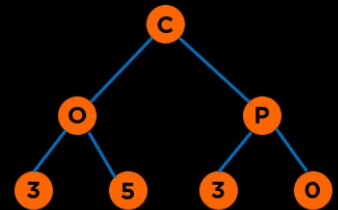


# Heaps



# Categories of Data Structures

Linear Ordered

Lists

Stacks

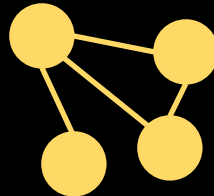
Queues



Non-linear Ordered

Trees

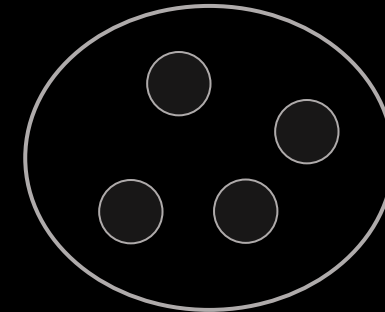
Graphs



Not Ordered

Sets

Tables/Maps



# Recap

- **Splay Trees**

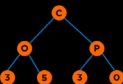
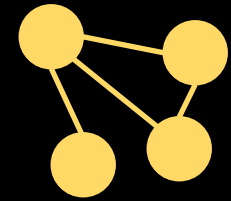
- **Performance**

- **Red Black Trees**

- **Properties**
  - **Use Cases**

Non-linear Ordered

Trees



# Agenda

- **Priority Queues**

- **Motivation**
- **Ways of Implementation**

- **Heaps**

- **Properties**
- **Implementation**
- **Insertion**
- **Deletion**
- **Heap Sort**

# Priority Queues

# Problem

## Queues

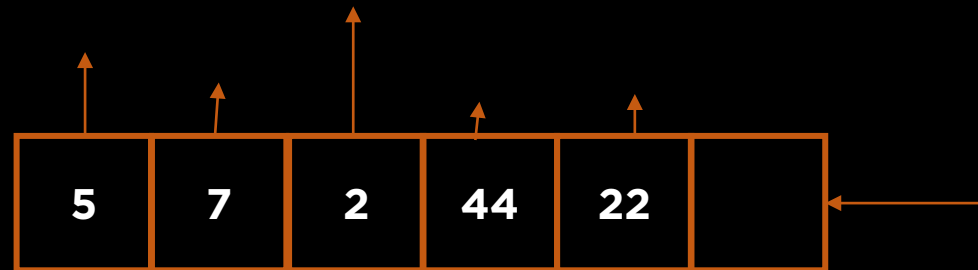
- Queue supported FIFO principle
- Here, “**first-in**” basis was the priority
- What if we want to generalize this feature of **priority**?



# Problem

## Enter Priority Queue!

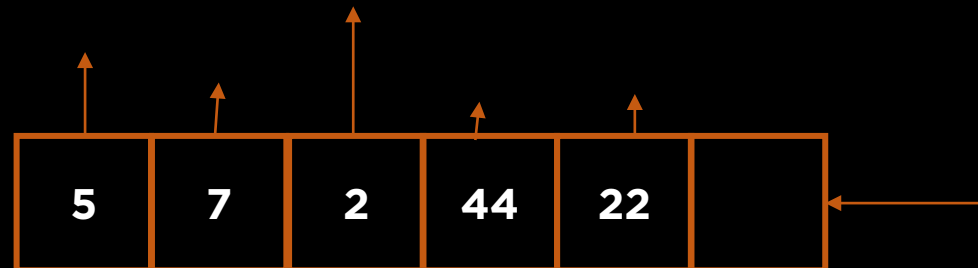
- All elements inserted have some priority
- Elements with **highest** or **lowest** priority is removed first



# Problem

## Priority Queue

- A priority queue is a generalization of a queue where each element is assigned a priority and elements come out in order by priority

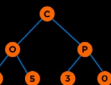
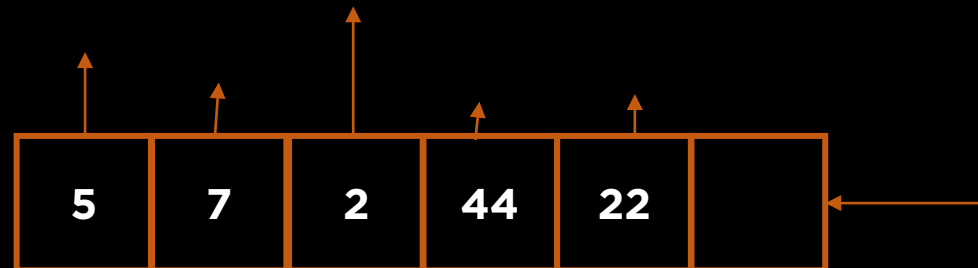




# Problem

## Priority Queue (Central Idea)

- Keep track of highest or lowest priority in a fast way
- Abstract Data Type
  - Insertion (p) – Adds a new element with priority p
  - ExtractMin() or ExtractMax() – Extracts the element with min or max priority

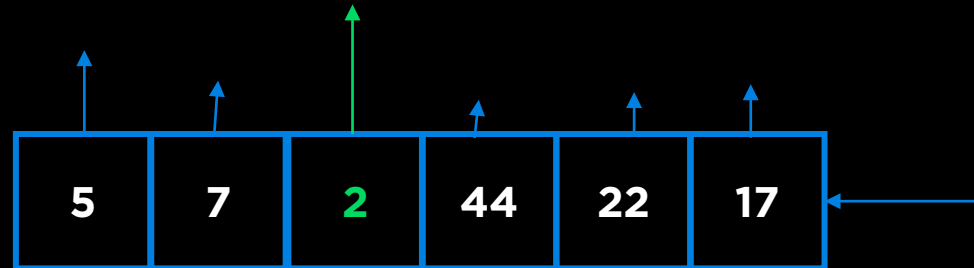


# Problem

Insert (17)

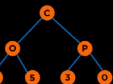


ExtractMin()



# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?



# Priority Queues

How can we design this data structure so that **Insert** and **Extract()** operations are fast?

Approach 1: **Unsorted Array**



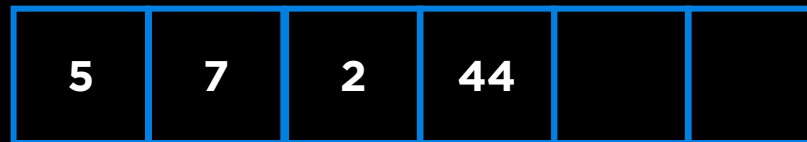
**Insert (p)**

**ExtractMin()**

# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

## Approach 1: Unsorted Array



### Insert (p)

Add p at the end of the array:  $O(1)$

### ExtractMin()

Find the min in the array and then shift:  $O(n)$

# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

## Approach 2: Sorted Array



Insert (p)

ExtractMin()

# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

## Approach 2: Sorted Array

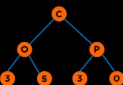


### Insert (p)

Find a position for p in  $O(\log n)$  using Binary Search, then shift elements:  $O(n)$

### ExtractMin()

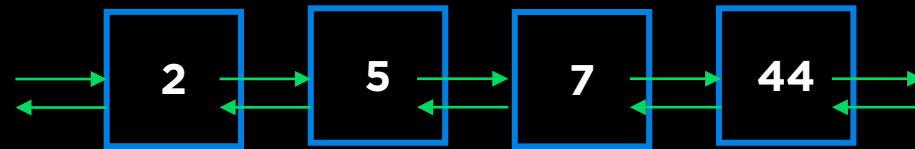
Find the min in the array at first place:  $O(1)$



# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

## Approach 3: Sorted List



Insert (p)

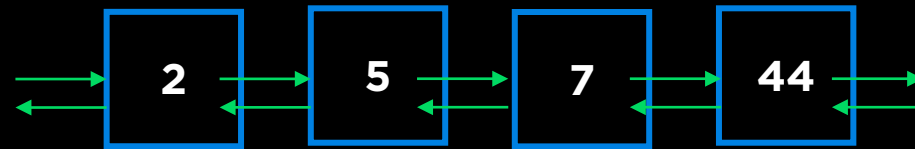
ExtractMin()



# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

## Approach 3: Sorted List



### Insert (p)

Find a position for p in  $O(n)$  using Linear Search, then add in  $O(1)$ :  $O(n)$

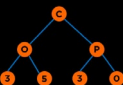
### ExtractMin()

Find the min in the list at first place:  $O(1)$

# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

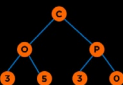
	Insert	ExtractMin
Unsorted Array/List	$O(1)$	$O(n)$
Sorted Array/List	$O(n)$	$O(1)$



# Priority Queues

How can we design this data structure so that Insert and Extract() operations are fast?

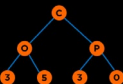
	Insert	ExtractMin
Unsorted Array/List	$O(1)$	$O(n)$
Sorted Array List	$O(n)$	$O(1)$
Binary Heap	$O(\log n)$	$O(\log n)$



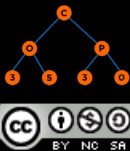
# Problem

## Use Cases

- **Huffman Trees**
- **Dijkstra's Shortest Path Algorithm**
- **Prim's Algorithm for calculating Minimum Spanning Tree**
- **Scheduling Job**
- **K largest elements**
- **Heap Sort**
- **Many more ...**

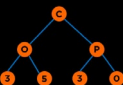
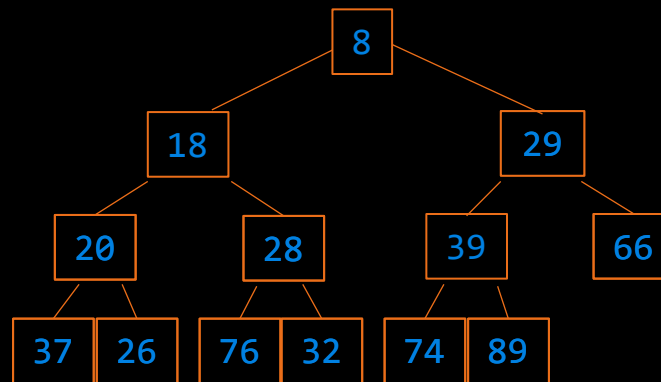


# Heaps



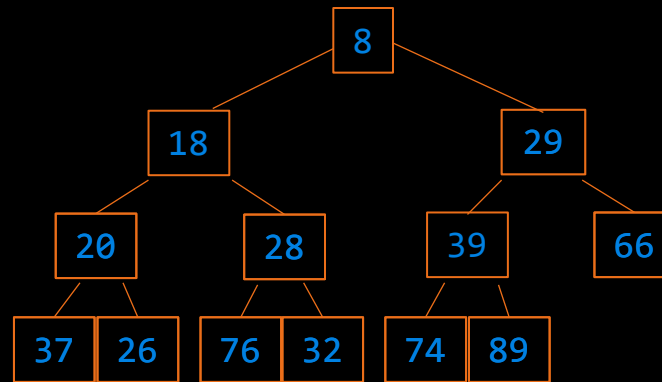
# Binary Heap

- **Complete Binary Tree**
- **Each Node is less than its children for a min-heap and Each Node is greater than its children for a max-heap**
- **Root is the smallest for a min-heap and largest element for a max-heap**
- **Only the root can be removed (ExtractMin or ExtractMax)**



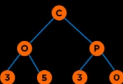
# Binary Heap

## Heap Representation



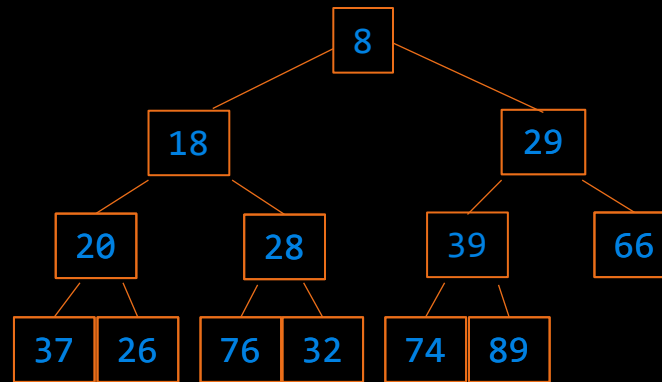
```
class HeapNode
{
    int value;
    HeapNode* left;
    HeapNode* right;
}
```

left and right are min-heaps



# Binary Heap

## Heap Representation



```
int Heap[];
```

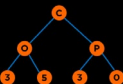
For a node at position  $p$ ,

L. child position:  $2p + 1$

R. child position:  $2p + 2$

A node at position  $c$  can find its parent at  $\text{floor}((c - 1)/2)$

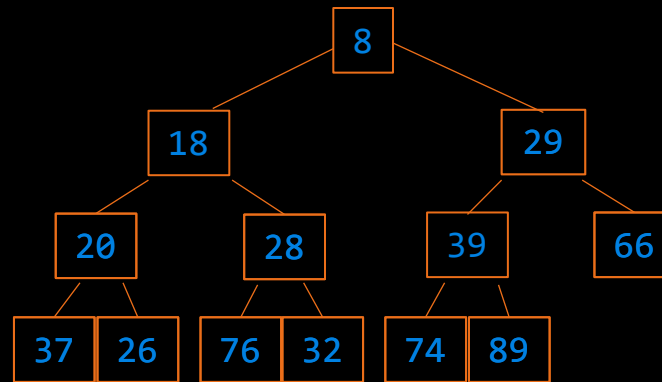
0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	66	37	26	76	32	74	89	





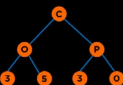
# Binary Heap Insertion

## Heap Insertion



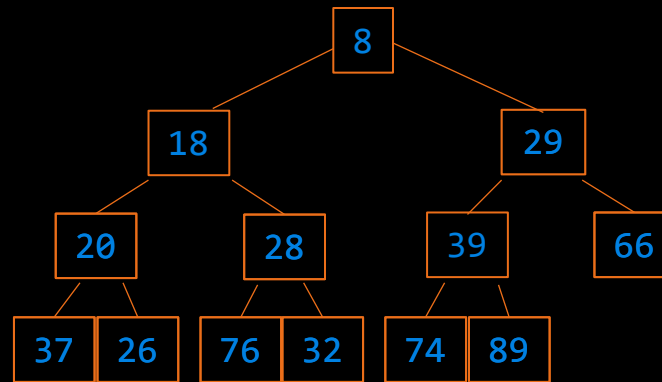
### Algorithm for Inserting in a Heap

1. Insert the new item in the next position at the bottom of the heap.
2. **while** new item is not at the root and new item is smaller than its parent
3.       Swap the new item with its parent, moving the new item up the heap.



# Binary Heap Insertion

## Heap Insertion



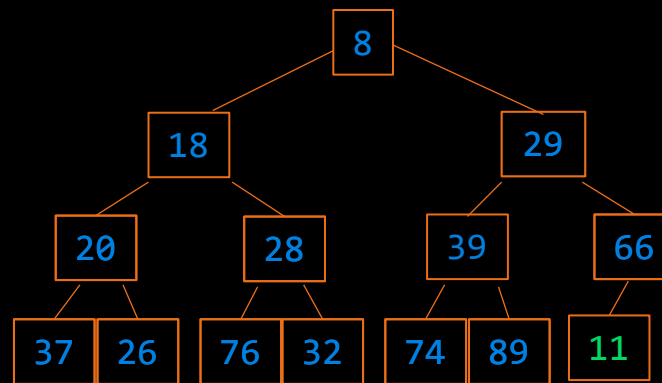
1. Insert the new element at the end of the array and set child to `arr.size() - 1`
2. Set parent to  $(\text{child} - 1) / 2$
3. while ( $\text{parent} \geq 0$  and  $\text{arr}[\text{parent}] > \text{arr}[\text{child}]$ )
  - Swap  $\text{arr}[\text{parent}]$  and  $\text{arr}[\text{child}]$
  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	66	37	26	76	32	74	89	

# Binary Heap Insertion

## Heap Insertion



insert 11

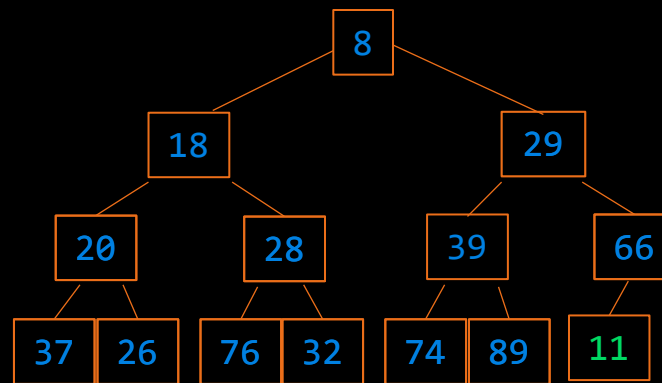
0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	66	37	26	76	32	74	89	11

1. Insert the new element at the end of the array and set child to `arr.size() - 1`
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3. while ( $\text{parent} \geq 0$  and  $\text{arr}[\text{parent}] > \text{arr}[\text{child}]$ )
  - Swap  $\text{arr}[\text{parent}]$  and  $\text{arr}[\text{child}]$
  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

child = 13

# Binary Heap Insertion

## Heap Insertion



1. Insert the new element at the end of the array and set child to `arr.size() - 1`
2. Set parent to  $(\text{child} - 1) / 2$
3. while (`parent >= 0` and `arr[parent] > arr[child]`)
  - Swap `arr[parent]` and `arr[child]`
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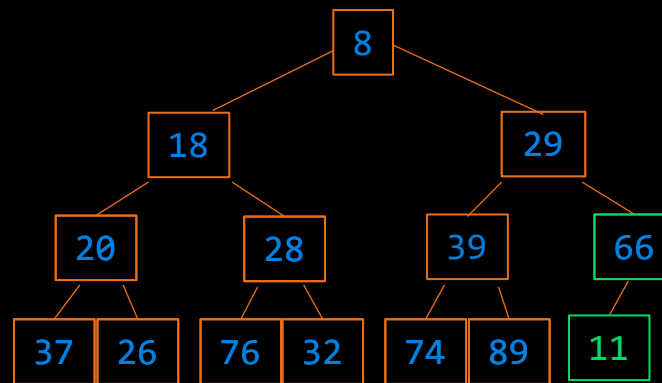
child = 13  
parent = 6

insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	66	37	26	76	32	74	89	11

# Binary Heap Insertion

## Heap Insertion

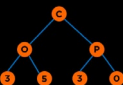


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  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

child = 13  
parent = 6

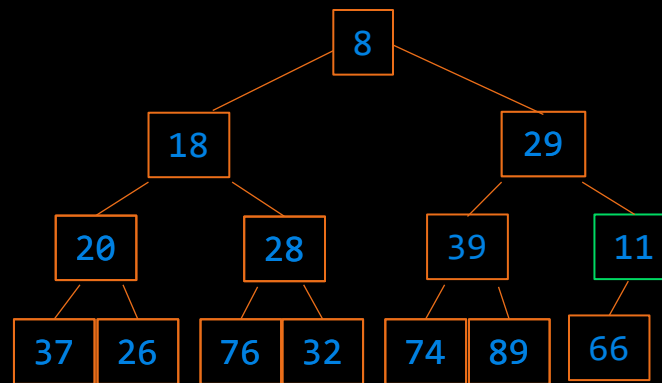
insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	66	37	26	76	32	74	89	11



# Binary Heap Insertion

## Heap Insertion



1. Insert the new element at the end of the array and set child to `arr.size() - 1`
2. Set parent to  $(\text{child} - 1) / 2$
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  - Set child equal to parent
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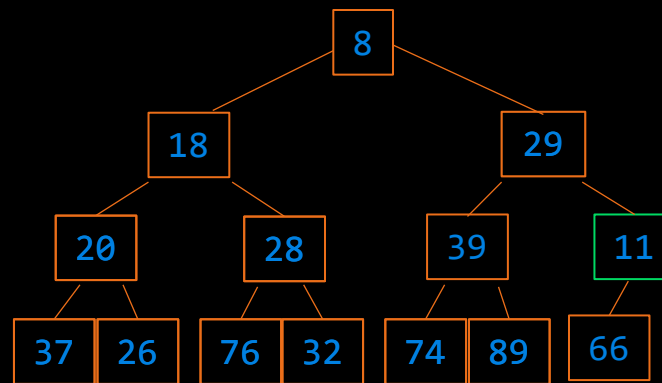
child = 13  
parent = 6

insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	11	37	26	76	32	74	89	66

# Binary Heap Insertion

## Heap Insertion



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  - Set child equal to parent
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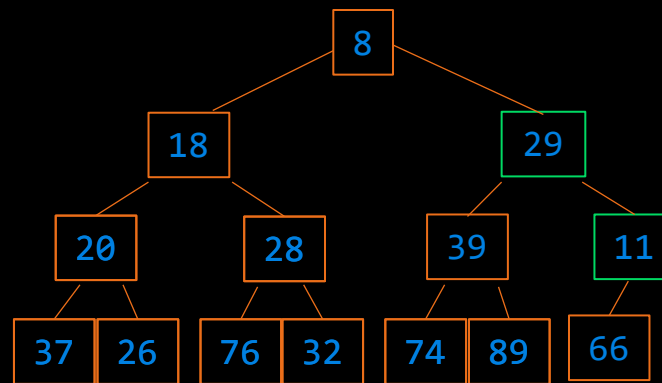
child = 13 | 6  
parent = 6 | 2

insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	11	37	26	76	32	74	89	66

# Binary Heap Insertion

## Heap Insertion

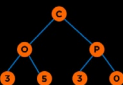


1. Insert the new element at the end of the array and set child to `arr.size() - 1`
2. Set parent to  $(\text{child} - 1) / 2$
3. `while (parent >= 0 and arr[parent] > arr[child])`
  - Swap `arr[parent]` and `arr[child]`
  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

child = 13 | 6  
parent = 6 | 2

insert 11

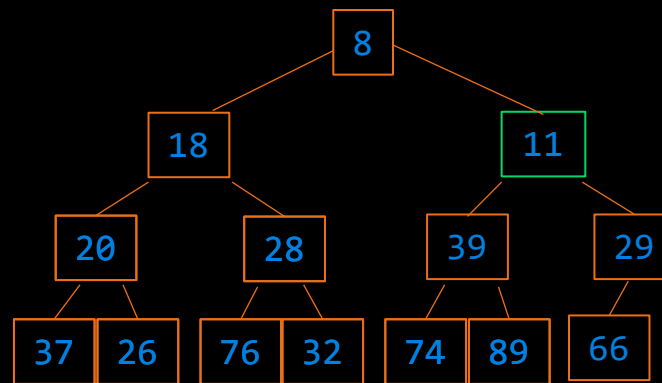
0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	29	20	28	39	11	37	26	76	32	74	89	66





# Binary Heap Insertion

## Heap Insertion

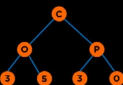


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  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

child = 13 | 6  
parent = 6 | 2

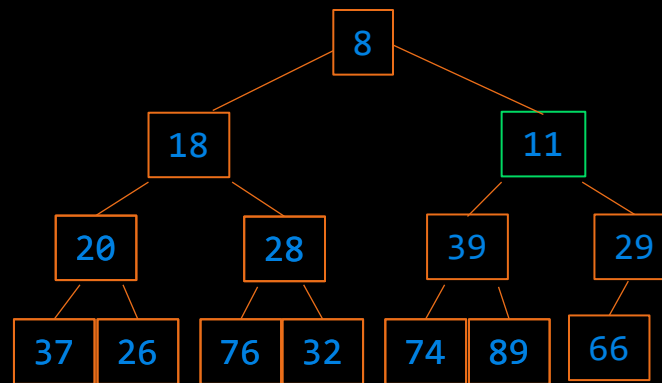
insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	11	20	28	39	29	37	26	76	32	74	89	66



# Binary Heap Insertion

## Heap Insertion

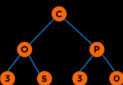


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3. while (`parent >= 0` and `arr[parent] > arr[child]`)
  - Swap `arr[parent]` and `arr[child]`
  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

child = 13 | 6 | 2  
parent = 6 | 2 | 0

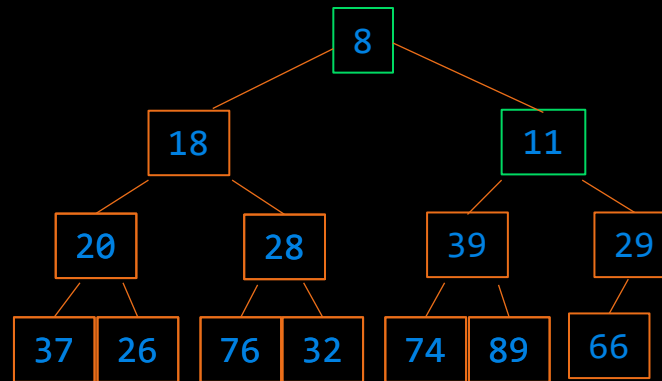
insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	11	20	28	39	29	37	26	76	32	74	89	66



# Binary Heap Insertion

## Heap Insertion

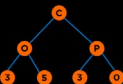


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2. Set parent to  $(\text{child} - 1) / 2$
3. while (`parent >= 0` and `arr[parent] > arr[child]`)
  - Swap `arr[parent]` and `arr[child]`
  - Set child equal to parent
  - Set parent equal to  $(\text{child}-1)/2$

child = 13 | 6 | 2  
parent = 6 | 2 | 0

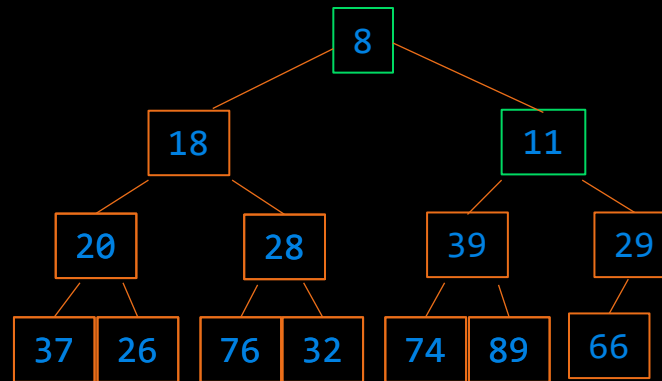
insert 11

0	1	2	3	4	5	6	7	8	9	10	11	12	13
8	18	11	20	28	39	29	37	26	76	32	74	89	66



# Binary Heap Insertion

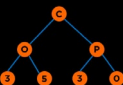
## Heap Insertion



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2. Set parent to  $(\text{child} - 1) / 2$
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  - Swap `arr[parent]` and `arr[child]`
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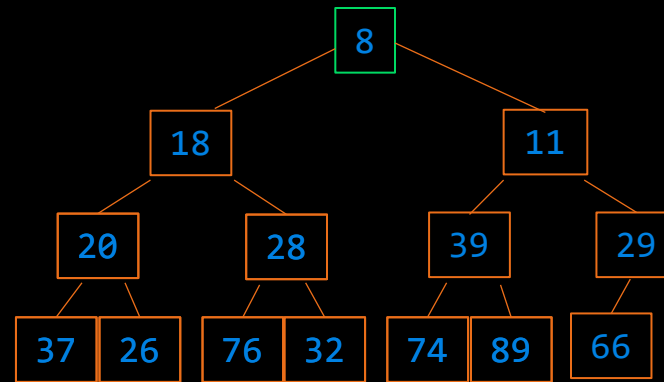
child = 13 | 6 | 2  
parent = 6 | 2 | 0

$O(\log n)$  time to insert!



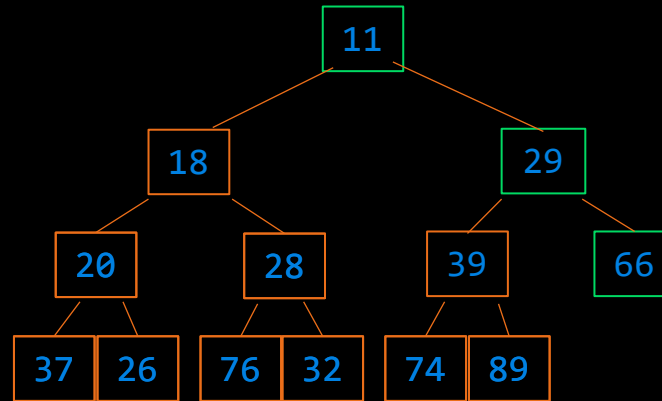
# Binary MinHeap Deletion

## Heap Deletion (ExtractMin)

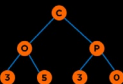


# Binary MinHeap Deletion

## Heap Deletion (ExtractMin)

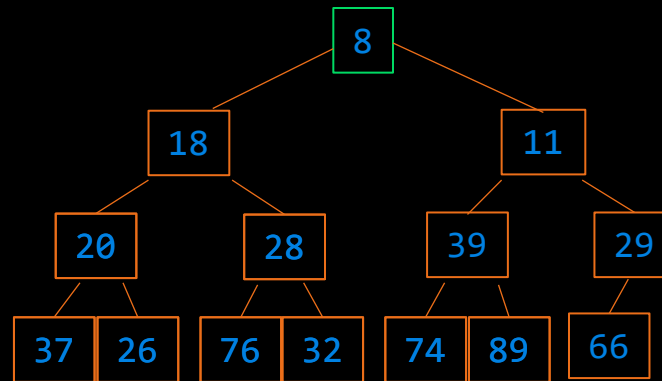


$O(\log n)$  time to ExtractMin!



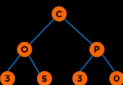
# Binary MinHeap Deletion

## Heap Deletion (ExtractMin)



### Algorithm for Removal from a Heap

1. Remove the item in the root node by replacing it with the last item in the heap (LIH).
2. **while** item LIH has children and item LIH is larger than either of its children
3.     Swap item LIH with its smaller child, moving LIH down the heap.



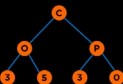
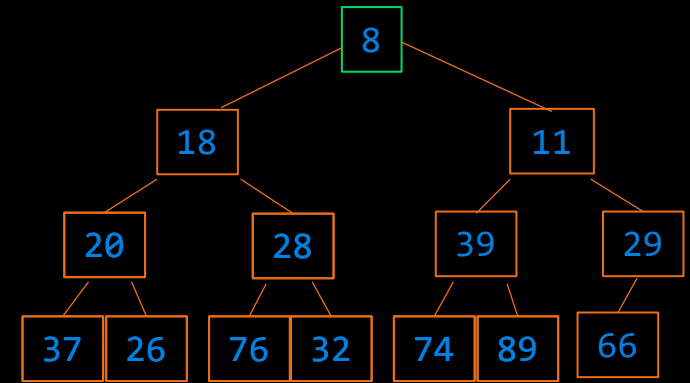
# Binary MinHeap Deletion

## Heap Deletion (ExtractMin)

```
//arr[] contains heap
//currentSize contains number of items in heap

//Remove the minimum item.
void extractMin( )
{
    arr[0] = arr[--currentSize];
    heapifyDown(0);
}

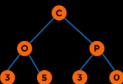
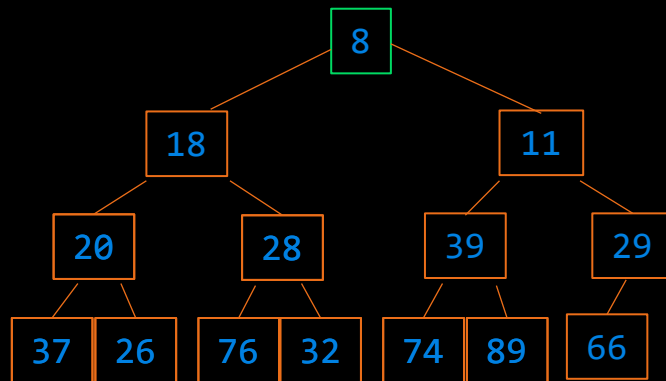
void heapifyDown(int index)
{
    1. if index is a leaf -> stop
    2. Find the smallest child of node at index
    3. Swap node at index with smallest_child_index
    4. heapifyDown(smallest_child_index)
}
```





# Heap Sort

- **Algorithm:**
  - Insert  $n$  items into heap
  - Remove  $n$  items from heap and place in array
- **Performance:**  $O(n \log n)$

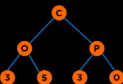
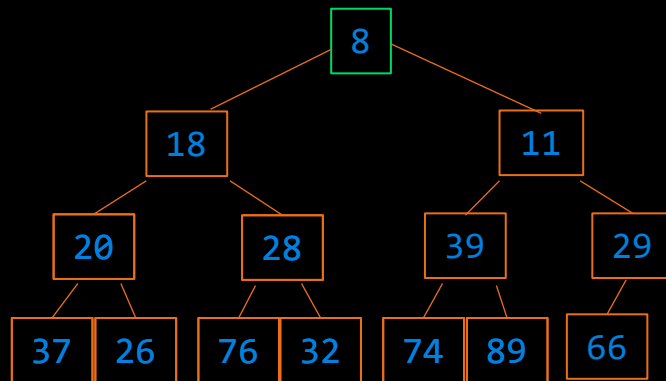


# Heap Sort

- **Algorithm:**

- Insert  $n$  items into heap –  $O(n \log n)$  + extra space
- Remove  $n$  items from heap and place in array –  $O(n \log n)$

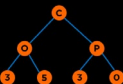
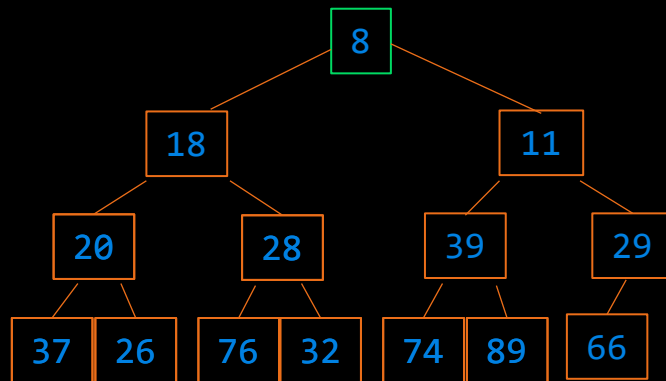
- **Performance:**  $O(n \log n)$



# Heap Building

- Building heap inplace:

```
for(i = size/2; i >= 0; i--)  
    heapifyDown(i)
```

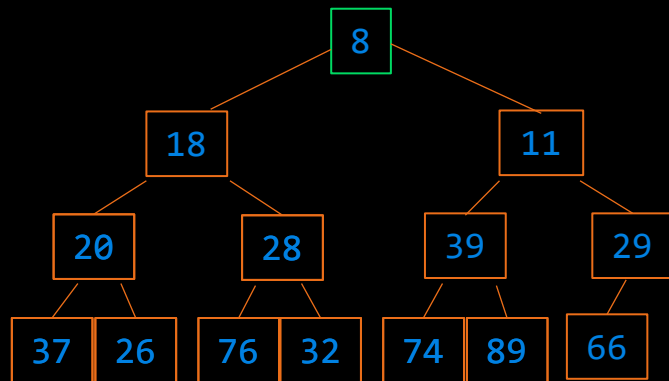


# Heap Sort

- **Algorithm:**

- Insert  $n$  items into heap –  $O(n \log n)$  + extra space
- Remove  $n$  items from heap and place in array –  $O(n \log n)$

- **Performance:**  $O(n \log n)$



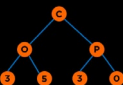
- **Building heap inplace in  $O(n)$ :**

```
for(i = size/2; i >= 0; i--)  
    heapifyDown(i)
```

- Since node is close to leaf, heapifyDown is faster

- 1 unit of time for second last level ( $n/2$  nodes),  $\log n$  for level 0 (1 node)

- $$T(\text{BuildHeap}) = n/2 \cdot 0 + n/4 \cdot 1 + n/8 \cdot 2 \dots$$
$$= n \cdot \text{SumofSeries}(i/2^{(i+1)}) = 2n$$

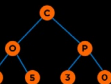


# Resources

- **Heap Visualization:** <https://www.cs.usfca.edu/~galles/visualization/Heap.html>
- **Proof:** <https://stackoverflow.com/questions/9755721/how-can-building-a-heap-be-on-time-complexity>

# Mentimeter

**Menti.com**  
**6266 4037**



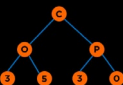
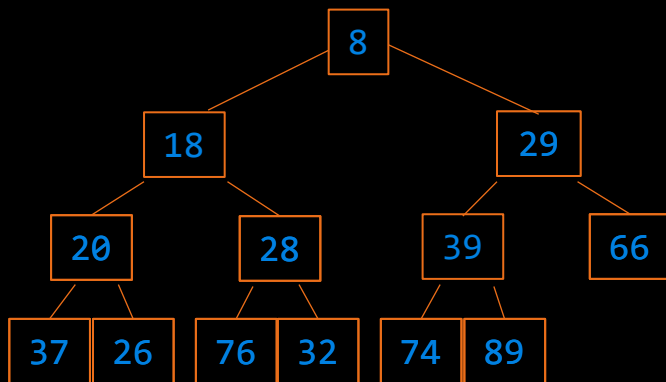
# K Largest Elements

Find the **largest K items** in a **stream of N items**

- Billions of Transactions in Stock Market
- Weather points of data
- Fraud Detection in Credit Cards

**Our interest:** Some Largest values/Smallest Values

**Constraint:**



# K Largest Elements – Idea 0

Find the **K largest items** in an **Unsorted List** : Sort the array and print `arr[n-k ... n]`

<https://stepik.org/lesson/390629/step/2?unit=379729>

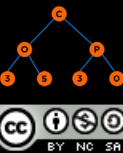


# K Largest Elements – Idea 0

Find the **K largest items** in an **Unsorted List** : Sort the array and print `arr[n-k ... n]`

**Complexity:**  $O(N \log N)$

<https://stepik.org/lesson/390629/step/2?unit=379729>



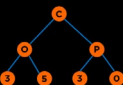
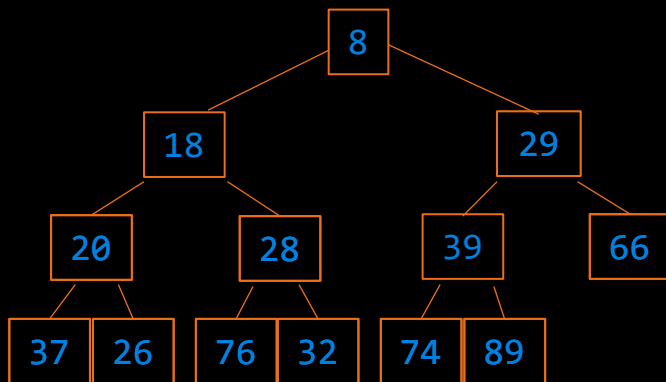
# K Largest Elements

Find the **largest K items** in a **stream of N items**

- Billions of Transactions in Stock Market
- Weather points of data
- Fraud Detection in Credit Cards

**Our interest:** Some Largest values/Smallest Values

**Constraint:** Can we do better than the Sort technique?



# K<sup>th</sup> Largest Elements – Idea 1

Find the K<sup>th</sup> largest item in an Unsorted List (Max Heap)

# K<sup>th</sup> Largest Elements – Idea 1

Find the **K<sup>th</sup> largest item** in an Unsorted List (Max Heap)

```
1.  int kthlargest(vector<int>& nums, int k)
2.  {
3.      //build a max heap
4.      priority_queue<int> pq(nums.begin(), nums.end());
5.      //Remove top k-1 elements
6.      for (int i = k - 1; i > 0; i--)
7.          pq.pop();
8.      return pq.top();
9.  }
```

**Complexity:**

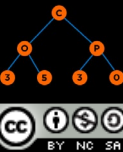
**, Space:**

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8.      return pq.top();
9.  }
```

**Complexity:**  $O(N + K \log N)$  using Max Heaps, Space:  $O(N)$



# K<sup>th</sup> Largest Elements – Idea 1

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9.  }
```

**Complexity:**  $O(N + K \log N)$  using **Max Heaps**, **Space:**  $O(N)$

**Too much Time and Space!**



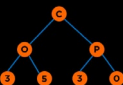
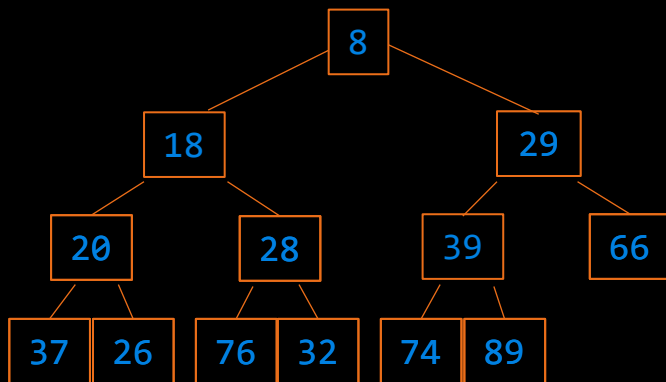
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- Fraud Detection in Credit Cards

**Our interest:** Some Largest values/Smallest Values

**Constraint:** Can't store N items



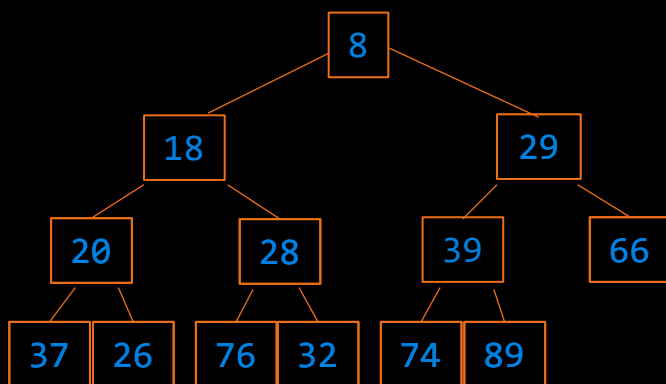
# K Largest Elements – Idea 2

Find the **largest K items** in a **stream of N items**

- Billions of Transactions in Stock Market
- Weather points of data
- Fraud Detection in Credit Cards

**Our interest:** Some Largest values/Smallest Values

**Constraint:** Can't store N items

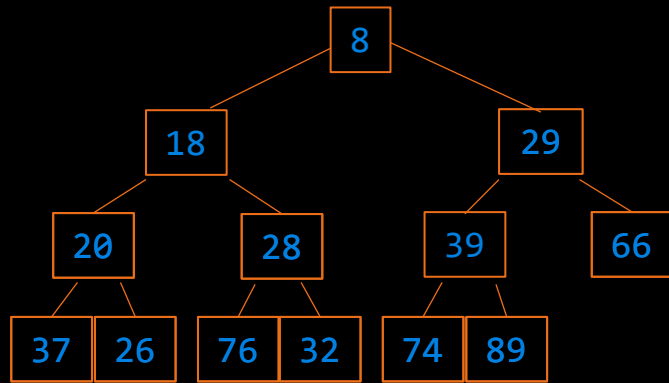


**Idea:** Use a Min Priority Queue

1. Push items into a Minimum Priority Queue
2. Delete an element when the queue's size is greater than K

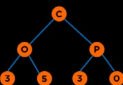


# K Largest Elements – Idea 2



**Idea: Use a Min Priority Queue**

1. Push items into a Minimum Priority Queue
2. Delete an element when the queue's size is greater than K



# K<sup>th</sup> Largest Elements – Idea 2

Find the **K<sup>th</sup> largest item** in an Unsorted List (Min Heap)

```
1.  int kthlargest(vector<int>& nums, int k)
2.  {
3.      //min heap
4.      priority_queue<int, vector<int>, greater<int>> pq;
5.      for (int i : nums)
6.      {
7.          if(pq.size() > k && i < pq.top())
8.              continue;
9.          pq.push(i);
10.         if (pq.size() > k)
11.             pq.pop();
12.     }
13.     return pq.top();
14. }
```

**Complexity:**

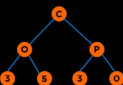
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9.          pq.push(i);
10.         if (pq.size() > k)
11.             pq.pop();
12.     }
13.     return pq.top();
14. }
```

**Complexity:**  $O(N \log K)$  using Min Heaps, Space:  $O(K)$



# Running Median Problem

Find the **Median** of Running Integers

Stream: 5, 11, 22, 0, 2, 54, 8, 9

<https://stepik.org/lesson/390629/step/4?unit=379729>

# Running Median Problem

Find the **Median** of Running Integers

**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

Adding an Element

Rebalancing

Returning Median

Stream: 5, 11, 22, 0, 2, 54, 8, 9

<https://stepik.org/lesson/390629/step/4?unit=379729>

# Running Median Problem

Find the **Median** of Running Integers

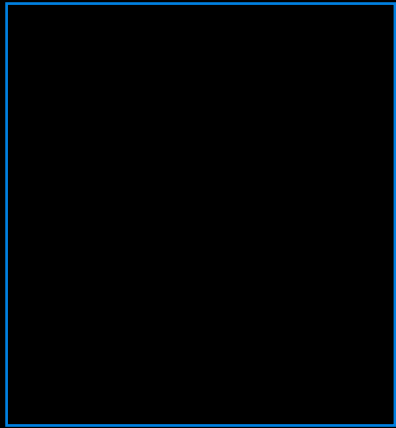
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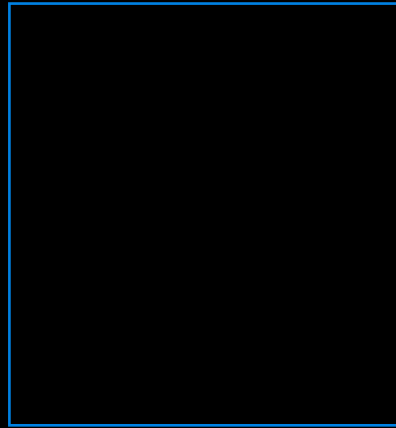
Adding an Element

Rebalancing

Returning Median

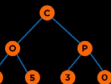


Max Heap: Lowers



Min Heap: Highers

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

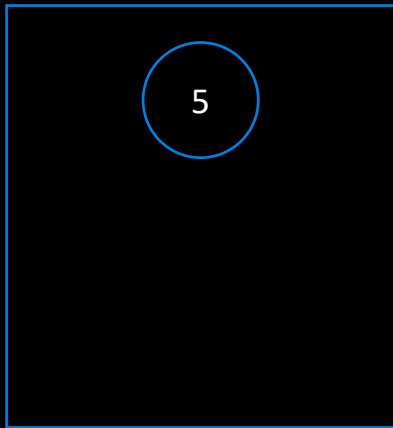
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

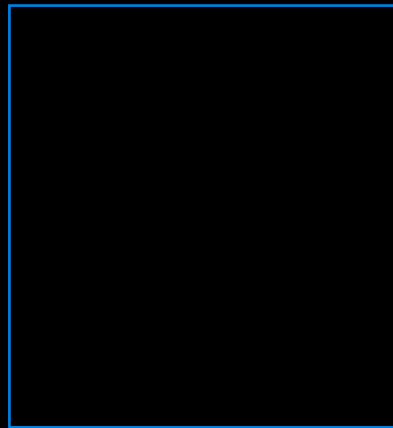
Adding an Element

Rebalancing

Returning Median



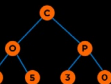
Max Heap: Lower



Min Heap: Higher

If both the heaps are empty add, 5 to lower

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

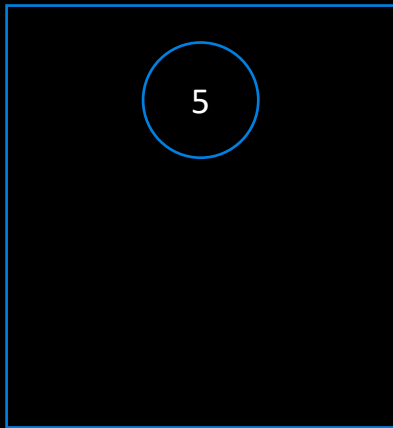
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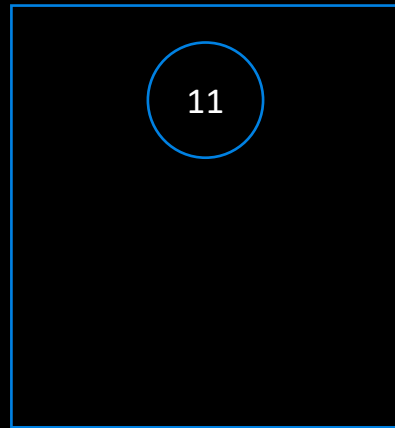
Adding an Element

Rebalancing

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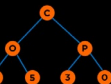
Max Heap: Lower



Min Heap: Higher

11 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher

Stream: 5, 11, 22, 0, 2, 54, 8, 9





# Running Median Problem

Find the **Median** of Running Integers

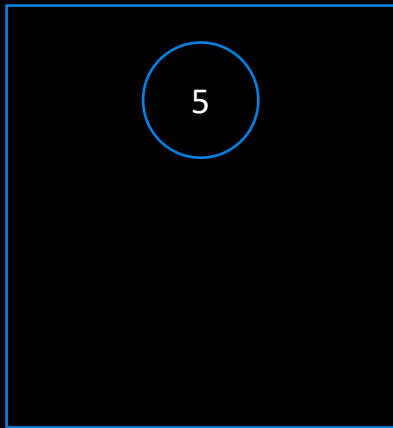
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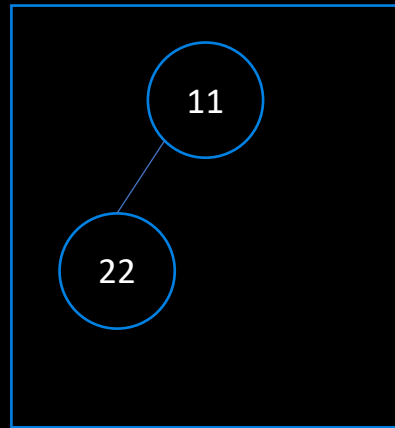
Adding an Element

Rebalancing

Returning Median



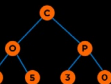
Max Heap: Lower



Min Heap: Higher

22 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

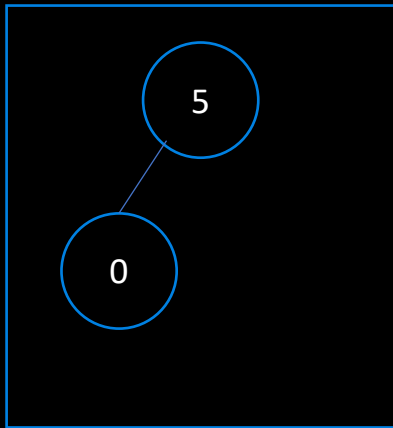
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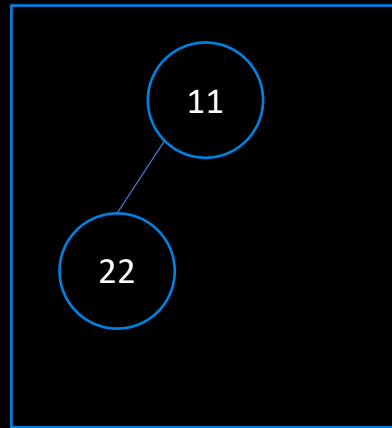
Adding an Element

Rebalancing

Returning Median



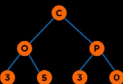
Max Heap: Lower



Min Heap: Higher

0 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

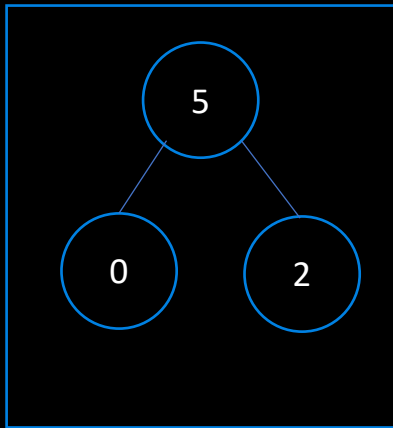
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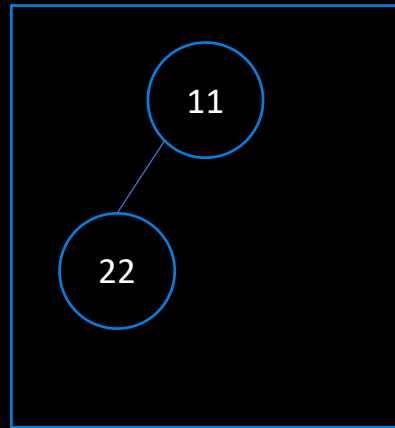
Adding an Element

Rebalancing

Returning Median



Max Heap: Lower



Min Heap: Higher

2 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher

Stream: 5, 11, 22, 0, 2, 54, 8, 9

# Running Median Problem

Find the **Median** of Running Integers

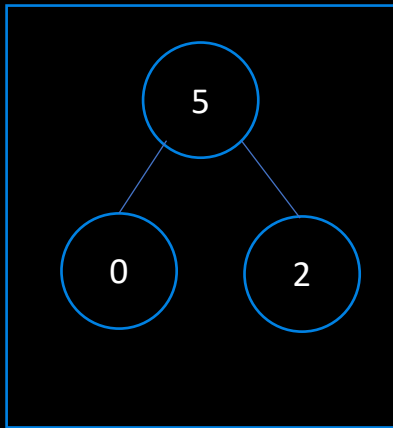
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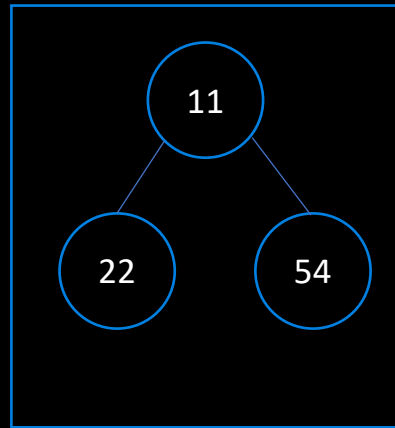
Adding an Element

Rebalancing

Returning Median



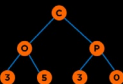
Max Heap: Lower



Min Heap: Higher

54 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

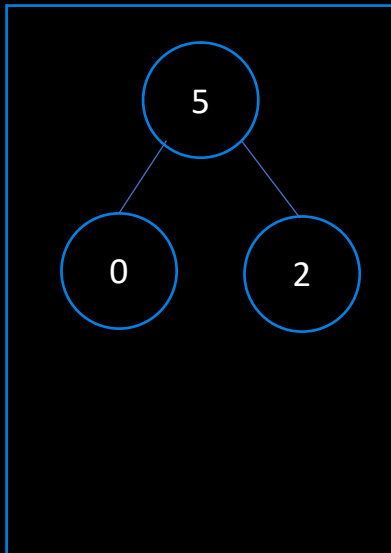
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**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

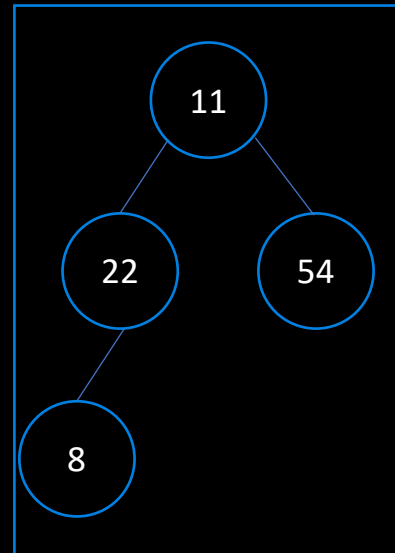
Adding an Element

Rebalancing

Returning Median



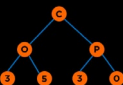
Max Heap: Lower



Min Heap: Higher

8 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

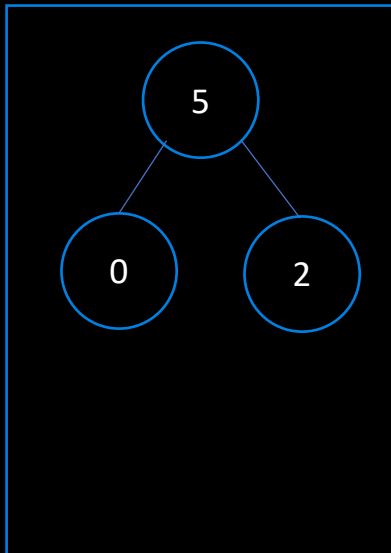
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

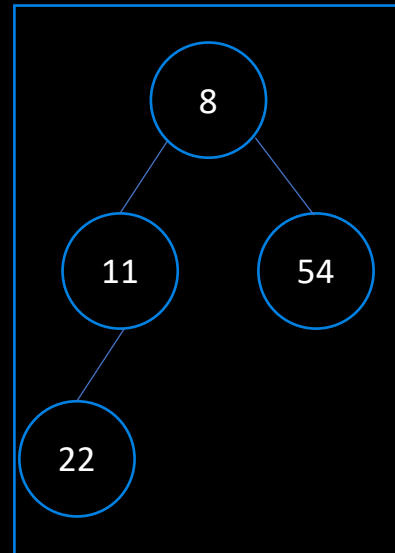
Adding an Element

Rebalancing

Returning Median



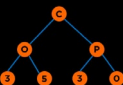
Max Heap: Lower numbers



Min Heap: Higher numbers

8 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher numbers. Min Heap: Higher numbers - HeapifyUp.

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

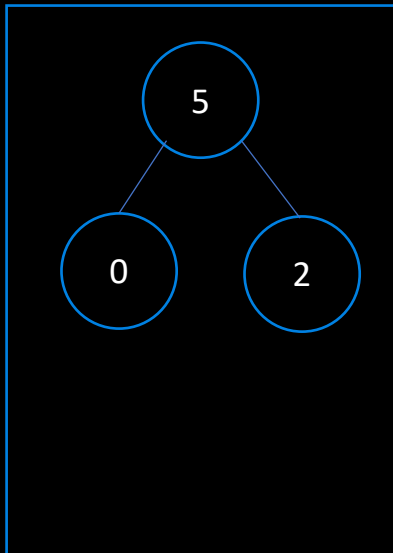
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

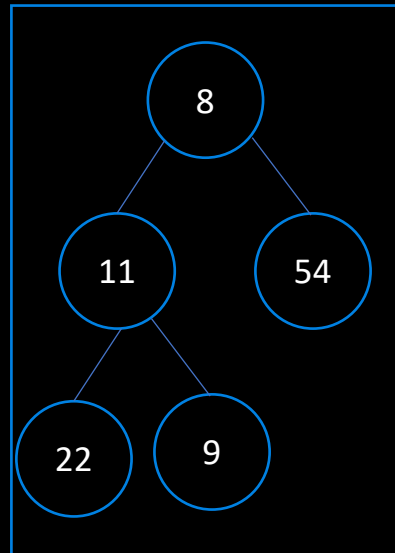
Adding an Element

Rebalancing

Returning Median



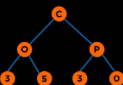
Max Heap: Lower numbers



Min Heap: Higher numbers

9 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher.

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

Find the **Median** of Running Integers

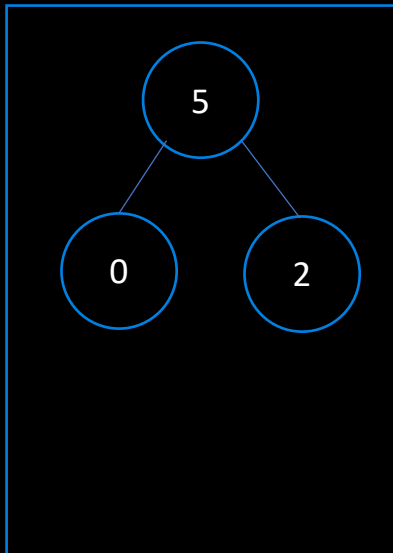
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

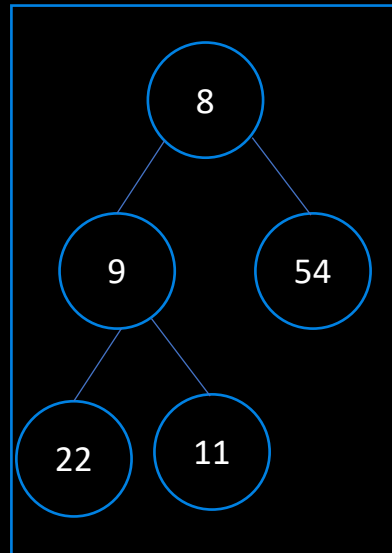
Adding an Element

Rebalancing

Returning Median



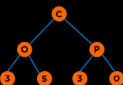
Max Heap: Lower



Min Heap: Higher

9 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher. Min Heap: Higher - HeapifyUp.

Stream: 5, 11, 22, 0, 2, 54, 8, 9





# Running Median Problem

Find the **Median** of Running Integers

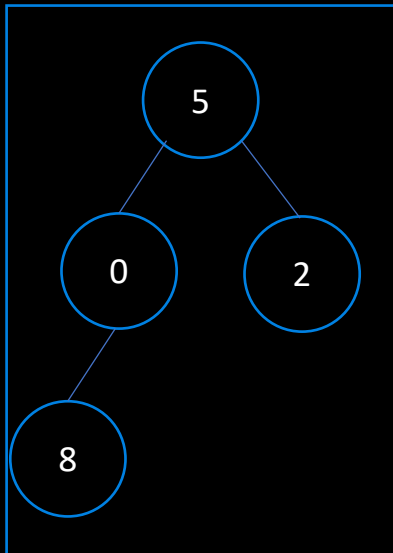
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

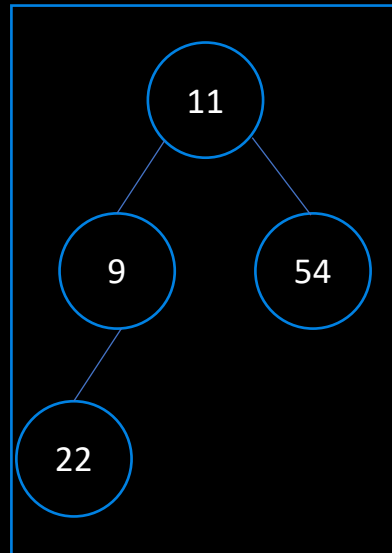
Adding an Element

Rebalancing

Returning Median



Max Heap: Lower numbers



Min Heap: Higher numbers

9 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher. Rebalancing. Move root of larger heap to smaller heap.

Stream: 5, 11, 22, 0, 2, 54, 8, 9

# Running Median Problem

Find the **Median** of Running Integers

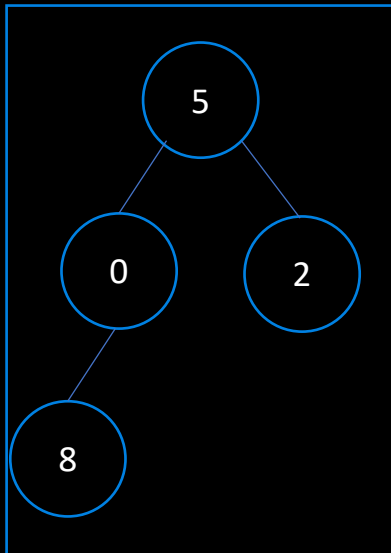
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

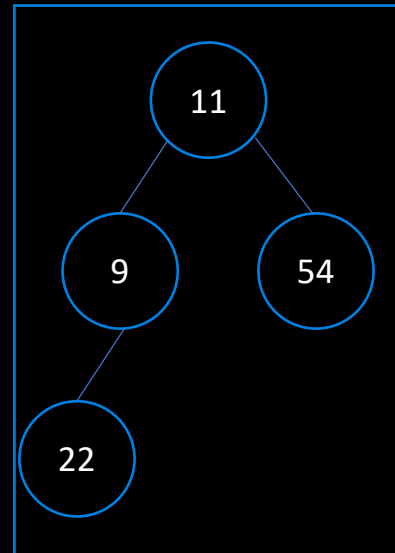
Adding an Element

Rebalancing

Returning Median



Max Heap: Lower numbers



Min Heap: Higher numbers

9 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher. Heapify up in lowers and Heapify down in higher.

Stream: 5, 11, 22, 0, 2, 54, 8, 9

# Running Median Problem

Find the **Median** of Running Integers

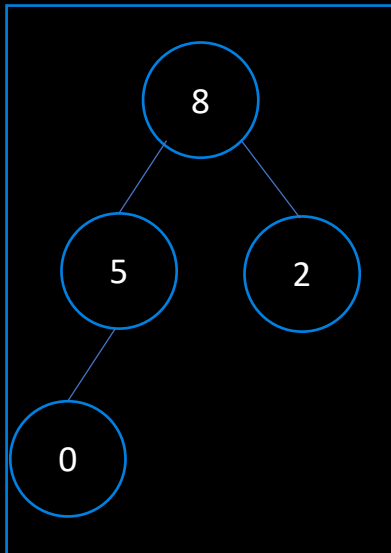
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

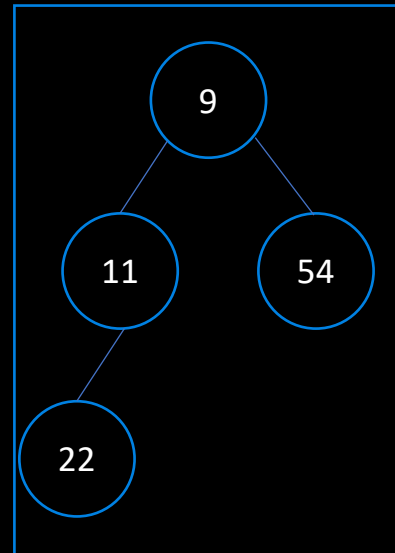
Adding an Element

Rebalancing

Returning Median



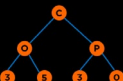
Max Heap: Lower numbers



Min Heap: Higher numbers

9 is compared with root of lowers. If it is less than the root, add to lowers. Otherwise add to higher. Heapify up in lowers and Heapify down in higher.

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

## Find the Median of Running Integers

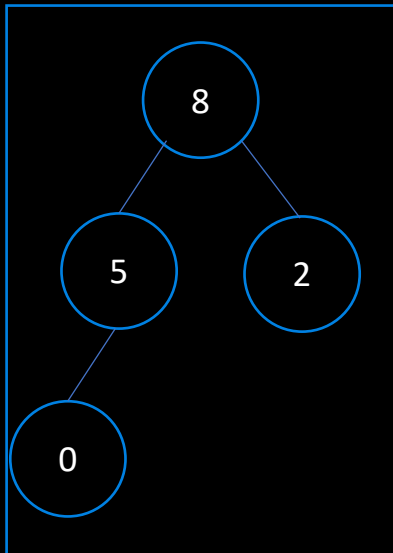
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

**Constraint:** Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

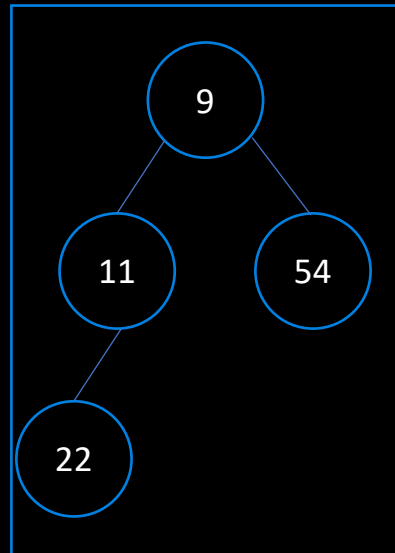
Adding an Element

Rebalancing

Returning Median



Max Heap: Lower

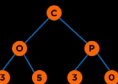


Min Heap: Higher

Median: Average of two roots if heaps are of equal size; Otherwise, the root of larger heap

Median = 8.5

Stream: 5, 11, 22, 0, 2, 54, 8, 9



# Running Median Problem

## Find the Median of Running Integers

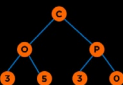
**Idea:** Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher numbers

```
Max heap, lowers stores elements to the left of median
Min heap, highers stores elements to the right of median

1. Adding an Element, e:
   if lowers.size = 0 or e < lowers.root:
       lowers.add(e)
   else
       highers.add(e)

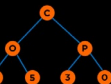
2. Rebalancing:
   Find biggerHeap and smallerHeap from highers and lowers
   if (biggerHeap.size - smallerHeap.size) = 2:
       smallerHeap.add(biggerHeap.extractMin())

3. Returning Median:
   if size of both heaps are equal:
       return (lowers.max + highers.min)/2
   else
       return the root of bigger heap (lowers.max or higher.min)
```



# Resources

- Running Medians Video:  
<https://www.youtube.com/watch?v=VmogG01IjYc>



# Questions

