CSE 332 Autumn 2024 Lecture 8: Heaps and Dictionaries

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ADT: Priority Queue

- What is it?
  - A collection of items and their “priorities”
  - Allows quick access/removal to the “top priority” thing
    - Usually a smaller priority value means the item is “more important”
- What Operations do we need?
  - insert(item, priority)
    - Add a new item to the PQ with indicated priority
  - extract
    - Remove and return the “top priority” item from the queue
      - Usually the item with the smallest priority value
  - IsEmpty
    - Indicate whether or not there are items still on the queue
- Note: the “priority” value can be any type/class so long as it’s comparable (i.e. you can use “<“ or “compareTo” with it)

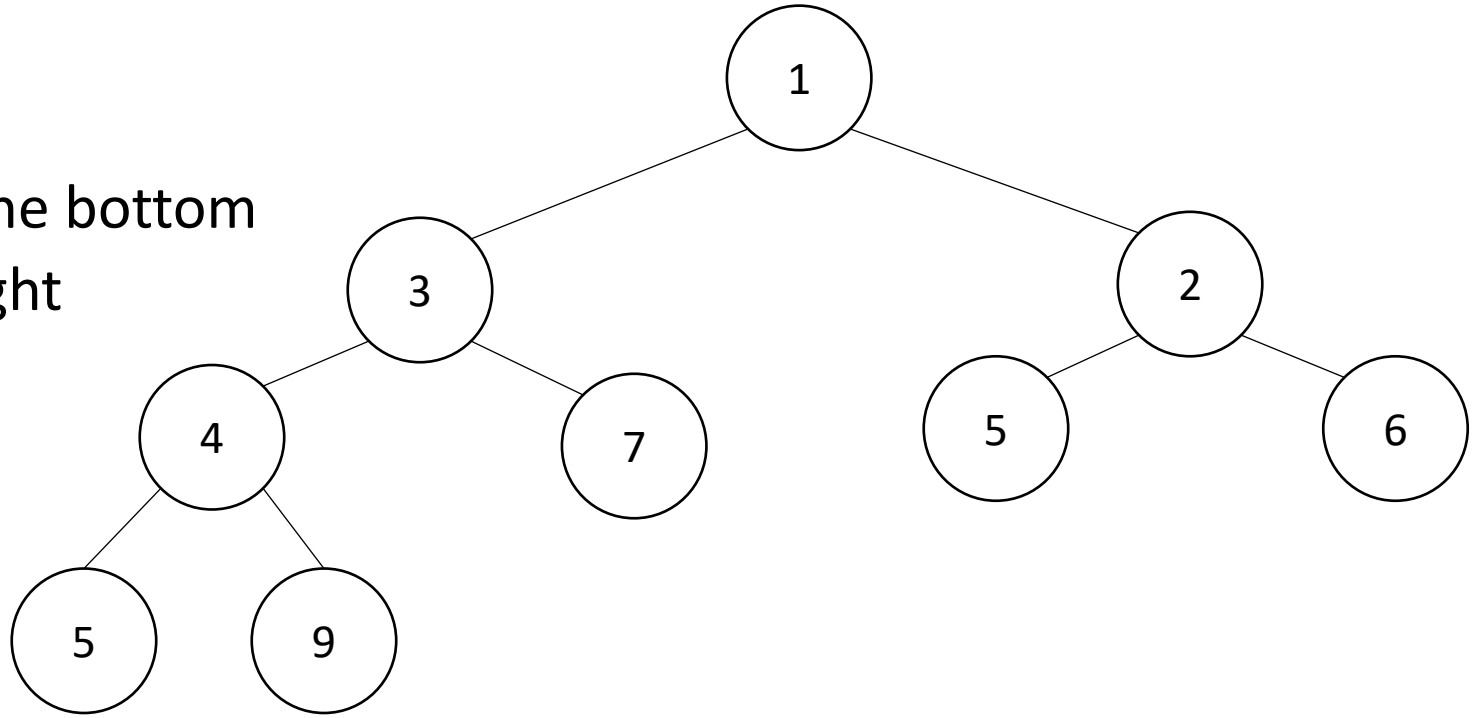
Thinking through implementations

Data Structure	Worst case time to insert	Worst case time to extract
Unsorted Array	$\Theta(1)$	$\Theta(n)$
Unsorted Linked List	$\Theta(1)$	$\Theta(n)$
Sorted Array	$\Theta(n)$	$\Theta(1)$
Sorted Linked List	$\Theta(n)$	$\Theta(1)$
Binary Search Tree	$\Theta(n)$	$\Theta(n)$
Binary Heap	$\Theta(\log n)$	$\Theta(\log n)$

For simplicity, Assume we know the maximum size of the PQ in advance (otherwise we'd do an amortized analysis, but get the same answers…)

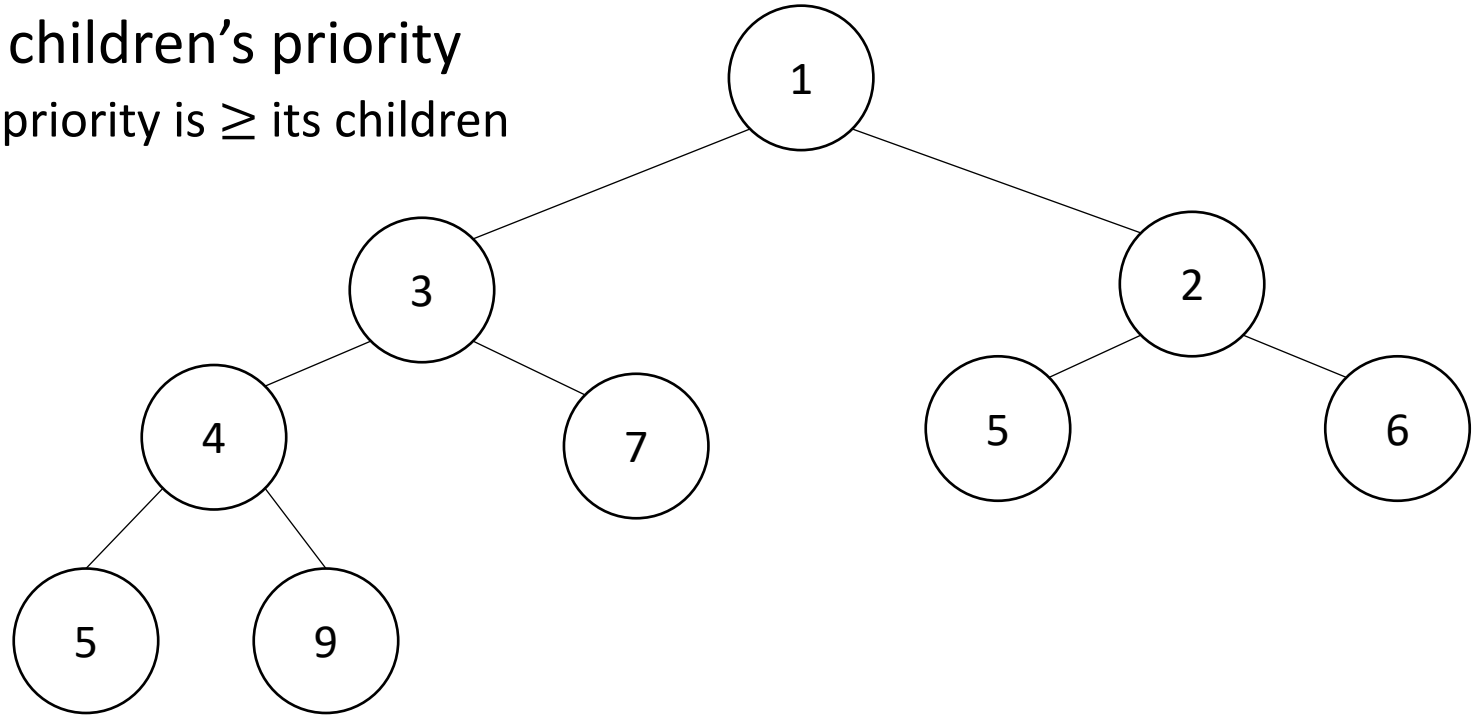
Trees for Heaps

- Binary Trees:
  - The branching factor is 2
  - Every node has ≤ 2 children
- Complete Tree:
  - All “layers” are full, except the bottom
  - Bottom layer filled left-to-right



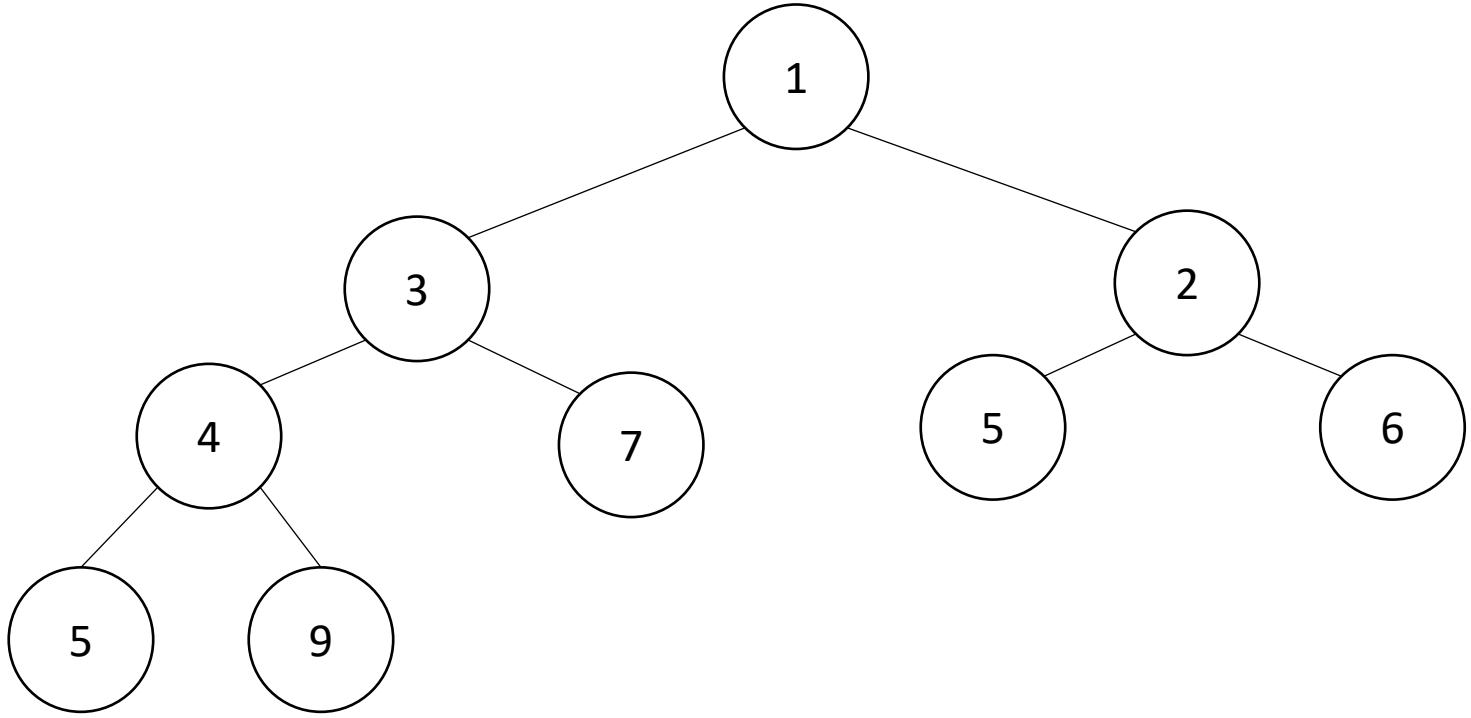
(Min) Heap Data Structure

- Keep items in a complete binary tree
- Maintain the "(Min) Heap Property" of the tree
  - Every node's priority is $\leq$ its children's priority
  - Max Heap Property: every node's priority is $\geq$ its children



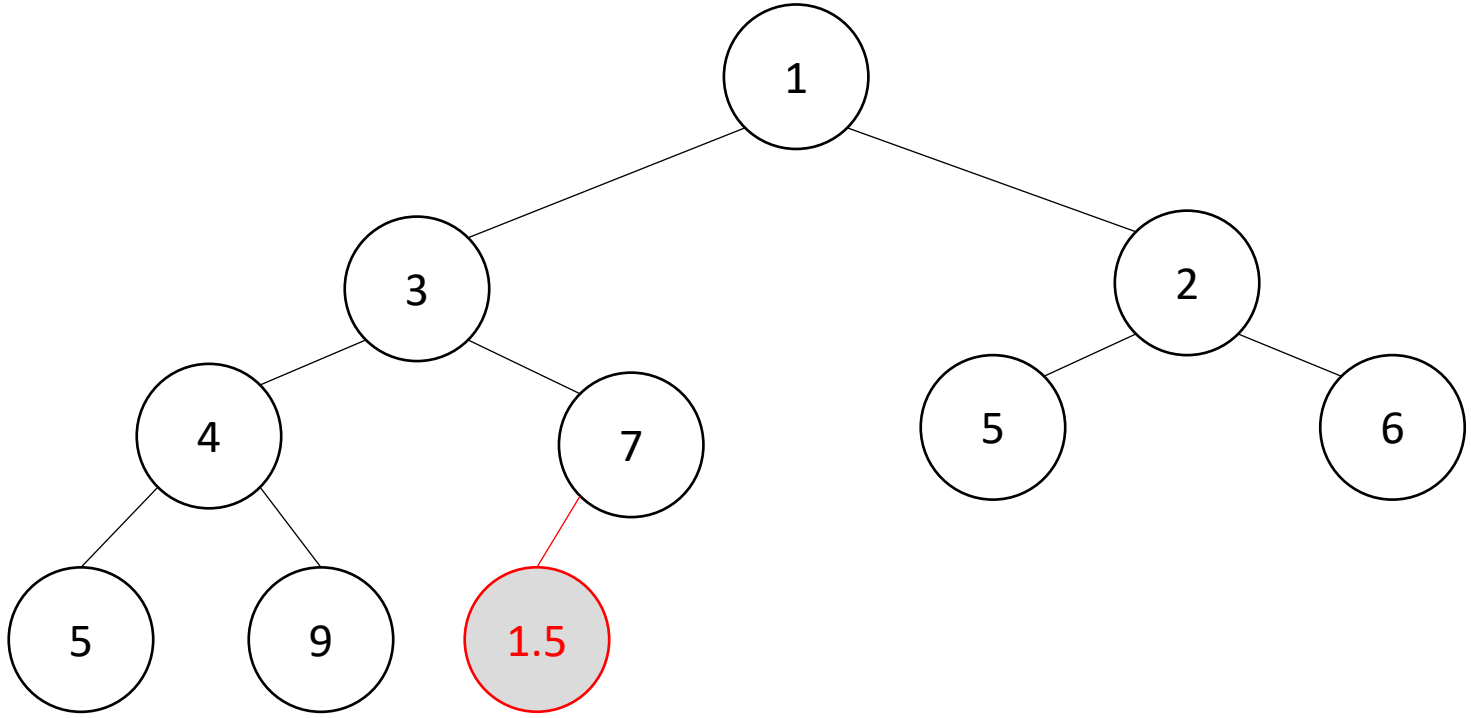
Heap Insert

1.5




```
insert(item, priority){
    put item in the “next open” spot (keep tree complete)
    while (priority < parent’s priority){
        swap item with parent
    }
}
```

Heap Insert

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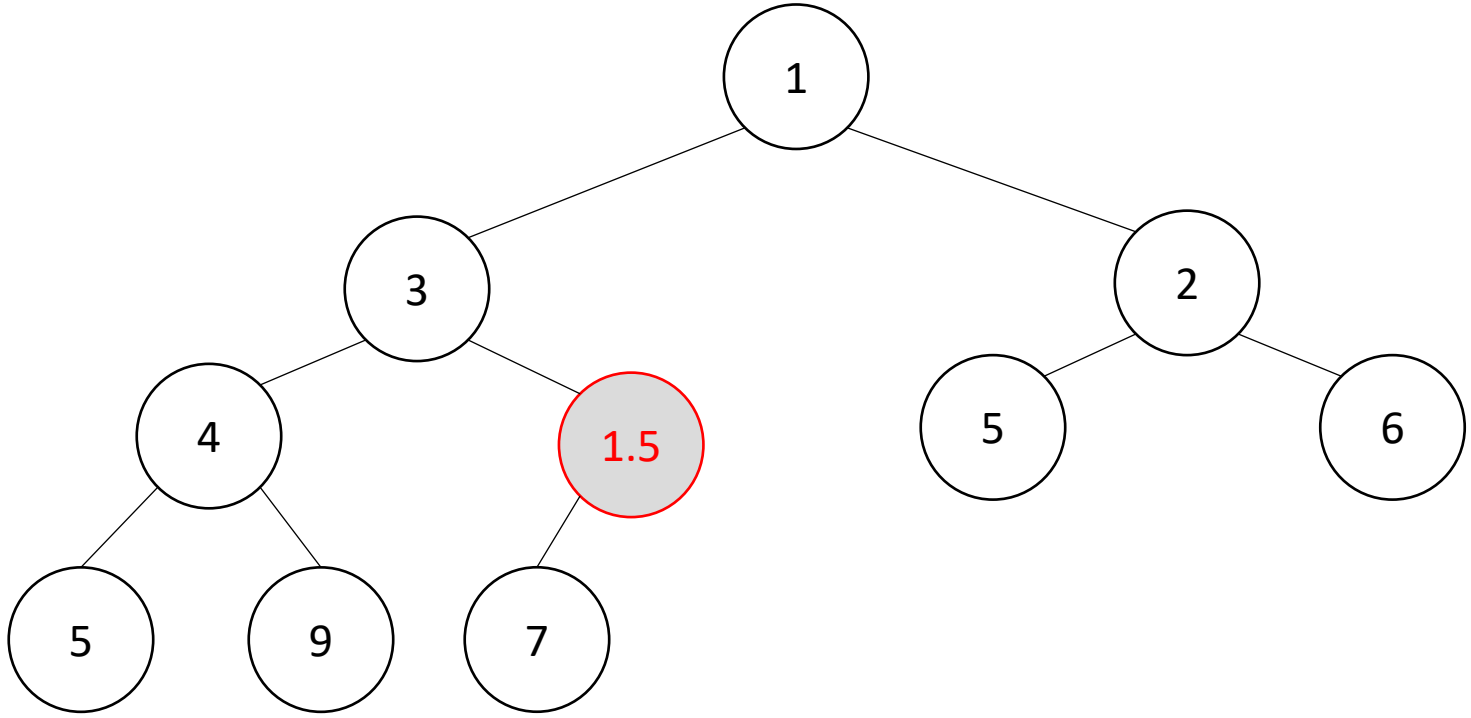


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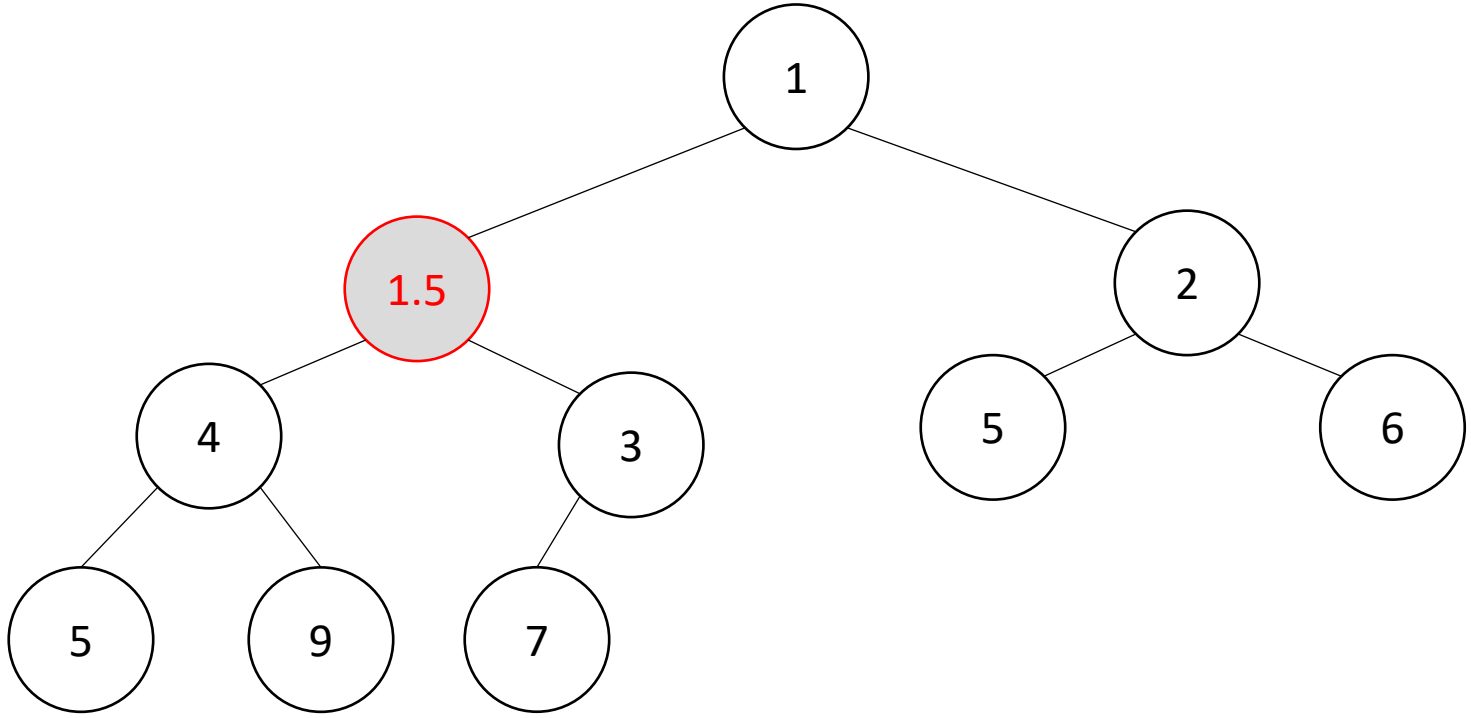
Percolate Up

Heap Insert

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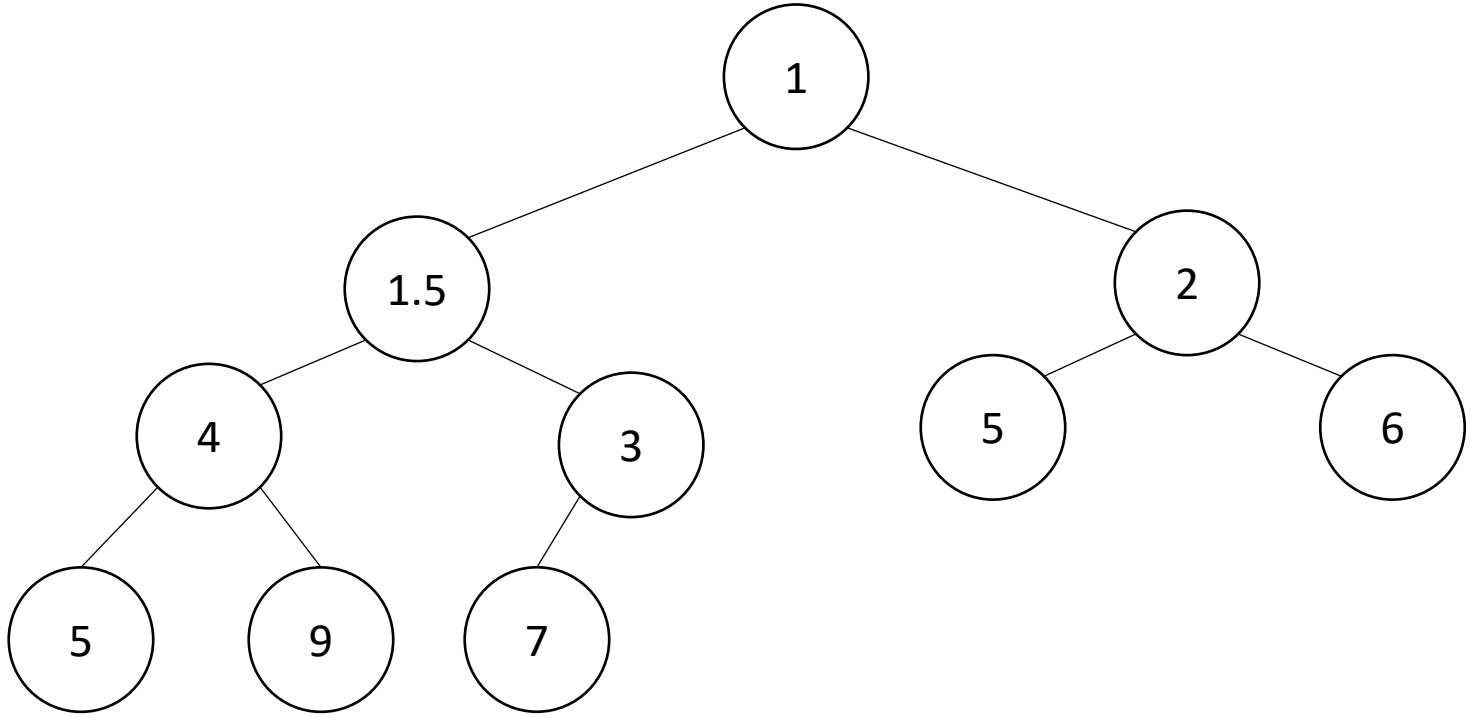


```
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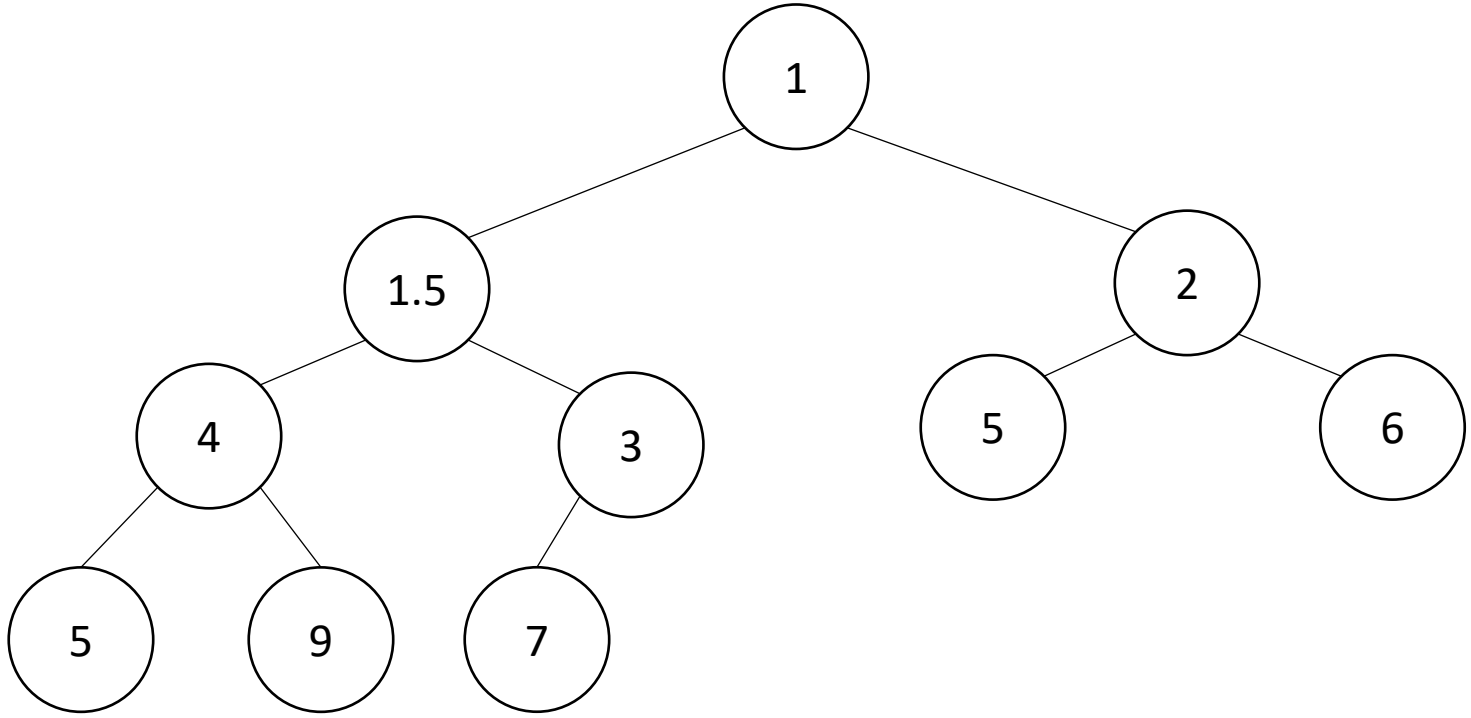
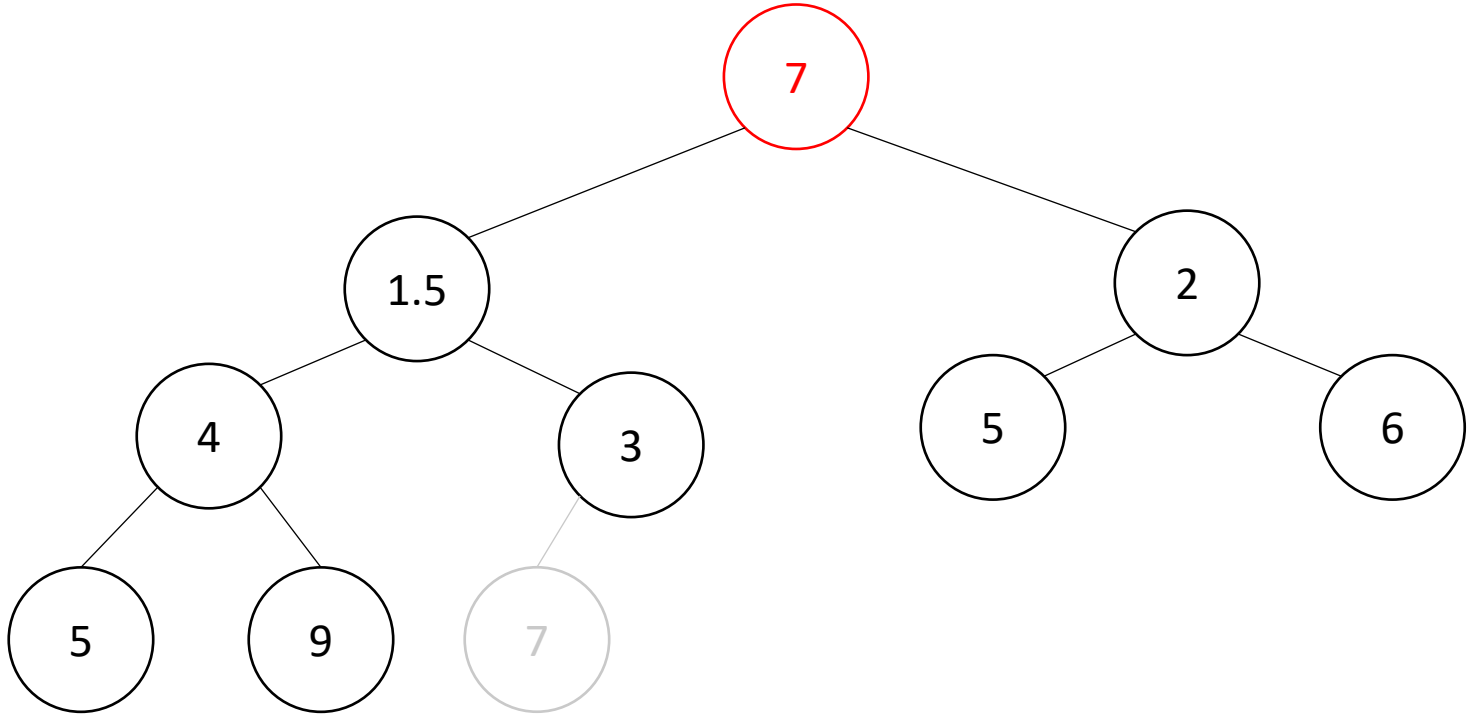
Heap extract




```
extract(){
    min = root
    curr = bottom-right item
    move curr to the root
    while(curr > curr.left || curr > curr.right){
        swap curr with its smallest child
    }
    return min
}
```

Heap extract

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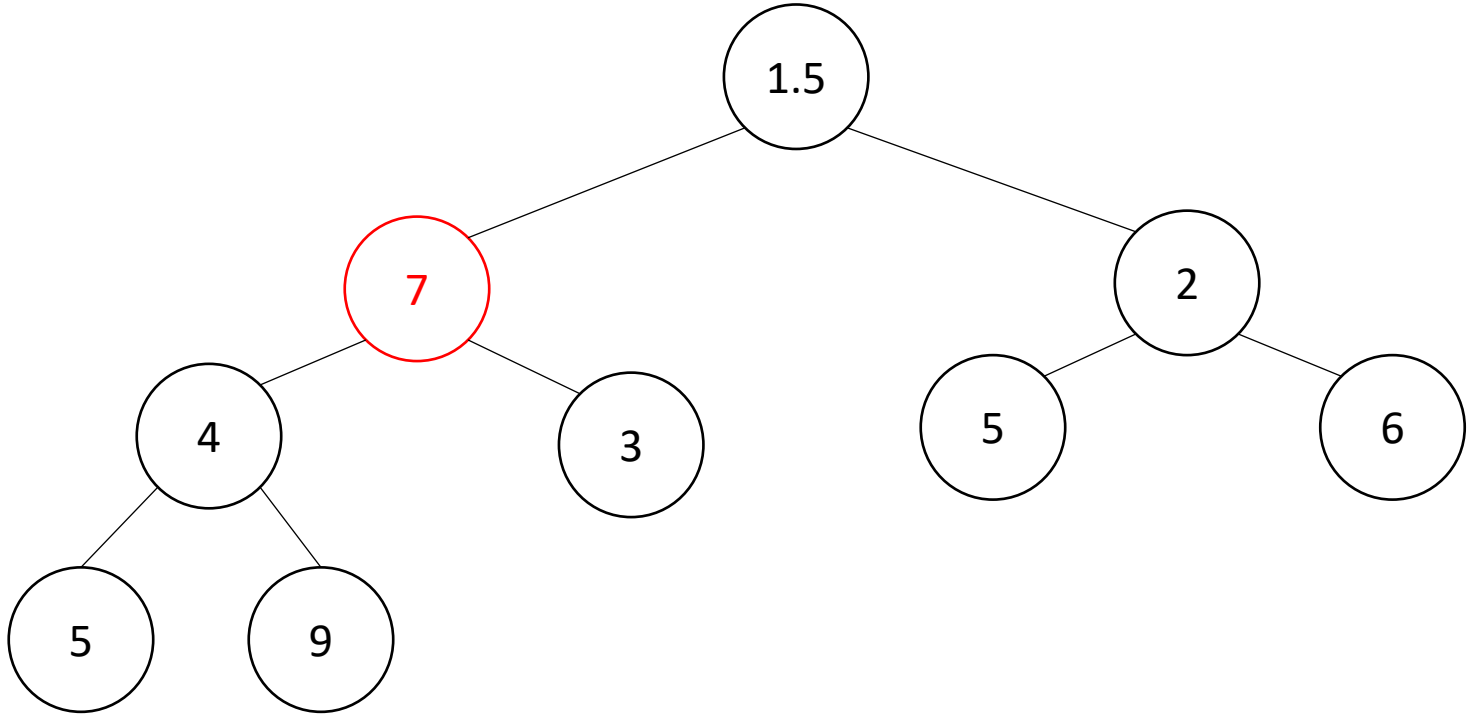


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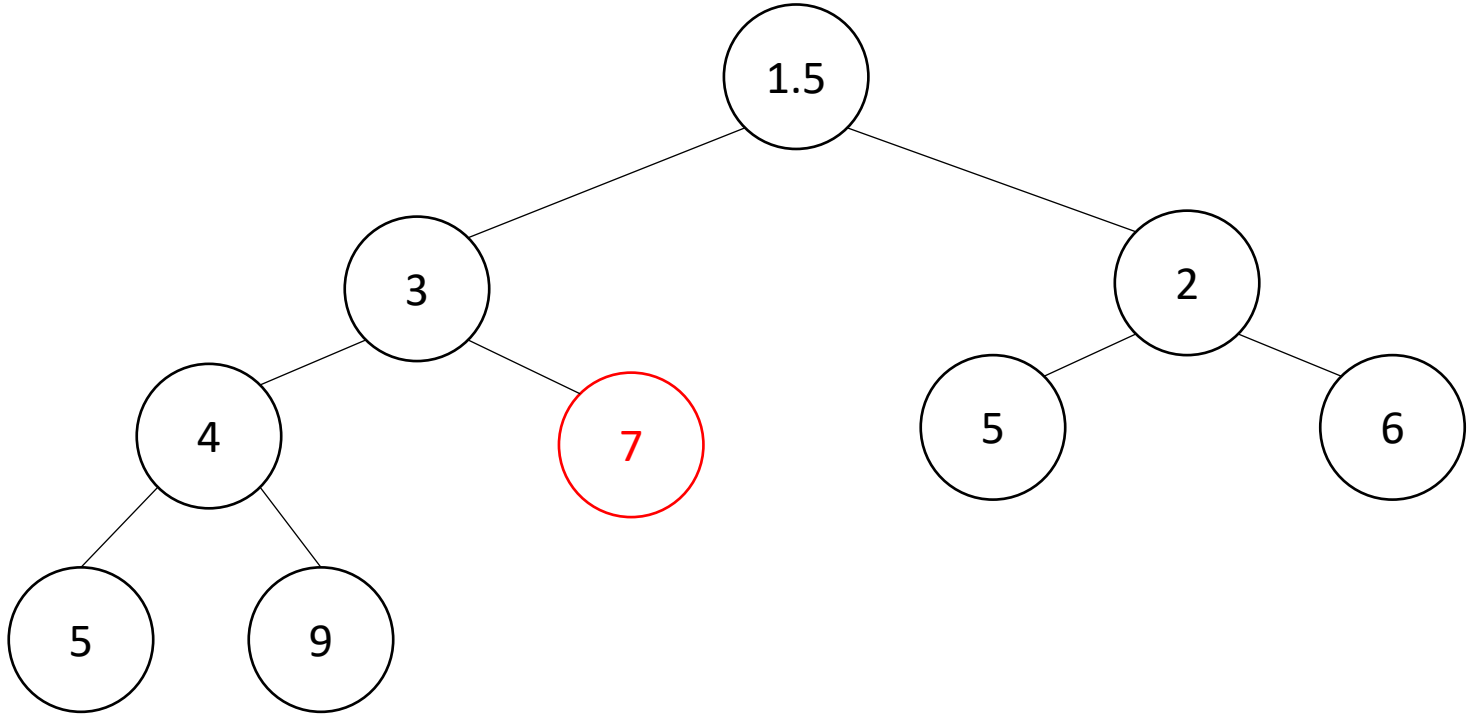
Percolate Down

Heap extract

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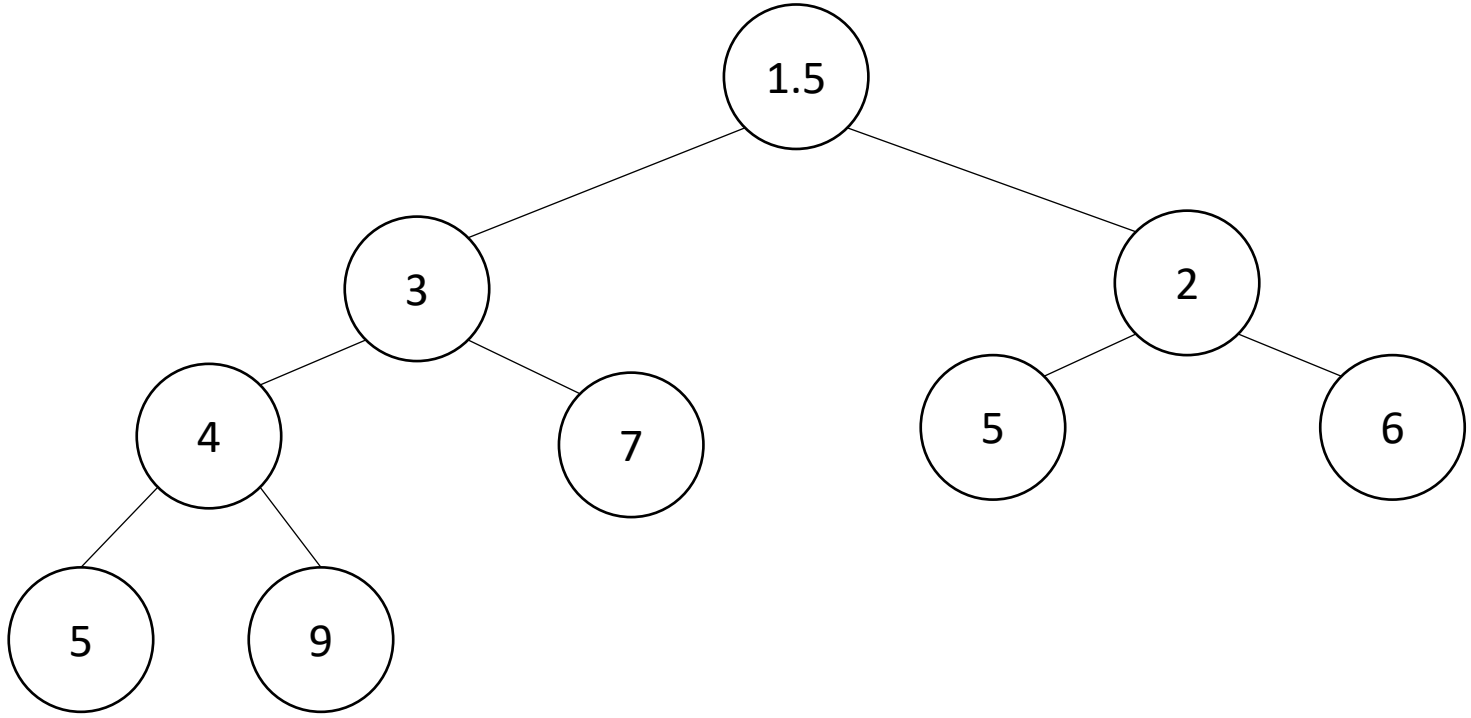
Percolate Down

Heap extract

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    }
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}
```

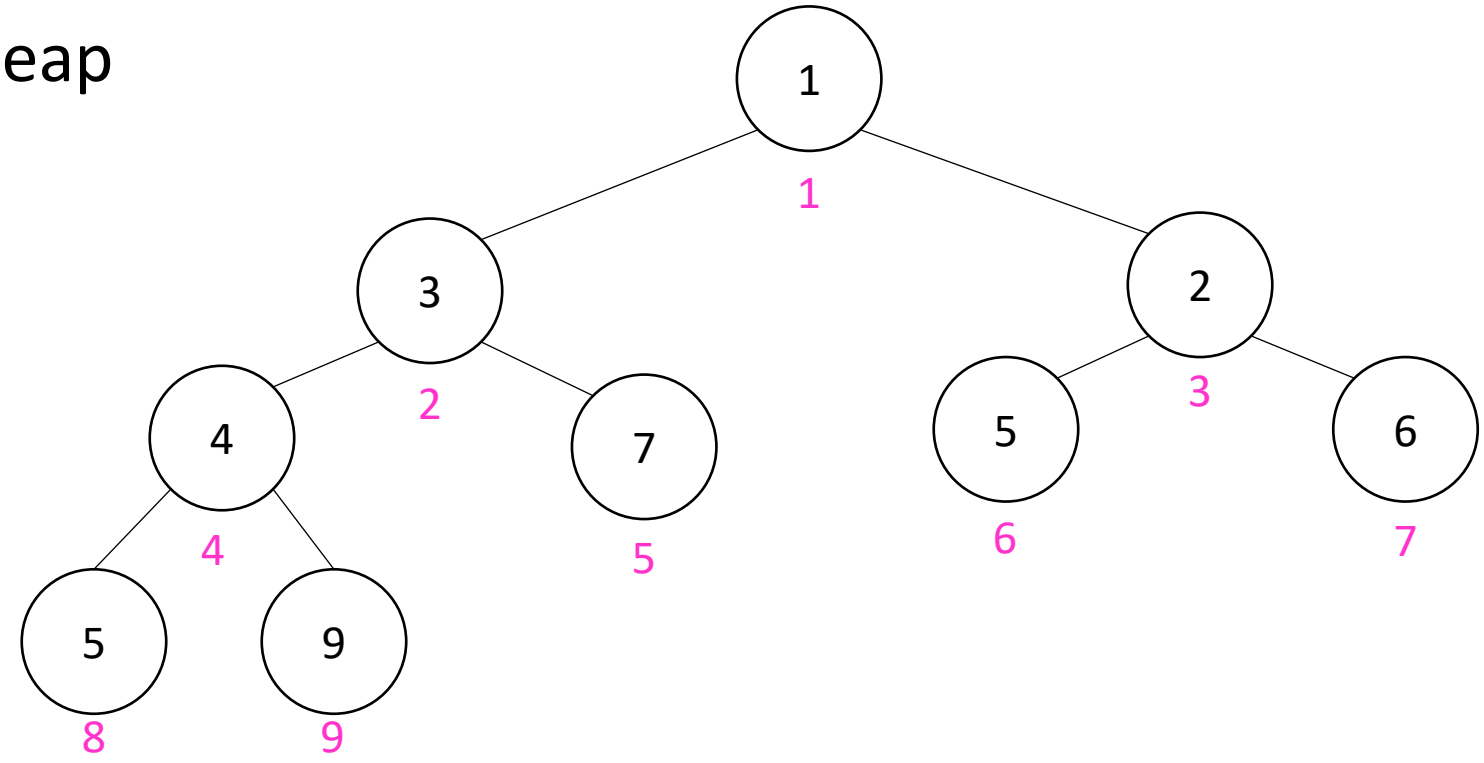
Percolate Up and Down (for a Min Heap)

- Goal: restore the “Heap Property”
- Percolate Up:
  - Take a node that may be smaller than a parent, repeatedly swap with a parent until it is larger than its parent
- Percolate Down:
  - Take a node that may be larger than one of its children, repeatedly swap with smallest child until both children are larger
- Worst case running time of each:
  - $\Theta(\log n)$

Representing a Heap

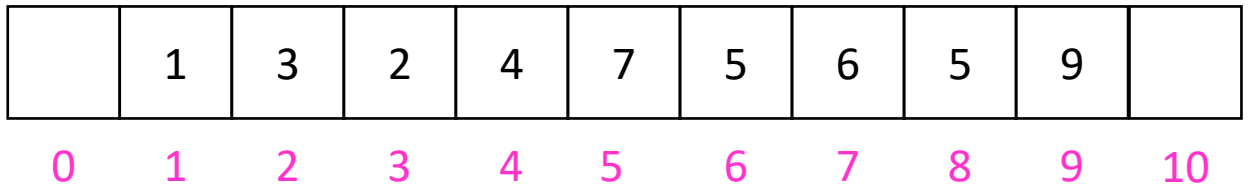
	1	3	2	4	7	5	6	5	9
0	1	2	3	4	5	6	7	8	9

- Every complete binary tree with the same number of nodes uses the same positions and edges
- Use an array to represent the heap
- Index of root:
- Parent of node i:
- Left child of node i:
- Right child of node i:
- Location of the leaves:

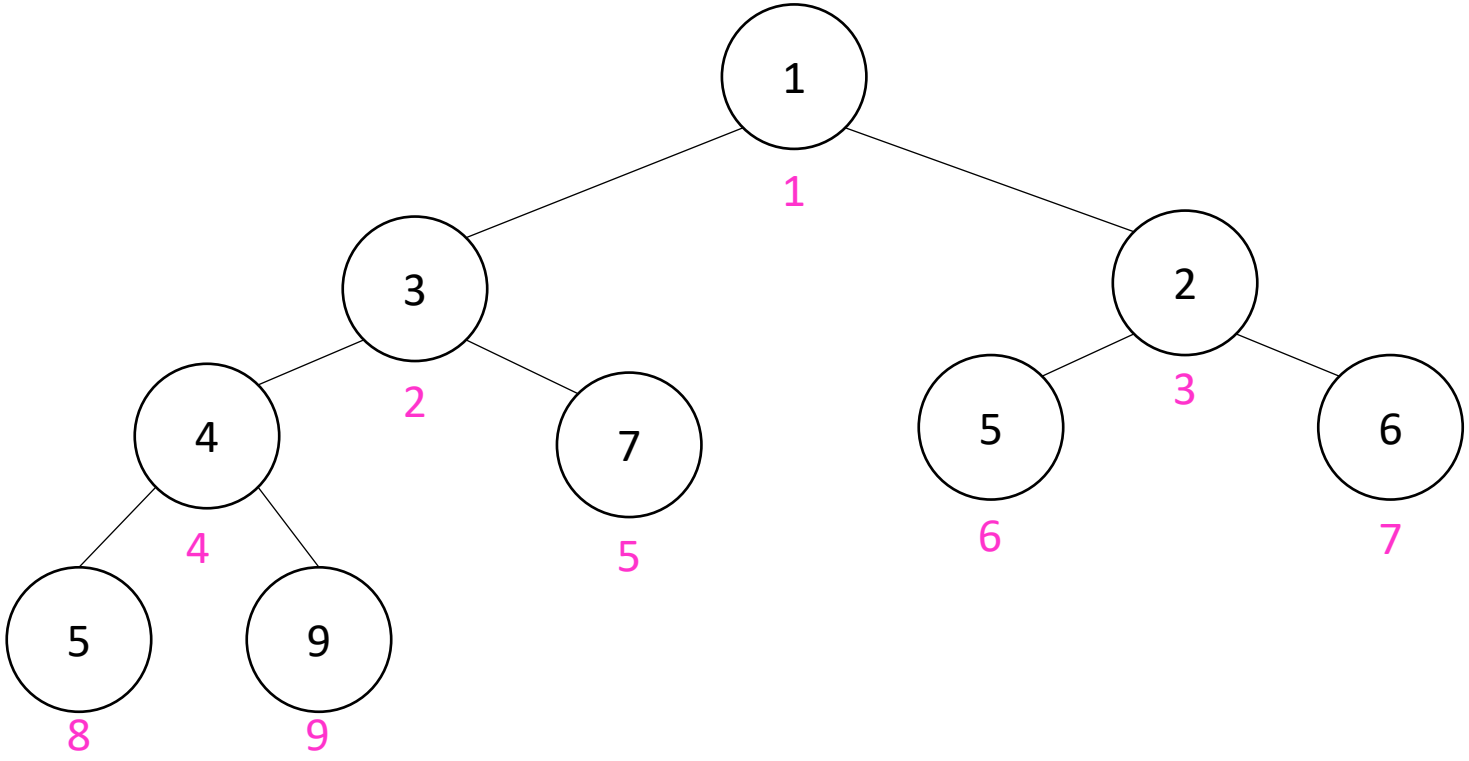


Insert Psuedocode

For simplicity, assume is the same as priority




```
insert(item){
    if(size == arr.length – 1){resize();}
    size++;
    arr[size] = item;
    percolateUp(size)
}
```



Percolate Up

```
percolateUp(int i){
    int parent = i/2;  \\ index of parent
    Item val = arr[i];  \\ value at current location
    while(i > 1 && arr[i] < arr[parent]){  \\ until location is root or heap property holds
        arr[i] = arr[parent];  \\ move parent value to this location
        arr[parent] = val; \\ put current value into parent's location
        i = parent;  \\ make current location the parent
        parent = i/2;  \\ update new parent
    }
}
```

extract Psuedocode

```
extract(){
    theMin = arr[1];
    arr[1] = arr[size];
    size--;
    percolateDown(1);
    return theMin;
}
```

Percolate Down

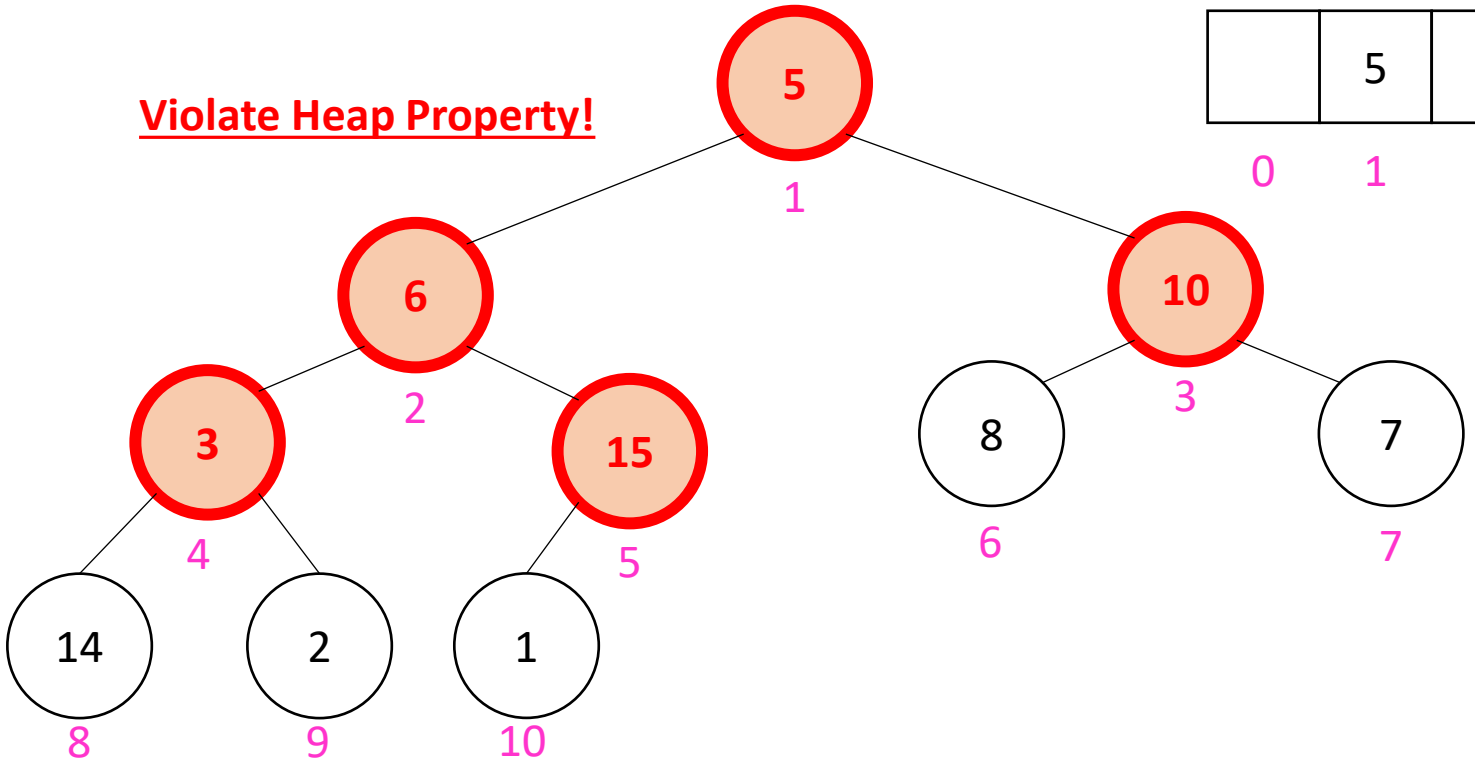
```
percolateDown(int i){
   int left = i*2;  \\ index of left child
   int right = i*2+1;  \\ index of right child
   Item val = arr[i];  \\ value at location
   while(left <= size){  \\ until location is leaf
      int toSwap = right;
      if(right > size || arr[left] < arr[right]){  \\ if there is no right child or if left child is smaller
         toSwap = left;  \\ swap with left
      } \\ now toSwap has the smaller of left/right, or left if right does not exist
      if (arr[toSwap] < val){  \\ if the smaller child is less than the current value
         arr[i] = arr[toSwap];
         arr[toSwap] = val; \\ swap parent with smaller child
         i = toSwap; \\ update current node to be smaller child
         left = i*2;
         right = i*2+1;
      }
      else{ return;} \\ if we don't swap, then heap property holds
   }
}
```

Other Operations

- Increase Key
  - Given the index of an item in the PQ, make its priority value larger
    - Min Heap: Then percolate Down
    - Max Heap: Then percolate Up
- Decrease Key
  - Given the index of an item in the PQ, make its priority value smaller
    - Min Heap: Then percolate Up
    - Max Heap: Then percolate Down
- Remove
  - Given the item at the given index from the PQ

Building a Heap From "Scratch"

- Suppose we had n items and wanted to "heapify" them



	5	6	10	3	15	8	7	14	2	1
0	1	2	3	4	5	6	7	8	9	10

Two ways for "fix" the heap:

1) Percolate Up
2) Percolate Down

Floyd's buildHeap method

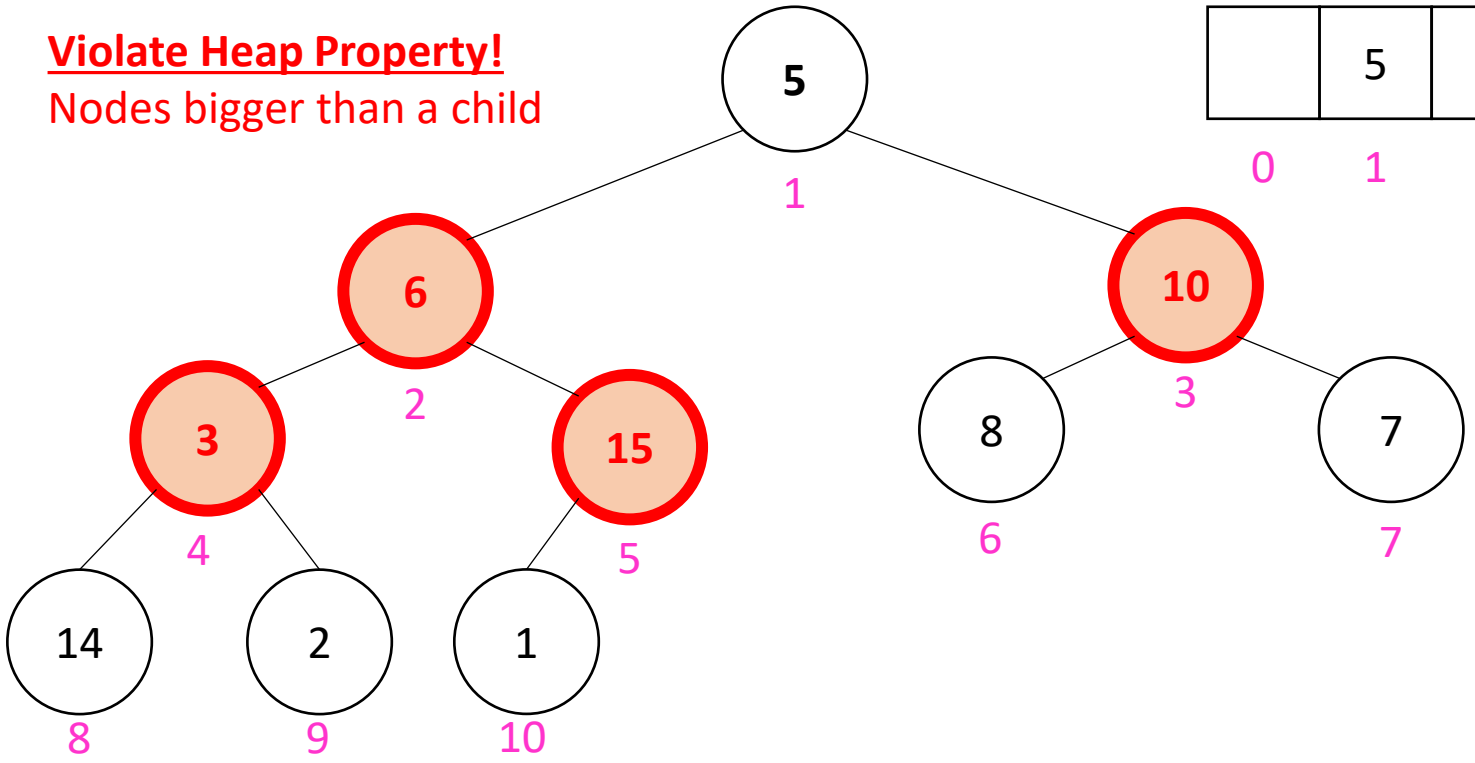
- Working towards the root, one row at a time, percolate down

```
buildHeap(){
    for(int i = size; i>0; i--){
        percolateDown(i);
    }
}
```

Floyd's buildHeap method

- Suppose we had n items and wanted to "heapify" them

Violate Heap Property!
Nodes bigger than a child



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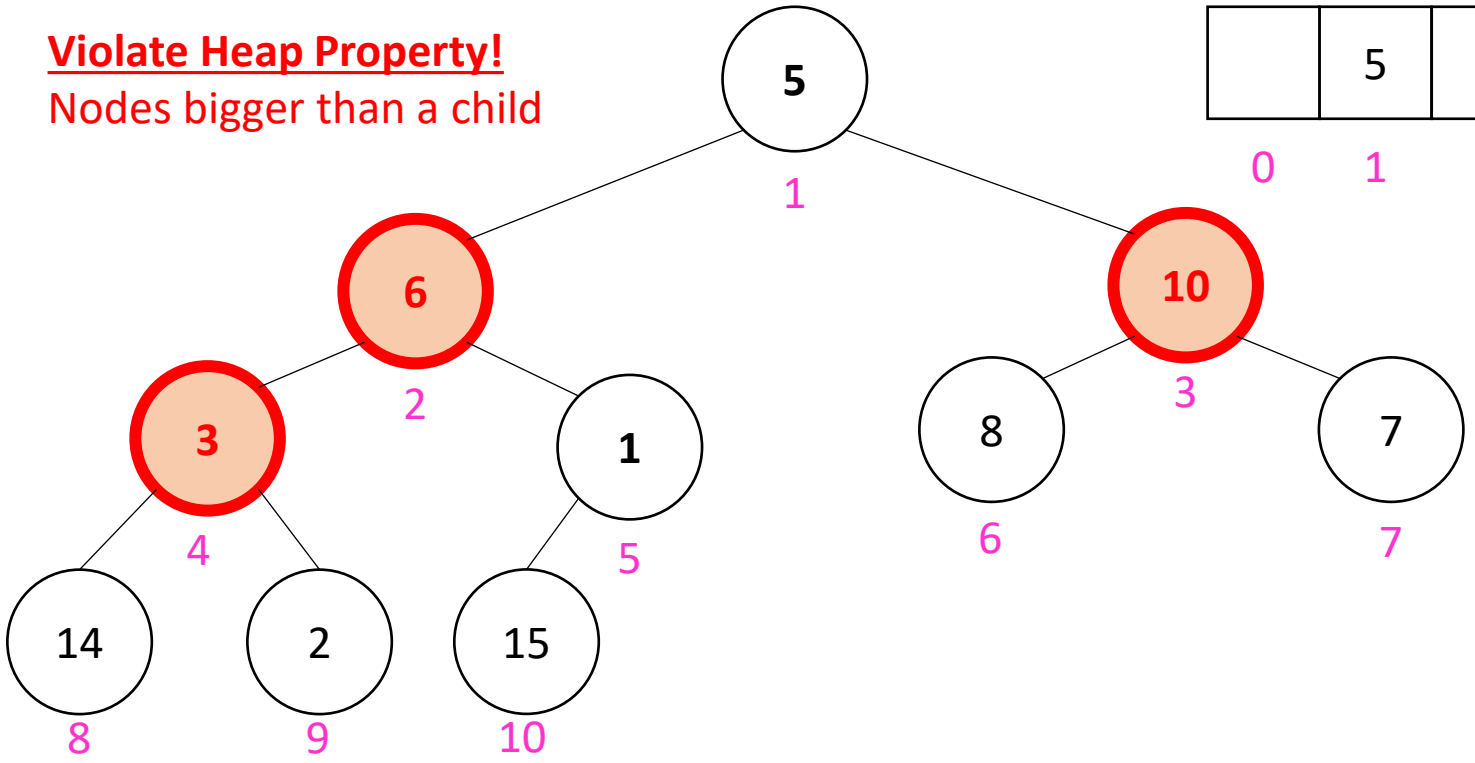

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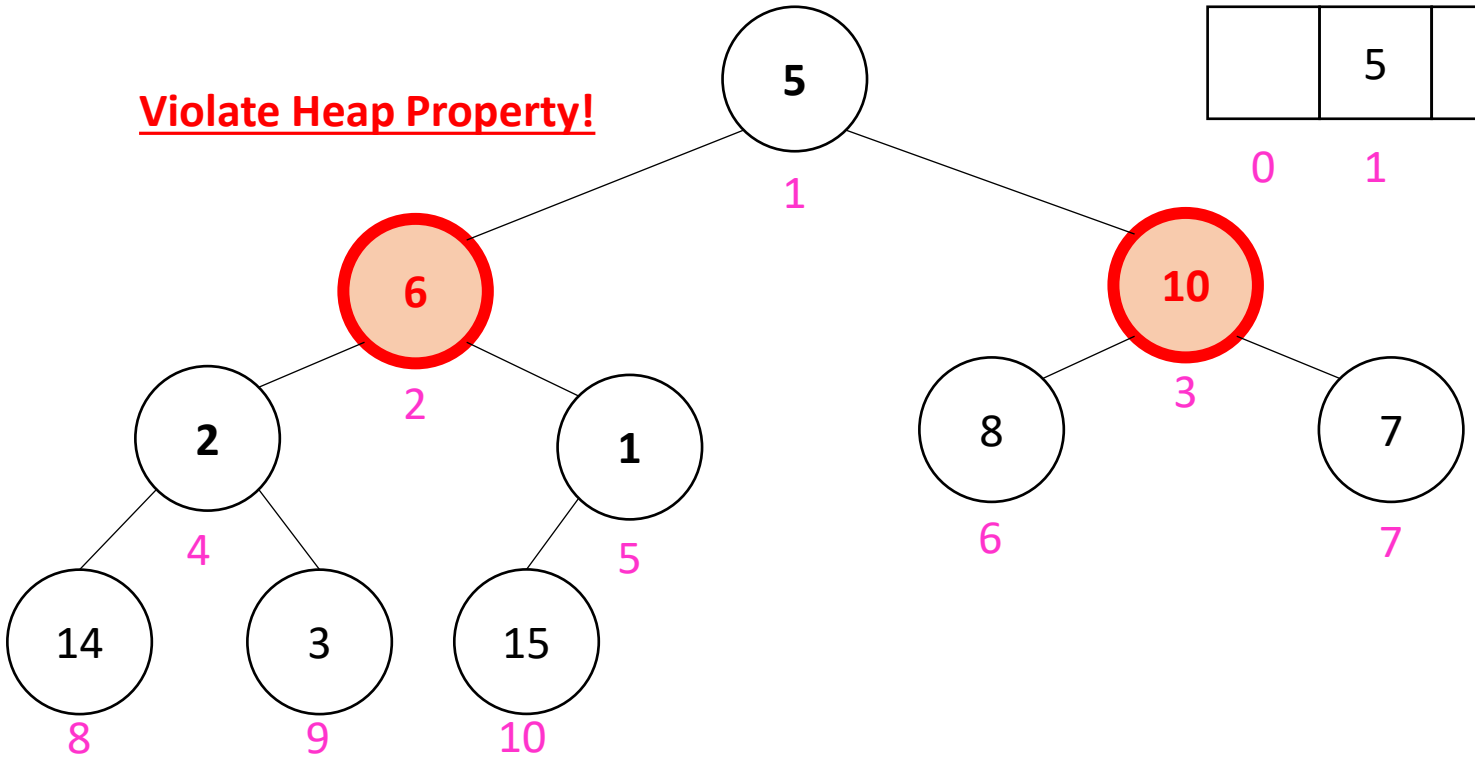

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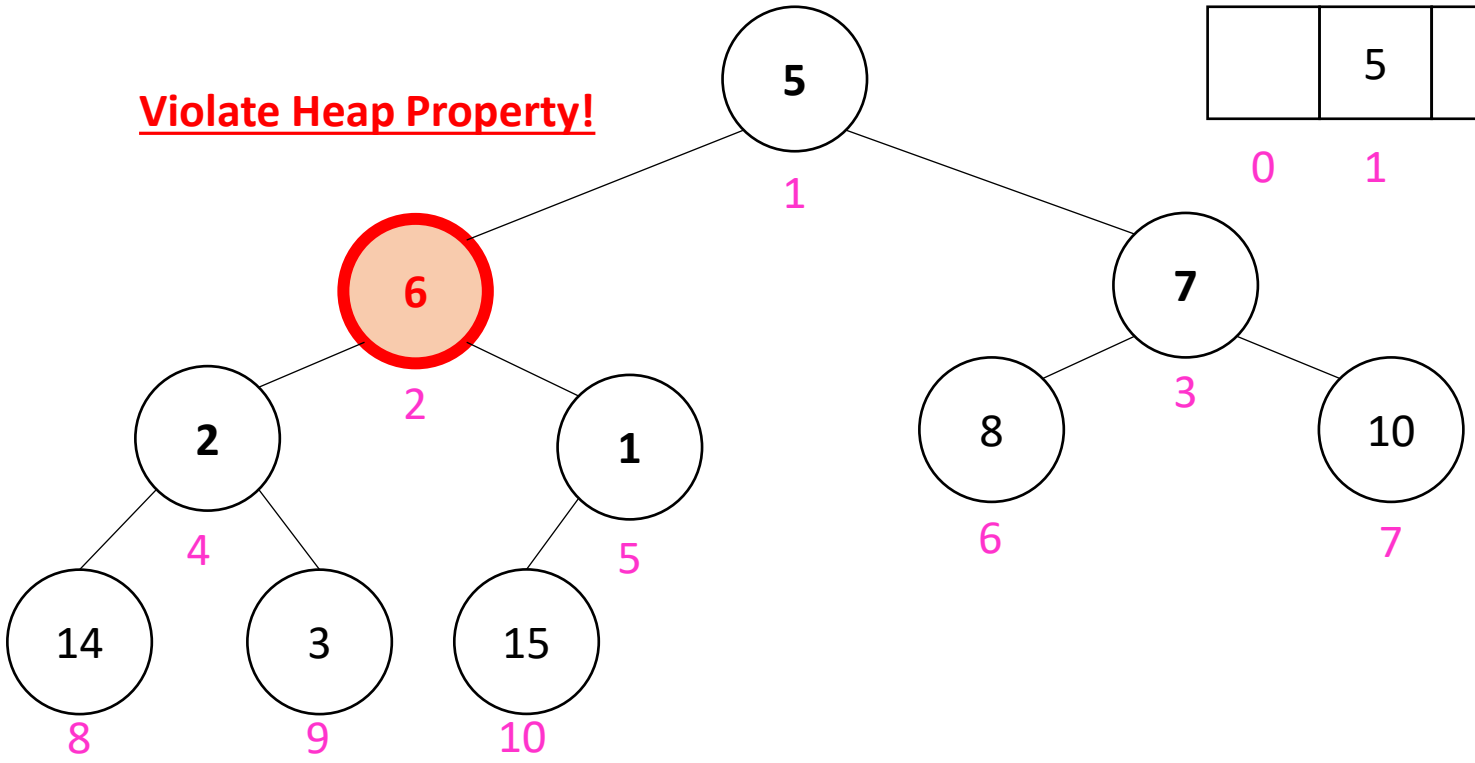

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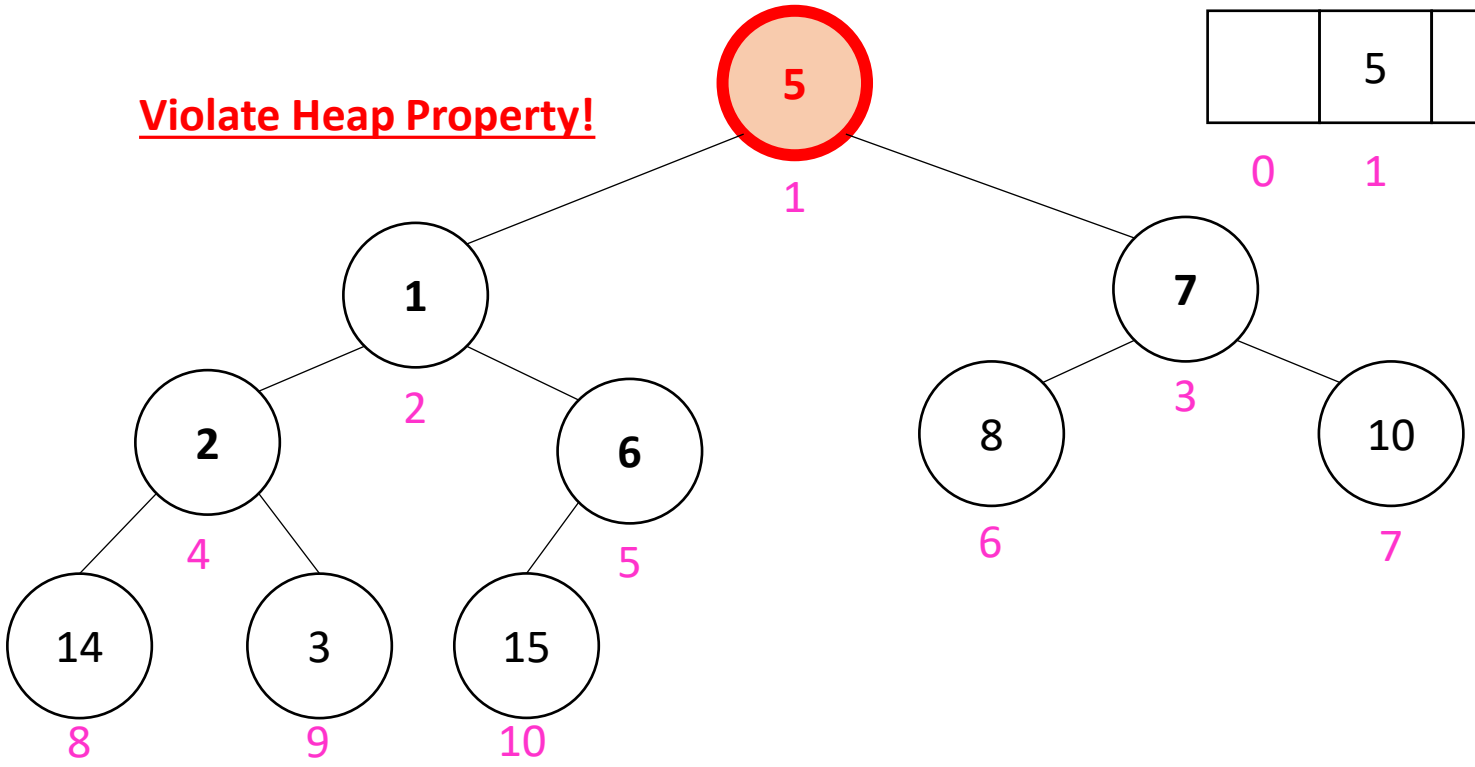

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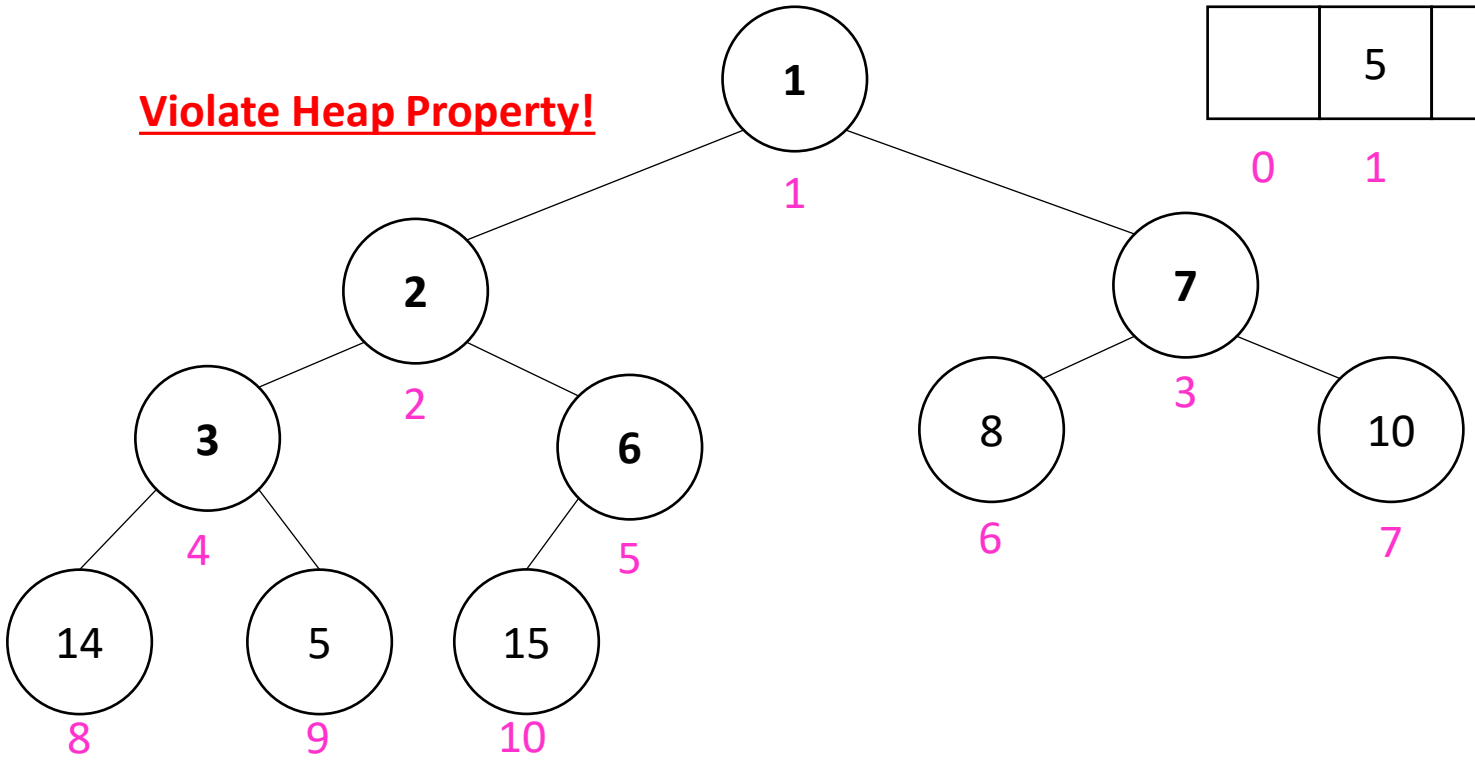

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```
buildHeap(){
    for(int i = size; i>0; i--){
        percolateDown(i);
    }
}
```

How long did this take?

```
buildHeap(){
    for(int i = size; i>0; i--){
        percolateDown(i);
    }
}
```

- Worst case running time of buildHeap:
- No node can percolate down more than the height of its subtree
  - When i is a leaf:
  - When i is second-from-last level:
  - When i is third-from-last level:
- Overall Running time:

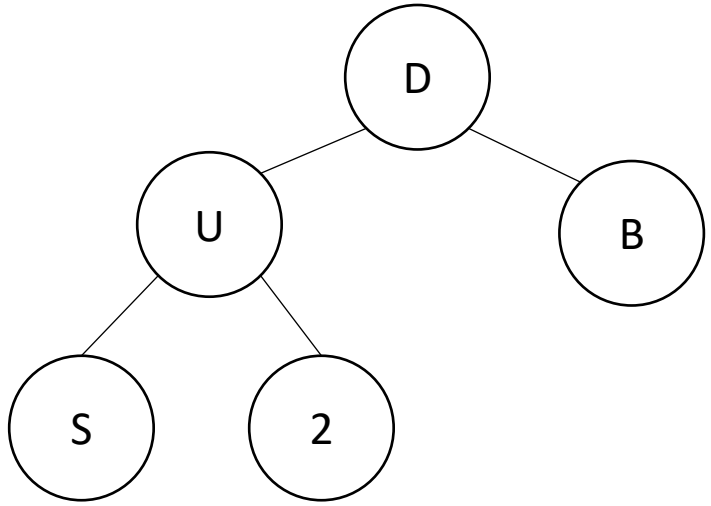
Dictionary (Map) ADT

- Contents:
  - Sets of key+value pairs
  - Keys must be comparable
- Operations:
  - insert(key, value)
    - Adds the (key,value) pair into the dictionary
    - If the key already has a value, overwrite the old value
      - Consequence: Keys cannot be repeated
  - find(key)
    - Returns the value associated with the given key
  - delete(key)
    - Remove the key (and its associated value)

Naïve attempts

Data Structure	Time to insert	Time to find	Time to delete
Unsorted Array	$\Theta(1)$	$\Theta(n)$	$\Theta(n)$
Unsorted Linked List	$\Theta(1)$	$\Theta(n)$	$\Theta(n)$
Sorted Array	$\Theta(n)$	$\Theta(\log n)$	$\Theta(n)$
Sorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Heap	$\Theta(\log n)$	$\Theta(n)$	$\Theta(n)$
Binary Search Tree (worst)	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Binary Search Tree (expected)	$\Theta(\log n)$	$\Theta(\log n)$	$\Theta(\log n)$

More Tree “Vocab”



- Traversal:
  - An algorithm for “visiting/processing” every node in a tree
- Pre-Order Traversal:
  - Root, Left Subtree, Right Subtree
  - D (U S 2) B
- In-Order Traversal:
  - Left Subtree, Root, Right Subtree
  - (S U 2) D B
- Post-Order Traversal
  - Left Subtree, Right Subtree, Root
  - S 2 U B D

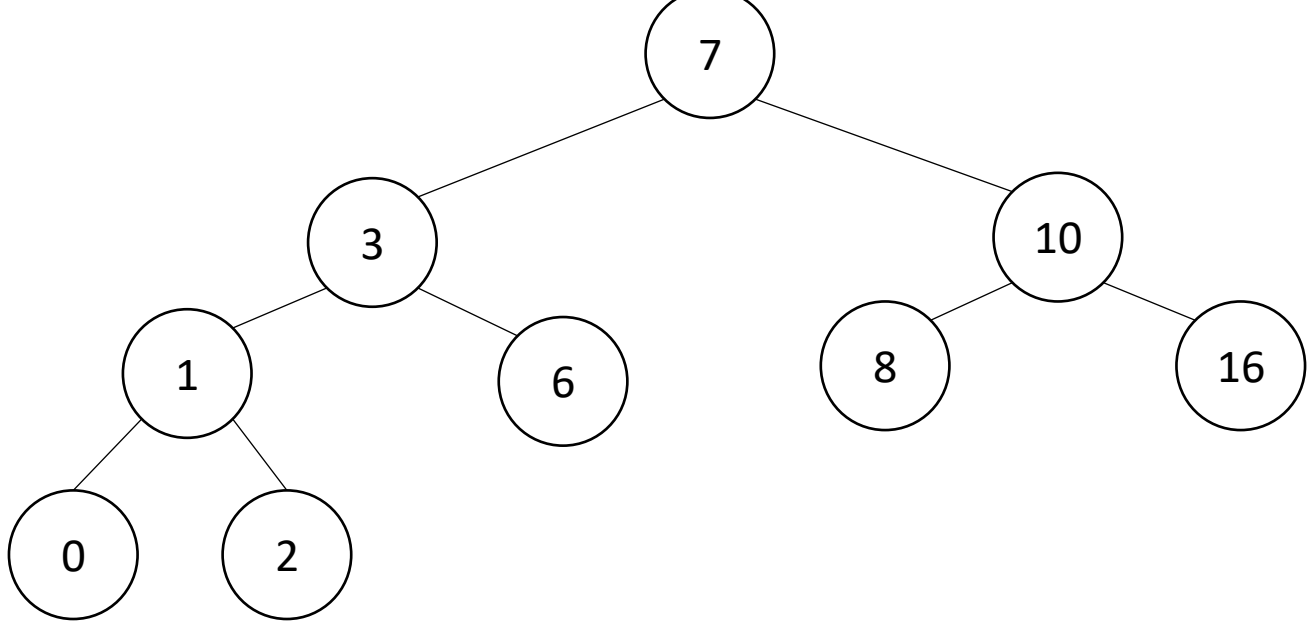
Name that Traversal!

```
AorderTraversal(root){
        if (root.left != Null){
                process(root.left);
        }
        if (root.right != Null){
                process(root.right);
        }
        process(root);
}
```

```
BorderTraversal(root){
        process(root);
        if (root.left != Null){
                process(root.left);
        }
        if (root.right != Null){
                process(root.right);
        }
}
```

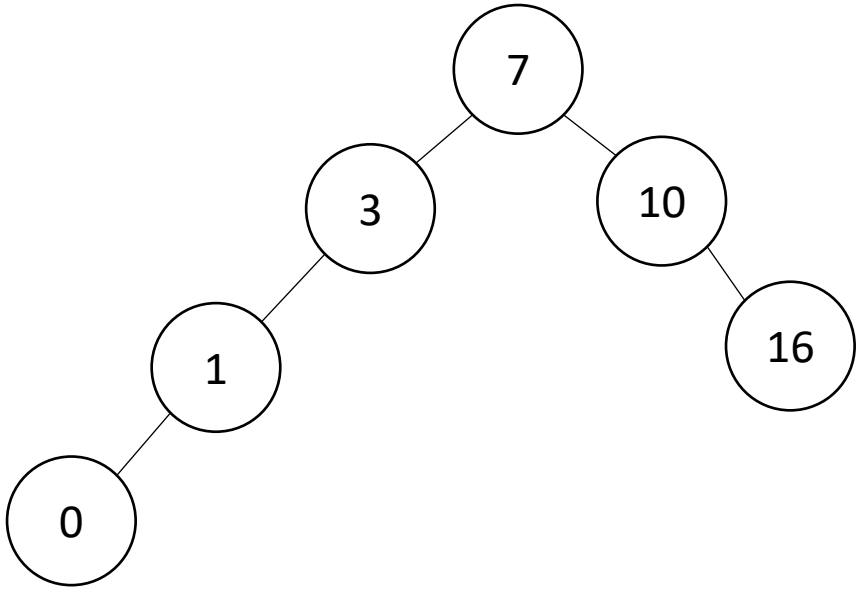
```
CorderTraversal(root){
        if (root.left != Null){
                process(root.left);
        }
        process(root)
        if (root.right != Null){
                process(root.right);
        }
}
```

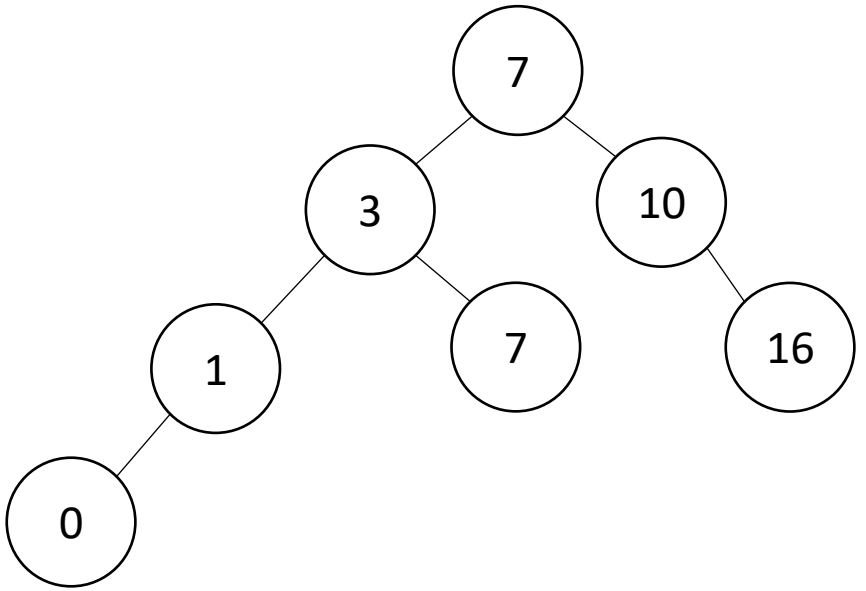
Binary Search Tree

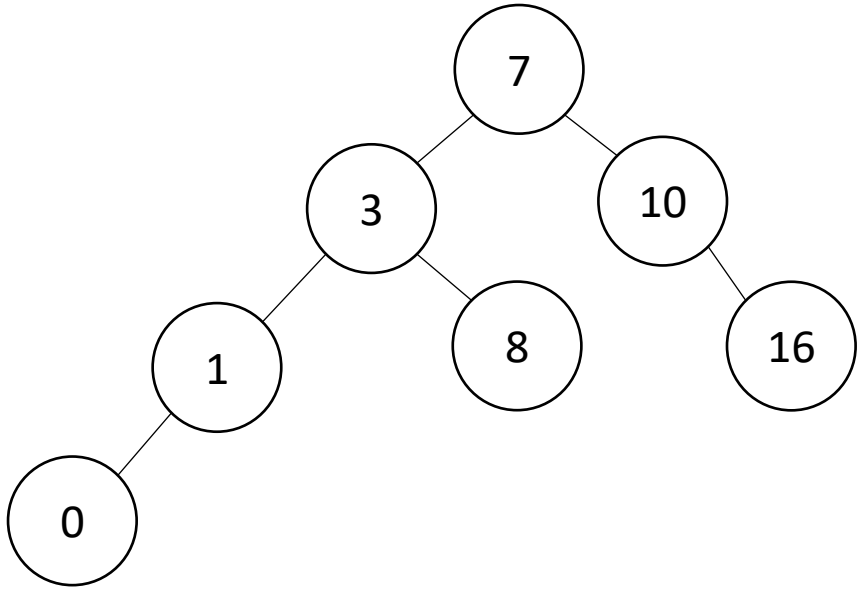


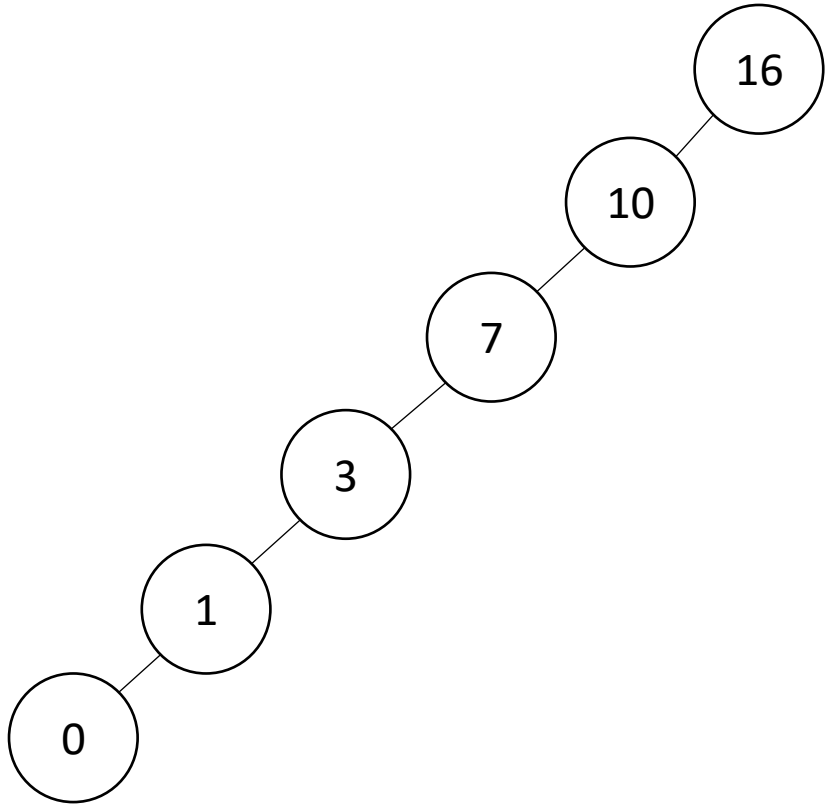
- Binary Tree
  - Definition:
    - Tree where each node has at most 2 children
- Order Property
  - All keys in the left subtree are smaller than the root
  - All keys in the right subtree are larger than the root
  - Consequence: cannot have repeated values

Are these BSTs?







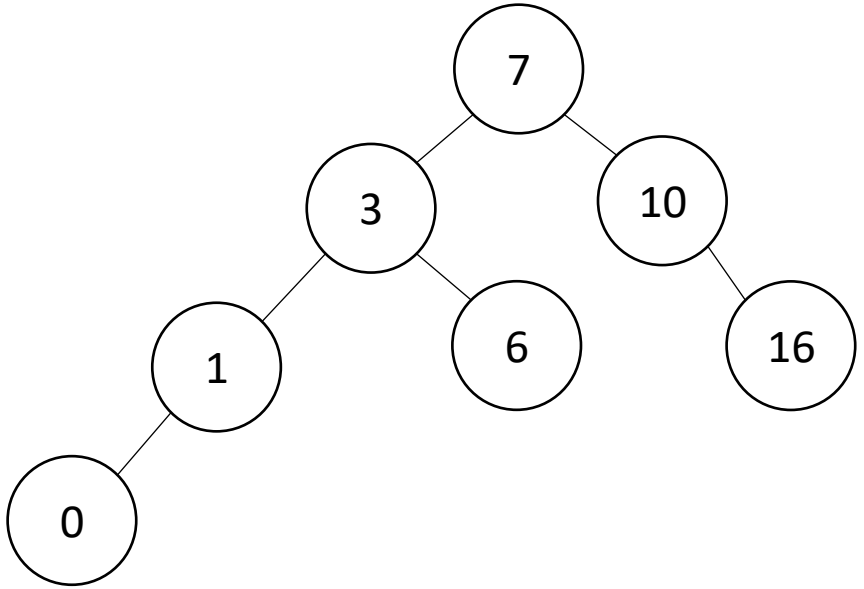


Aside: Why not use an array?

- We represented a heap using an array, finding children/parents by index
- We will represent BSTs with nodes and references. Why?
  - We might have “gaps” in our tree
  - Memory!
    - 2^n

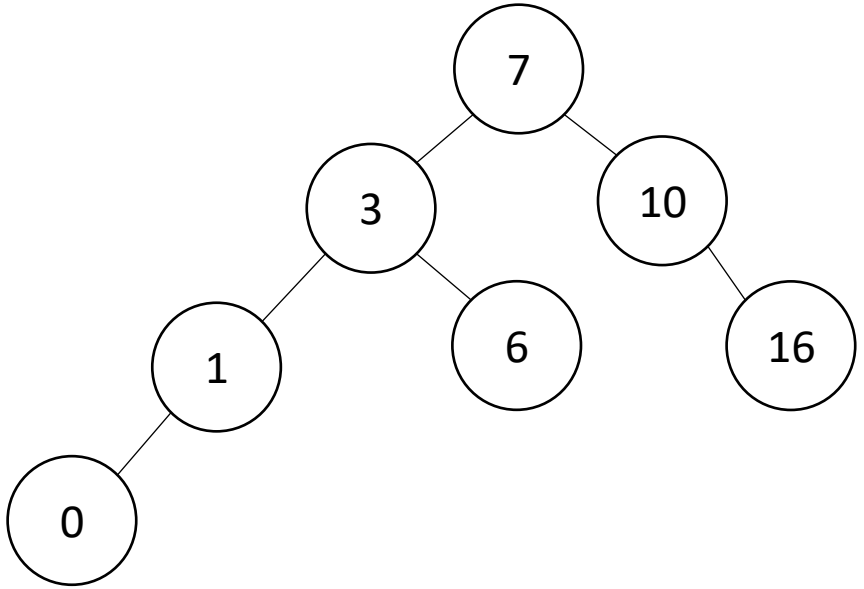
Find Operation (recursive)

```
find(key, root){
        if (root == Null){
                return Null;
        {
        if (key == root.key){
                return root.value;
        }
        if (key < root.key){
                return find(key, root.left);
        }
        if (key > root.key){
                return find(key, root.right);
        }
        return Null;
}
```



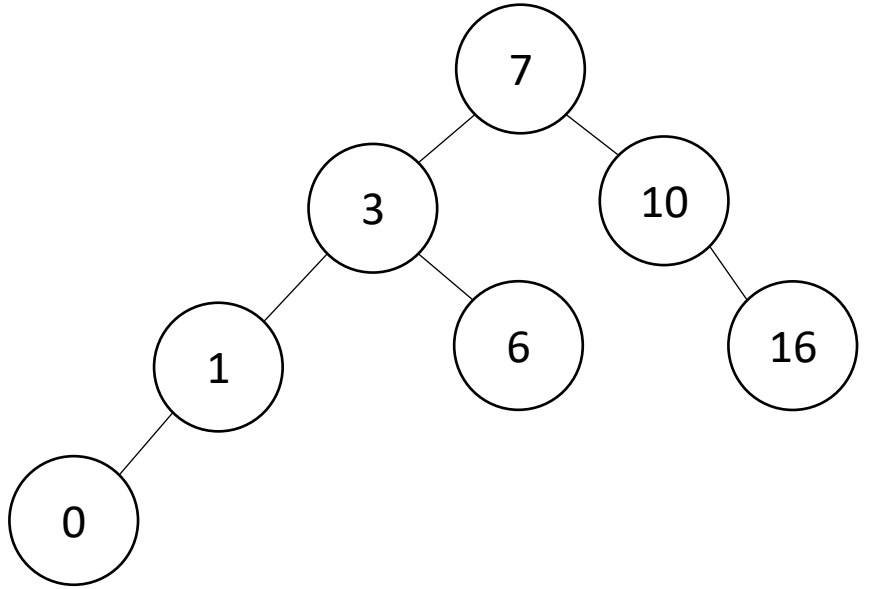
Find Operation (iterative)

```
find(key, root){
        while (root != Null && key != root.key){
                if (key < root.key){
                        root = root.left;
                }
                else if (key > root.key){
                        root = root.right;
                }
        }
        if (root == Null){
                return Null;
        }
        return root.value;
}
```



Insert Operation (recursive)

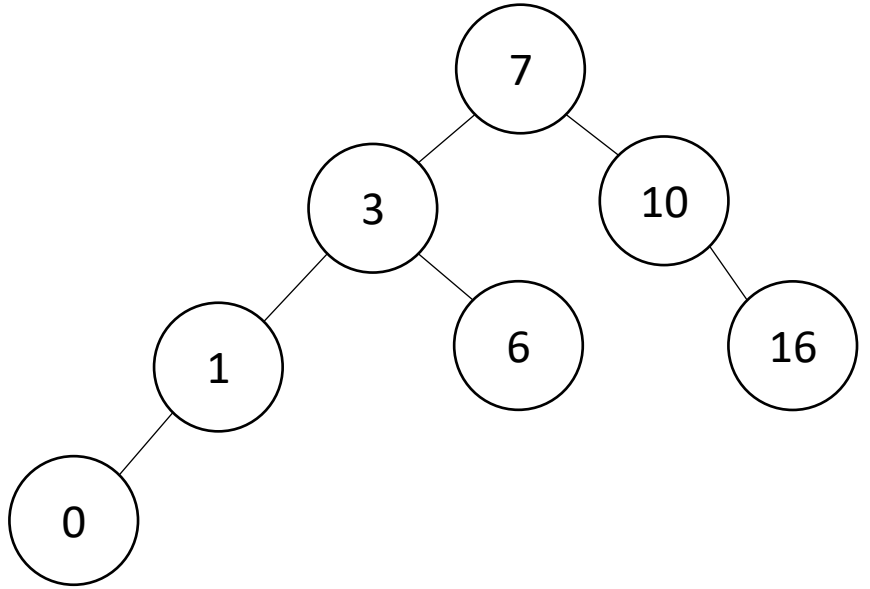
```
insert(key, value, root){
        root = insertHelper(key, value, root);
}
insertHelper(key, value, root){
        if(root == null)
                return new Node(key, value);
        if (root.key < key)
                root.right = insertHelper(key, value, root.right);
        else
                root.left = insertHelper(key, value, root.left);
        return root;
}
```



Note: Insert happens only at the leaves!

Insert Operation (iterative)

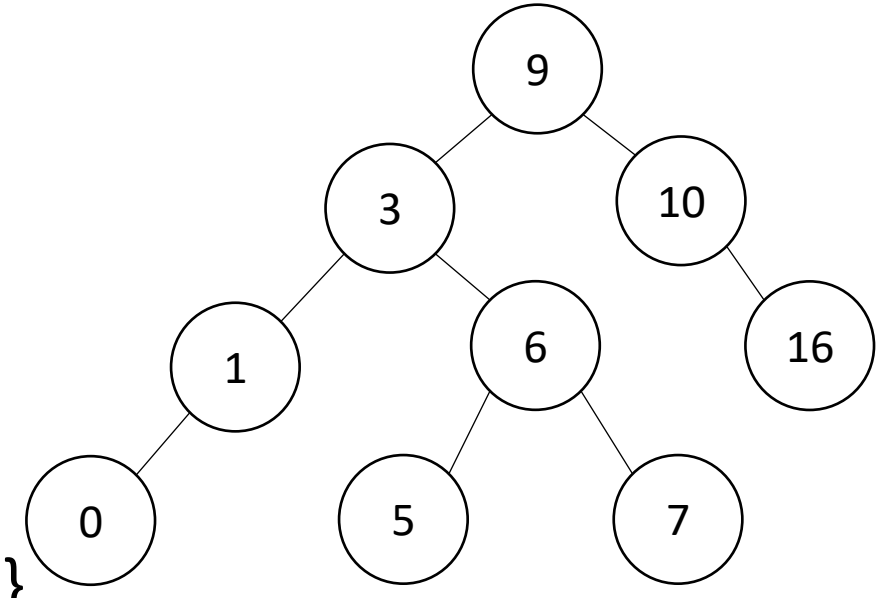
```
insert(key, value, root){
        if (root == Null){ this.root = new Node(key, value); }
        parent = Null;
        while (root != Null && key != root.key){
                parent = root;
                if (key < root.key){ root = root.left; }
                else if (key > root.key){ root = root.right; }
        }
        if (root != Null){ root.value = value; }
        else if (key < parent.key){ parent.left = new Node(key, value); }
        else{ parent.right = new Node (key, value); }
}
```



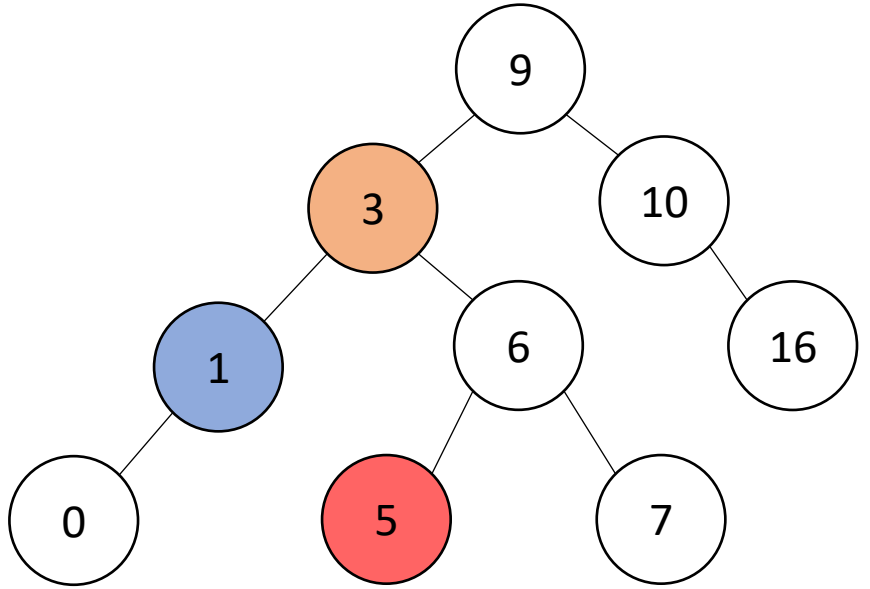
Note: Insert happens only at the leaves!

Delete Operation (iterative)

```
delete(key, root){
        while (root != Null && key != root.key){
                if (key < root.key){ root = root.left; }
                else if (key > root.key){ root = root.right; }
        }
        if (root == Null){ return; }
        // Now root is the node to delete, what happens next?
}
```



Delete – 3 Cases

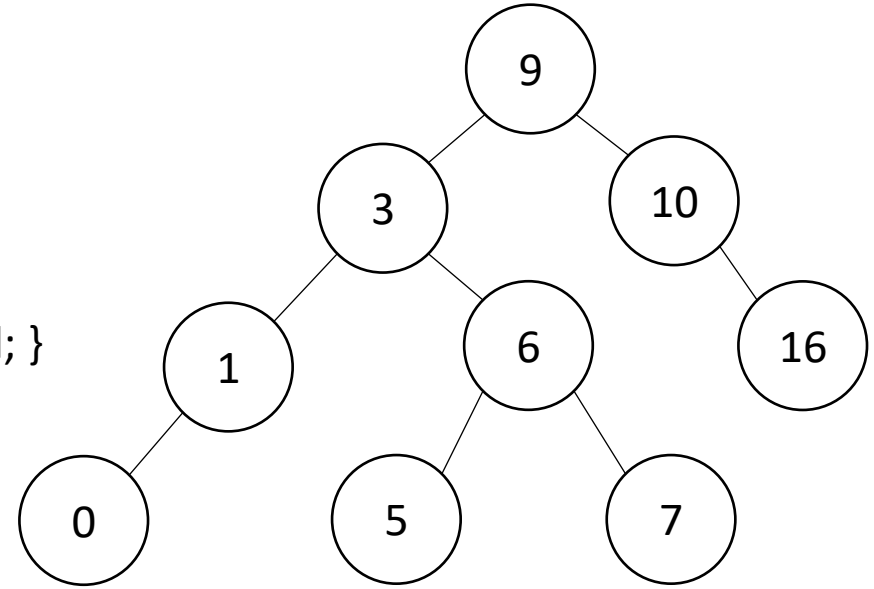


- 0 Children (i.e. it's a leaf)
- 1 Child
  - Replace the deleted node with its child
- 2 Children
  - Replace the deleted with the largest node to its left or else the smallest node to its right

Finding the Max and Min

- Max of a BST:
  - Right-most Thing

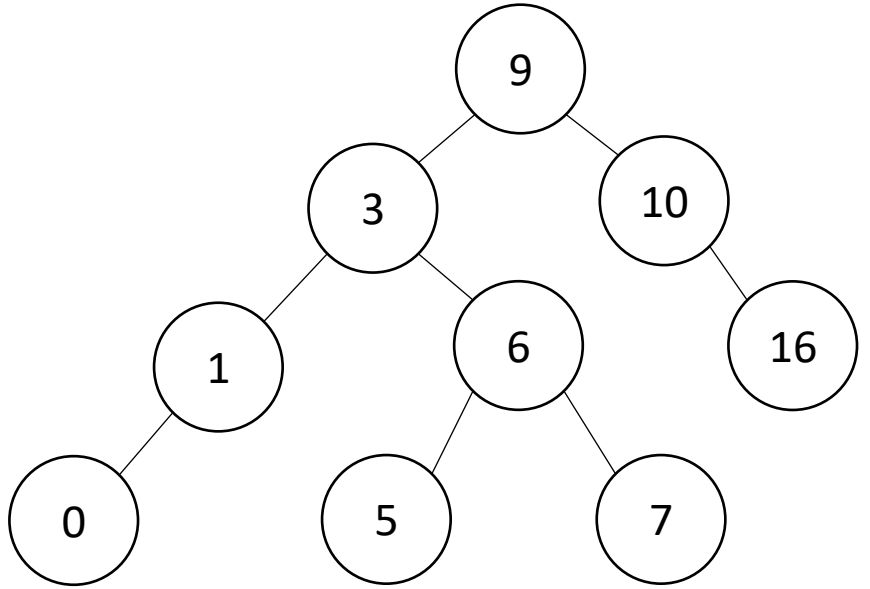
```
maxNode(root){
        if (root == Null){ return Null; }
        while (root.right != Null){
                root = root.right;
        }
        return root;
}
```



- Min of a BST:
  - Left-most Thing

```
minNode(root){
        if (root == Null){ return Null; }
        while (root.left != Null){
                root = root.left;
        }
        return root;
}
```

Delete Operation (iterative)




```
delete(key, root){
        while (root != Null && key != root.key){
                if (key < root.key){ root = root.left;  }
                else if (key > root.key){ root = root.right; }
        }
        if (root == Null){ return; }
        if (root has no children){
                make parent point to Null Instead;
        }
        if (root has one child){
                make parent point to that child instead;
        }
        if (root has two children){
                make parent point to either the max from the left or min from the right
        }
}
```