

CMSC 132: Object-Oriented Programming II



Heaps & Priority Queues

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Overview

- **Binary trees**
 - **Complete**
- **Heaps**
 - **Insert**
 - **getSmallest**
- **Heap applications**
 - **Heapsort**
 - **Priority queues**

Complete Binary Trees

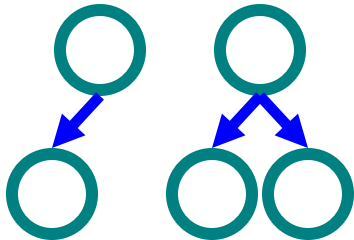
■ An binary tree (height h) where

■ Perfect tree to level $h-1$

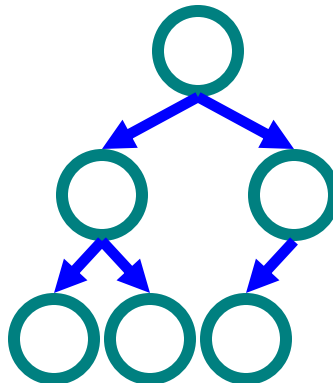
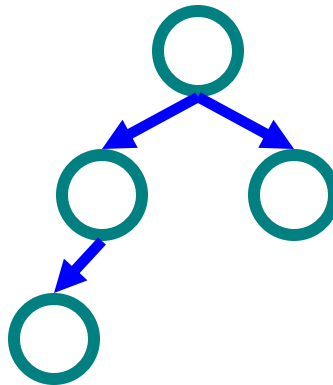
■ Leaves at level h are as far left as possible



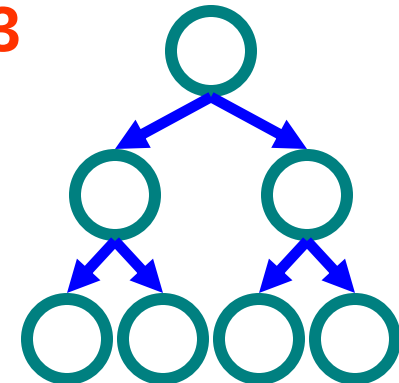
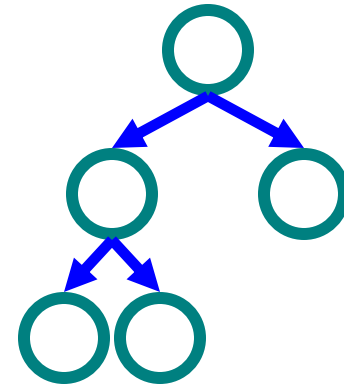
$h = 1$



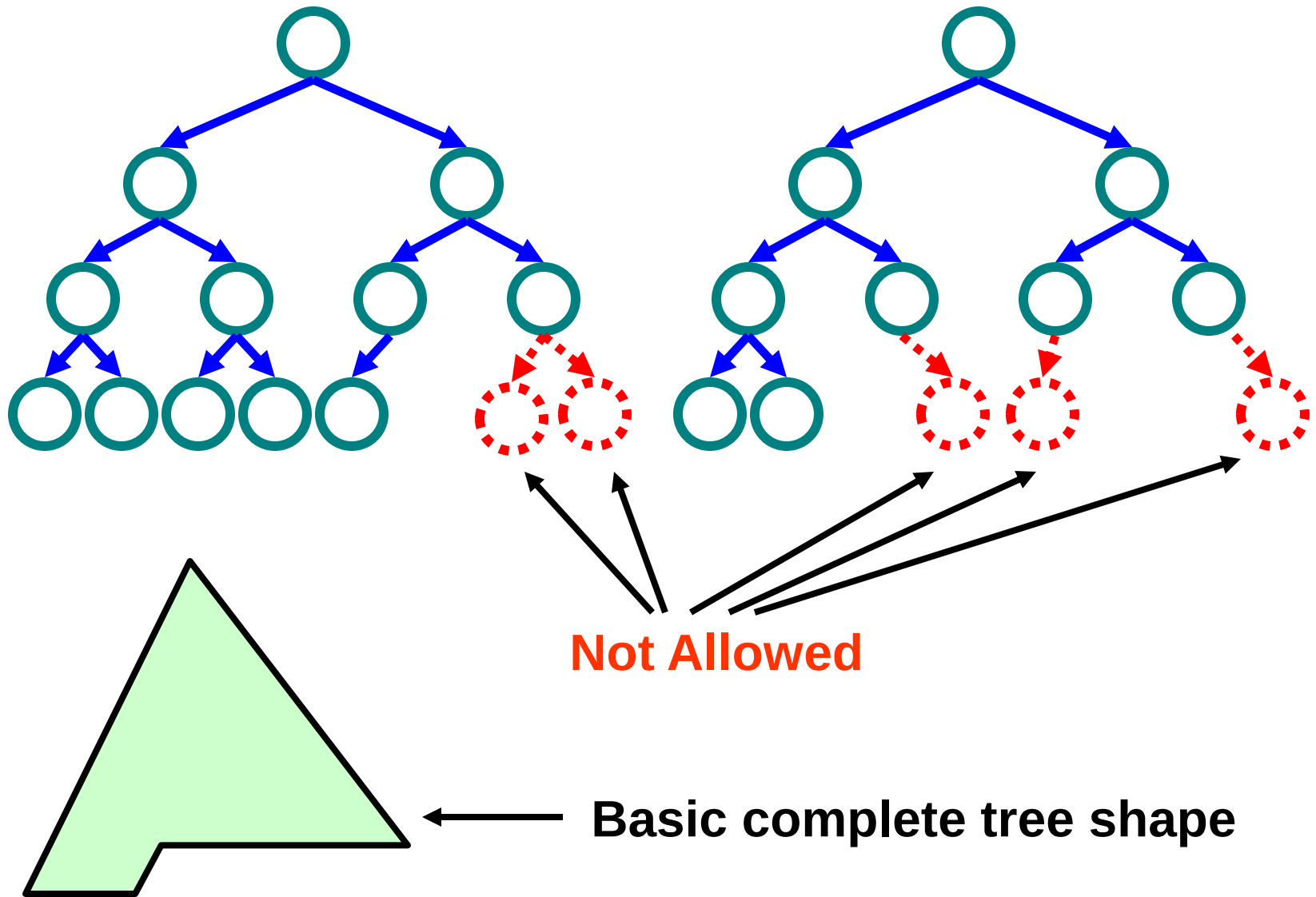
$h = 2$



$h = 3$



Complete Binary Trees



Heaps

■ Two key properties

- Complete binary tree

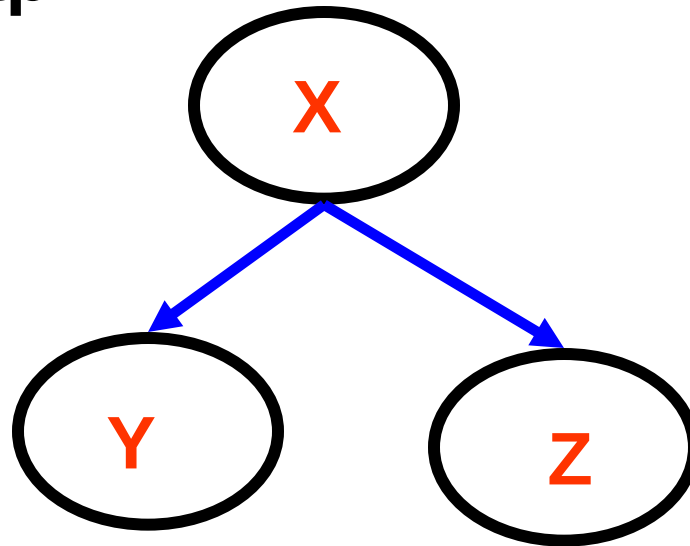
- Value at node

- Smaller than or equal to values in subtrees

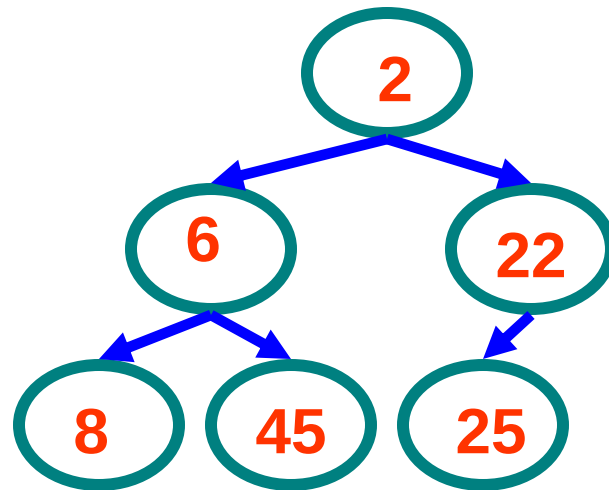
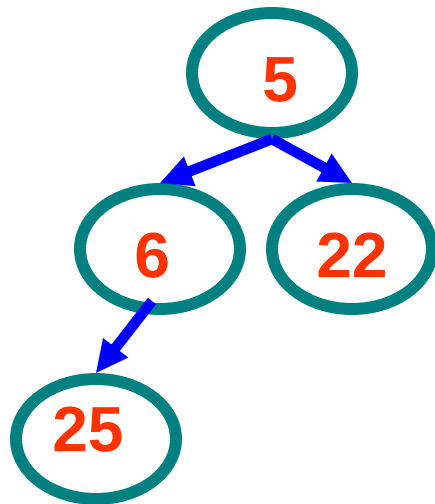
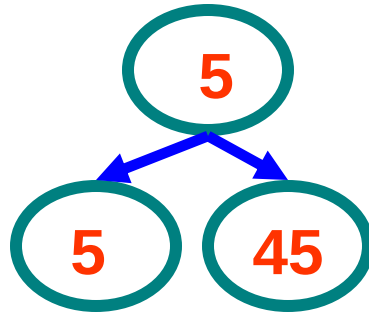
■ Example heap

- $X \leq Y$

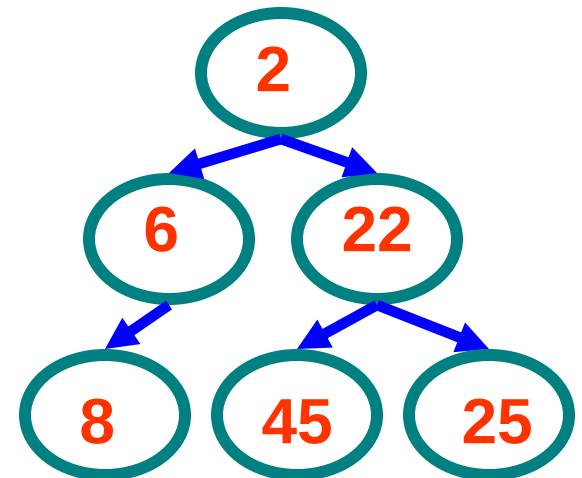
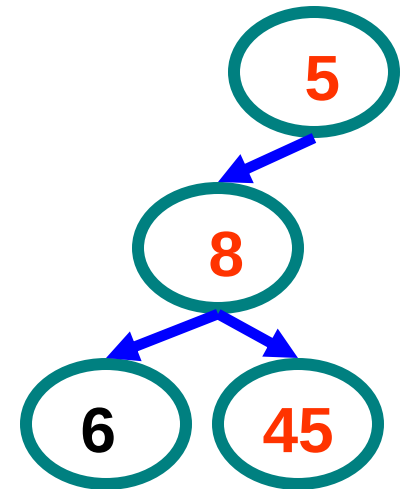
- $X \leq Z$



Heap & Non-heap Examples



Heaps



Non-heaps

Heap Properties

- Heaps are balanced trees
 - $\text{Height} = \log_2(n) = O(\log(n))$
- Can find smallest element easily
 - Always at top of heap!
- Can organize heap to find **maximum** value
 - Value at node larger than values in subtrees
 - Heap can track either min or max, but not both

Heap

■ Key operations

- Insert (X)
- getSmallest ()

■ Key applications

- Heapsort
- Priority queue

Heap Operations – Insert(X)

■ Algorithm

1. Add X to end of tree

2. While (X < parent)

 Swap X with parent // X bubbles up tree

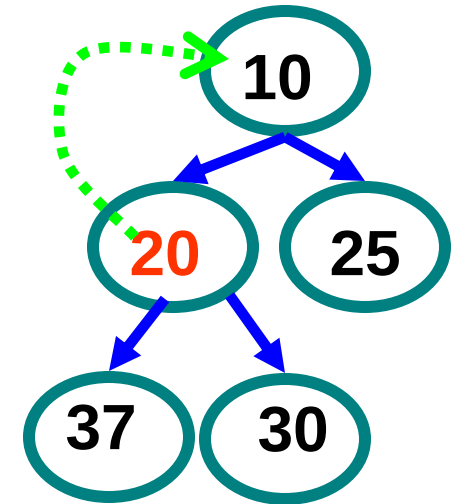
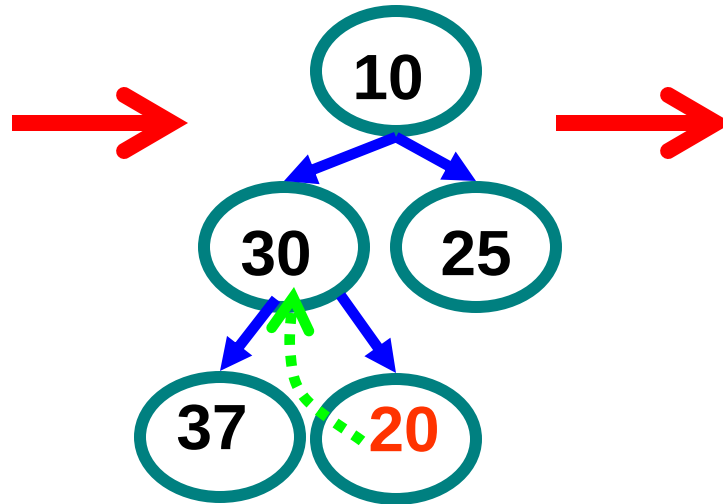
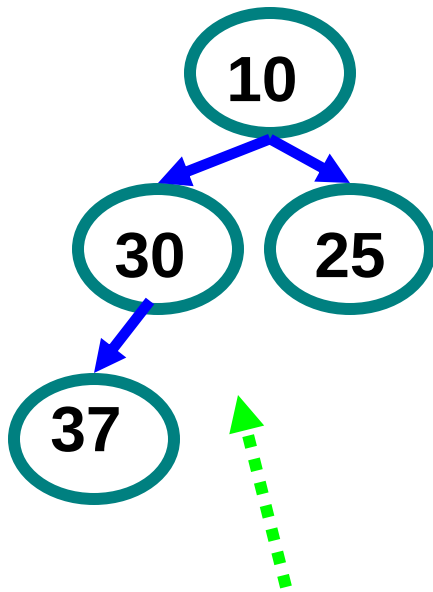
■ Complexity

■ # of swaps proportional to height of tree

■ $O(\log(n))$

Heap Insert Example

■ Insert (20)



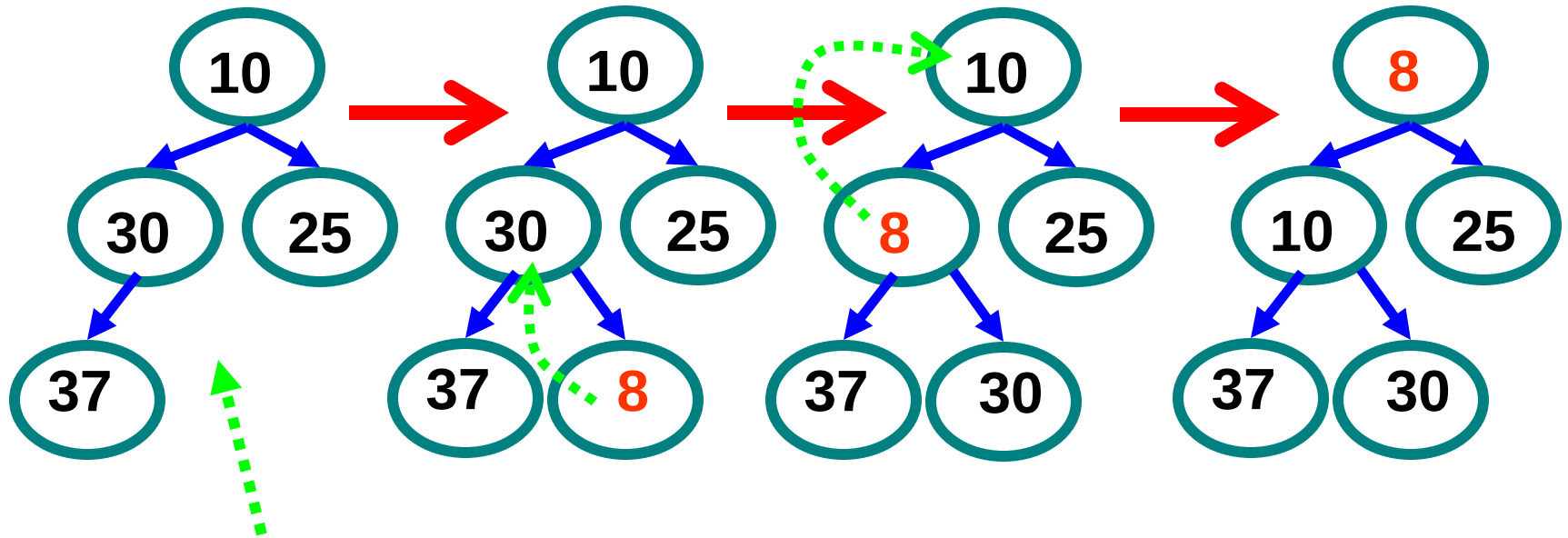
1) Insert to
end of tree

2) Compare to parent,
swap if parent key larger

3) Insert
complete

Heap Insert Example

■ Insert (8)



1) Insert to
end of tree

2) Compare to parent,
swap if parent key larger

3) Insert
complete

Heap Operation – getSmallest()

■ Algorithm

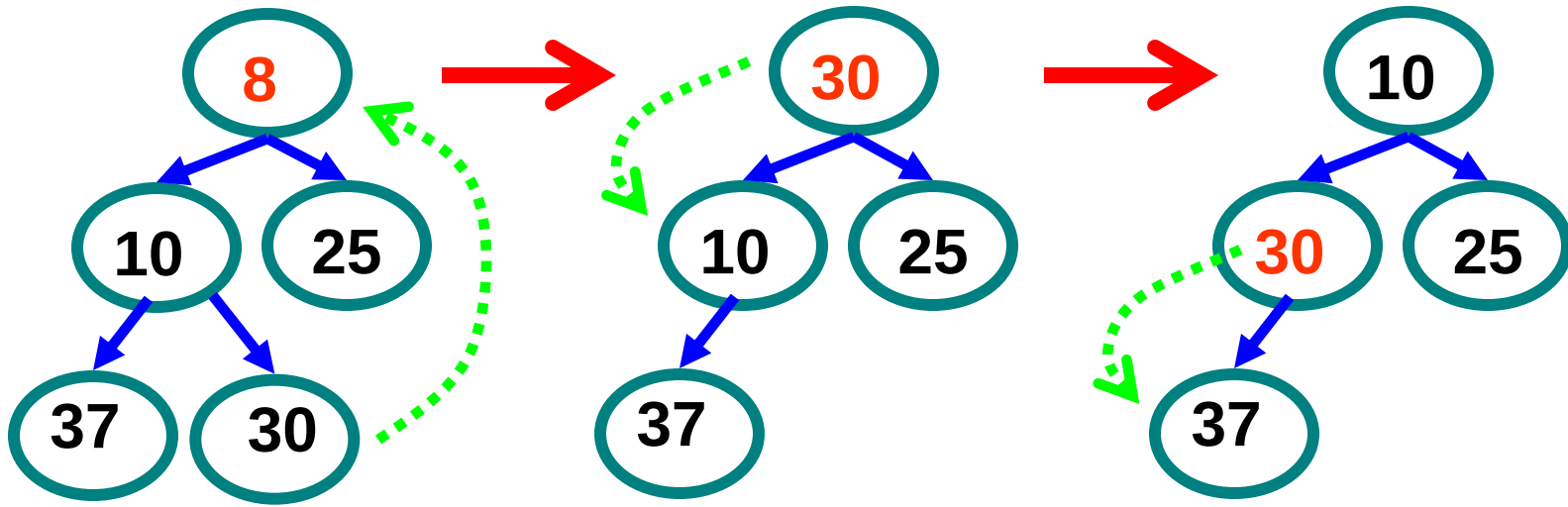
1. Get smallest node at root
2. Replace root with X at end of tree
3. While ($X > \text{child}$)
 Swap X with smallest child // X drops down tree
4. Return smallest node

■ Complexity

- # swaps proportional to height of tree
- $O(\log(n))$

Heap GetSmallest Example

■ getSmallest ()



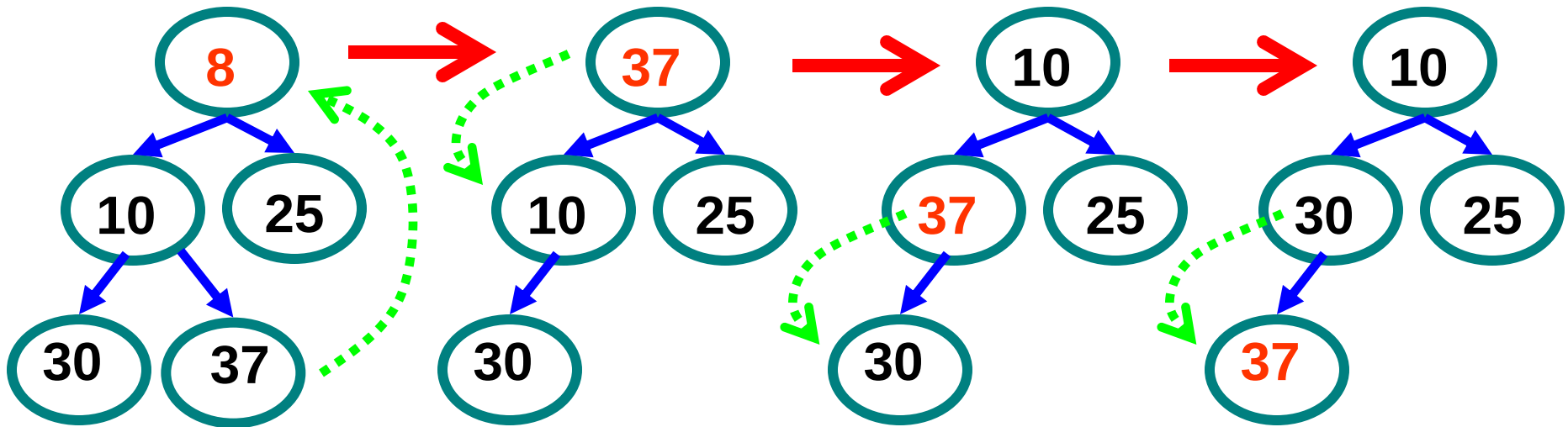
1) Replace root
with end of tree

2) Compare node to
children, if larger swap
with smallest child

3) Repeat swap
if needed

Heap GetSmallest Example

■ getSmallest ()



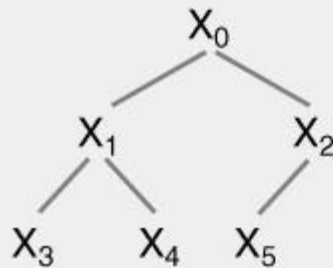
1) Replace root
with end of tree

2) Compare node to
children, if larger swap
with smallest child

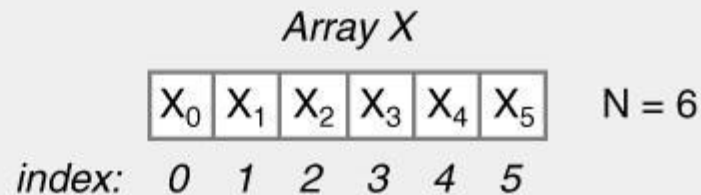
3) Repeat swap
if needed

Heap Implementation

- Can implement heap as array
 - Store nodes in array elements
 - Assign location (index) for elements using formula



(a) Heap represented as a tree



(b) Heap represented as an array

Heap Implementation

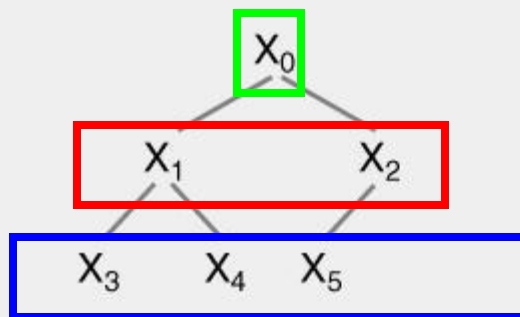
■ Observations

- Compact representation
- Edges are implicit (no storage required)
- Works well for complete trees (no wasted space)

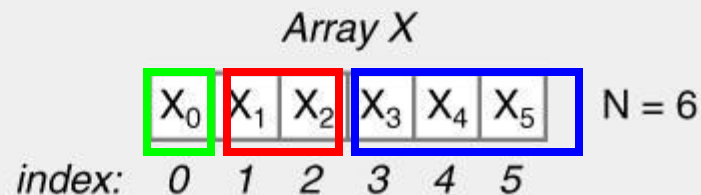
Heap Implementation

■ Calculating node locations

- Array index i starts at 0
- $\text{Parent}(i) = \lfloor (i - 1) / 2 \rfloor$
- $\text{LeftChild}(i) = 2 \times i + 1$
- $\text{RightChild}(i) = 2 \times i + 2$



(a) Heap represented as a tree

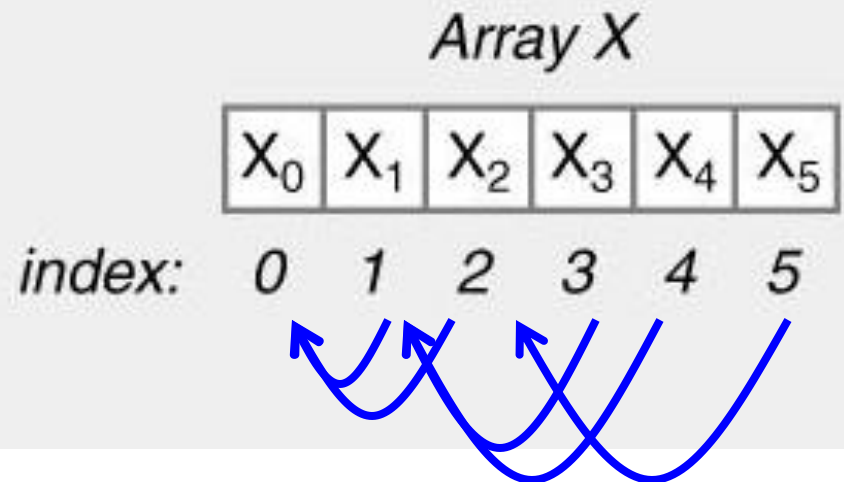
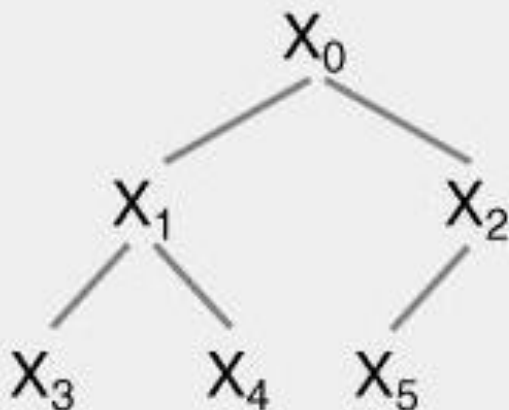


(b) Heap represented as an array

Heap Implementation

■ Example

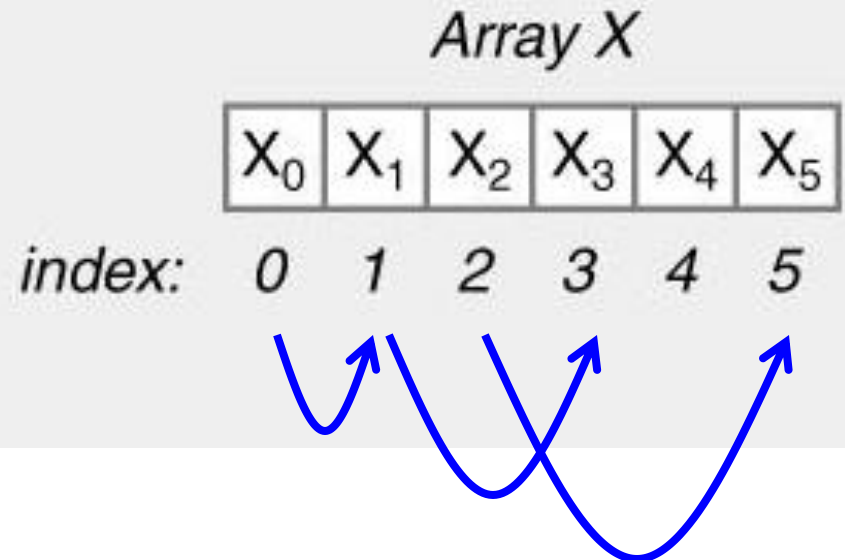
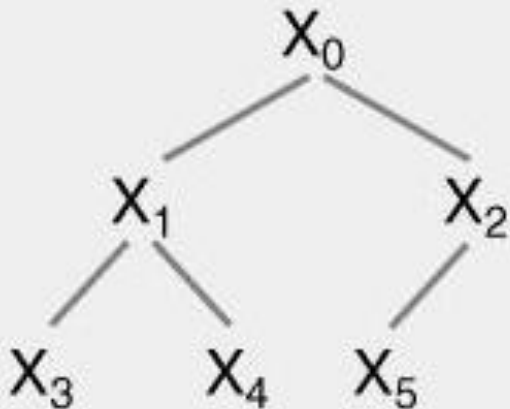
- $\text{Parent}(1) = \lfloor (1 - 1) / 2 \rfloor = \lfloor 0 / 2 \rfloor = 0$
- $\text{Parent}(2) = \lfloor (2 - 1) / 2 \rfloor = \lfloor 1 / 2 \rfloor = 0$
- $\text{Parent}(3) = \lfloor (3 - 1) / 2 \rfloor = \lfloor 2 / 2 \rfloor = 1$
- $\text{Parent}(4) = \lfloor (4 - 1) / 2 \rfloor = \lfloor 3 / 2 \rfloor = 1$
- $\text{Parent}(5) = \lfloor (5 - 1) / 2 \rfloor = \lfloor 4 / 2 \rfloor = 2$



Heap Implementation

■ Example

- $\text{LeftChild}(0) = 2 \times 0 + 1 = 1$
- $\text{LeftChild}(1) = 2 \times 1 + 1 = 3$
- $\text{LeftChild}(2) = 2 \times 2 + 1 = 5$

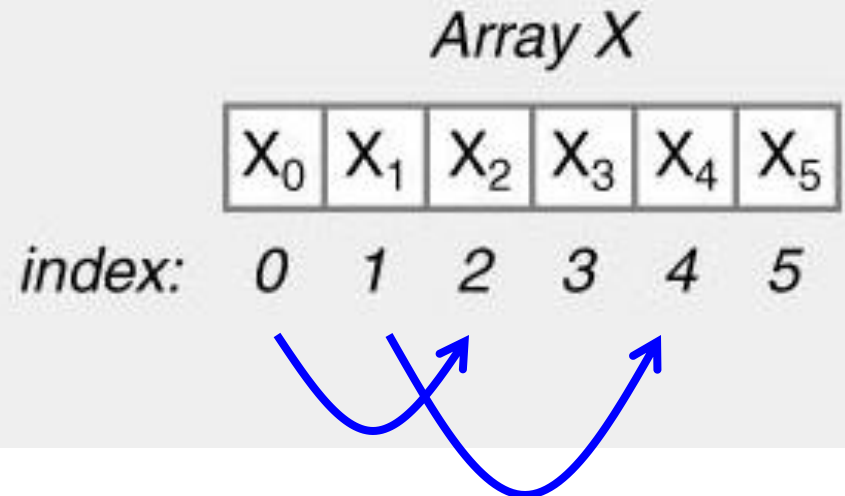
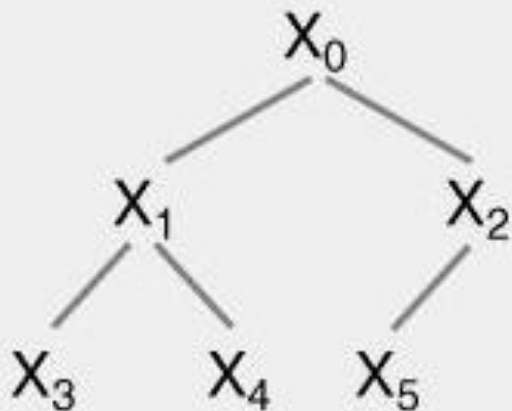


Heap Implementation

■ Example

■ $\text{RightChild}(0) = 2 \times 0 + 2 = 2$

■ $\text{RightChild}(1) = 2 \times 1 + 2 = 4$



Heap Application – Heapsort

- **Use heaps to sort values**
 - **Heap keeps track of smallest element in heap**
- **Algorithm**
 1. **Create heap**
 2. **Insert values in heap**
 3. **Remove values from heap (in ascending order)**
- **Complexity**
 - **$O(n \log(n))$**

Heapsort Example

- **Input**
 - 11, 5, 13, 6, 1
- **View heap during insert, removal**
 - As tree
 - As array

Heapsort – Insert Values

(a) Insert 11

11

(b) Insert 5



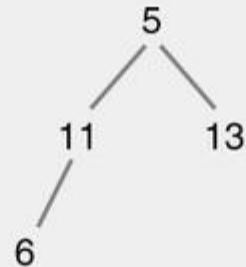
(c) Rebuild heap



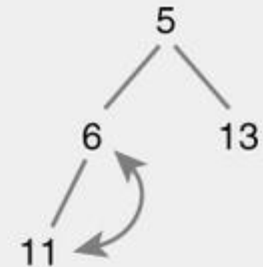
(d) Insert 13



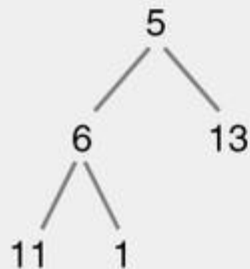
(e) Insert 6



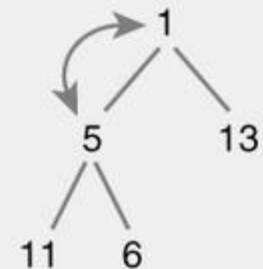
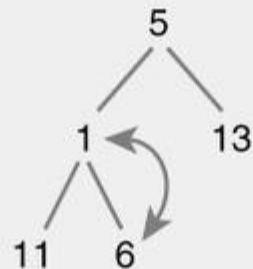
(f) Rebuild heap



(g) Insert 1

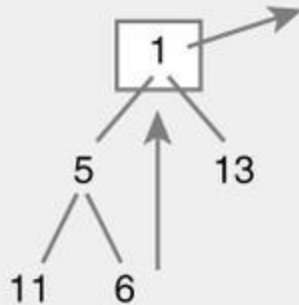


(h) Rebuild heap

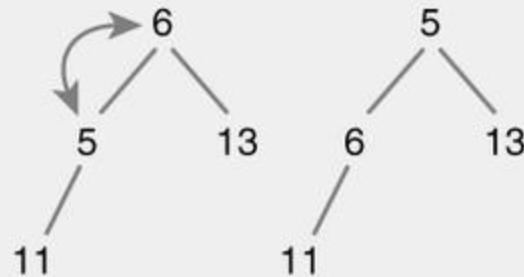


Heapsort – Remove Values

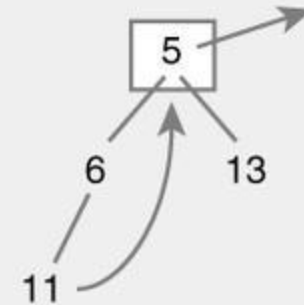
(a) Print root = 1



(b) Rebuild heap



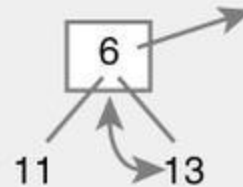
(c) Print root = 5



(d) Rebuild heap



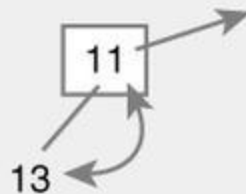
(e) Print root = 6



(f) Rebuild heap



(g) Print root = 11



(h) Rebuild heap

13

(f) Print root = 13



Done

Heapsort – Insert in to Array 1

■ Input

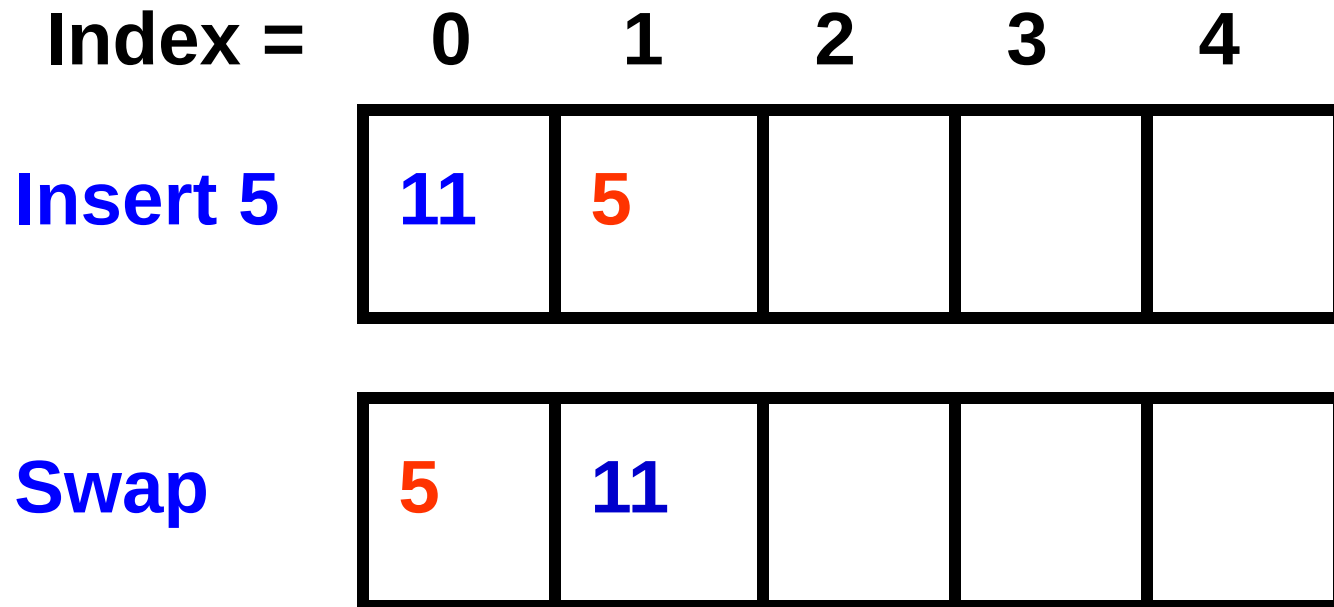
■ 11, 5, 13, 6, 1

Index =	0	1	2	3	4
Insert 11	11				

Heapsort – Insert in to Array 2

■ Input

■ 11, 5, 13, 6, 1



Heapsort – Insert in to Array 3

■ Input

■ 11, 5, 13, 6, 1

Index =	0	1	2	3	4
Insert 13	5	11	13		

Heapsort – Insert in to Array 4

■ Input

■ 11, 5, 13, 6, 1

Index =	0	1	2	3	4
Insert 6	5	11	13	6	

Swap	5	6	13	11	
------	---	---	----	----	--

...

Heapsort – Remove from Array 1

■ Input

■ 11, 5, 13, 6, 1

Index = 0 1 2 3 4

Remove root

1	5	13	11	6
---	---	----	----	---

Replace

6	5	13	11	
---	---	----	----	--

Swap w/ child

5	6	13	11	
---	---	----	----	--

Heapsort – Remove from Array 2

■ Input

■ 11, 5, 13, 6, 1

Index = 0 1 2 3 4

Remove root

5	6	13	11	
---	---	----	----	--

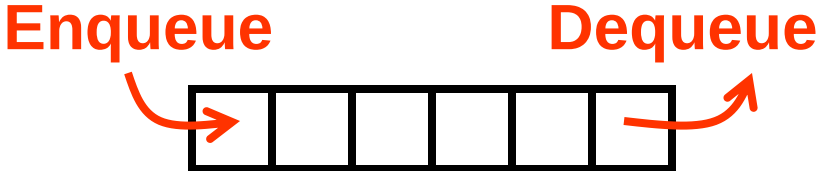
Replace

11	6	13		
----	---	----	--	--

Swap w/ child

6	11	13		
---	----	----	--	--

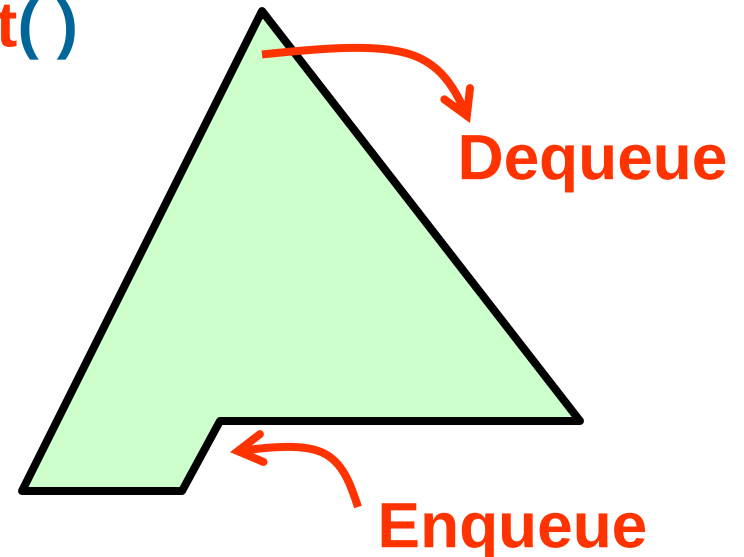
Heap Application – Priority Queue

- Queue
 - Linear data structure
 - First-in First-out (FIFO)
 - Implement as array / linked list
- 
- The diagram illustrates a queue implemented as an array. It consists of a horizontal row of six empty square cells. Above the first cell is the word "Enqueue" in red, with a red curved arrow pointing from it into the first cell. Above the last cell is the word "Dequeue" in red, with a red curved arrow pointing from it away from the last cell.

Heap Application – Priority Queue

■ Priority queue

- Elements are assigned **priority** value
- Higher priority elements are taken out first
- Implement as heap
 - Enqueue $\Rightarrow$ **insert()**
 - Dequeue $\Rightarrow$ **getSmallest()**



Priority Queue

■ Properties

- Lower value = higher priority
- Heap keeps highest priority items in front

■ Complexity

- Enqueue $\Rightarrow$ **insert()** $= O(\log(n))$
- Dequeue $\Rightarrow$ **getSmallest()** $= O(\log(n))$
- For any heap

Heap vs. Binary Search Tree

■ Binary search tree

- Keeps values in sorted order
- Find any value
 - $O(\log(n))$ for balanced tree
 - $O(n)$ for degenerate tree (worst case)

■ Heap

- Keeps smaller values in front
- Find **minimum** value
 - $O(\log(n))$ for any heap