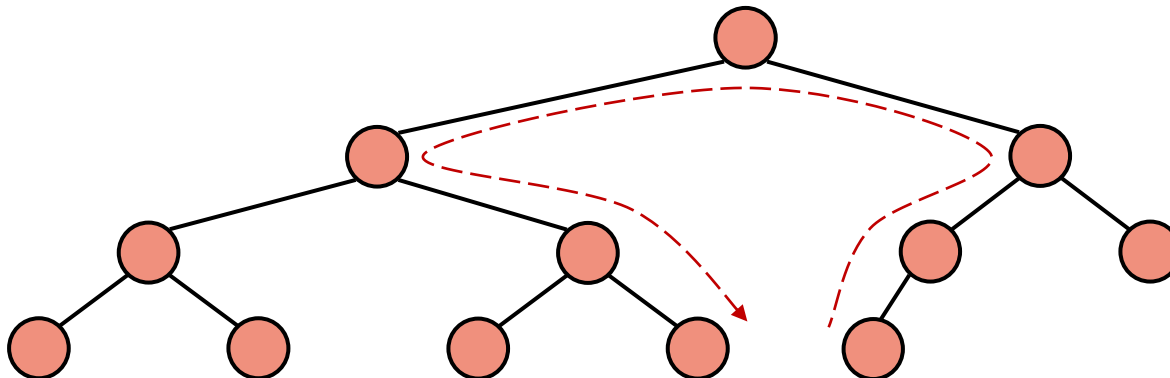




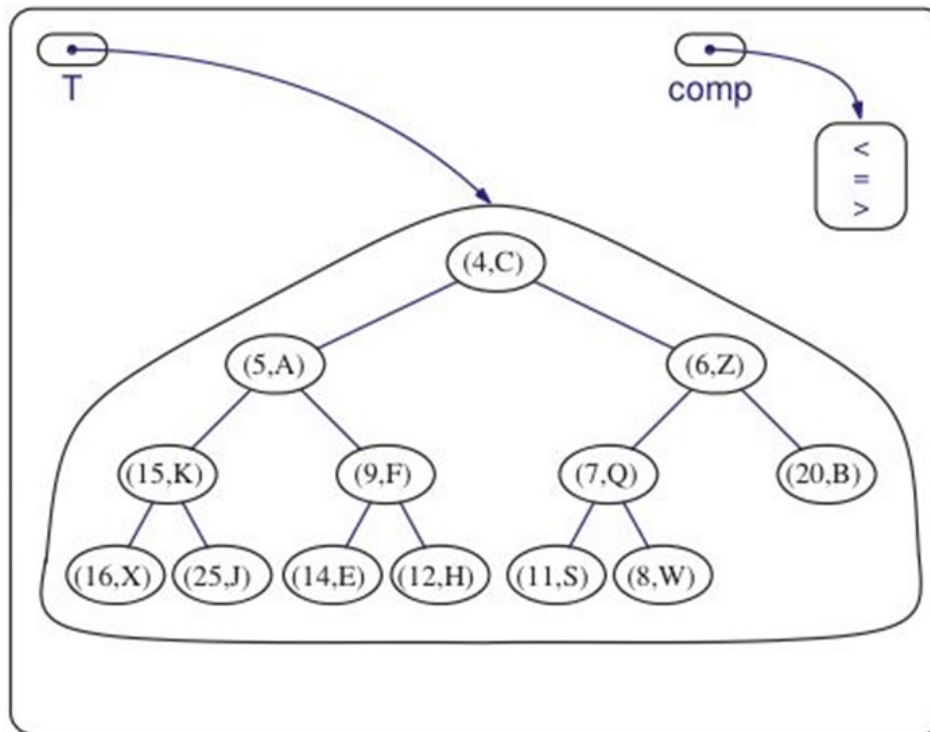
# Finding next last node after deletion

- start from the (old) last node
- go up until a right child or the root is reached
- if we reach the root then need to close a level
- otherwise, go to the sibling (left child of parent)
- go down right until a leaf is reached

Complexity of this search is  $O(\log n)$  because the height is  $\log n$ .  
Thus, overall complexity of deletion is  $O(\log n)$  time



# Heap-based implementation of a priority queue



Operation	Time
size, isEmpty	$O(1)$
min,	$O(1)$
insert	$O(\log n)$
removeMin	$O(\log n)$

# Heap-Sort

Consider a priority queue with  $n$  items implemented with a heap:

- the space used is  $O(n)$
- methods **insert** and **remove\_min** take  $O(\log n)$

Recall that priority-queue sorting uses:

- $n$  insert ops
- $n$  remove\_min ops

**Heap-sort** is the version of priority-queue sorting that implements the priority queue with a heap. It runs in  $O(n \log n)$  time.

# Heap-in-array implementation

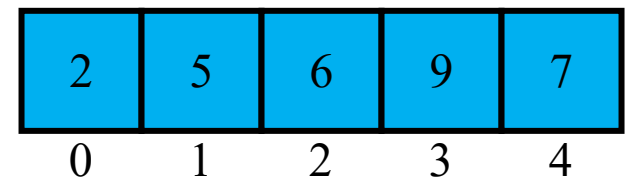
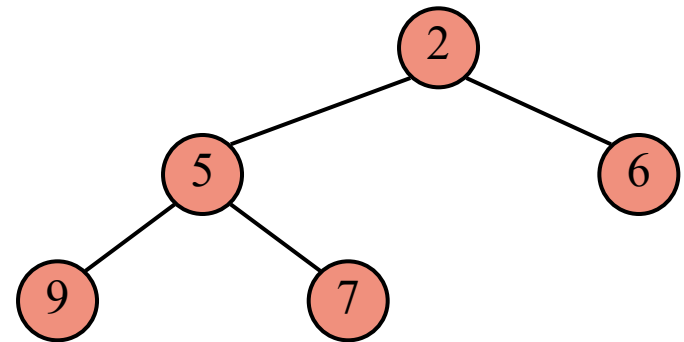
We can represent a heap with  $n$  keys by means of an array of length  $n$

Special nodes:

- root is at 0
- last node is at  $n-1$

For the node at index  $i$ :

- the left child is at index  $2i+1$
- the right child is at index  $2i+2$
- Parent is at index  $\lfloor (i-1)/2 \rfloor$



# Refinements and Generalization

Heap-sort can be arranged to work in place using part of the array for the output and part for the priority queue

A heap on  $n$  keys can be constructed in  $O(n)$  time. But the  $n$  `remove_min` still take  $O(n \log n)$  time

Sometimes it is useful to support a few more operations (all are given a pointer to  $e$ ):

- `remove(e)`: Remove item  $e$  from the priority queue
- `replace_key(e, k)`: update key of item  $e$  with  $k$
- `replace_value(e, v)`: update value of item  $e$  with  $v$

## Summary: Priority queue implementations

Method	Unsorted List	Sorted List	Heap
size, isEmpty	$O(1)$	$O(1)$	$O(1)$
insert	$O(1)$	$O(n)$	$O(\log n)$
min	$O(n)$	$O(1)$	$O(1)$
removeMin	$O(n)$	$O(1)$	$O(\log n)$
remove	$O(1)$	$O(1)$	$O(\log n)$
replaceKey	$O(1)$	$O(n)$	$O(\log n)$
replaceValue	$O(1)$	$O(1)$	$O(1)$

# Implementing a Priority Queue

Entries: An object that keeps track of the associations between keys and values

Comparators: A function or an interface to compare entry objects

**compare**(a, b): returns an integer **i** such that

- **i** < 0 if **a** < **b**,
- **i** = 0 if **a** = **b**
- **i** > 0 if **a** > **b**

**Warning:** do not assume that **compare(a,b)** is always -1, 0, 1

## Stock Application Revisited



Online trading system where orders are stored in two priority queues (one for sell orders and one for buy orders) as  $(p, t, s)$  entries:

- The key is  $(p, t)$ , the price of the order  $p$  and the time  $t$  such that we first sort by  $p$  and break ties with  $t$
- The value is  $s$ , the number of shares the order is for

How do we implement the following:

- What should we do when a new order is placed?
- What if someone wishes to cancel their order before it executes?
- What if someone wishes to update the price or number of shares for their order?