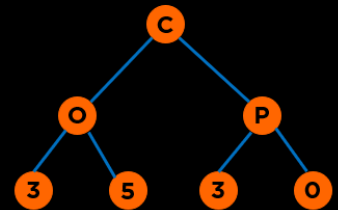


Heaps



Categories of Data Structures

Linear Ordered

Lists

Stacks

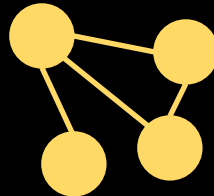
Queues



Non-linear Ordered

Trees

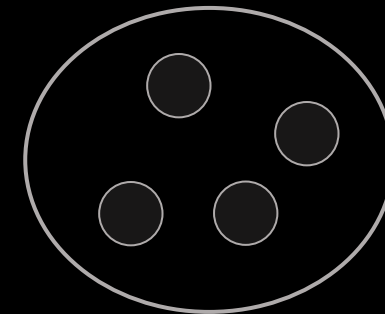
Graphs



Not Ordered

Sets

Tables/Maps



Recap

- **Splay Trees**

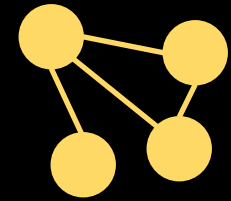
- **Performance**

- **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

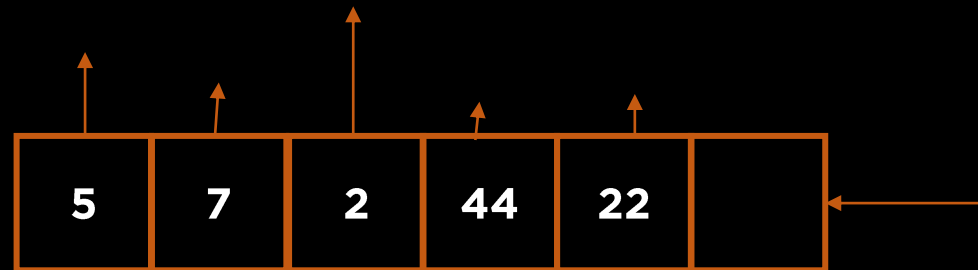
- Queue supported FIFO principle
- Here, “**first-in**” basis was the priority
- What if we want to generalize this feature of **priority**?



Problem

Enter Priority Queue!

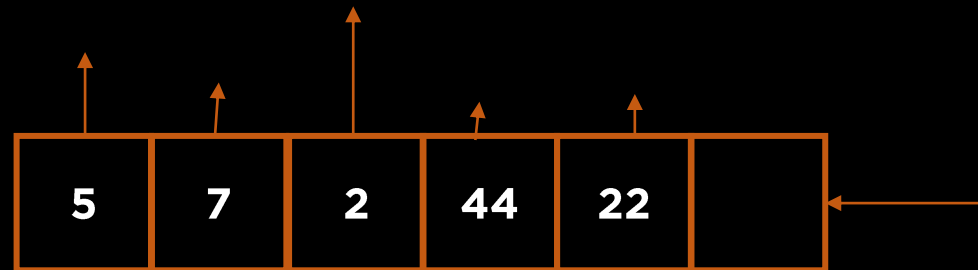
- All elements inserted have some priority
- Elements with **highest** or **lowest** priority is removed first



Problem

Priority Queue

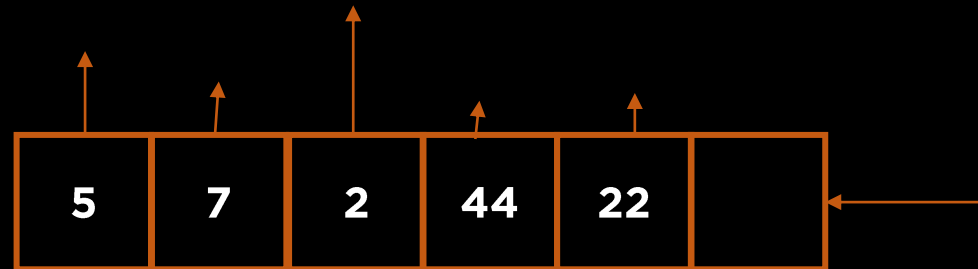
- A priority queue is a generalization of a queue where each element is assigned a priority and elements come out in order by priority



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

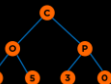
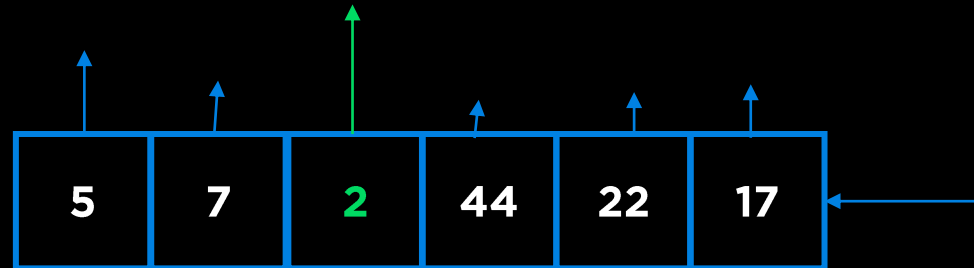


Problem

Insert (17)



ExtractMin()



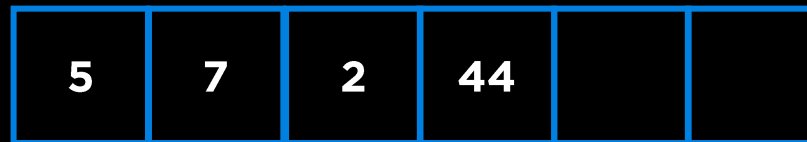
Priority Queues

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



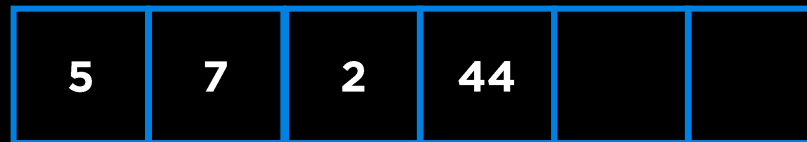
Insert (p)

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: $O(n)$

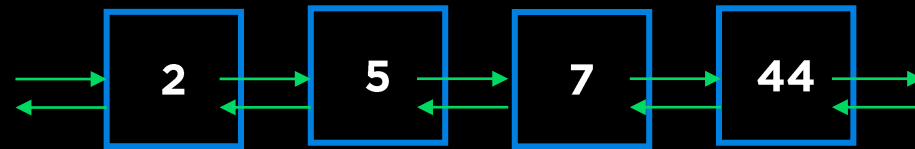
ExtractMin()

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



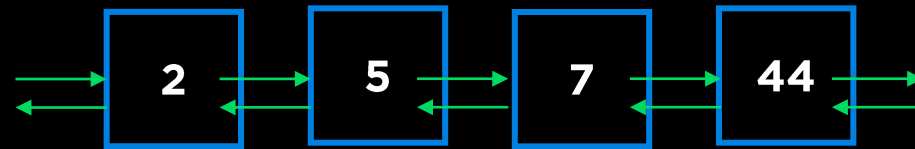
Insert (p)

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 $O(1)$: $O(n)$

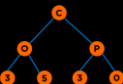
ExtractMin()

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?

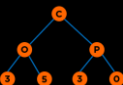
| | Insert | ExtractMin |
|---------------------|--------|------------|
| Unsorted Array/List | $O(1)$ | $O(n)$ |
| Sorted Array/List | $O(n)$ | $O(1)$ |



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 | $O(\log n)$ | $O(\log n)$ |

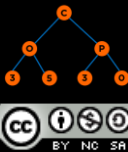


Problem

Use Cases

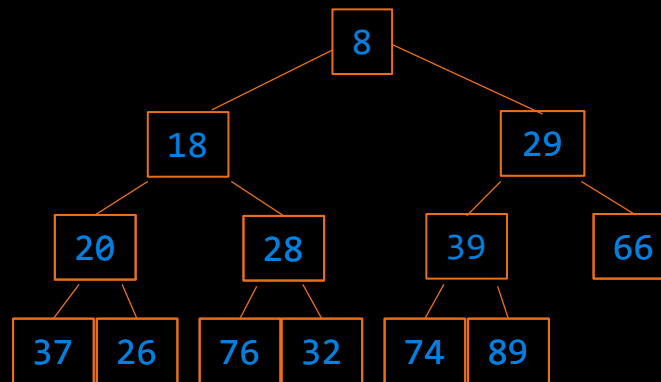
- **Huffman Trees**
- **Dijkstra's Shortest Path Algorithm**
- **Prim's Algorithm for calculating Minimum Spanning Tree**
- **Scheduling Job**
- **K largest elements**
- **Heap Sort**
- **Many more ...**

Heaps



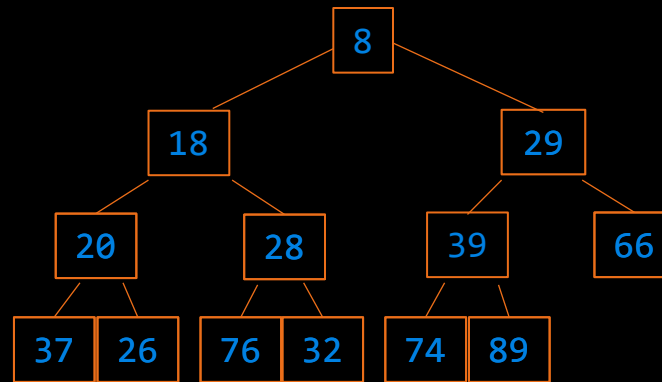
Binary Heap

- **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)**



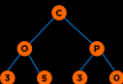
Binary Heap

Heap Representation



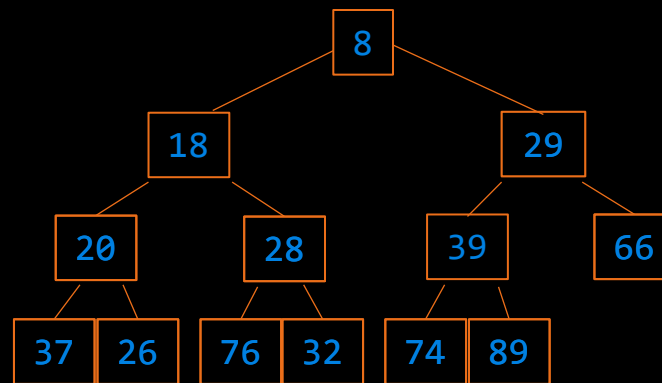
```
class HeapNode
{
    int value;
    HeapNode* left;
    HeapNode* right;
}
```

left and right are min-heaps



Binary Heap

Heap Representation



```
int Heap[];
```

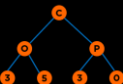
For a node at position p ,

L. child position: $2p + 1$

R. child position: $2p + 2$

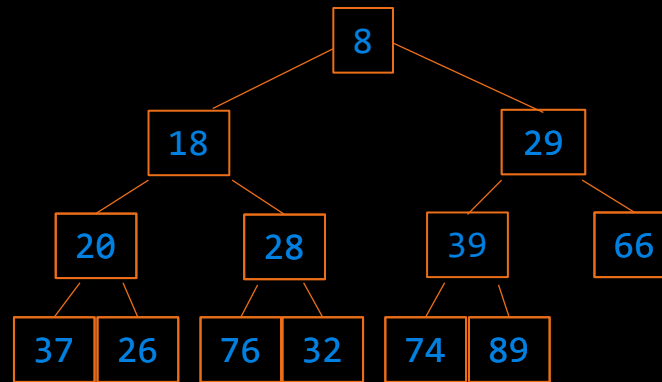
A node at position c can find its parent at $\text{floor}((c - 1)/2)$

| | | | | | | | | | | | | | |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 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 | |



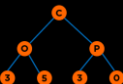
Binary Heap Insertion

Heap Insertion



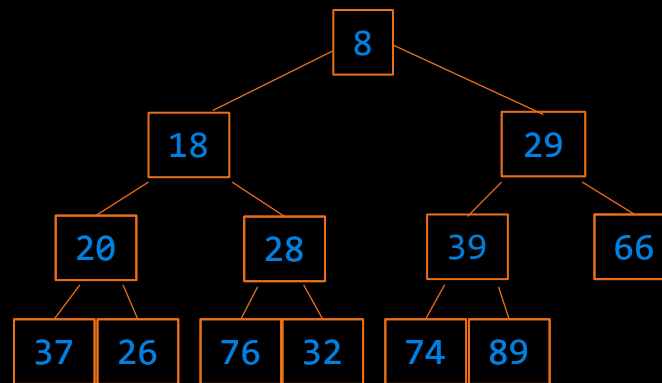
Algorithm for Inserting in a Heap

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



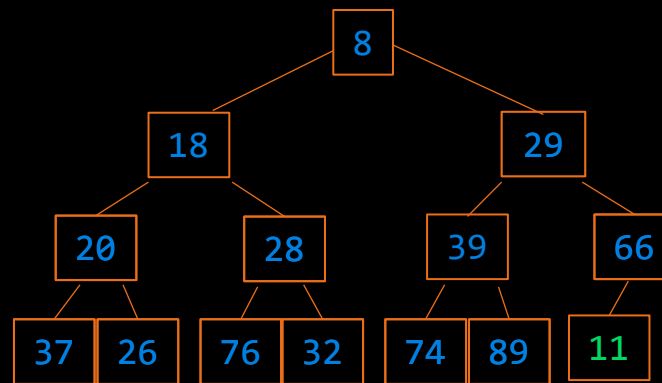
1. Insert the new element at the end of the array and set child to `arr.size() - 1`
2. Set parent to $(\text{child} - 1) / 2$
3. while ($\text{parent} \geq 0$ and $\text{arr}[\text{parent}] > \text{arr}[\text{child}]$)
 - Swap $\text{arr}[\text{parent}]$ and $\text{arr}[\text{child}]$
 - Set child equal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



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 $(\text{child}-1)/2$

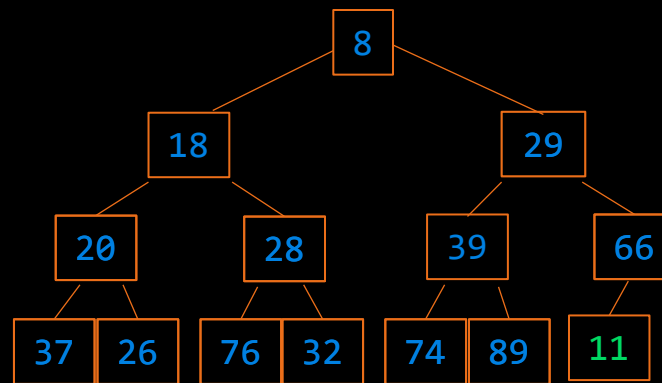
child = 13

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

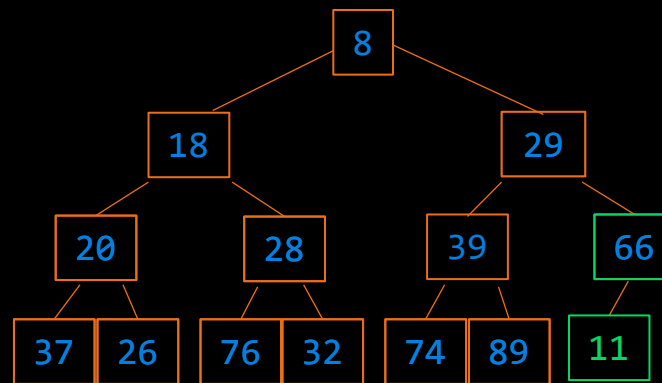
child = 13
parent = 6

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



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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 $(\text{child}-1)/2$

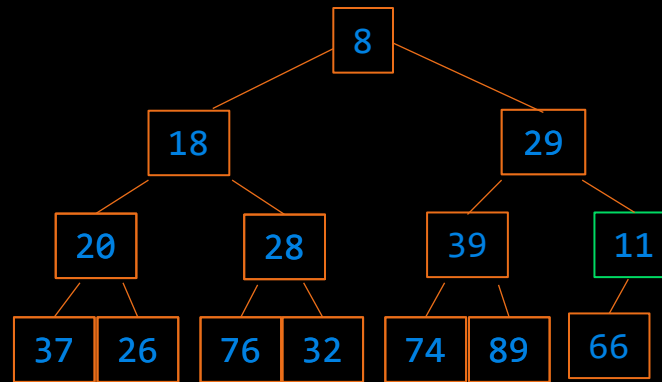
child = 13
parent = 6

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 $(\text{child}-1)/2$

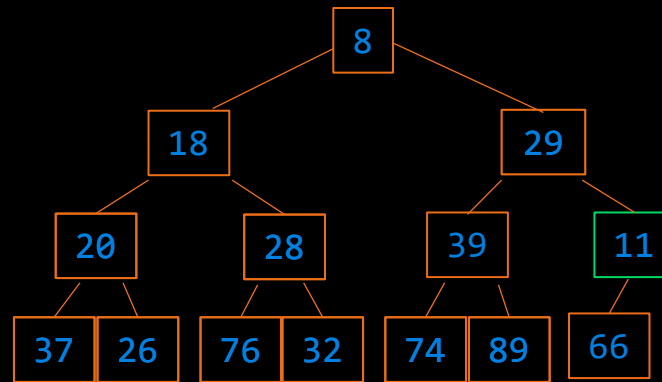
child = 13
parent = 6

insert 11

| | | | | | | | | | | | | | |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 8 | 18 | 29 | 20 | 28 | 39 | 11 | 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]`
 - Set child equal to parent
 - Set parent equal to $(\text{child}-1)/2$

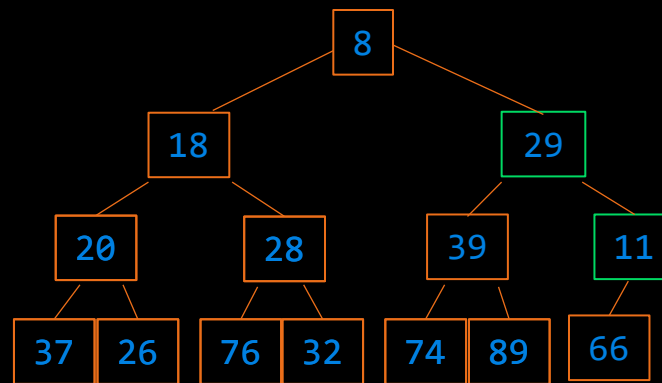
child = 13 | 6
parent = 6 | 2

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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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 $(\text{child}-1)/2$

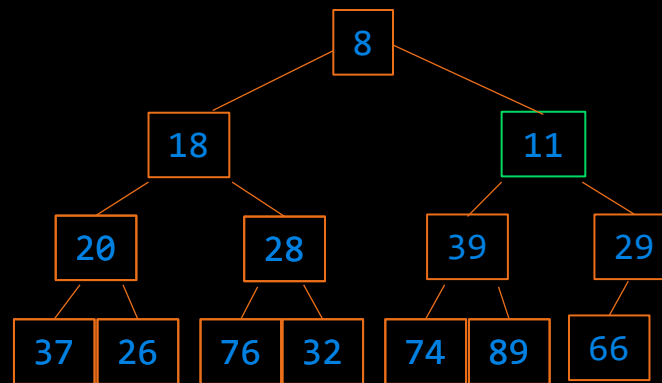
child = 13 | 6
parent = 6 | 2

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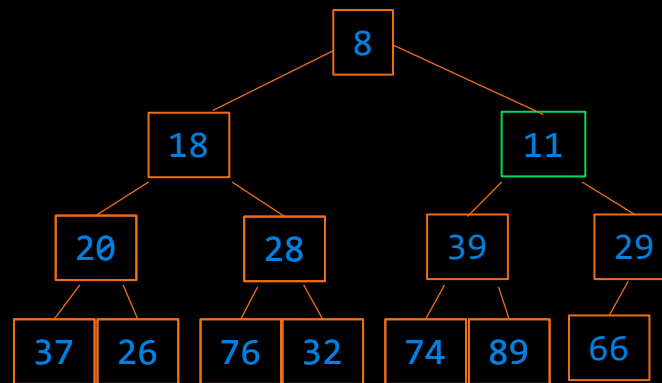
child = 13 | 6
parent = 6 | 2

insert 11

| | | | | | | | | | | | | | |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 8 | 18 | 11 | 20 | 28 | 39 | 29 | 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 ($\text{parent} \geq 0$ and $\text{arr}[\text{parent}] > \text{arr}[\text{child}]$)
 - Swap $\text{arr}[\text{parent}]$ and $\text{arr}[\text{child}]$
 - Set child equal to parent
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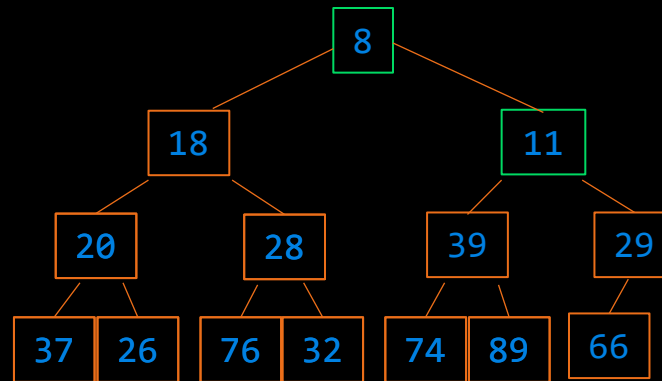
child = 13 | 6 | 2
parent = 6 | 2 | 0

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



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 $(\text{child}-1)/2$

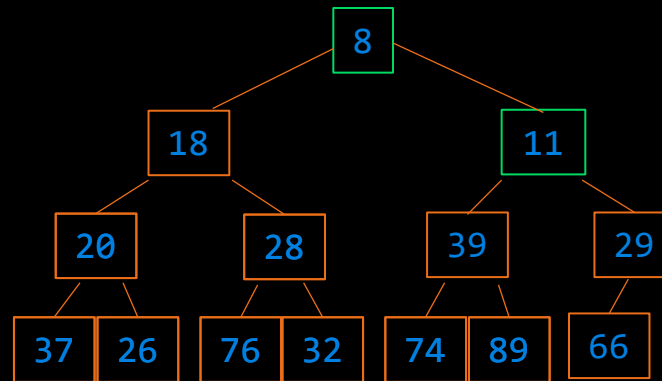
child = 13 | 6 | 2
parent = 6 | 2 | 0

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

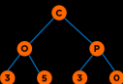
Heap Insertion



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 $(\text{child}-1)/2$

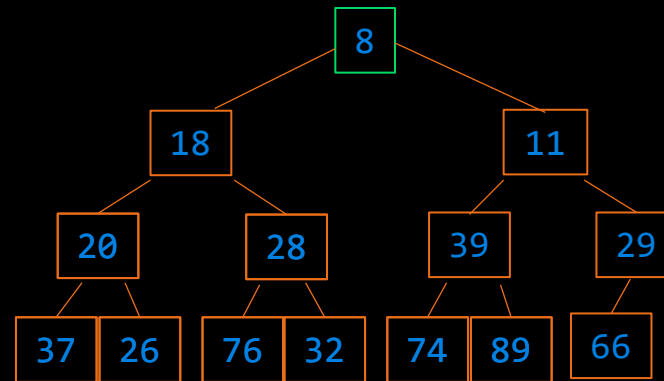
child = 13 | 6 | 2
parent = 6 | 2 | 0

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



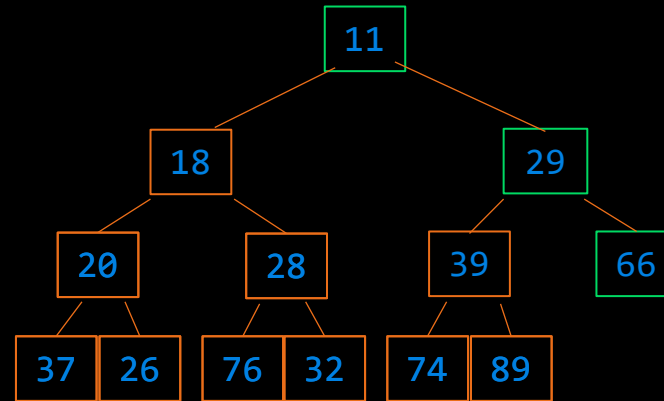
Binary MinHeap Deletion

Heap Deletion (ExtractMin)



Binary MinHeap Deletion

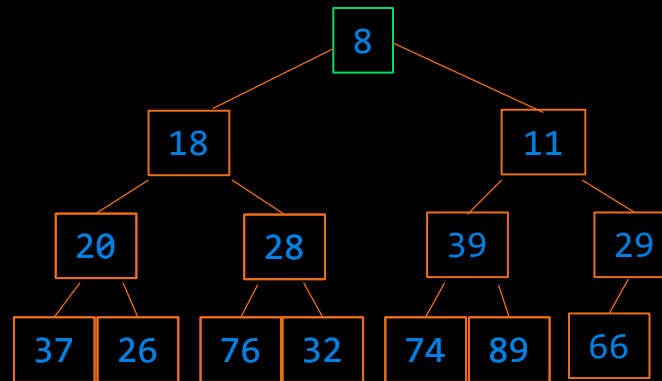
Heap Deletion (ExtractMin)



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

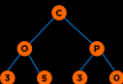
Binary MinHeap Deletion

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.



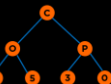
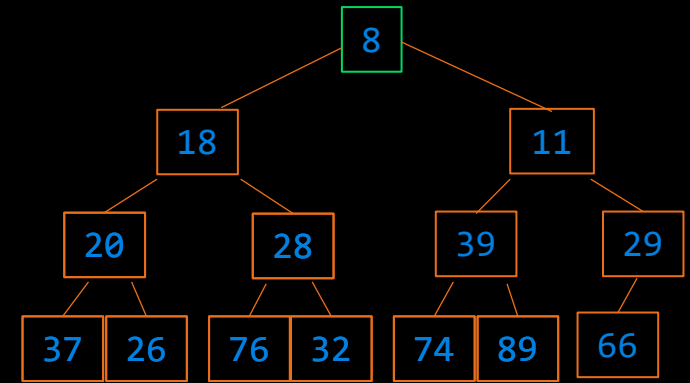
Binary MinHeap Deletion

Heap Deletion (ExtractMin)

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

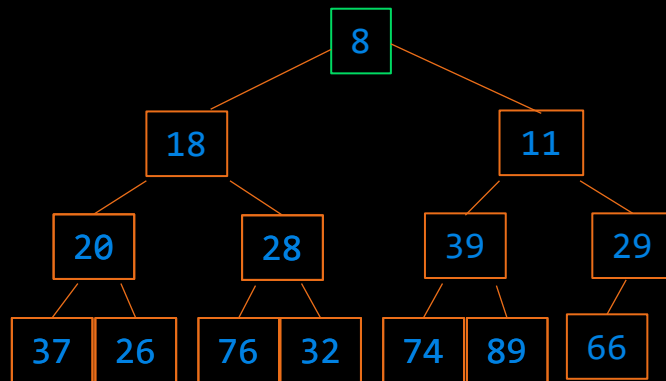
//Remove the minimum item.
void extractMin( )
{
    arr[0] = arr[--currentSize];
    heapifyDown(0);
}

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

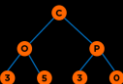
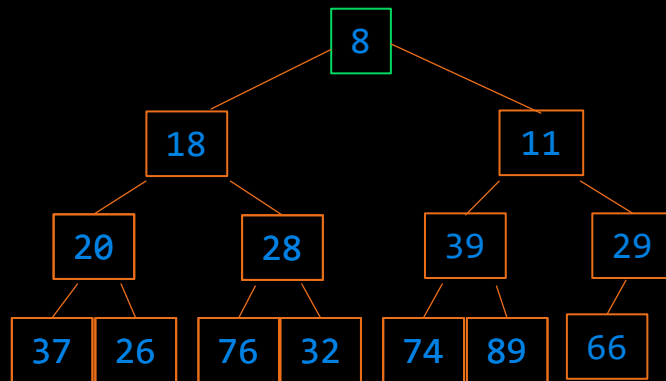


Heap Sort

- **Algorithm:**

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

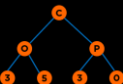
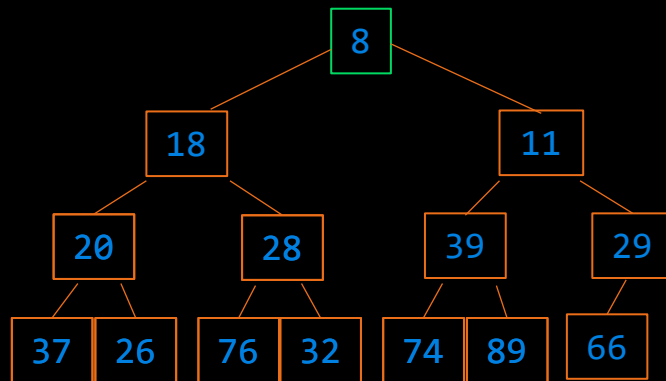
- **Performance:** $O(n \log n)$



Heap Building

- Building heap inplace:

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

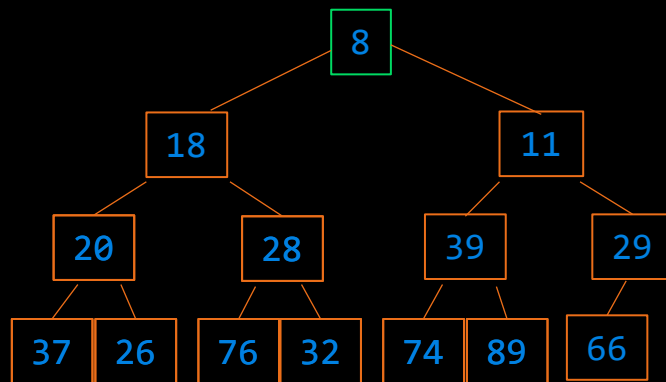


Heap Sort

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



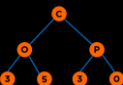
- **Building heap inplace in $O(n)$:**

```
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)

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

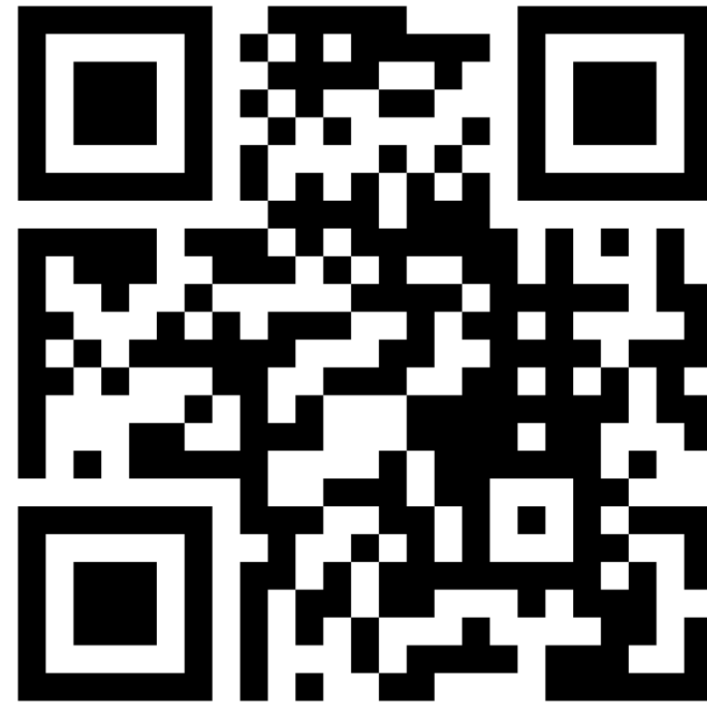


Resources

- **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
6025 9468



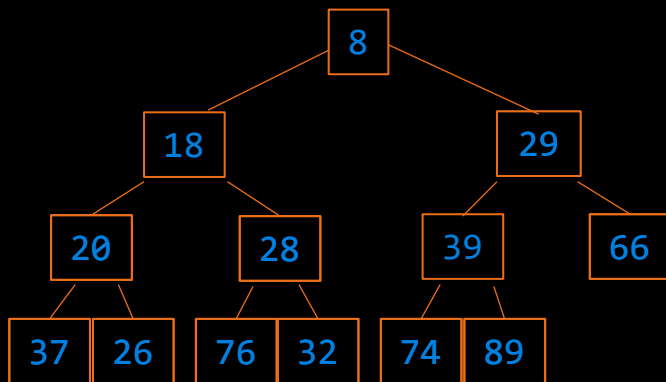
K Largest Elements

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>

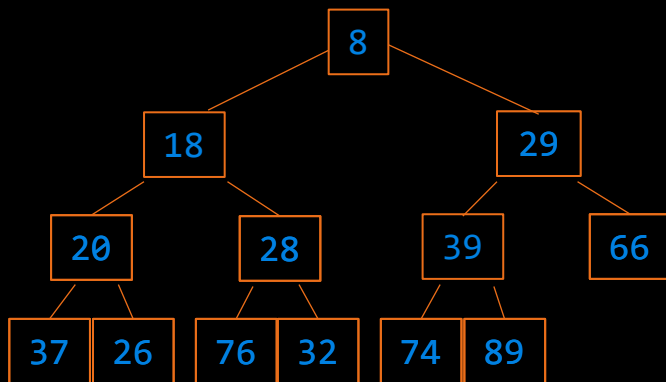
K Largest Elements

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?



Kth Largest Elements – Idea 1

Find the Kth largest item in an Unsorted List (Max Heap)

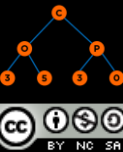
Kth Largest Elements – Idea 1

Find the Kth 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:

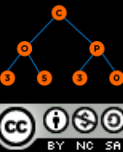


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9.  }
```

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



Kth Largest Elements – Idea 1

Find the Kth largest item in an Unsorted List (Max Heap)

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9.  }
```

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

Too much Time and Space!



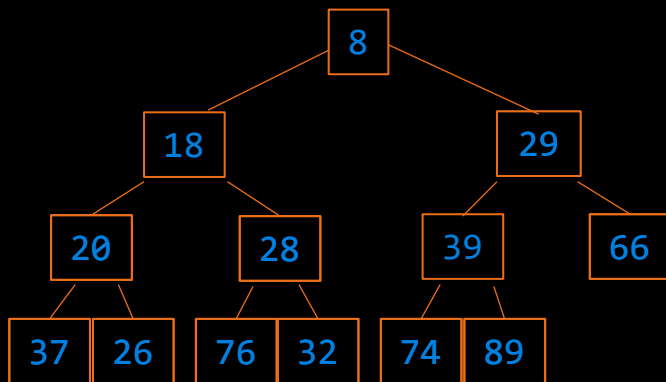
K Largest Elements

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't store N items



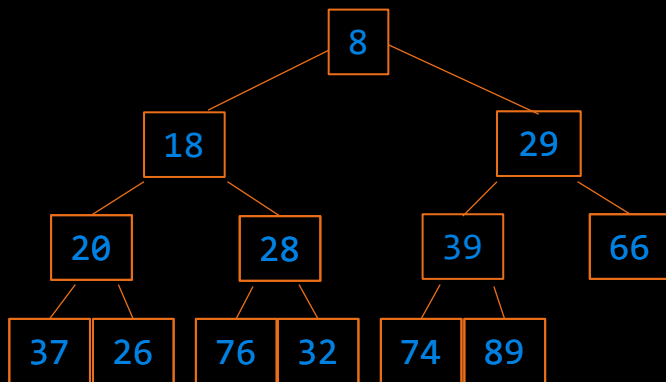
K Largest Elements – Idea 2

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

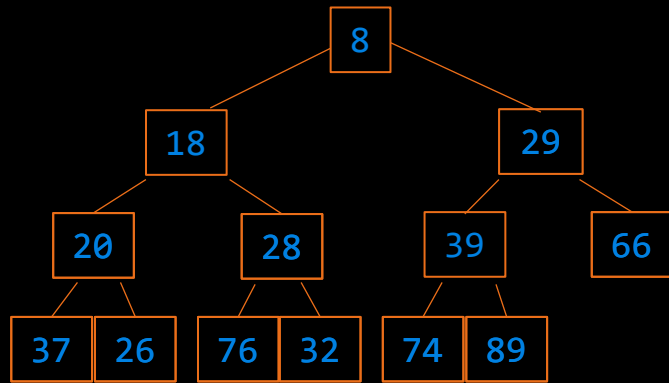
Constraint: Can't store N items



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

Kth Largest Elements – Idea 2

Find the **Kth 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:

, Space:

Kth Largest Elements – Idea 2

Find the Kth largest item in an Unsorted List (Min Heap)

```
1.  int kthlargest(vector<int>& nums, int k)
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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

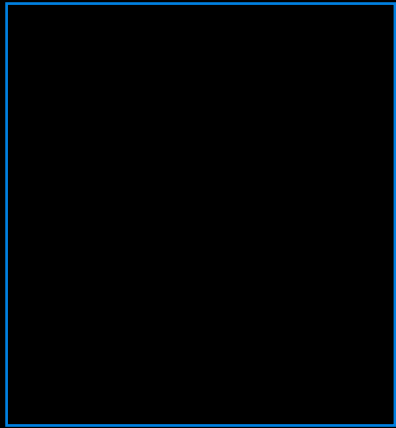
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Constraint: Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

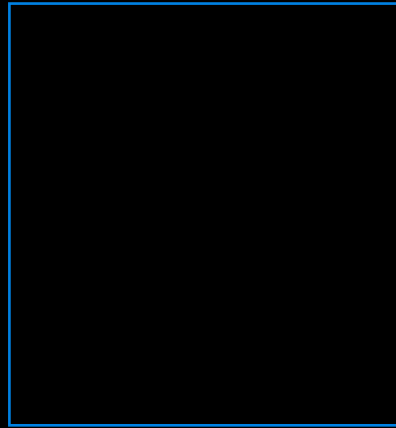
Adding an Element

Rebalancing

Returning Median

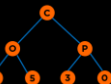


Max Heap: Lowers



Min Heap: Highers

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



Running Median Problem

Find the **Median** of Running Integers

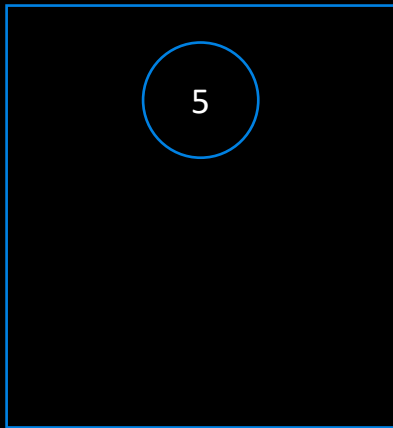
Idea: Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

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

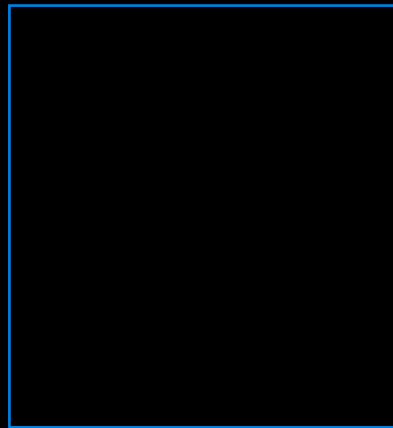
Adding an Element

Rebalancing

Returning Median



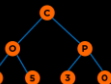
Max Heap: Lower



Min Heap: Higher

If both the heaps are empty add, 5 to lowers

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



Running Median Problem

Find the **Median** of Running Integers

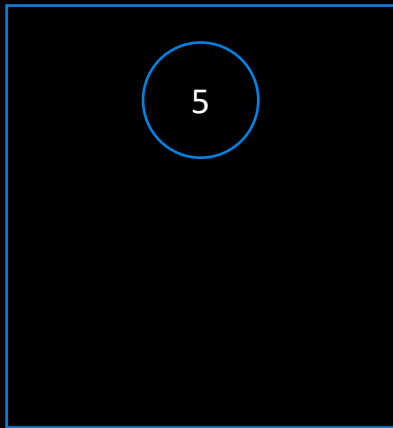
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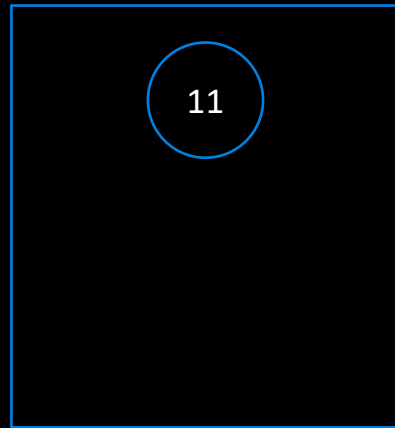
Adding an Element

Rebalancing

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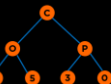
Max Heap: Lower



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

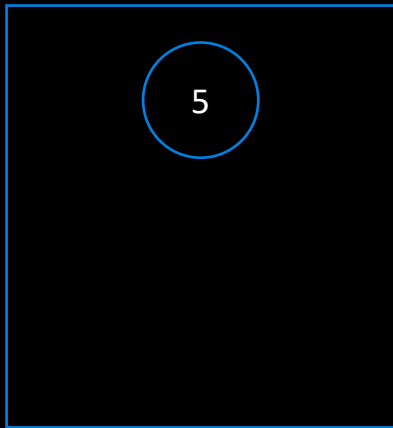
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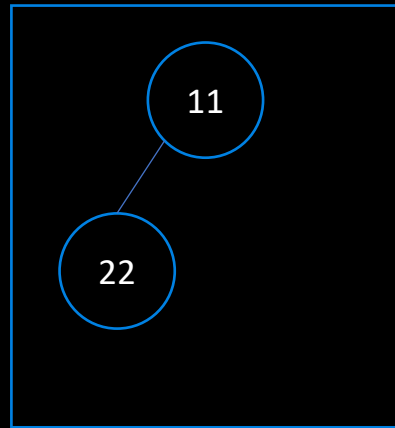
Adding an Element

Rebalancing

Returning Median



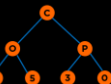
Max Heap: Lower



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

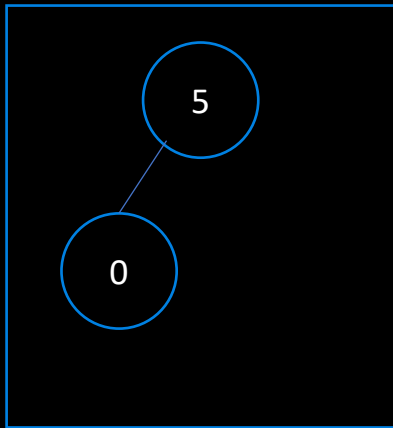
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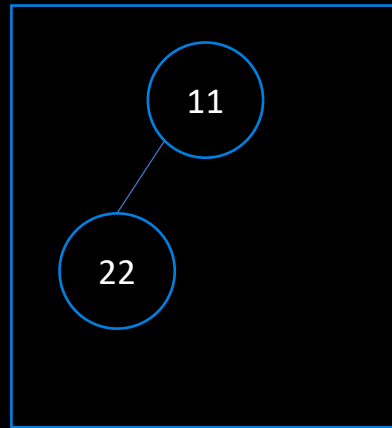
Adding an Element

Rebalancing

Returning Median



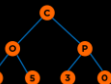
Max Heap: Lower



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

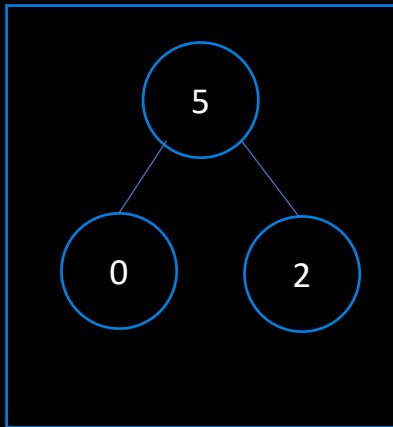
Idea: Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

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

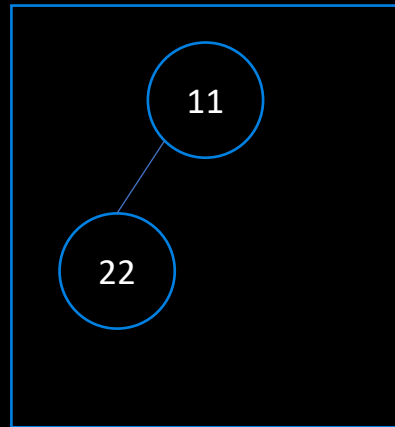
Adding an Element

Rebalancing

Returning Median



Max Heap: Lower numbers



Min Heap: Higher numbers

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

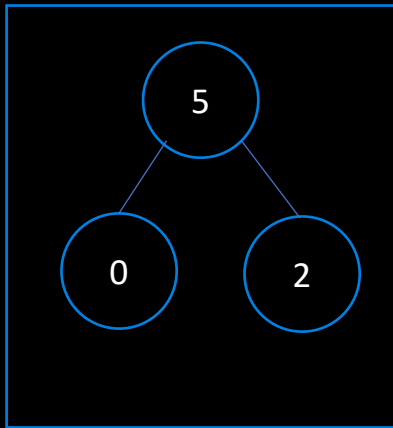
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Constraint: Min and Max Heap Properties + Size of Min Heap and Max Heap differ by at most 1

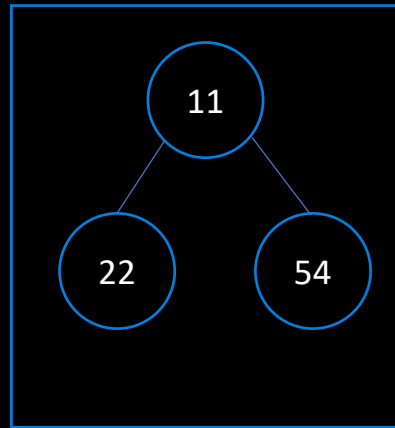
Adding an Element

Rebalancing

Returning Median



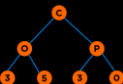
Max Heap: Lower numbers



Min Heap: Higher numbers

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

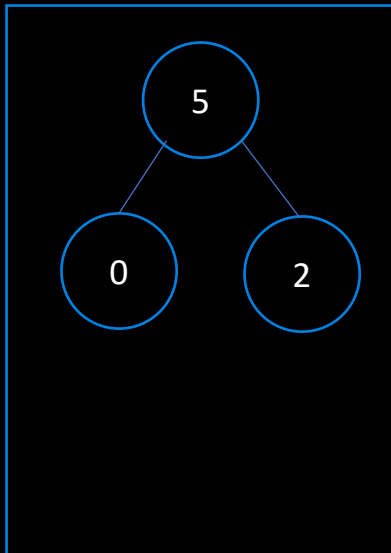
Idea: Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

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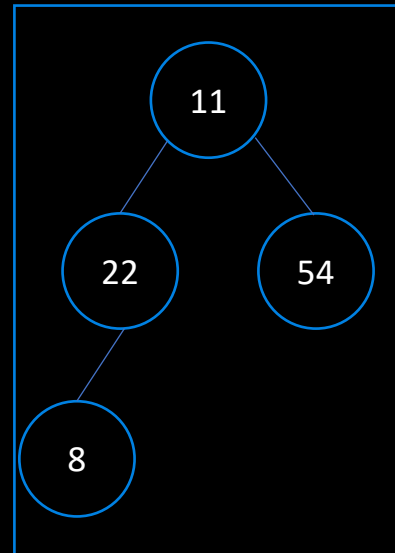
Adding an Element

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

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

Running Median Problem

Find the **Median** of Running Integers

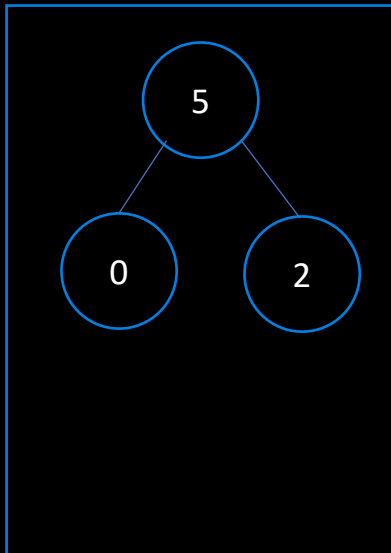
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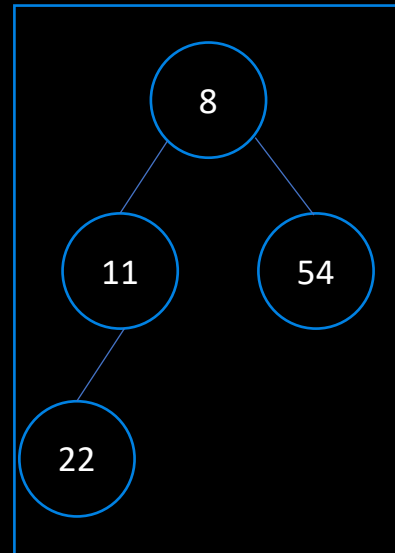
Adding an Element

Rebalancing

Returning Median



Max Heap: Lower 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

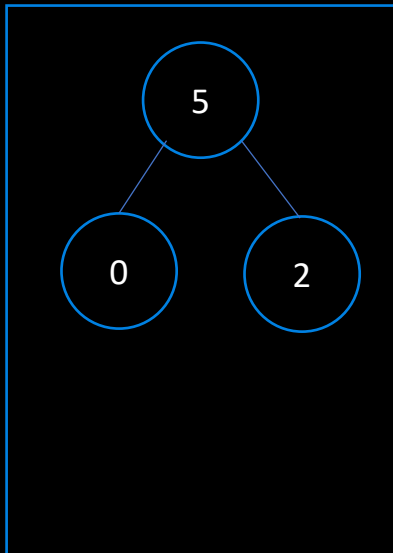
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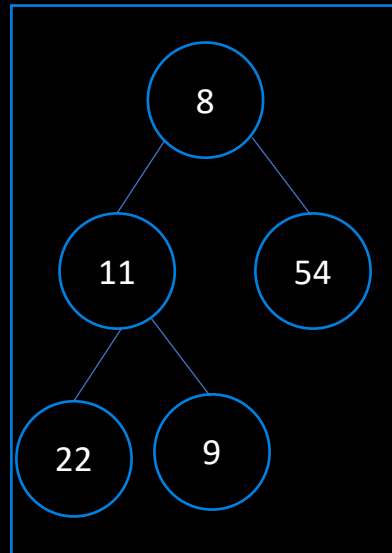
Adding an Element

Rebalancing

Returning Median



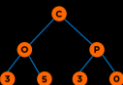
Max Heap: Lower numbers



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

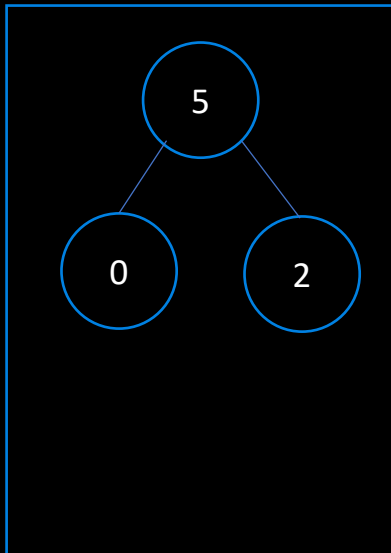
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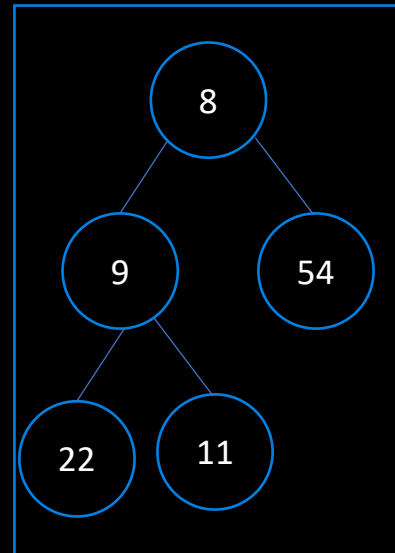
Adding an Element

Rebalancing

Returning Median



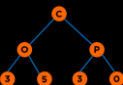
Max Heap: Lower numbers



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 numbers. Min Heap: Higher numbers - HeapifyUp.

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



Running Median Problem

Find the **Median** of Running Integers

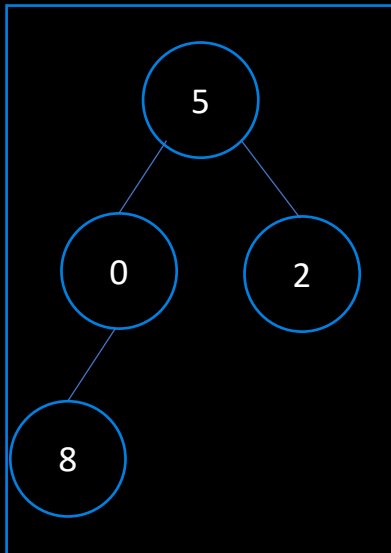
Idea: Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

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

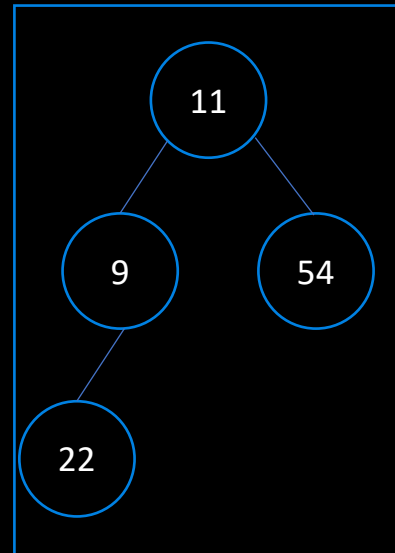
Adding an Element

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. 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

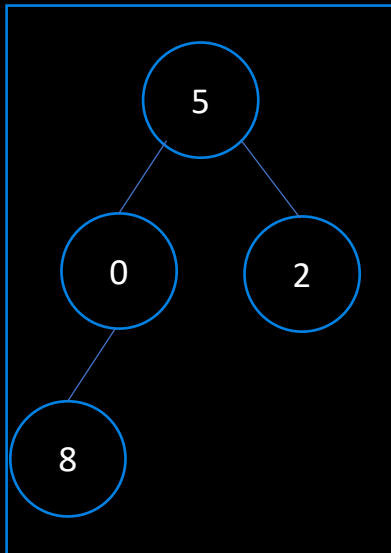
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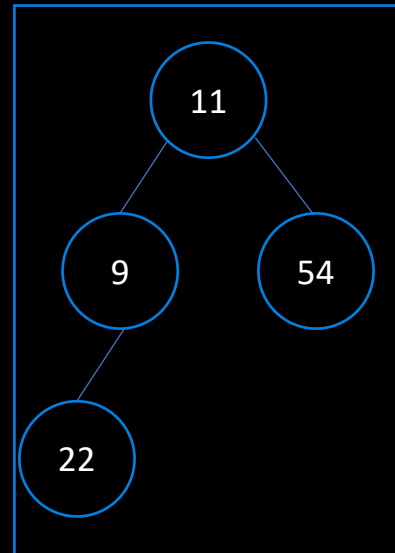
Adding an Element

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

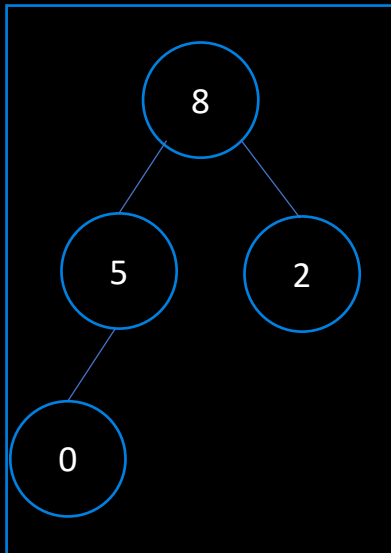
Idea: Use a Max Heap to keep a track of lower numbers and a Min Heap to keep track of higher

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

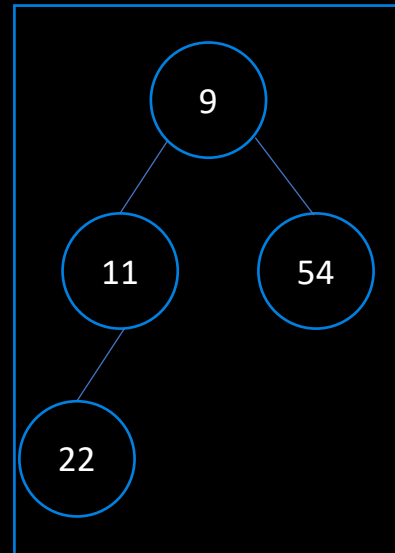
Adding an Element

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

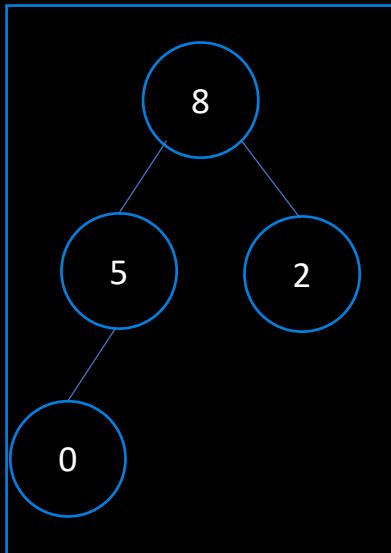
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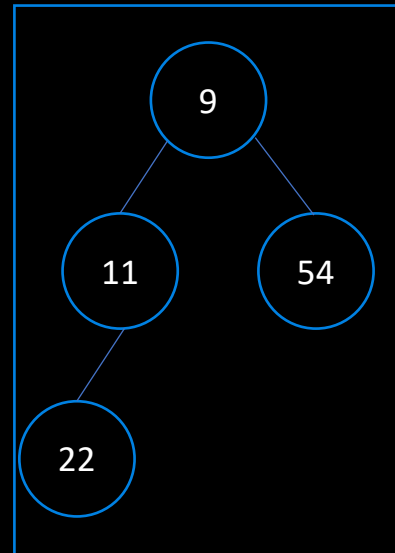
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Max Heap: Lower

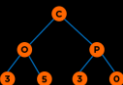


Min Heap: Higher

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

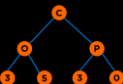
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```
Max heap, lowers stores elements to the left of median
Min heap, highers stores elements to the right of median

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 highers.min)
```



Resources

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

Questions