

Heapsort

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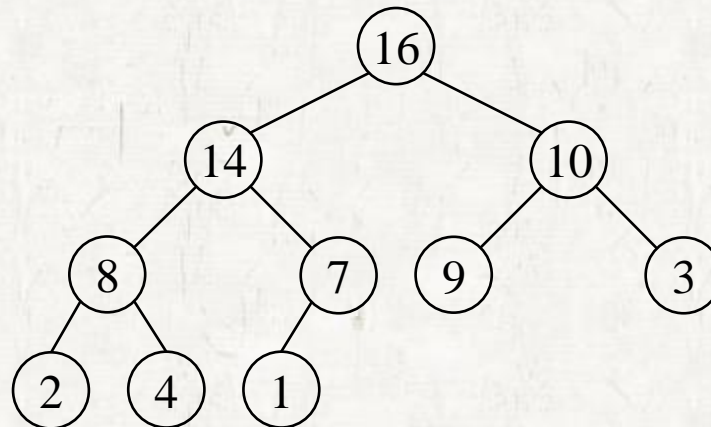
- Heaps
- Building a heap
- The heapsort algorithm
- Priority queues

Heapsort

- Like merge sort
 - Running time is $O(n \lg n)$
- Like insertion sort
 - Heapsort sorts in place.

Heaps

- The shape of a (binary) heap
 - A nearly *complete binary tree*.
 - Complete binary tree is in which all leaves have the same depth and all internal nodes have degree 2.



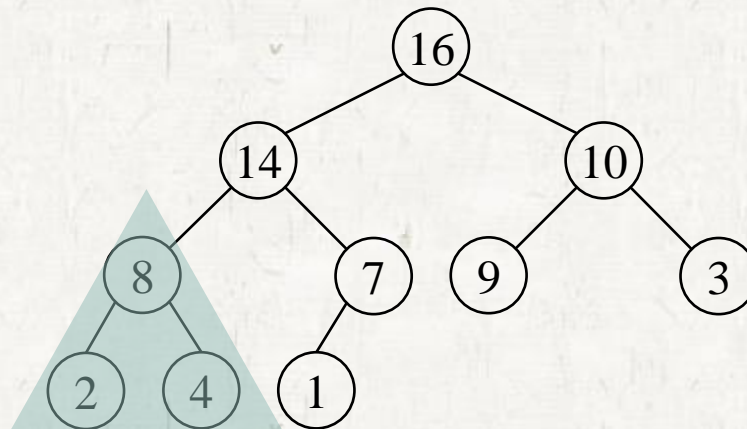
Heaps

- Heap property
 - 2 kinds of binary heaps
 - *max-heaps* and *min-heaps*

Heaps

• *max-heap property*

- $A[\text{PARENT}(i)] \geq A[i]$
 - The parent is bigger than its child.
 - The root node has the largest element.
 - The root of any subtree has the largest element among the subtree.



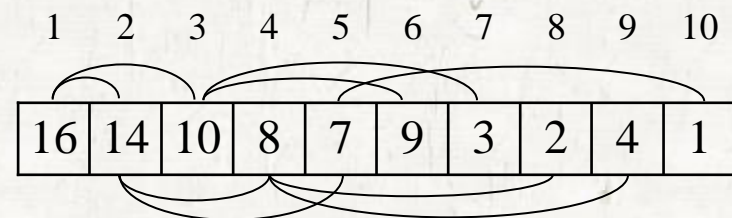
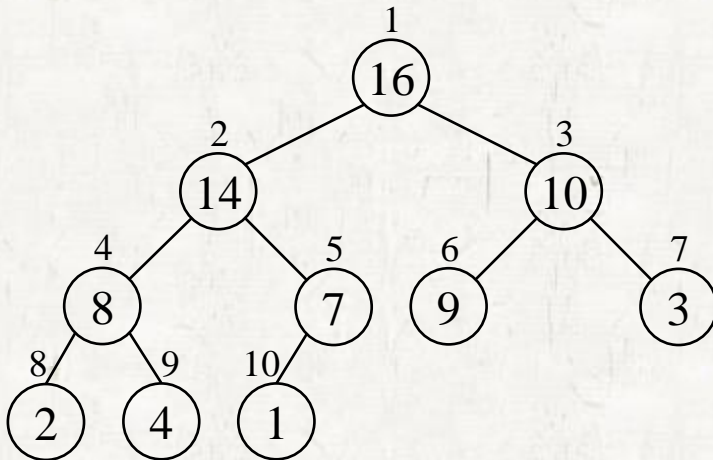
Heaps

• *min-heap property*

- $A[\text{PARENT}(i)] \leq A[i]$
 - A child is bigger than its parent.
 - The root node has the smallest element.

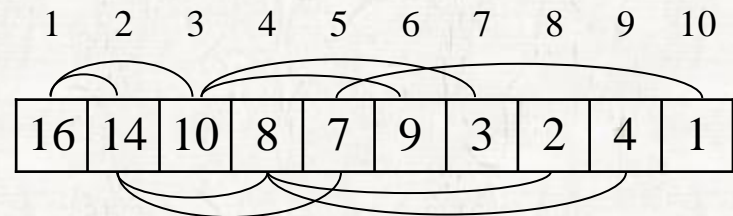
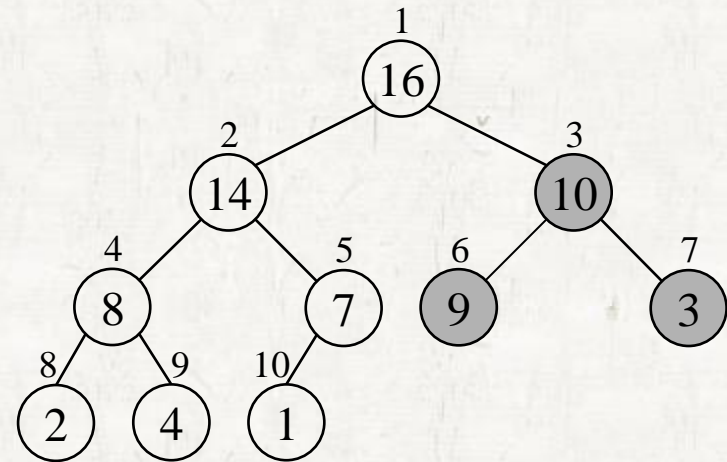
Heaps

- A heap can be stored in an array.
 - The root is stored in $A[1]$.
 - All elements are stored in level order.



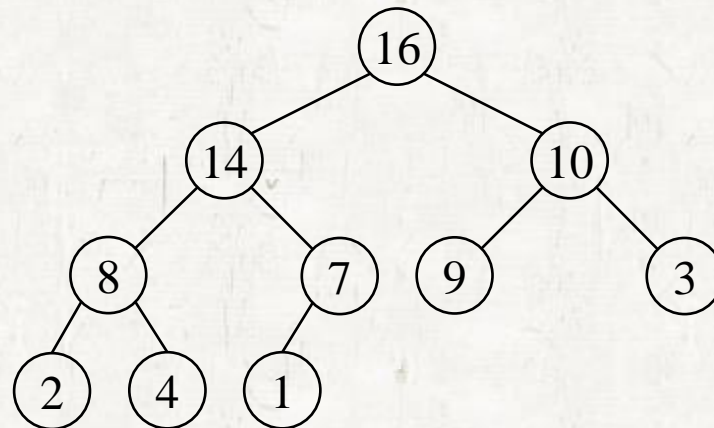
Heaps

- $\text{PARENT}(i)$ $\left\lfloor \frac{i}{2} \right\rfloor$
return
- $\text{LEFT}(i)$
return $2i$
- $\text{RIGHT}(i)$
return $2i + 1$



Heaps

- The height of a node
 - The number of edges on the longest simple downward path from the node to a leaf.



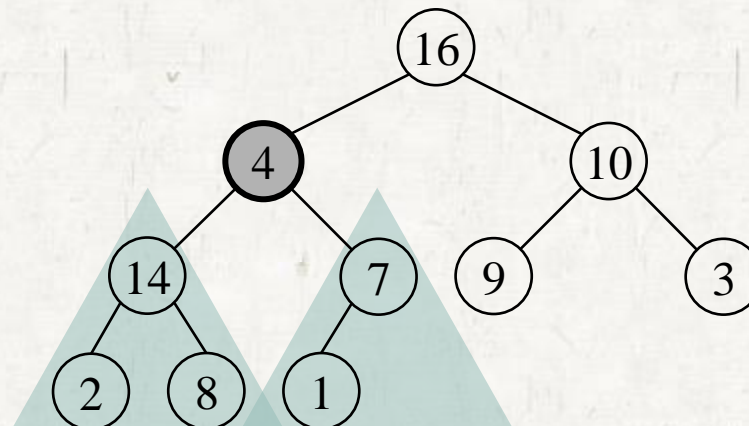
Heaps

- The height of a heap
 - The height of the root.
 - $\Theta(\lg n)$
 - Since a heap of n elements is based on a complete binary tree.

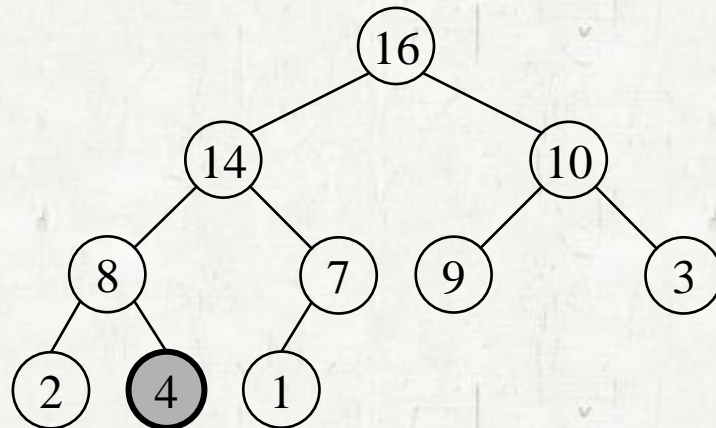
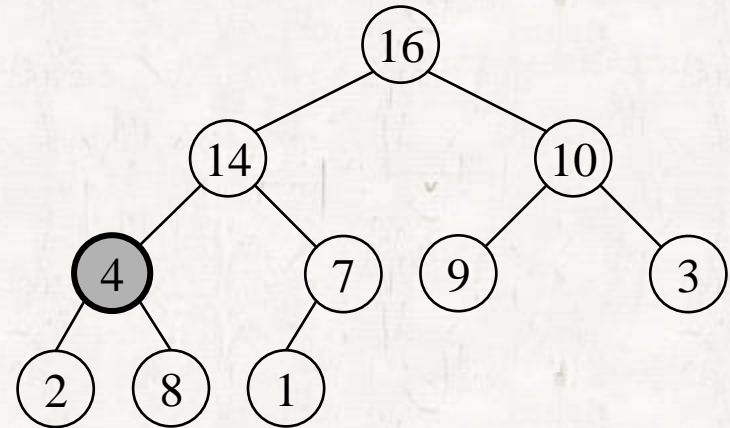
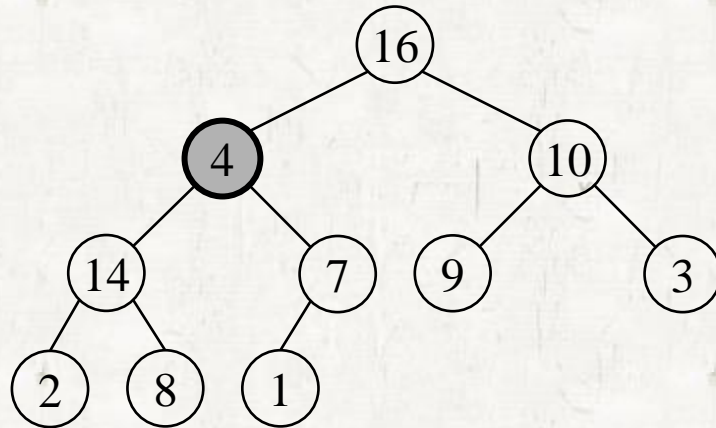
Maintaining the heap property

• Max-Heapify

- Input : A node whose left and right subtrees are max-heaps, but the value at the node may be smaller than those of its children, thus violating the max-heap property.
- Let the value at the node “float down” in the max-heap so that the subtree rooted at the node becomes a max-heap.



Maintaining the heap property



Maintaining the heap property

- The running time of MAX-HEAPIFY
 - $T(n)$ where n is the number of nodes in the subtree.
 - $\Theta(1)$ time to exchange values
 - $O(h) = O(\lg n)$ time in total

Maintaining the heap property

• BUILD-MAX-HEAP

BUILD-MAX-HEAP(*A*)

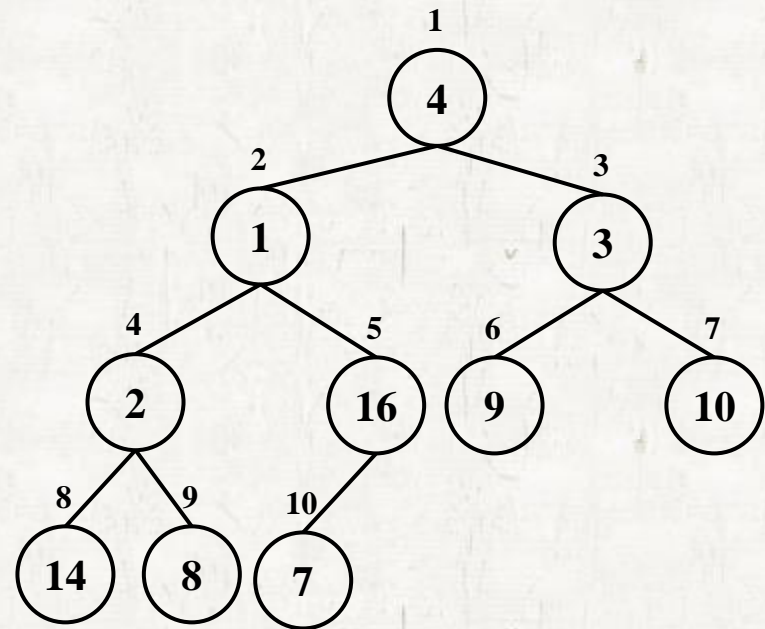
1. $A.heap-size = A.length$
2. **for** $i = \lfloor A.length/2 \rfloor$ **downto** 1
3. MAX-HEAPIFY(*A*, *i*)

Building a heap

• BUILD-MAX-HEAP

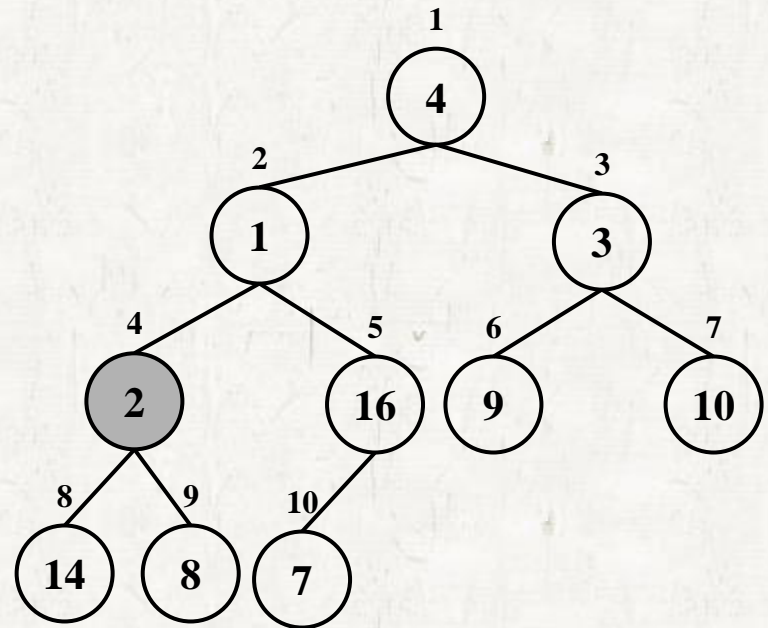
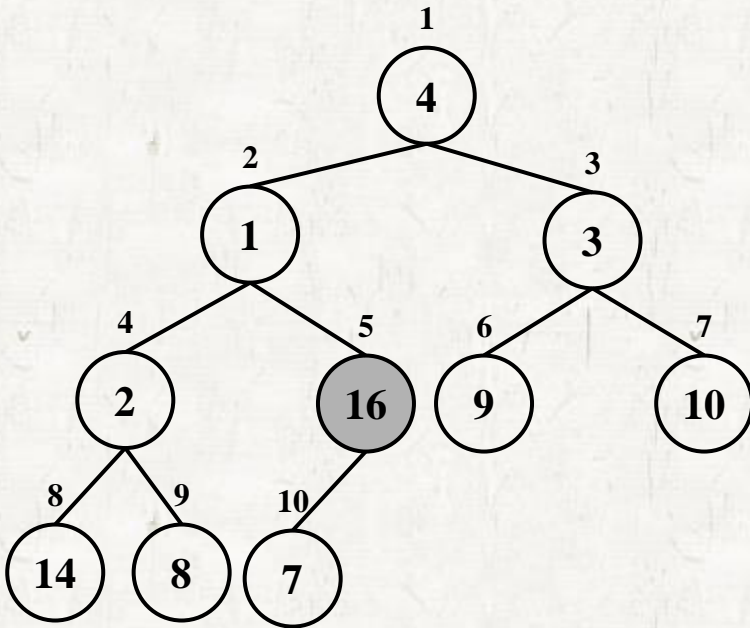
- The input array with 10 elements and its binary tree representation.

4	1	3	2	16	9	10	14	8	7
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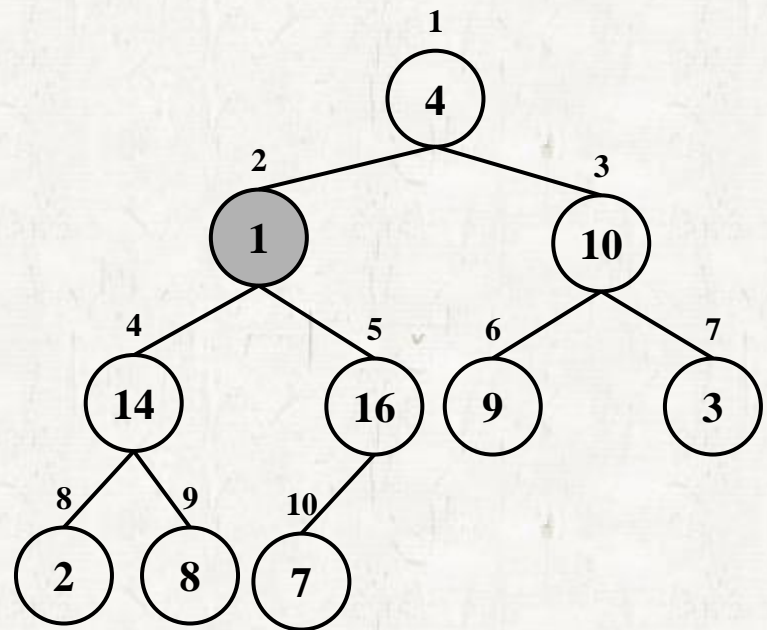
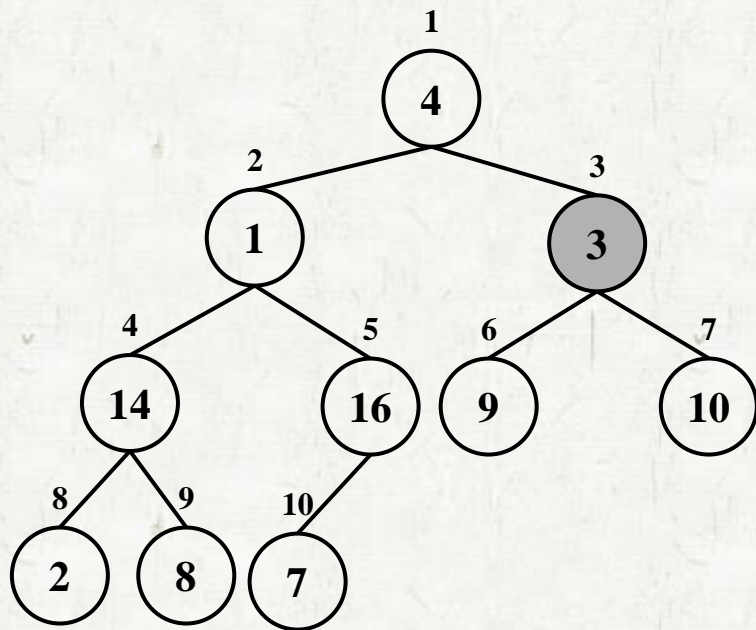


Building a heap

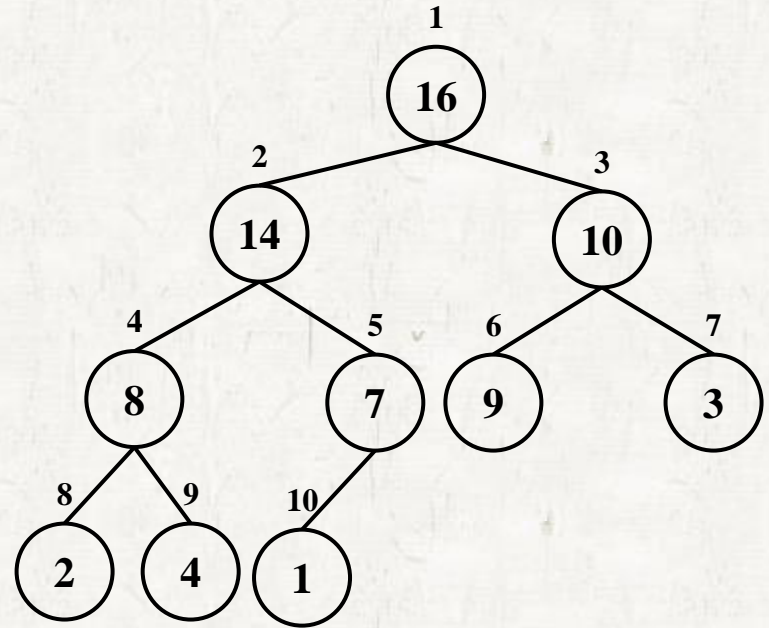
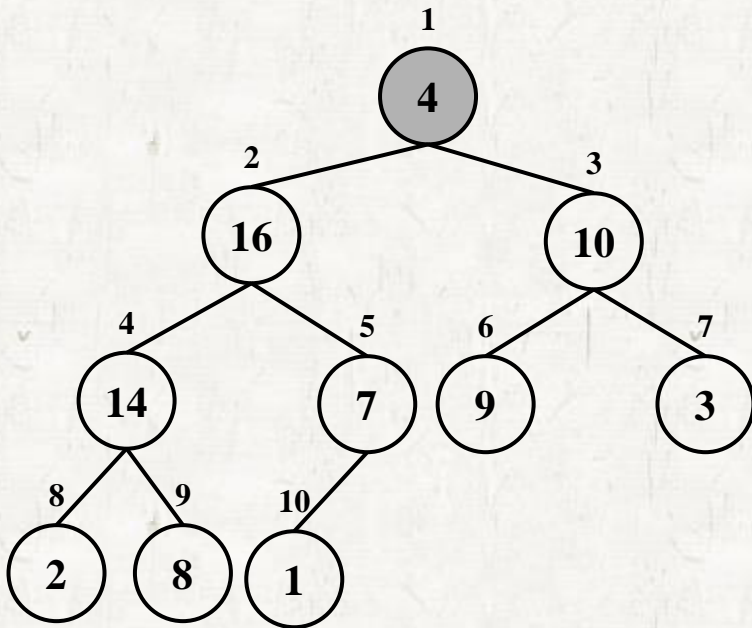
- Call MAX-HEAPIFY(A, i) at the rightmost node that has the child from the bottom. $i = \lfloor A.length/2 \rfloor$



Building a heap



Building a heap



Building a heap

- Running time

- Upper bound

- Each call to MAX-HEAPIFY costs $O(\lg n)$ time, and there are $O(n)$ such calls, Thus, the running time is $O(n \lg n)$.

Building a heap

- Running time

- Tighter bound

- The time for MAX-HEAPIFY to run at a node varies with the height of the node in the tree, and the heights of most nodes are small.
 - Our tighter analysis relies on the properties that an n -element heap has height $\lceil \lg n \rceil$ and at most $\lceil n/2^{h+1} \rceil$ nodes of any height h .

Building a heap

• Tighter bound

- The running time of MAX-HEAPIFY on a node of height h is $O(h)$, so the total cost of BUILD-MAX-HEAP is

$$\sum_{h=0}^{\lfloor \lg n \rfloor} \left\lceil \frac{n}{2^{h+1}} \right\rceil O(h) = O\left(n \sum_{h=0}^{\lfloor \lg n \rfloor} \frac{h}{2^h}\right)$$

- The last summation can be evaluated as follows.

$$\sum_{h=0}^{\infty} \frac{h}{2^h} = \frac{1/2}{(1-1/2)^2} = 2$$

Building a heap

- Thus, the running time of BUILD-MAX-HEAP can be bounded as

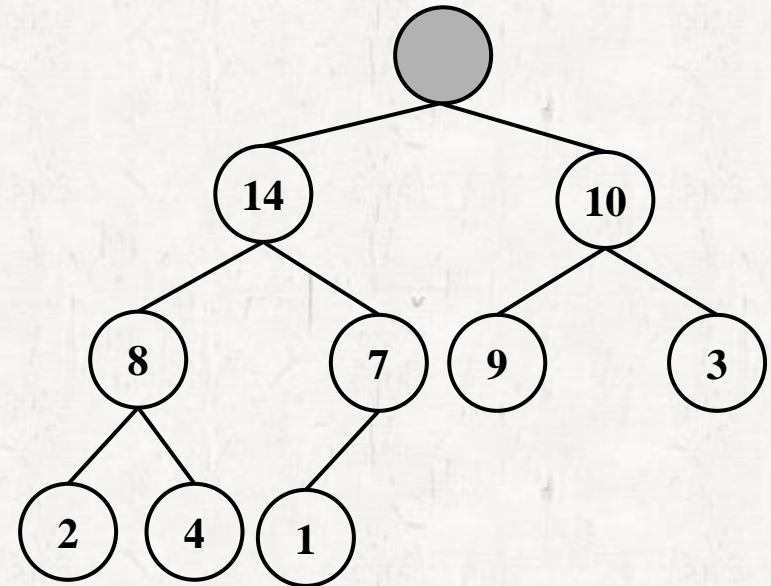
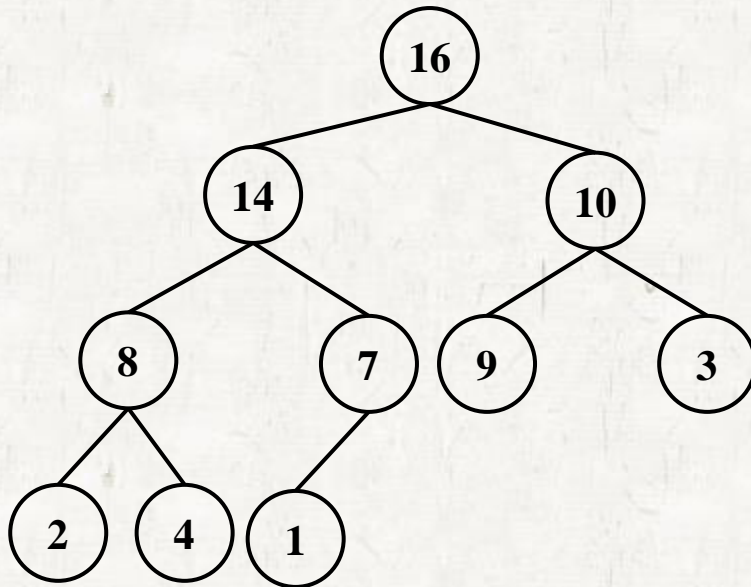
$$O\left(n \sum_{h=0}^{\lfloor \lg n \rfloor} \frac{h}{2^h}\right) = O\left(n \sum_{h=0}^{\infty} \frac{h}{2^h}\right) = O(n)$$

- Hence, we can build a max-heap in linear time.

Extract-Max

Extract-Max

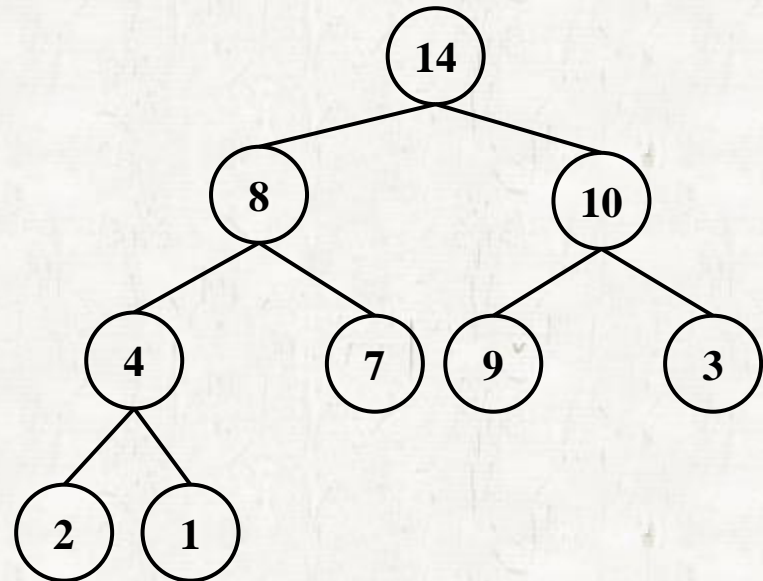
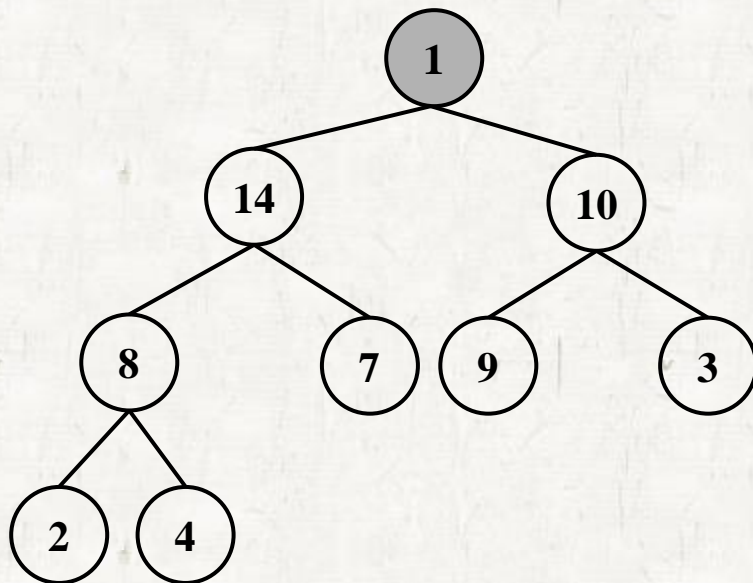
- Remove the maximum element from a heap
- Restore the structure to a heap



Extract-Max

• Extract-Max

- Restore the structure to a heap

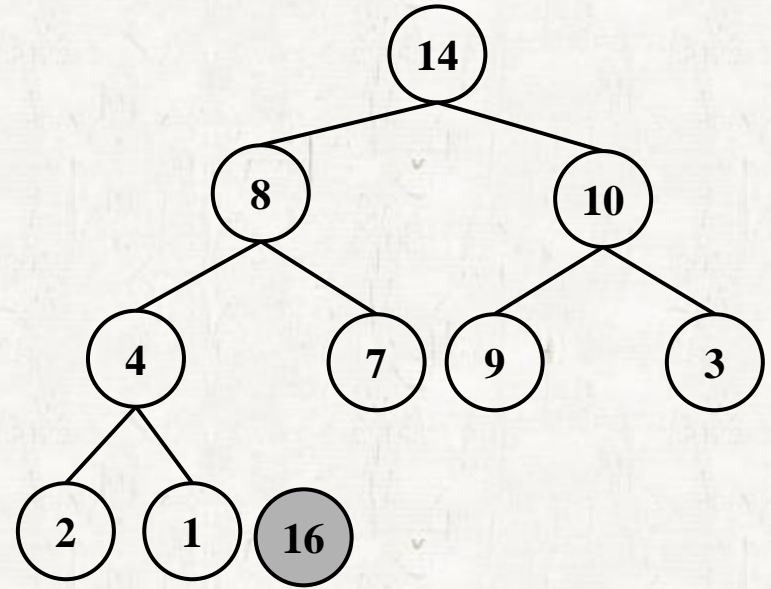
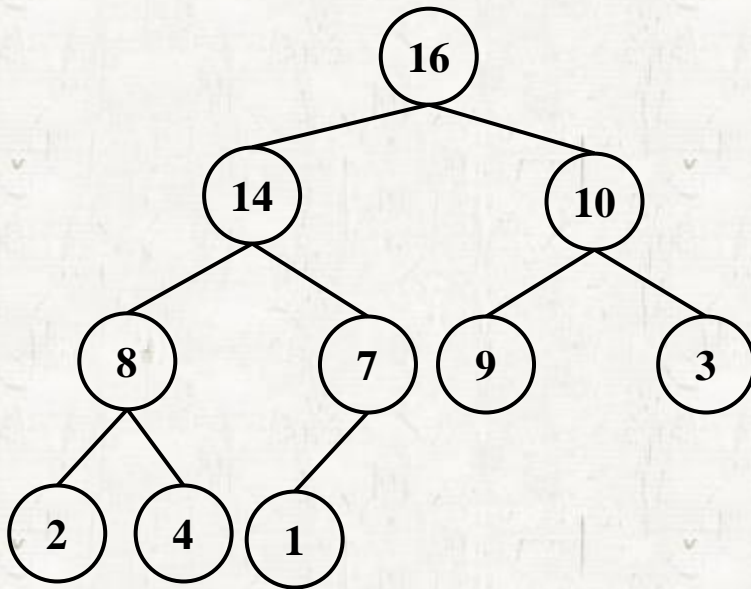


- $O(\lg n)$

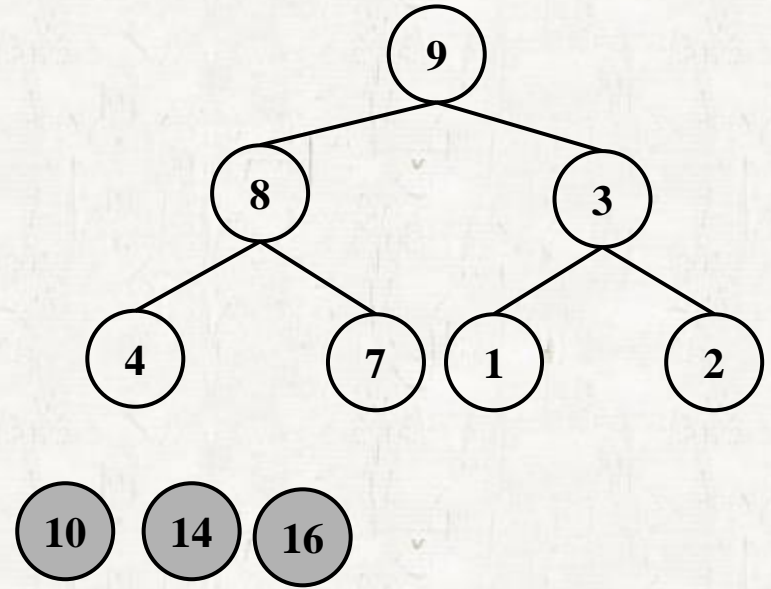
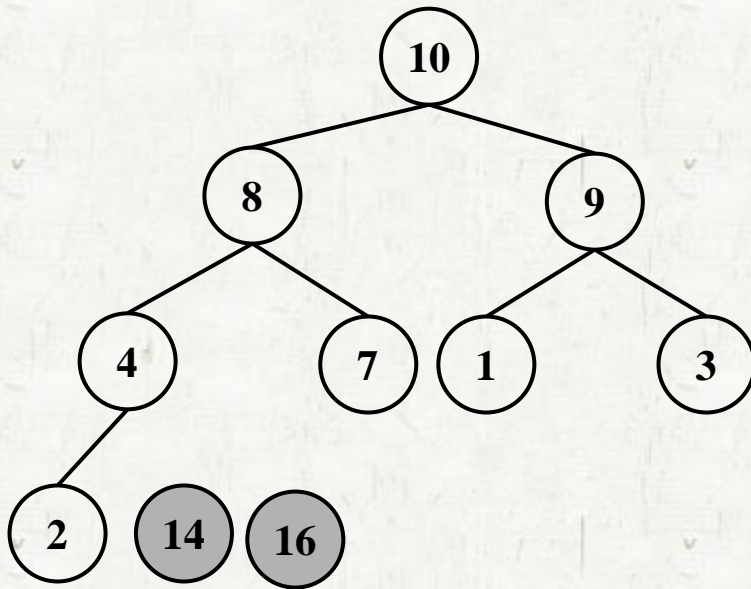
Heapsort

- The Heapsort algorithm
 - BUILD-MAX-HEAP on $A[1..n]$
 - $O(n)$ time.
 - Extract Max for n times
 - $O(n \lg n)$ time.

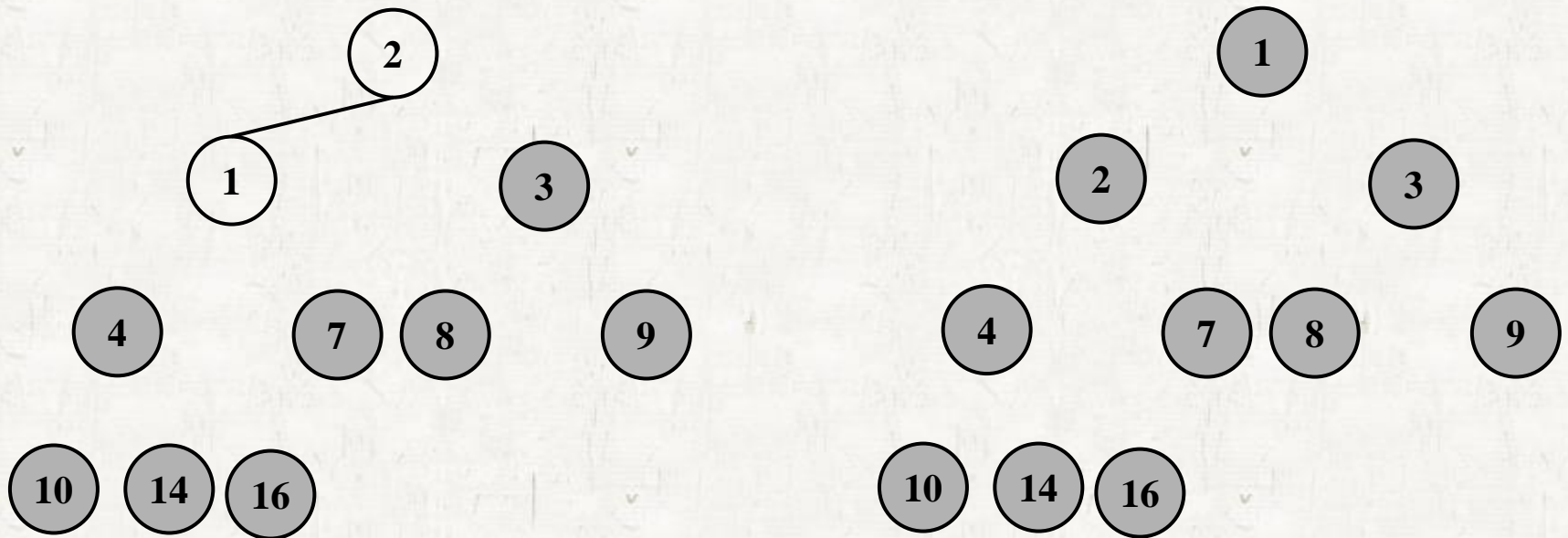
Heapsort



Heapsort



Heapsort



1	2	3	4	7	8	9	10	14	16
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Heapsort

HEAPSORT(A)

1. **BUILD-MAX-HEAP(A)**
2. **for** $i = A.length$ **downto** 2
3. exchange $A[1]$ with $A[i]$
4. $A.heap-size = A.heap-size - 1$
5. **MAX-HEAPIFY(A, 1)**

Heapsort

- The running time of Heapsort
 - $O(n \lg n)$
 - BUILD-MAX-HEAP: $O(n)$
 - MAX-HEAPFY: $O(\lg n)$

Priority queues

● Priority Queue

- A data structure for maintaining a set S of elements, each with an associated value called a key.
- A max-priority queue operations.
 - INSERT(S, x) inserts the element x into the set S .
 - MAXIMUM(S) returns the element of S with the largest key.
 - EXTRACT-MAX(S) removes and returns the element of S with the largest key.
 - INCREASE-KEY(S, x, k) increases the value of element x 's key to the new value k ,

Priority queues

● MAXIMUM

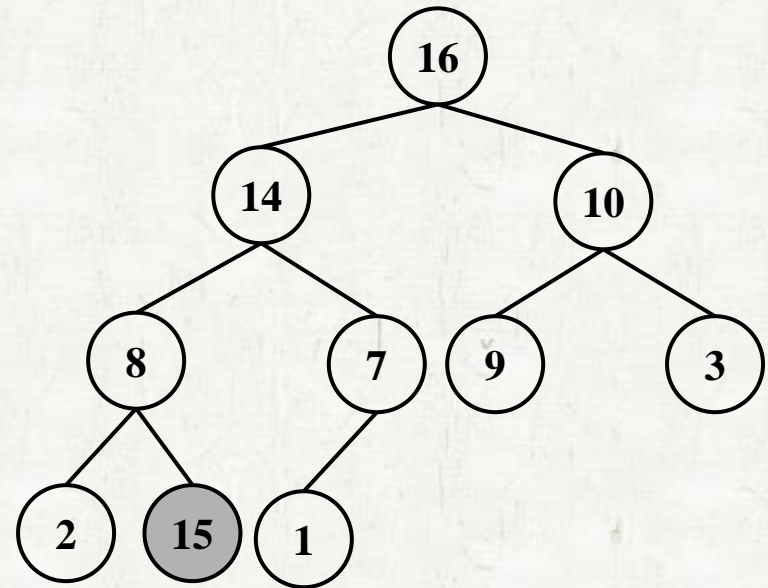
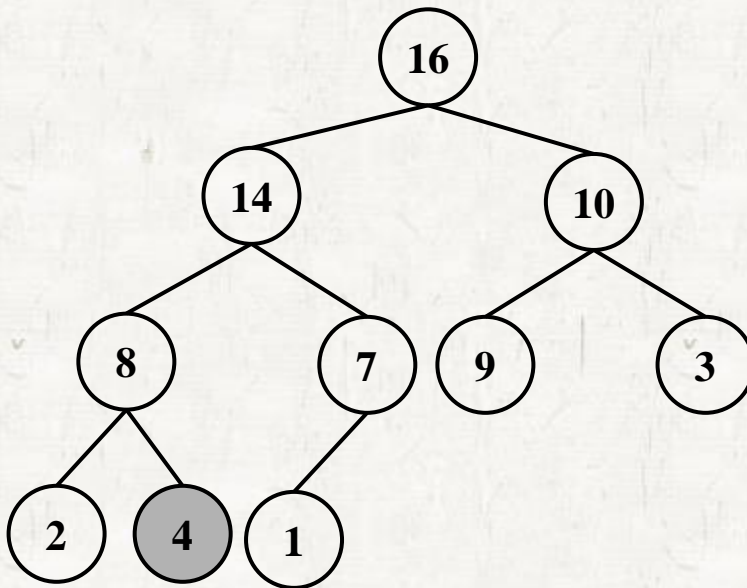
- Read the max value
- $O(1)$ time

● EXTRACT-MAX

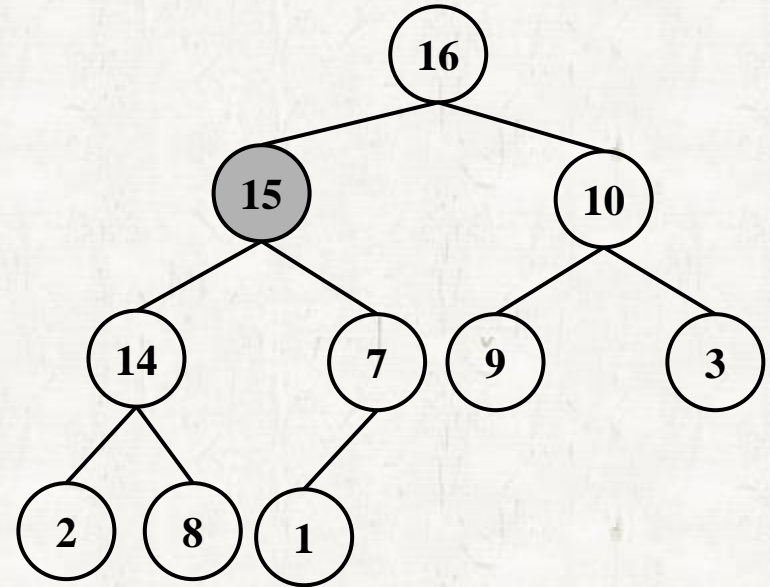
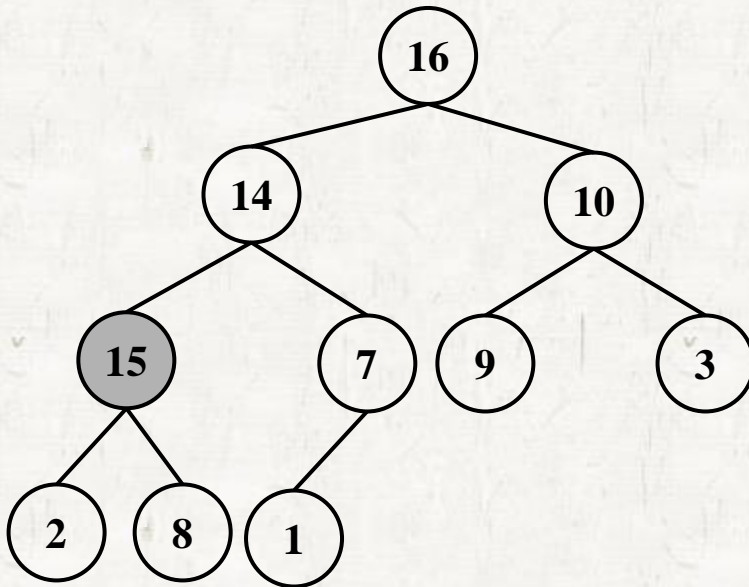
- Remove the max value + MAX-HEAPIFY
- $O(\lg n)$

Priority queues

● INCREASE-KEY



Priority queues



Priority queues

● HEAP-INCREASE-KEY

- $O(\lg n)$ time.

Priority queues

● INSERT

- $O(\lg n)$ time.

MAX-HEAP-INSERT(A, key)

1. $A.heap-size = A.heap-size + 1$

2. $A[A.heap-size] = -\infty$

3. **HEAP-INCREASE-KEY**($A, A.heap-size, key$)

Self-study

● Exercise 6.3-1

- BUILD-MAX-HEAP on $A = \langle 5, 3, 17, 10, 84, 19, 6, 22, 9 \rangle$

● Exercise 6.4-1

- HEAPSORT on $A = \langle 5, 13, 2, 25, 7, 17, 20, 8, 4 \rangle$

● Exercise 6.5-8 (6.5-7 in the 2nd ed.)

- Give an algorithm for HEAP-DELETE(A, i) in $O(\lg n)$ time.