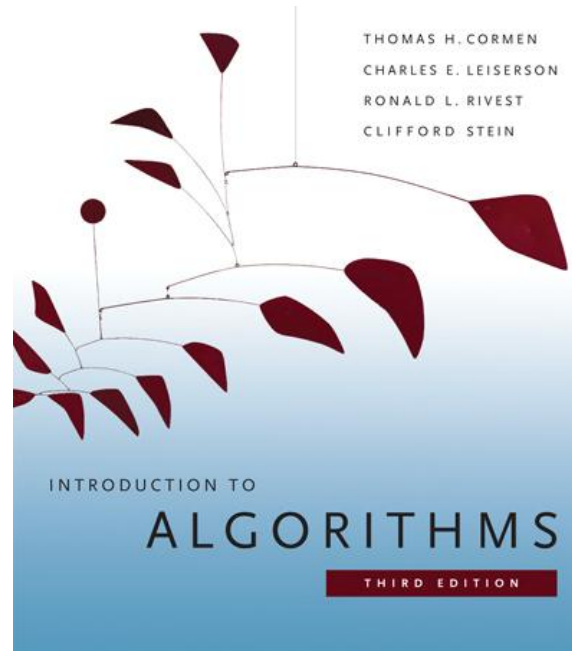


# 6.006- *Introduction to Algorithms*



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## *Lecture 4*

# Menu

- Priority Queues
- Heaps
- Heapsort

# Priority Queue

A data structure implementing a set  $S$  of elements, each associated with a key, supporting the following operations:

$\text{insert}(S, x)$  : insert element  $x$  into set  $S$

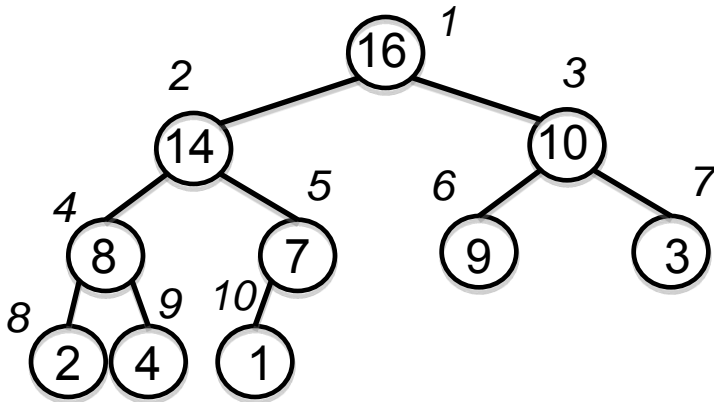
$\text{max}(S)$  : return element of  $S$  with largest key

$\text{extract\_max}(S)$  : return element of  $S$  with largest key and remove it from  $S$

$\text{increase\_key}(S, x, k)$  : increase the value of element  $x$ 's key to new value  $k$   
(assumed to be as large as current value)

# Heap

- Implementation of a priority queue
- An **array**, visualized as a nearly complete **binary tree**
- **Max Heap Property**: The key of a node is  $\geq$  than the keys of its children  
(**Min Heap** defined analogously)



1	2	3	4	5	6	7	8	9	10
16	14	10	8	7	9	3	2	4	1

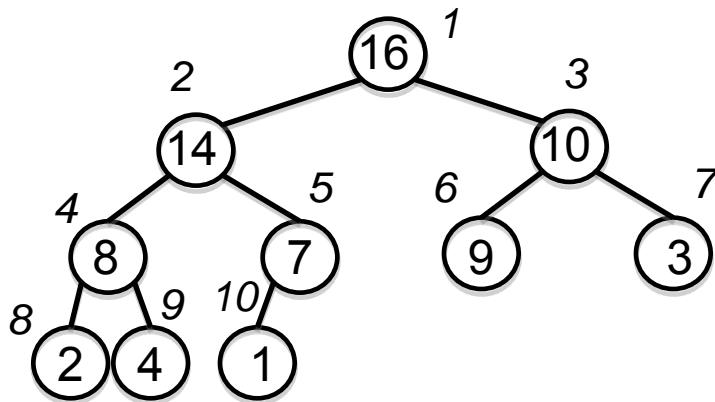
# Heap as a Tree

root of tree: first element in the array, corresponding to  $i = 1$

$\text{parent}(i) = i/2$ : returns index of node's parent

$\text{left}(i) = 2i$ : returns index of node's left child

$\text{right}(i) = 2i+1$ : returns index of node's right child



1	2	3	4	5	6	7	8	9	10
16	14	10	8	7	9	3	2	4	1

No pointers required! Height of a binary heap is  $O(\lg n)$

# Heap Operations

`build_max_heap` : produce a max-heap from an unordered array

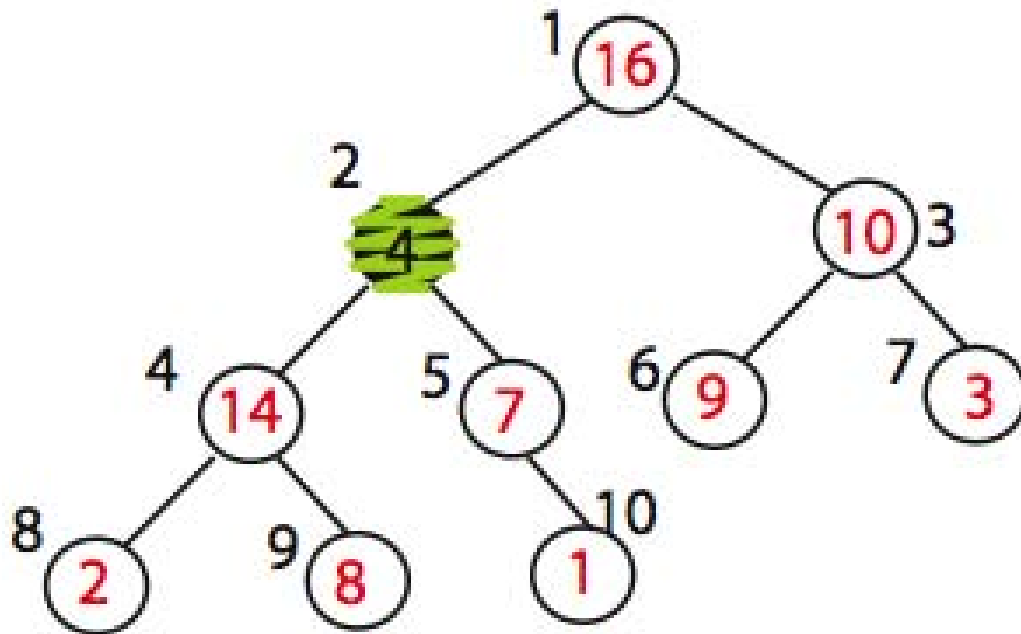
`max_heapify` : correct a **single** violation of the heap property in a subtree at its root

`insert, extract_max, heapsort`

# Max\_heapify

- Assume that the trees rooted at  $\text{left}(i)$  and  $\text{right}(i)$  are max-heaps
- If element  $A[i]$  violates the max-heap property, correct violation by “trickling” element  $A[i]$  down the tree, making the subtree rooted at index  $i$  a max-heap

# Max\_heapify (Example)

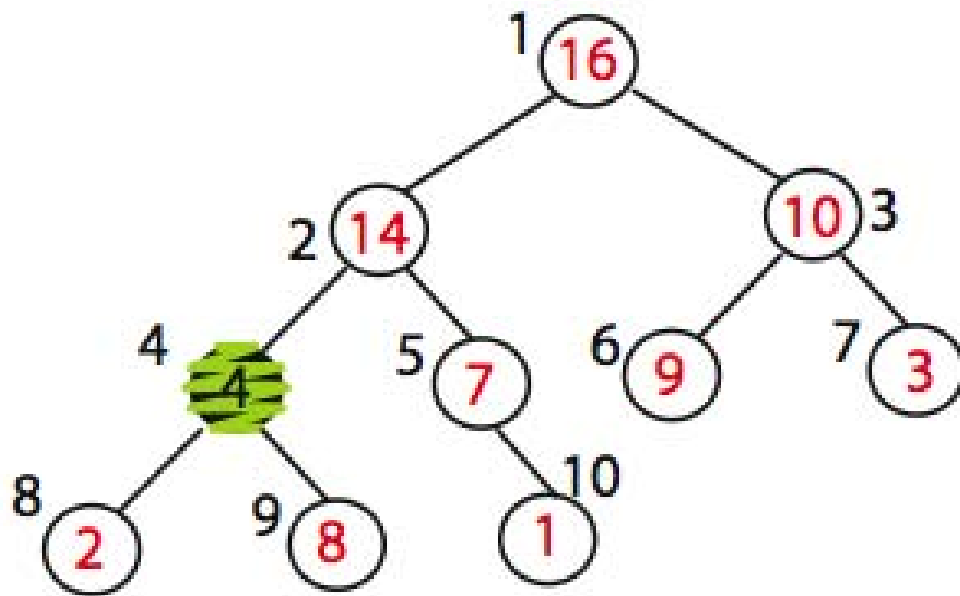


MAX\_HEAPIFY (A,2)  
heap\_size[A] = 10

Node 10 is the left child of node 5 but is drawn to the right for convenience

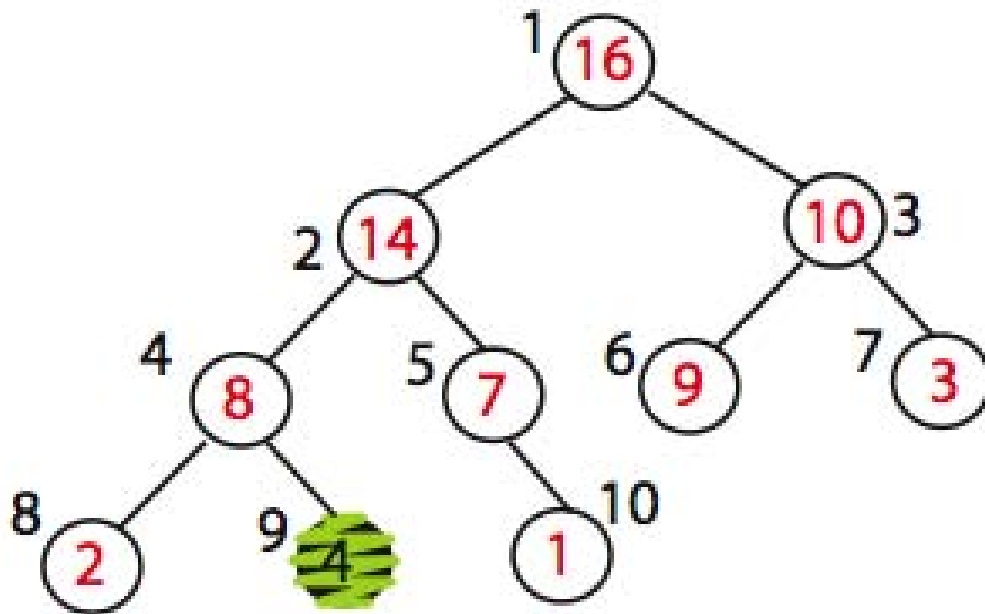


# Max\_heapify (Example)



Exchange A[2] with A[4]  
Call MAX\_HEAPIFY(A,4)  
because max\_heap property  
is violated

# Max\_heapify (Example)



Exchange A[4] with A[9]  
No more calls

Time=?  $O(\log n)$

# Max\_Heapify Pseudocode

$l = \text{left}(i)$

$r = \text{right}(i)$

if ( $l \leq \text{heap-size}(A)$  and  $A[l] > A[i]$ )

    then  $\text{largest} = l$      else  $\text{largest} = i$

if ( $r \leq \text{heap-size}(A)$  and  $A[r] > A[\text{largest}]$ )

    then  $\text{largest} = r$

if  $\text{largest} \neq i$

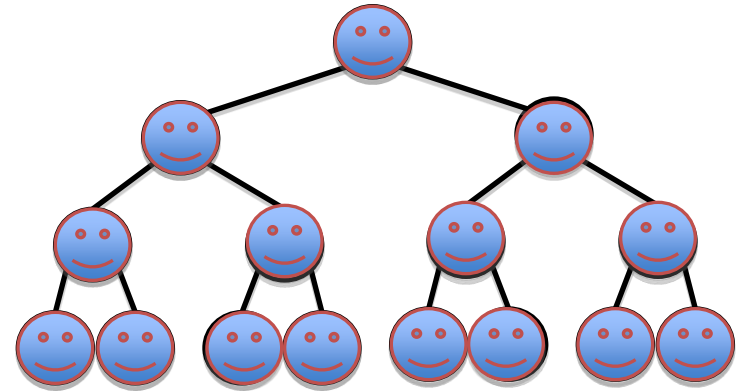
    then exchange  $A[i]$  and  $A[\text{largest}]$

    Max\_Heapify( $A, \text{largest}$ )

# Build\_Max\_Heap(A)

Converts  $A[1 \dots n]$  to a max heap

```
Build_Max_Heap(A):  
  for  $i = n/2$  downto 1  
    do Max_Heapify(A, i)
```



Why start at  $n/2$ ?

Because elements  $A[n/2 + 1 \dots n]$  are all leaves of the tree

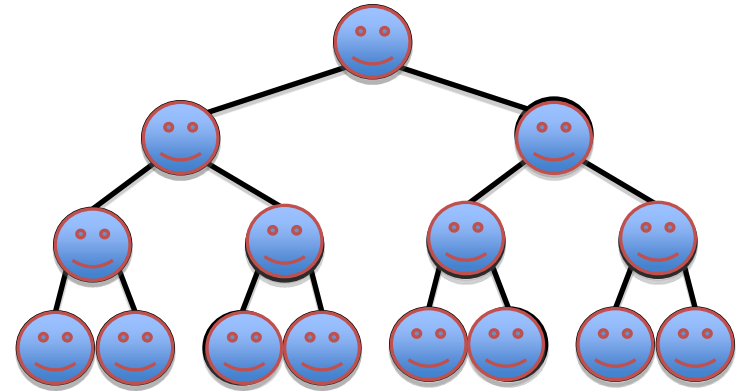
$2i > n$ , for  $i > n/2 + 1$

Time=?  $O(n \log n)$  via simple analysis

# Build\_Max\_Heap(A) Analysis

Converts  $A[1 \dots n]$  to a max heap

```
Build_Max_Heap(A):  
  for  $i = n/2$  downto 1  
    do Max_Heapify(A, i)
```

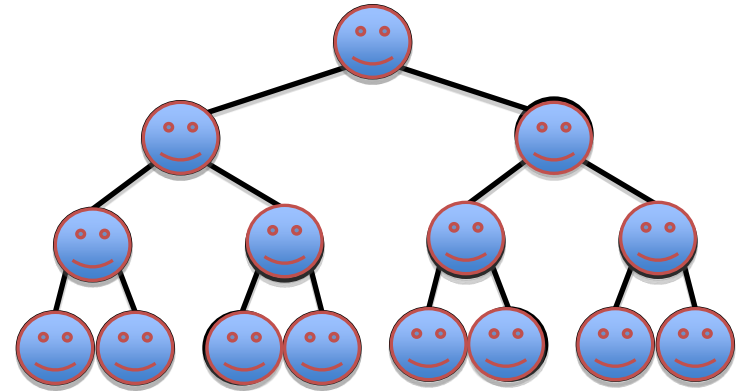


Observe however that Max\_Heapify takes  $O(1)$  for time for nodes that are one level above the leaves, and in general,  $O(l)$  for the nodes that are  $l$  levels above the leaves. We have  $n/4$  nodes with level 1,  $n/8$  with level 2, and so on till we have one root node that is  $\lg n$  levels above the leaves.

# Build\_Max\_Heap(A) Analysis

Converts  $A[1 \dots n]$  to a max heap

```
Build_Max_Heap(A):  
  for i=n/2 downto 1  
    do Max_Heapify(A, i)
```



Total amount of work in the for loop can be summed as:

$$n/4 (1 c) + n/8 (2 c) + n/16 (3 c) + \dots + 1 (\lg n c)$$

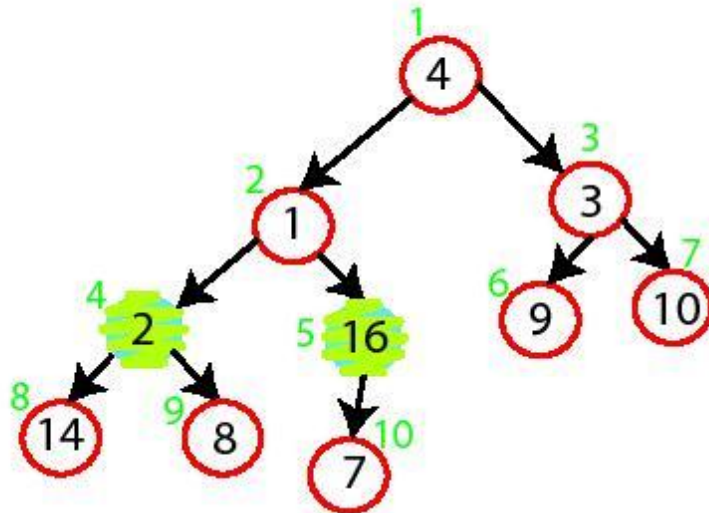
Setting  $n/4 = 2^k$  and simplifying we get:

$$c 2^k (1/2^0 + 2/2^1 + 3/2^2 + \dots (k+1)/2^k)$$

The term in brackets is bounded by a constant!

This means that Build\_Max\_Heap is  $O(n)$

# Build-Max-Heap Demo



A

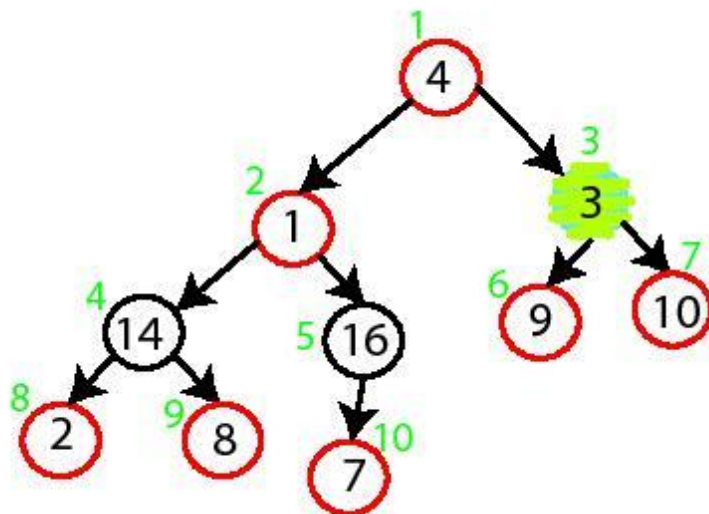
4	1	3	2	16	9	10	14	8	7
---	---	---	---	----	---	----	----	---	---

MAX-HEAPIFY (A,5)

no change

MAX-HEAPIFY (A,4)

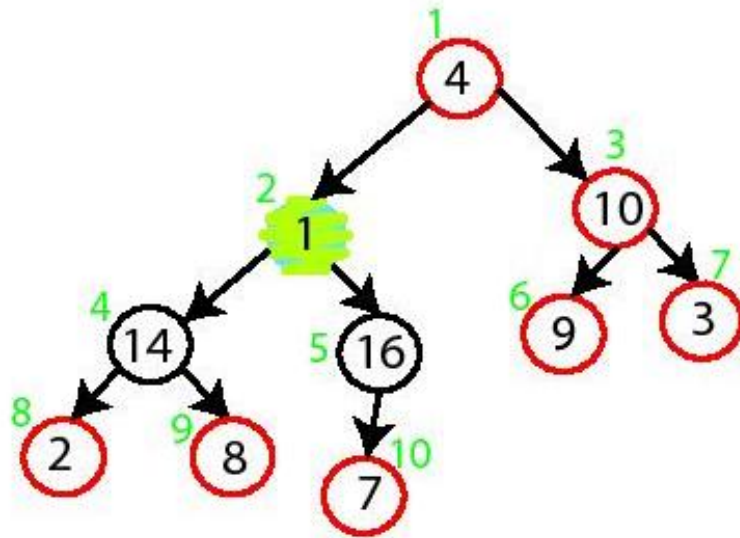
Swap A[4] and A[8]



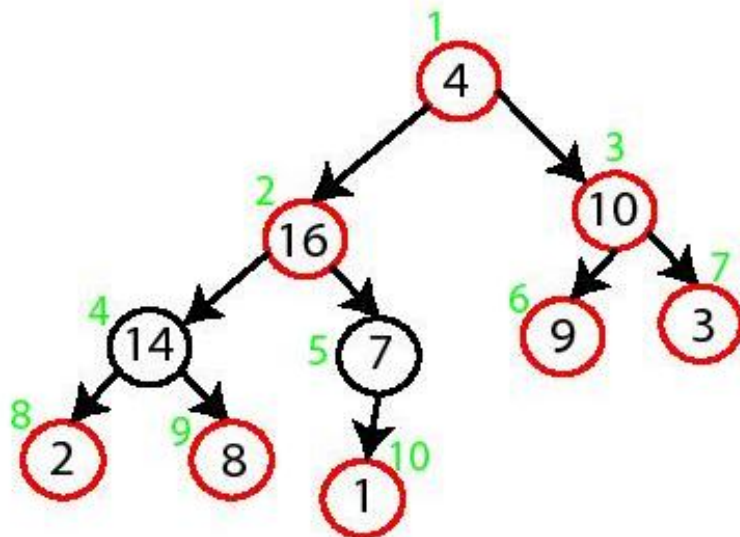
MAX-HEAPIFY (A,3)

Swap A[3] and A[7]

# Build-Max-Heap Demo



MAX-HEAPIFY (A,2)  
Swap A[2] and A[5]  
Swap A[5] and A[10]



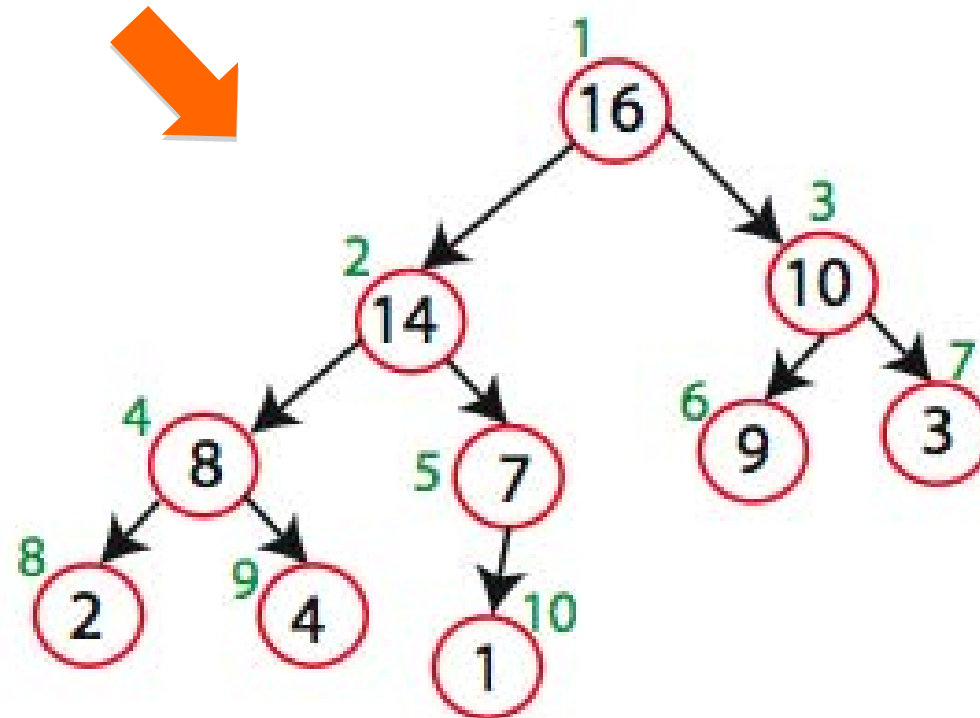
MAX-HEAPIFY (A,1)  
Swap A[1] with A[2]  
Swap A[2] with A[4]  
Swap A[4] with A[9]



# Build-Max-Heap

A

4	1	3	2	16	9	10	14	8	7
---	---	---	---	----	---	----	----	---	---



# Heap-Sort

Sorting Strategy:

1. Build Max Heap from unordered array;

# Heap-Sort

Sorting Strategy:

1. Build Max Heap from unordered array;
2. Find maximum element  $A[1]$ ;
3. Swap elements  $A[n]$  and  $A[1]$ :  
now max element is at the end of the array!

# Heap-Sort

Sorting Strategy:

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4. Discard node  $n$  from heap  
(by decrementing heap-size variable)

# Heap-Sort

Sorting Strategy:

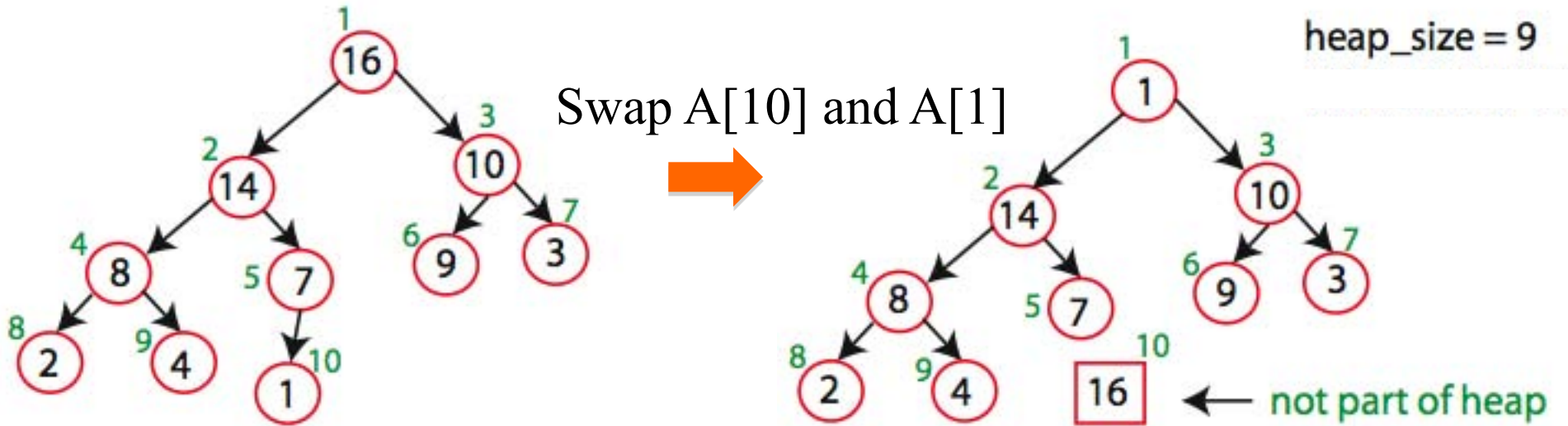
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5. New root may violate max heap property, but its children are max heaps. Run `max_heapify` to fix this.

# Heap-Sort

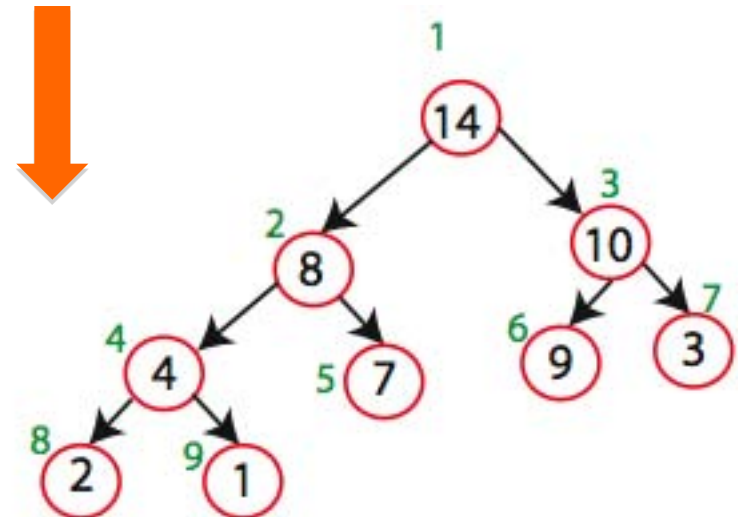
Sorting Strategy:

1. Build Max Heap from unordered array;
2. Find maximum element  $A[1]$ ;
3. Swap elements  $A[n]$  and  $A[1]$ :  
now max element is at the end of the array!
4. Discard node  $n$  from heap  
(by decrementing heap-size variable)
5. New root may violate max heap property, but its children are max heaps. Run `max_heapify` to fix this.
6. Go to Step 2 unless heap is empty.

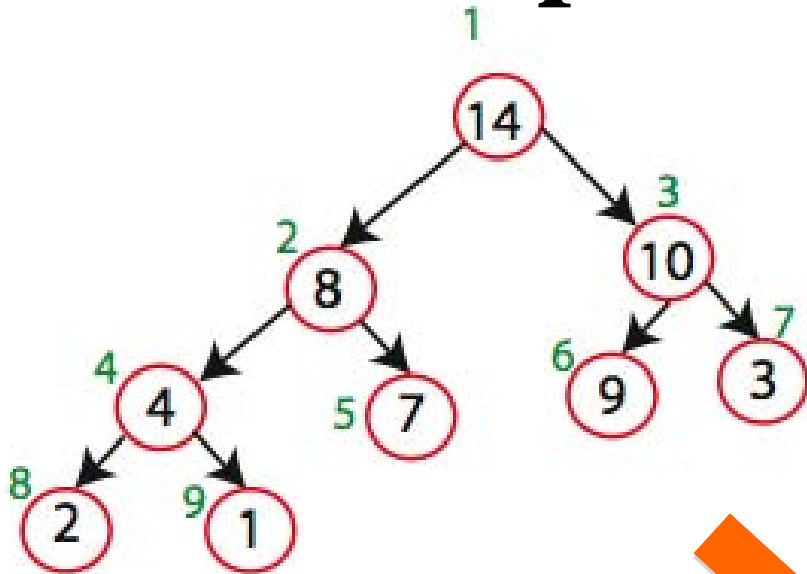
# Heap-Sort Demo



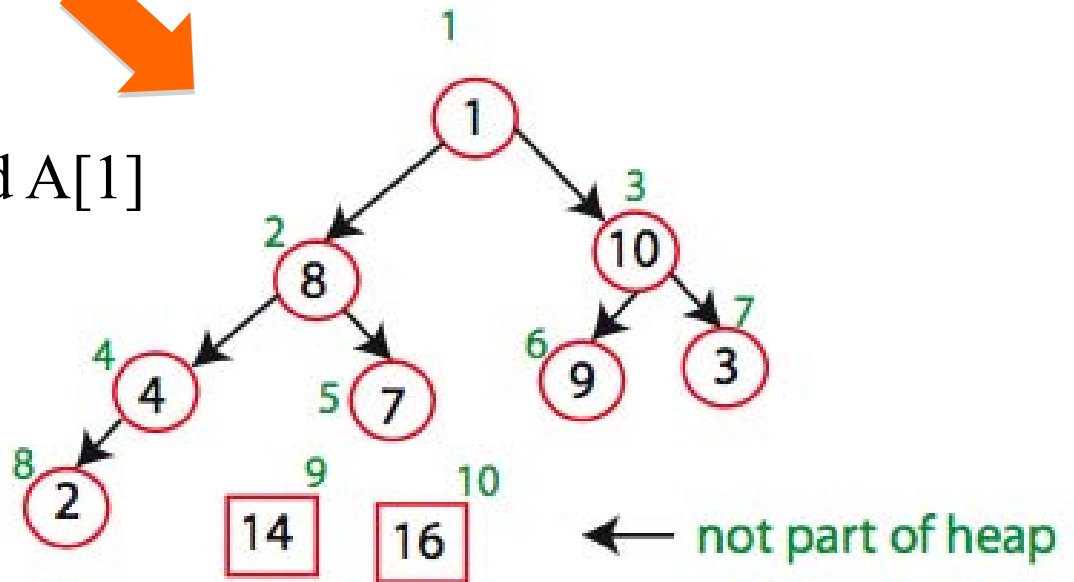
Max\_heapify(A,1)



# Heap-Sort Demo



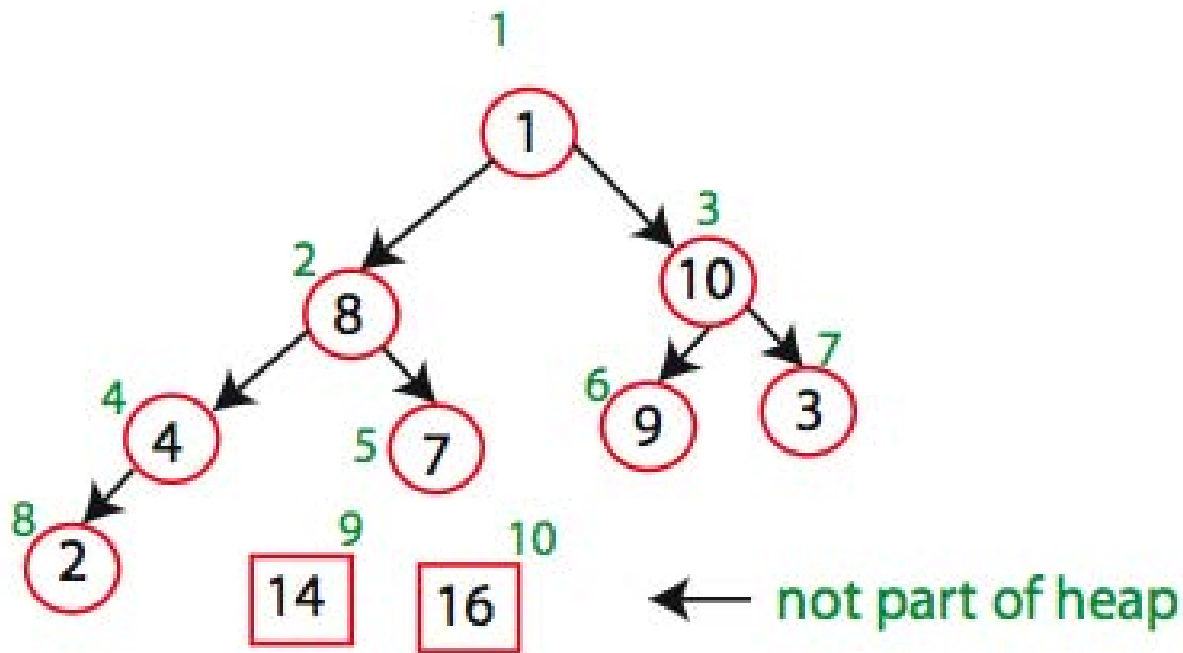
Swap  $A[9]$  and  $A[1]$



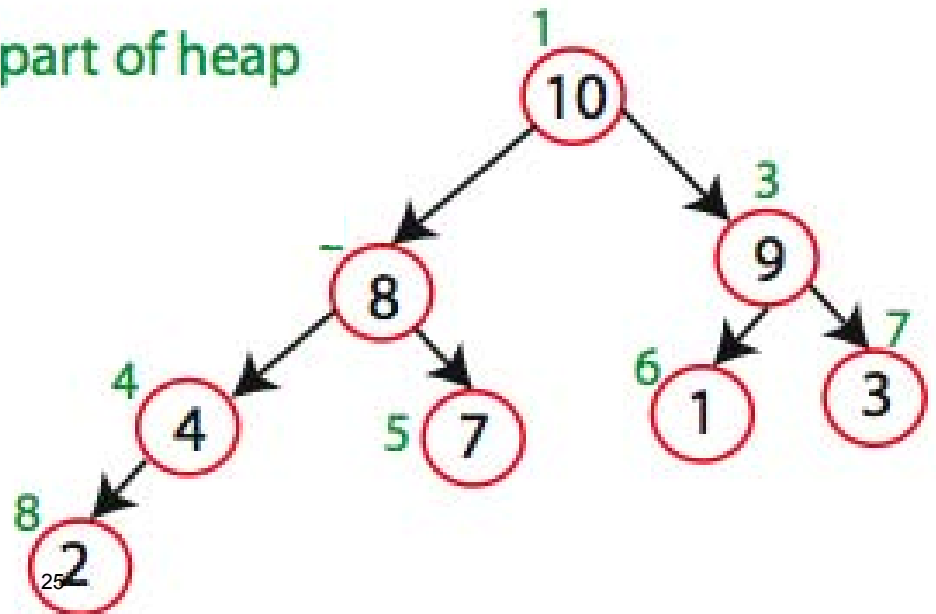
<sup>24</sup>  
 $\text{MAX\_HEAPIFY}(A,1)$



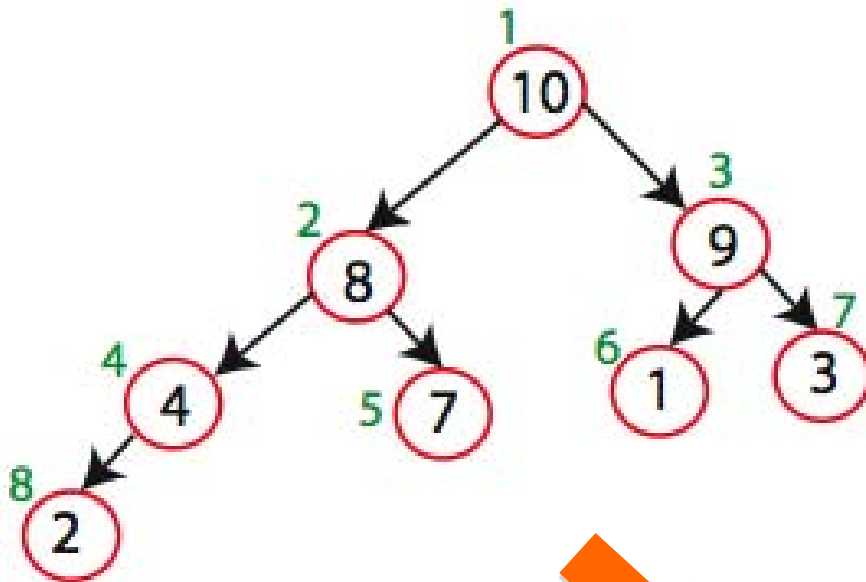
# Heap-Sort Demo



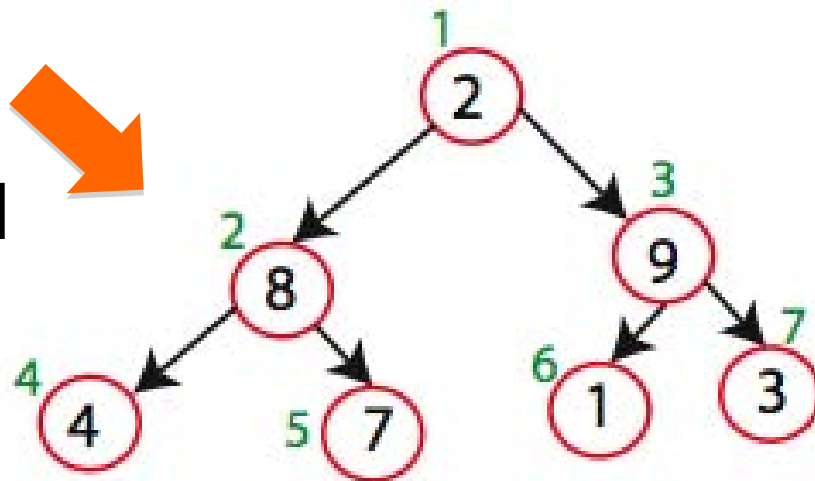
MAX\_HEAPIFY (A,1)



# Heap-Sort Demo



Swap  $A[8]$  and  $A[1]$



8  
10

9  
14

10  
16

26

← not part of heap

# Heap-Sort

Running time:

after  $n$  iterations the Heap is empty  
every iteration involves a swap and a max\_heapify  
operation; hence it takes  $O(\log n)$  time

Overall  $O(n \log n)$

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