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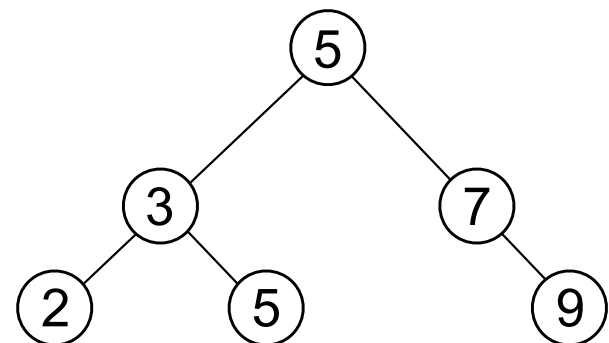
Data Structure and Algorithm

Lecture 7: Binary Search Tree (Cont.d), Midterm Exam Review

Instructor: Yong Liu

Binary Search Tree Property

- ▶ Binary search tree property:
 - ▶ If y is in left subtree of x ,
 - ▶ then $\text{key}[y] \leq \text{key}[x]$
 - ▶ If y is in right subtree of x ,
 - ▶ then $\text{key}[y] \geq \text{key}[x]$



$$\text{key}[\text{leftSubtree}(x)] \leq \text{key}[x] \leq \text{key}[\text{rightSubtree}(x)]$$

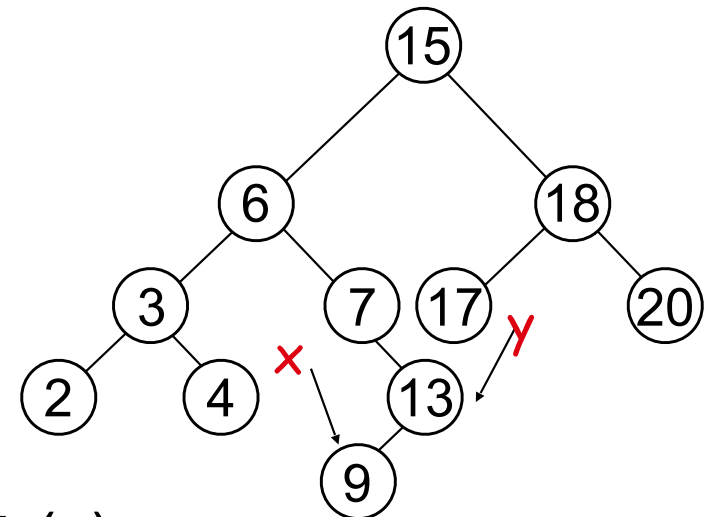
Successor

- ▶ *Def: successor* (x) = y , such that key [y] is the smallest key $>$ key [x]

E.g.: successor (15) = 17

successor (13) = 15

successor (9) = 13



- ▶ **Case 1: right (x) is non empty**

- ▶ *successor* (x) = the minimum in right (x)

- ▶ **Case 2: right (x) is empty**

- ▶ go up the tree until the current node is a left child:

successor (x) is the parent of the current node

- ▶ if you cannot go further (and you reached the root): x is

- ▶ the largest element

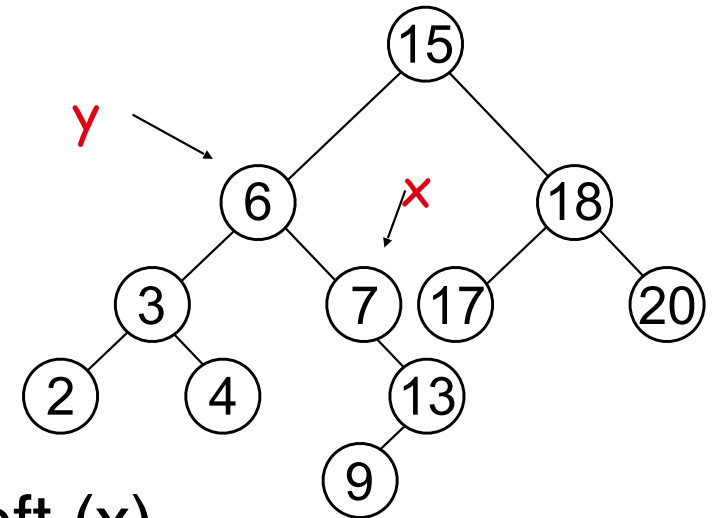
Predecessor

Def: predecessor (x) = y, such that key [y] is the biggest key < key [x]

E.g.: predecessor (15) = 13

predecessor (9) = 7

predecessor (7) = 6



Case 1: left (x) is non empty

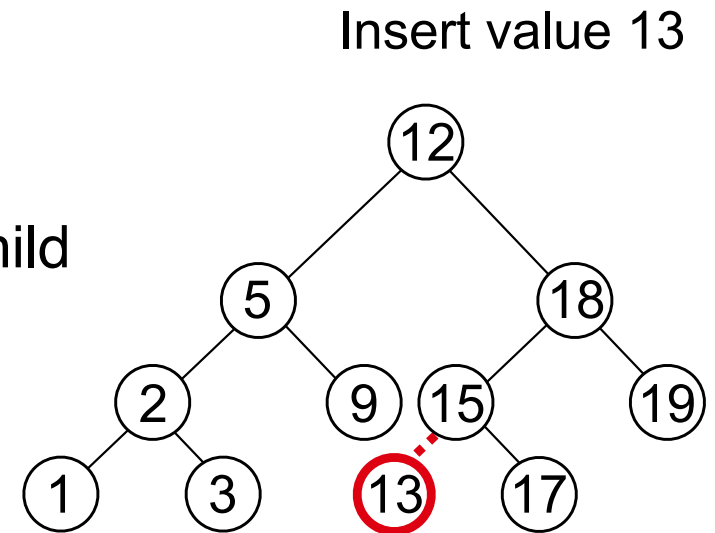
predecessor (x) = the maximum in left (x)

Case 2: left (x) is empty

- ▶ go up the tree until the current node is a right child:
predecessor (x) is the parent of the current node
- ▶ if you cannot go further (and you reached the root): x is the smallest element

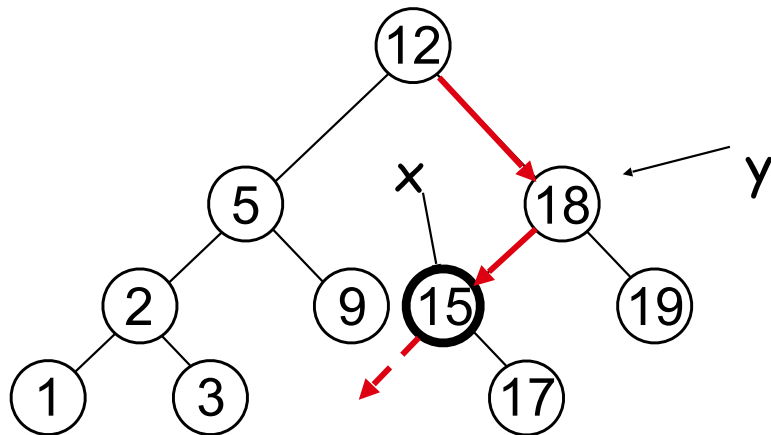
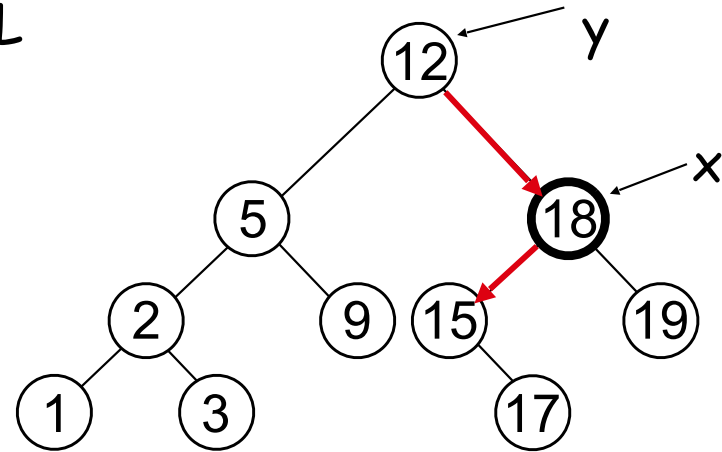
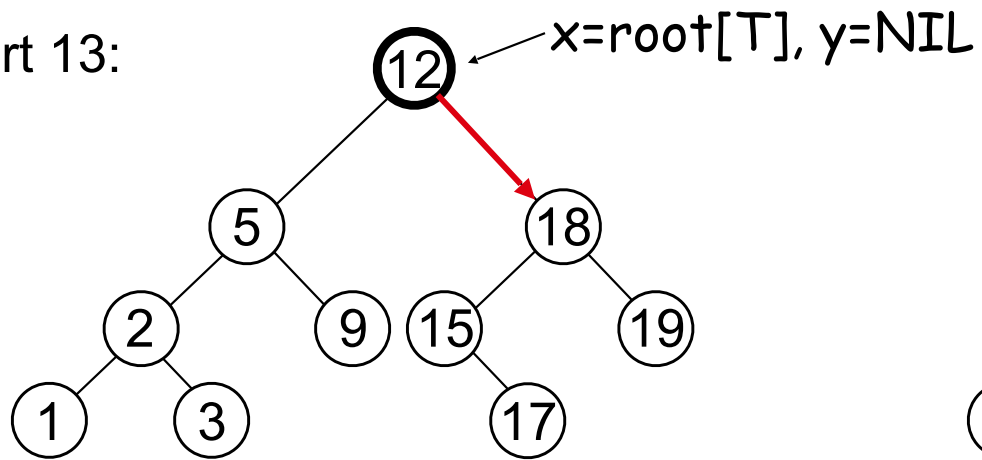
Insertion

- ▶ Goal:
 - ▶ Insert value v into a binary search tree
- ▶ Idea:
 - ▶ If $\text{key}[x] < v$ move to the right child of x , else move to the left child of x
 - ▶ When x is NIL, we found the correct position
 - ▶ If $v < \text{key}[y]$ insert the new node as y 's left child else insert it as y 's right child
 - ▶ Beginning at the root, go down the tree and maintain:
 - ▶ Pointer x : traces the downward path (current node)
 - ▶ Pointer y : parent of x ("trailing pointer")

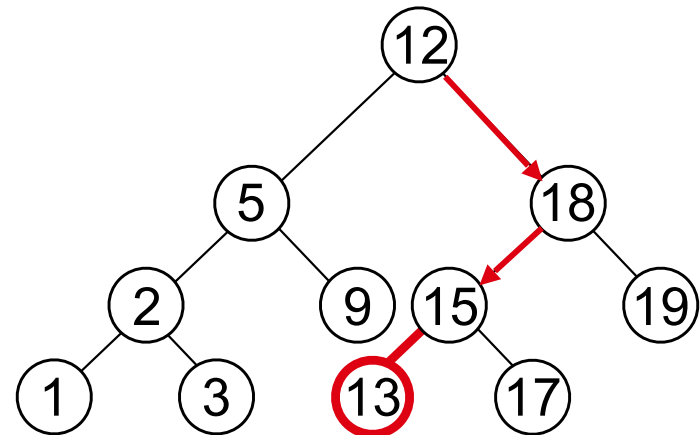


Insertion: Example

Insert 13:

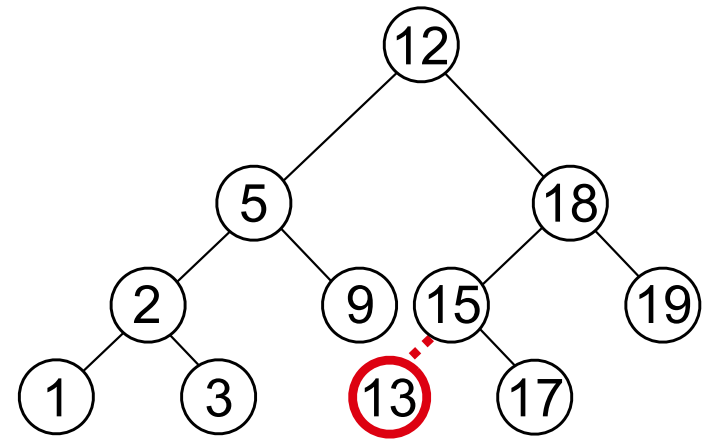


$x = \text{NIL}$
 $y = 15$



Tree Insertion

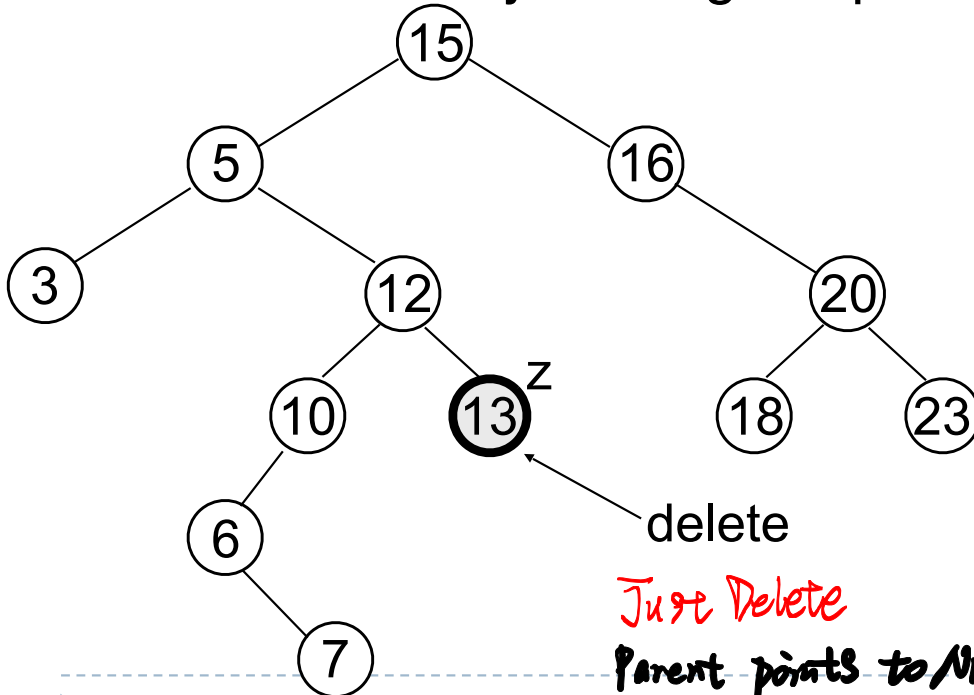
1. $y \leftarrow \text{NIL}$
2. $x \leftarrow \text{root}[T]$
3. **while** $x \neq \text{NIL}$
4. **do** $y \leftarrow x$
5. **if** $\text{key}[z] < \text{key}[x]$
6. **then** $x \leftarrow \text{left}[x]$
7. **else** $x \leftarrow \text{right}[x]$
8. $p[z] \leftarrow y$
9. **if** $y = \text{NIL}$
10. **then** $\text{root}[T] \leftarrow z$ // Tree T was empty
11. **else if** $\text{key}[z] < \text{key}[y]$
12. **then** $\text{left}[y] \leftarrow z$
13. **else** $\text{right}[y] \leftarrow z$



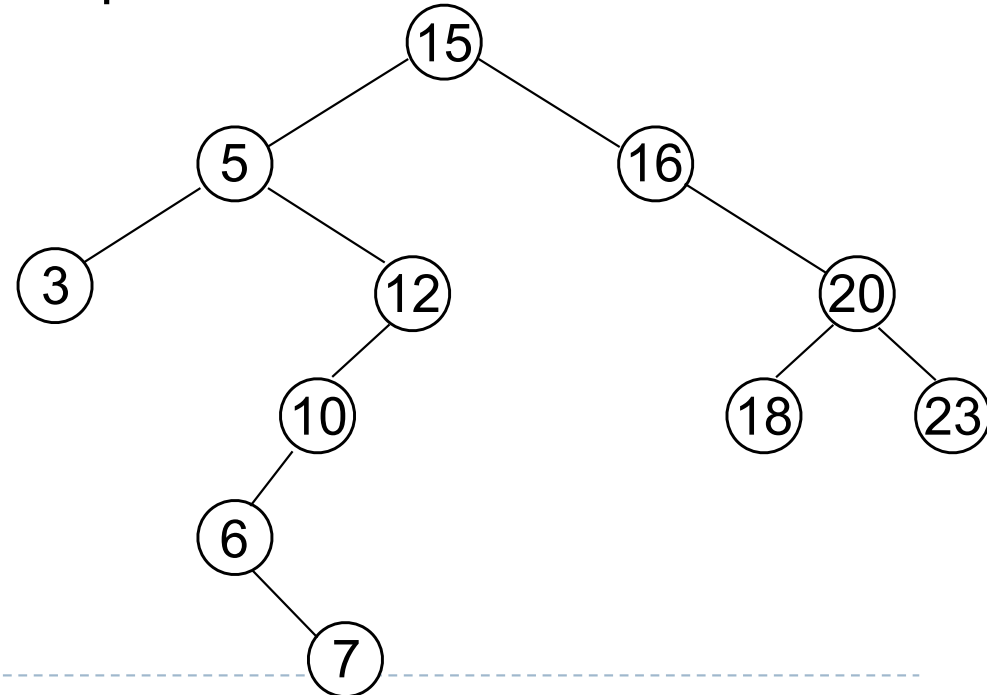
Running time: $O(h)$

Deletion

- ▶ Goal:
 - ▶ Delete a given node z from a binary search tree
- ▶ Idea:
 - ▶ Case 1: z has no children
 - ▶ Delete z by making the parent of z point to NIL



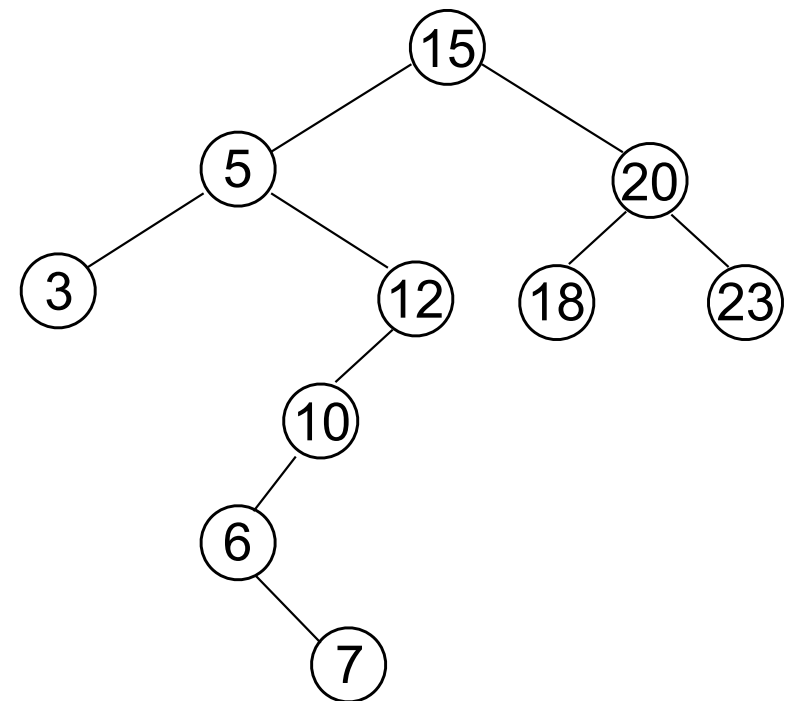
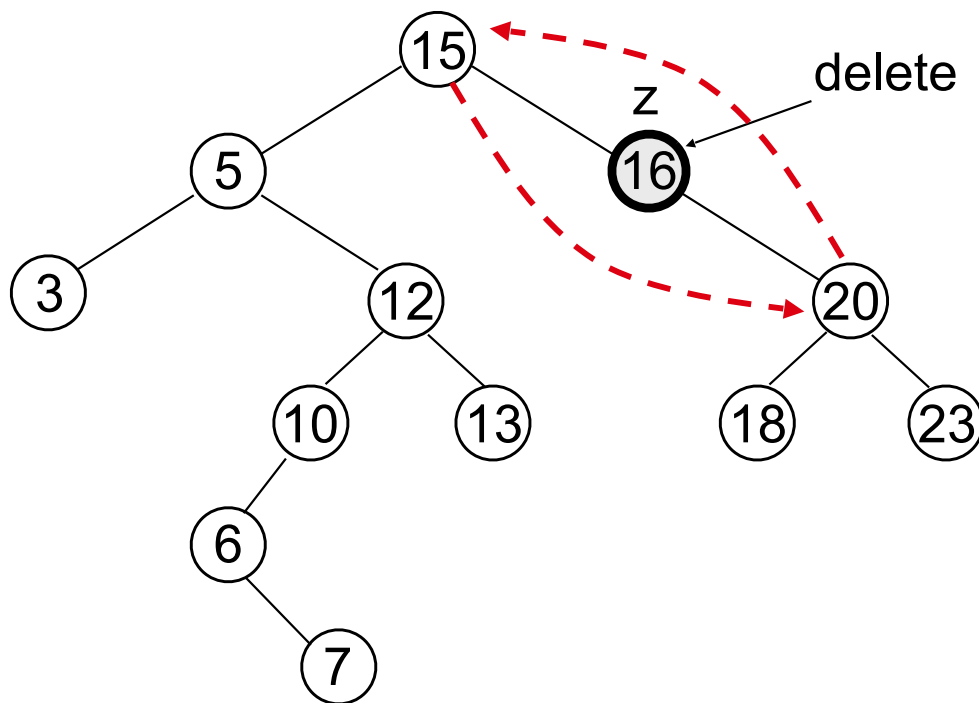
Just Delete
Parent points to Null



Deletion

- ▶ Case 2: z has one child

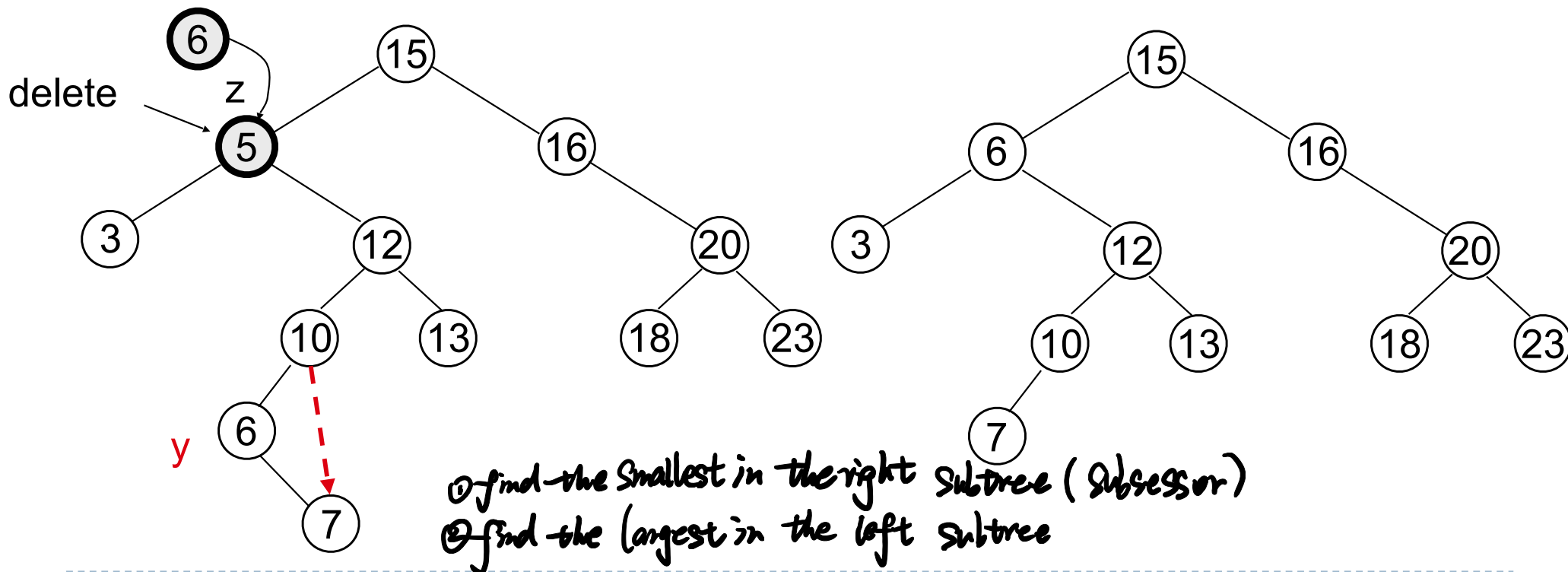
- ▶ Delete z by making the parent of z point to z's child, instead of to z *modify two pointers*



Deletion

▶ Case 3: z has two child

- ▶ z's successor (y) is the minimum node in z's right subtree
- ▶ y has either no children or one right child (but no left child)
- ▶ Delete y from the tree (via Case 1 or 2) *otherwise y is not successor*
- ▶ Replace z's key and satellite data with y's.



Binary Search Trees: Summary

- ▶ Operations on binary search trees:
 - ▶ SEARCH $O(h)$
 - ▶ PREDECESSOR $O(h)$
 - ▶ SUCCESSION $O(h)$
 - ▶ MINIMUM $O(h)$
 - ▶ MAXIMUM $O(h)$
 - ▶ INSERT $O(h)$
 - ▶ DELETE $O(h)$
- ▶ These operations are fast if the height of the tree is small

Binary Search Trees: Best & Worst case

- ▶ All BST operations are $O(h)$, where h is tree depth
- ▶ Best case running time is $O(\log N)$
 - ▶ Minimum h is $\log N$ for a binary tree with N nodes
- ▶ Worst case running time is $O(N)$
 - ▶ What happens when you Insert elements in ascending order?
 - ▶ Insert: 2, 4, 6, 8, 10, 12 into an empty BST

Balancing Binary Search Trees

- ▶ We have seen that all operations depend on the depth of the tree.
 - ▶ We don't want trees with nodes which have large height
 - ▶ This can be attained if both subtrees of each node have roughly the same height.
 - ▶ We want a tree with small height
 - ▶ Our goal is to keep the height of a binary search tree $O(\log N)$
 - ▶ Many algorithms exist for keeping binary search trees balanced, such trees are called balanced binary search trees.
- ⇒ AVL (Adelson-Velskii and Landis) trees → *Go Detail*
- {* B-trees
Red-black tree *> ⇒ Not Covered*

AVL - Good but not Perfect Balance

- ▶ **AVL trees** are height-balanced binary search trees where the height of the two subtrees of a node differs by at most one
- ▶ **Balance factor** of a node
 - ▶ $\text{height}(\text{left subtree}) - \text{height}(\text{right subtree})$
- ▶ An AVL tree has balance factor calculated at every node
 - ▶ For every node, heights of left and right subtree can differ by no more than 1

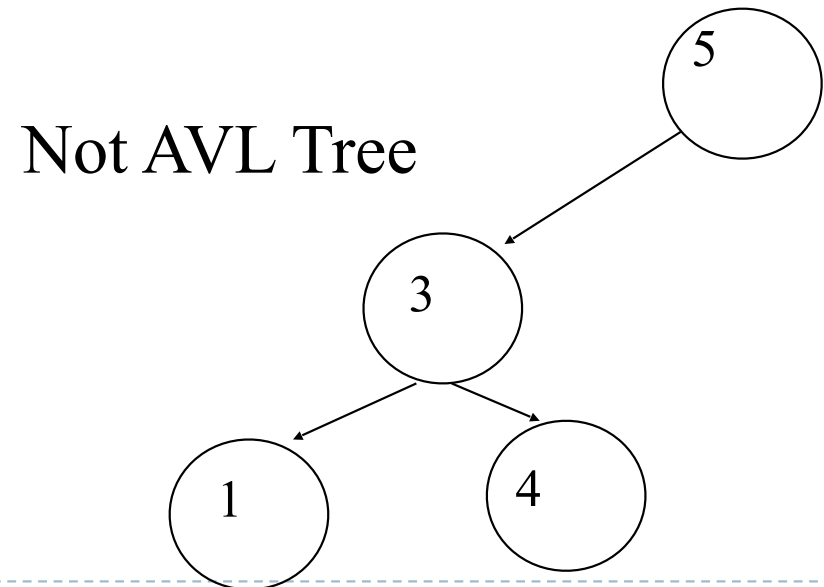
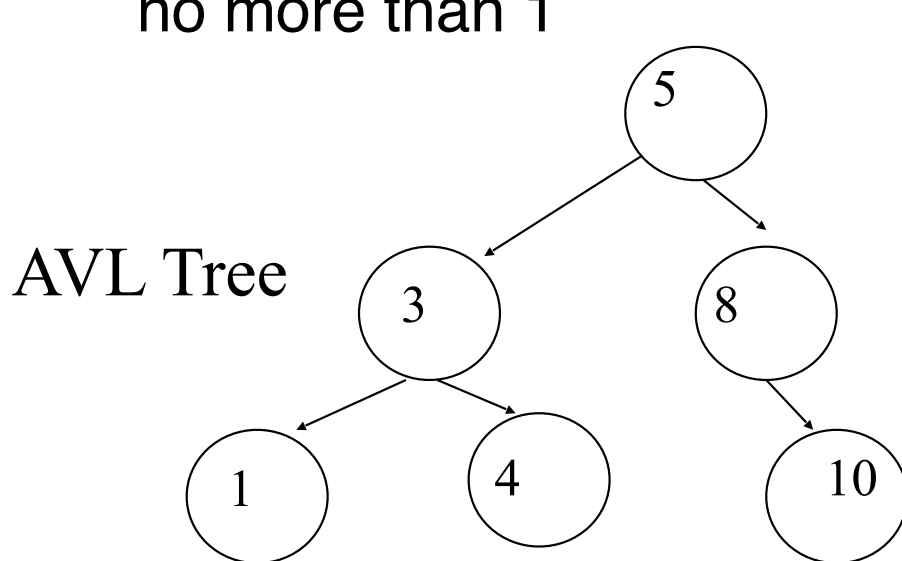
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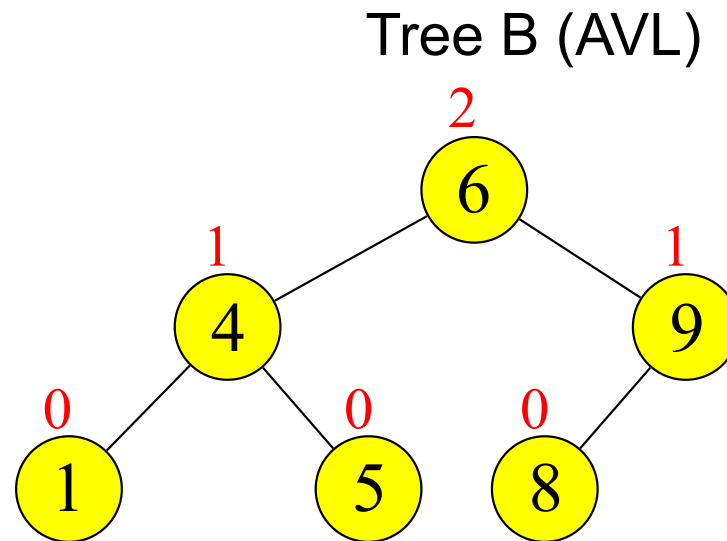
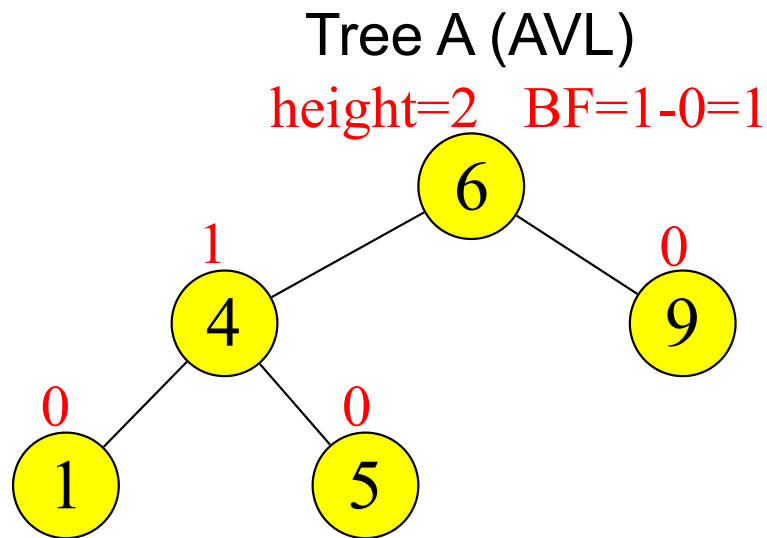
- ▶ **Balance factor** of a node

Factor $\text{height}(\text{left subtree}) - \text{height}(\text{right subtree})$

- ▶ An AVL tree has balance factor calculated at every node
 - ▶ For every node, heights of left and right subtree can differ by no more than 1



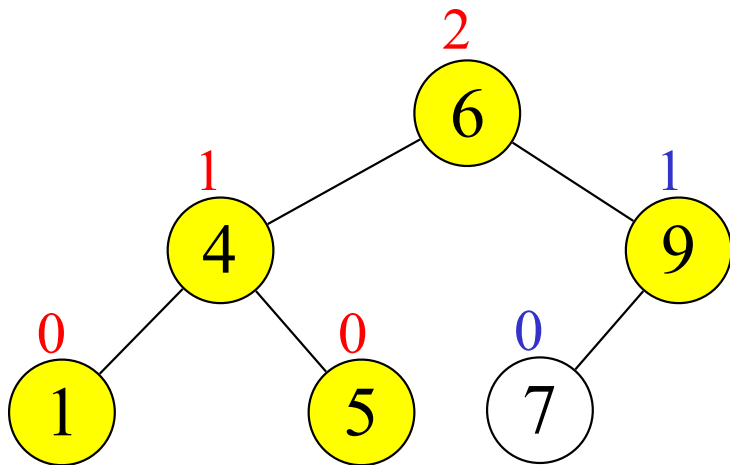
Node Heights



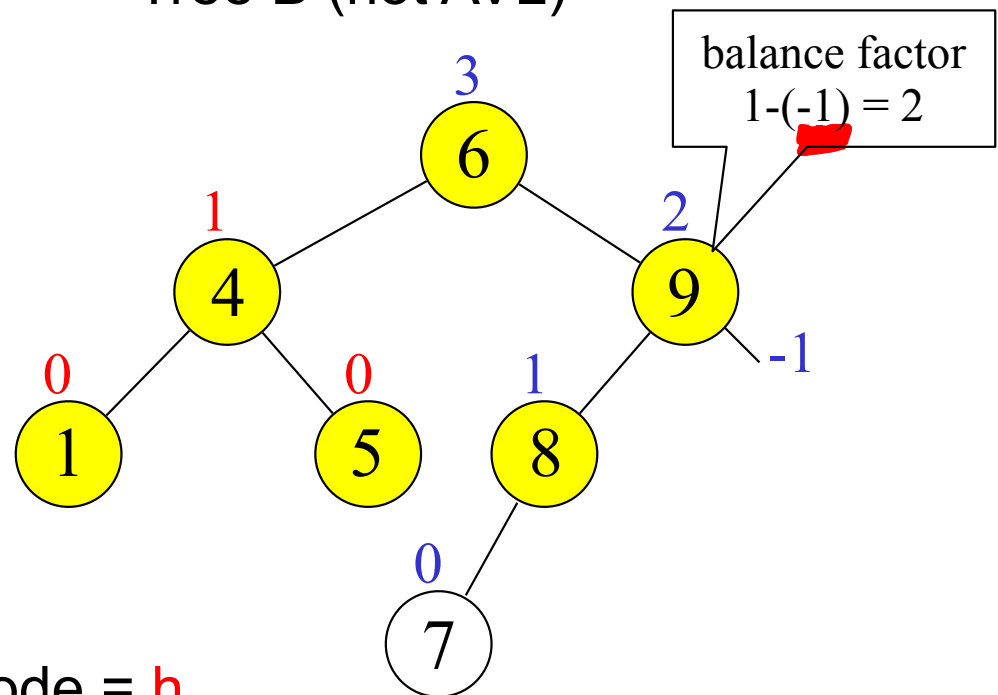
height of node = h
balance factor = $h_{\text{left}} - h_{\text{right}}$
empty height = -1

Node Heights after Insert 7

Tree A (AVL)



Tree B (not AVL)



height of node = h
balance factor = $h_{\text{left}} - h_{\text{right}}$
empty height = -1

Rotations

$$|height(L) - height(R)| \leq 1$$

insertion ↑
Delete ↓

- ▶ When the tree structure changes (e.g., insertion or deletion), we need to transform the tree to restore the AVL tree property.
- ▶ Since an insertion/deletion involves adding/deleting a single node, this can only increase/decrease the height of some subtree by 1
- ▶ Thus, if the AVL tree property is violated at a node x , it means that the heights of $left(x)$ and $right(x)$ **differ by exactly 2**.
- ▶ Rotations will be applied to x to restore the AVL tree property/balance.
- ▶ This is done using **single rotations or double rotations**.

Insertion

- ▶ First, insert the new key as a new leaf just as in ordinary binary search tree
- ▶ Then trace the path from the new leaf towards the root. For each node x encountered, check if heights of $\text{left}(x)$ and $\text{right}(x)$ differ by at most 1.
- ▶ If yes, proceed to $\text{parent}(x)$. If not, restructure by doing either a single rotation or a double rotation.
- ▶ For insertion, once we perform a rotation at a node x , we won't need to perform any rotation at any ancestor of x .

Insertion

- ▶ Let U be the node nearest to the inserted one which has an imbalance.

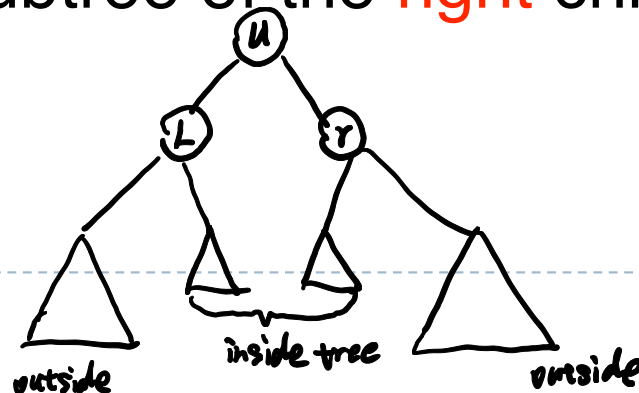
- ▶ There are 4 cases

Outside Cases (require single rotation) :

- ▶ Insertion in the **left** subtree of the **left** child of U
- ▶ Insertion in the **right** subtree of the **right** child of U

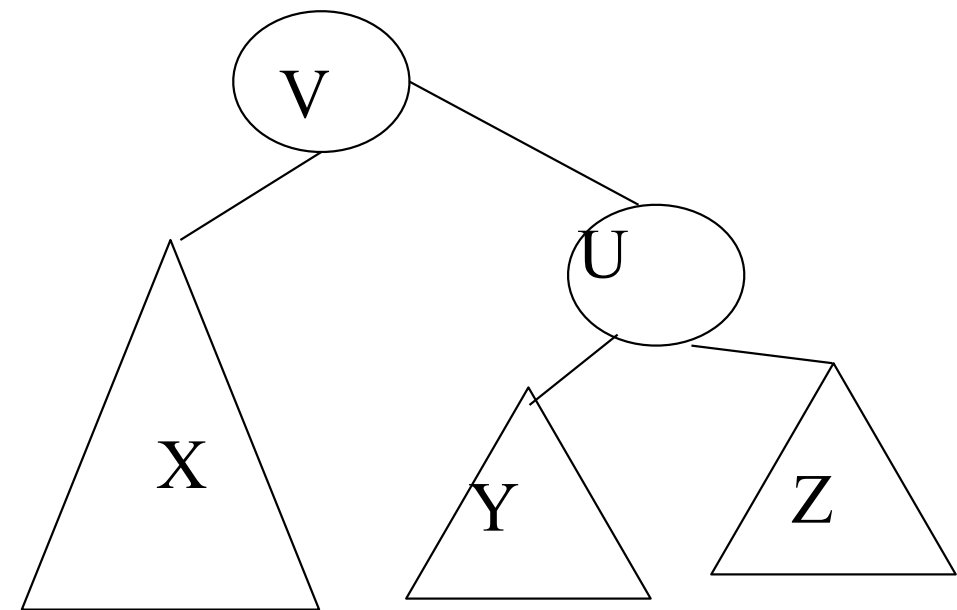
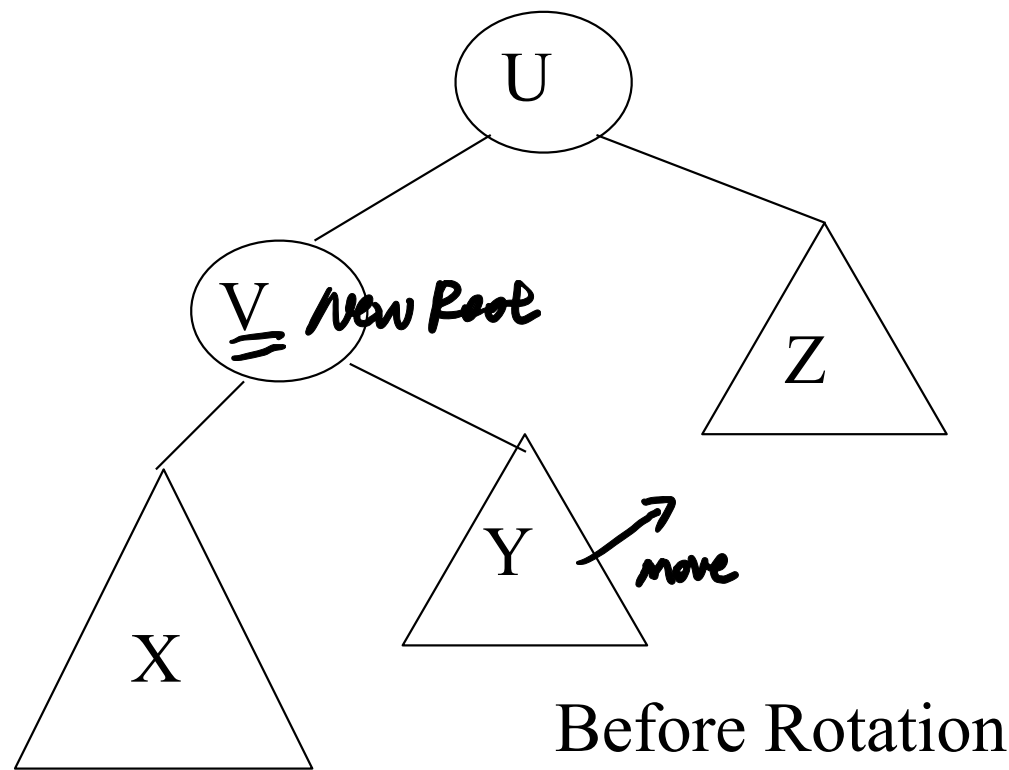
Inside Cases (require double rotation) :

- ▶ Insertion in the **right** subtree of the **left** child of U
- ▶ Insertion in the **left** subtree of the **right** child of U

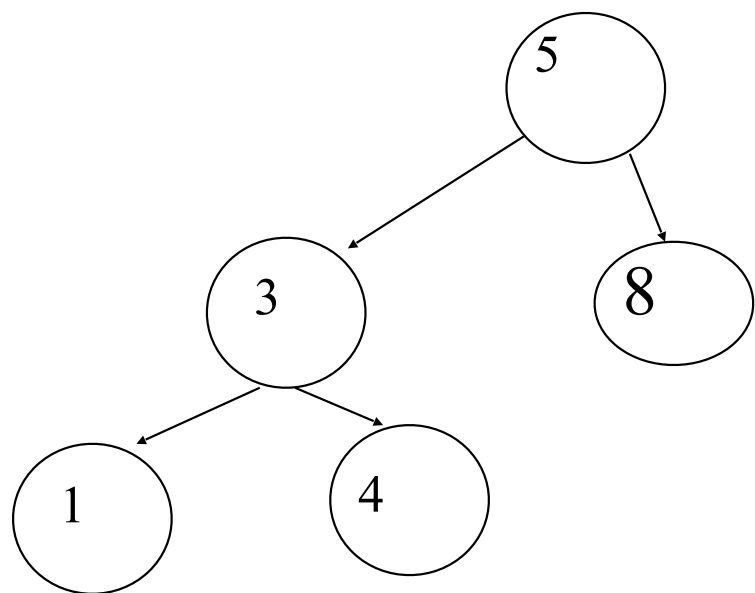


Insertion in left subtree of left child

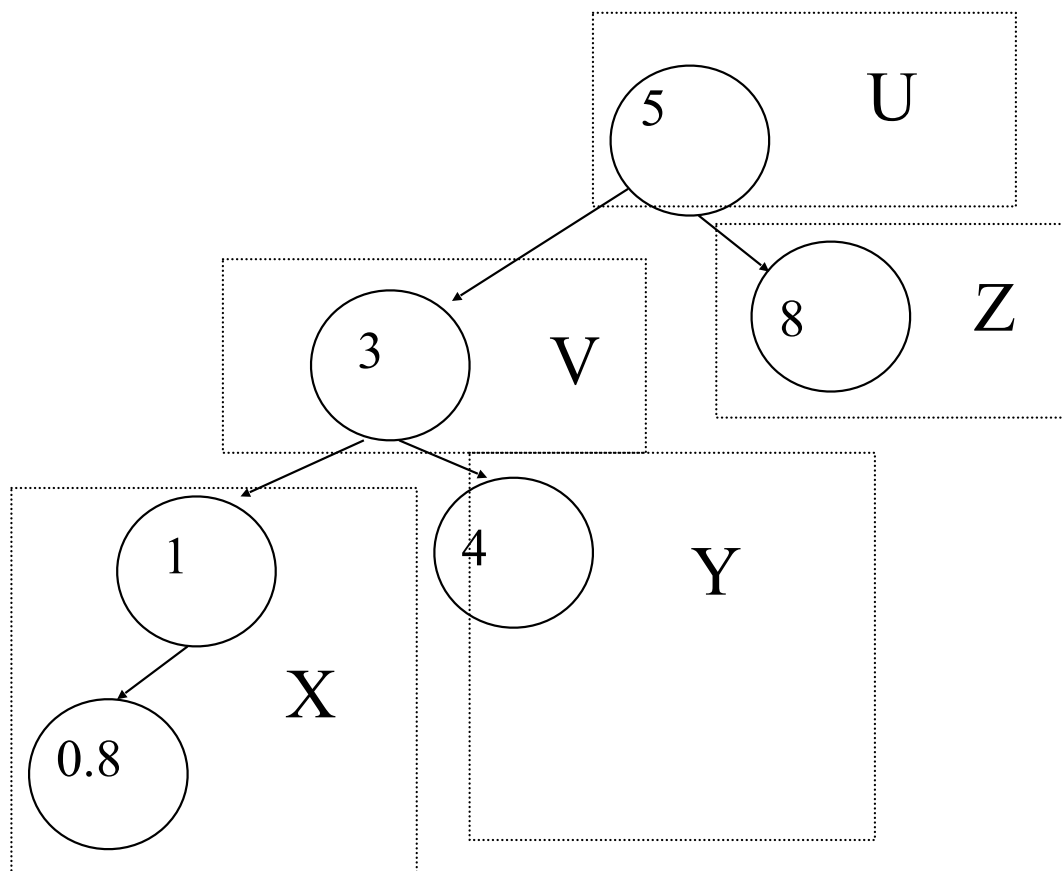
Single Rotation



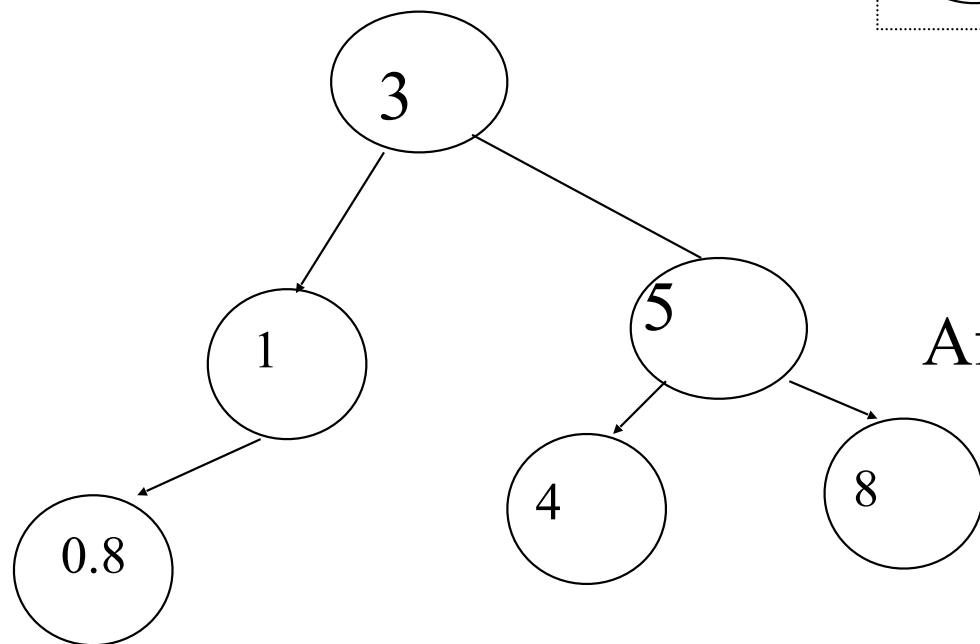
Let U be the node nearest to the inserted one which has an imbalance.



AVL Tree



Insert 0.8

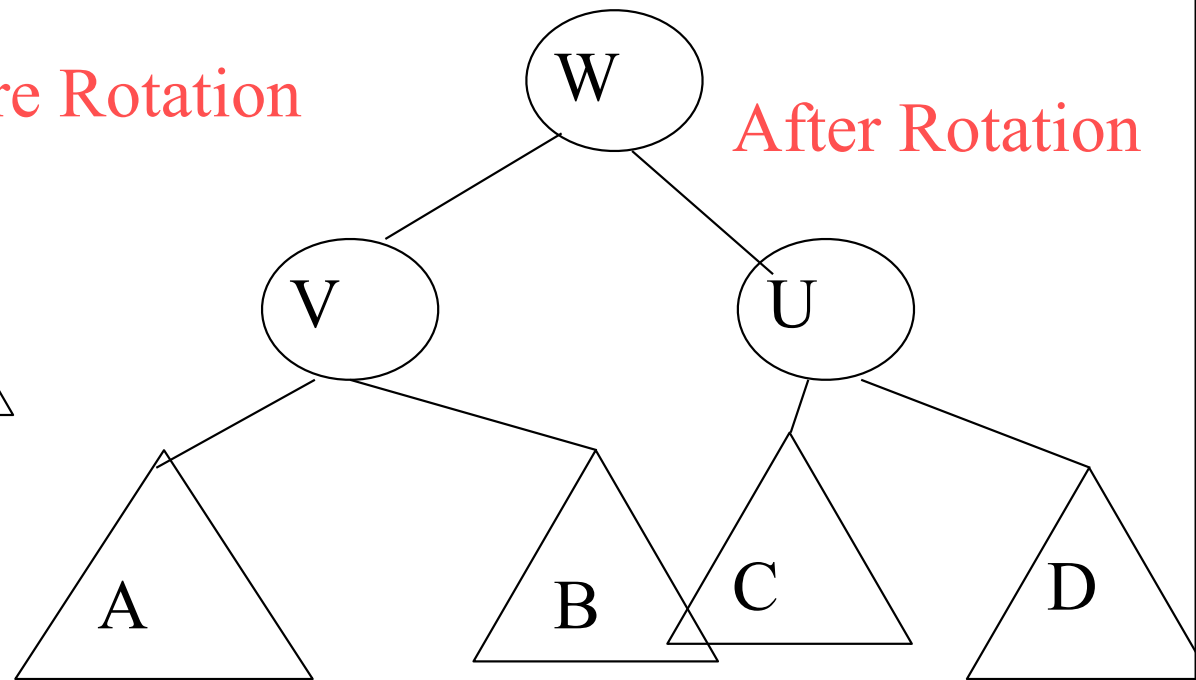
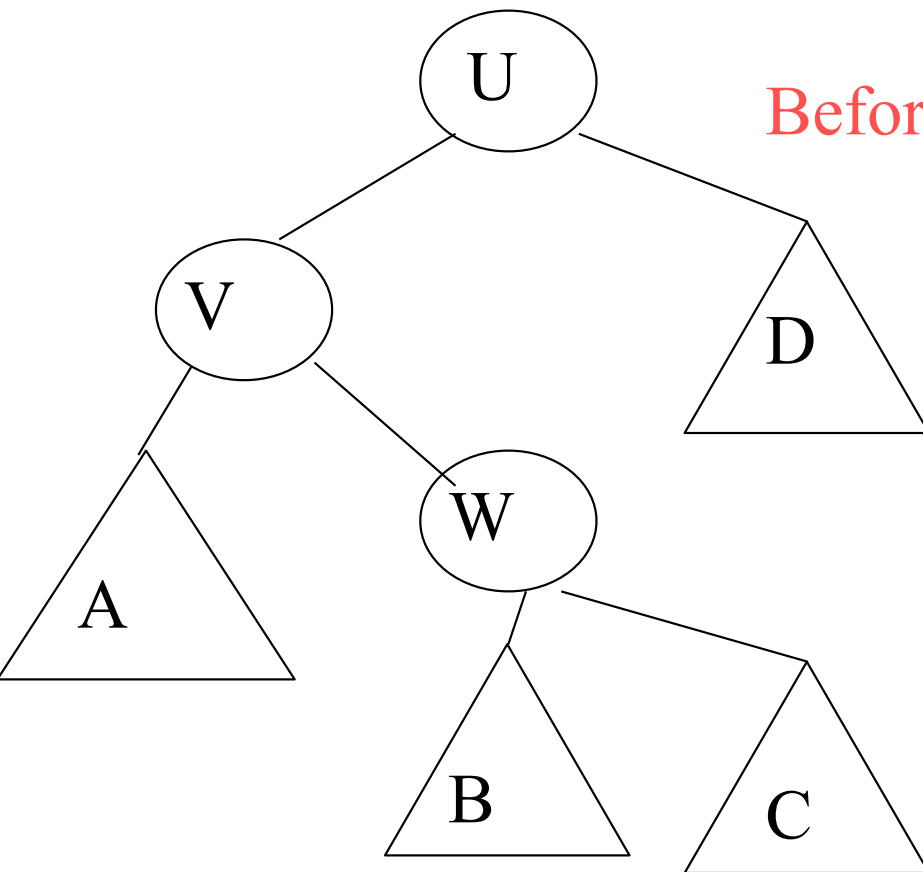


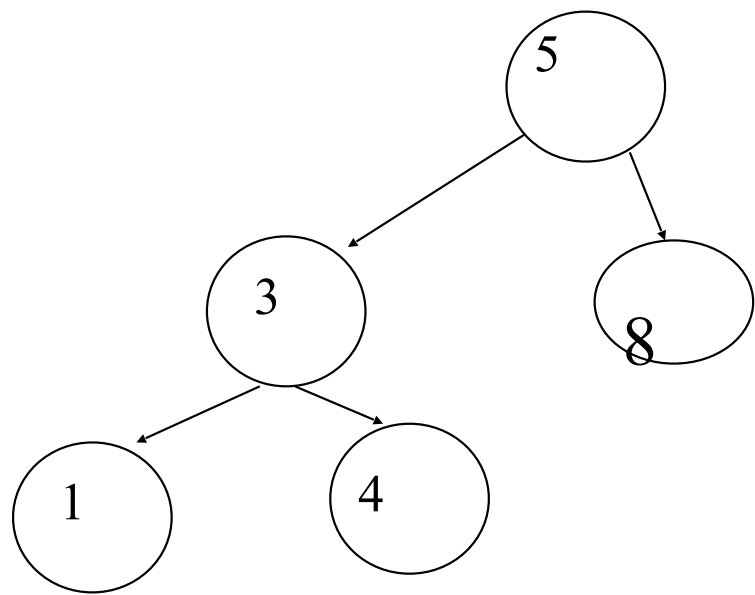
After Rotation

Double Rotation

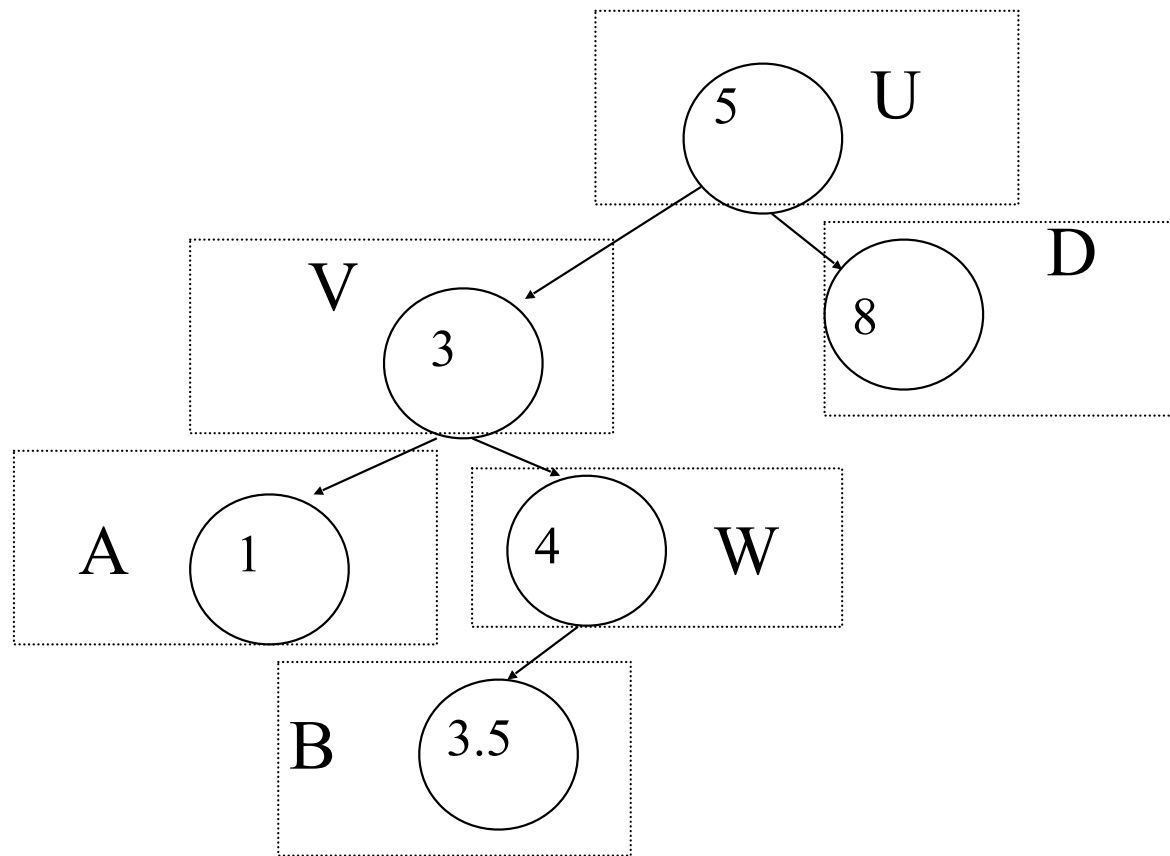
Suppose, imbalance is due to an insertion in the right subtree of left child

Single Rotation does not work!

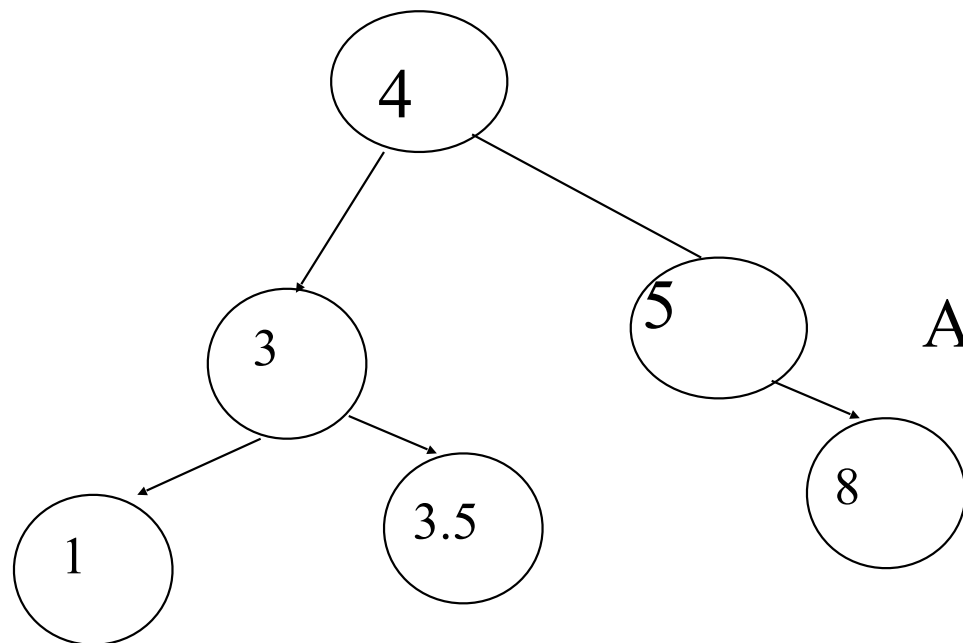




AVL Tree



Insert 3.5



After Rotation

Extended Example

Insert 3,2,1,4,5,6,7, 16,15,14

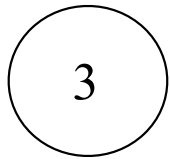


Fig 1

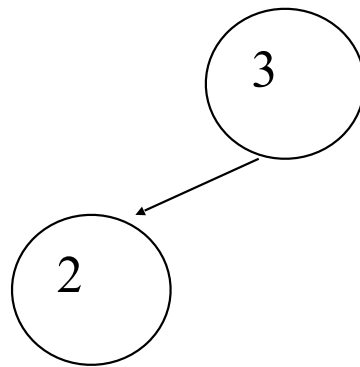


Fig 2

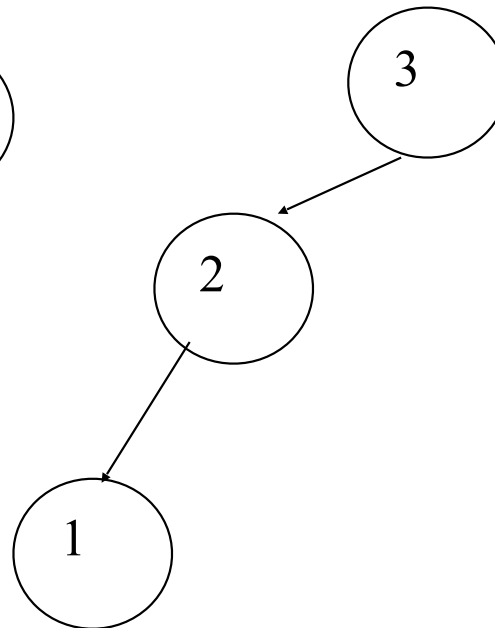


Fig 3

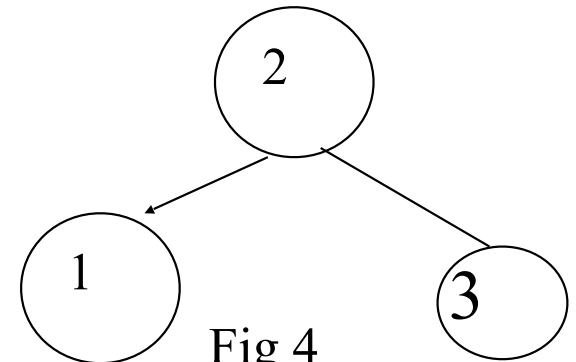


Fig 4

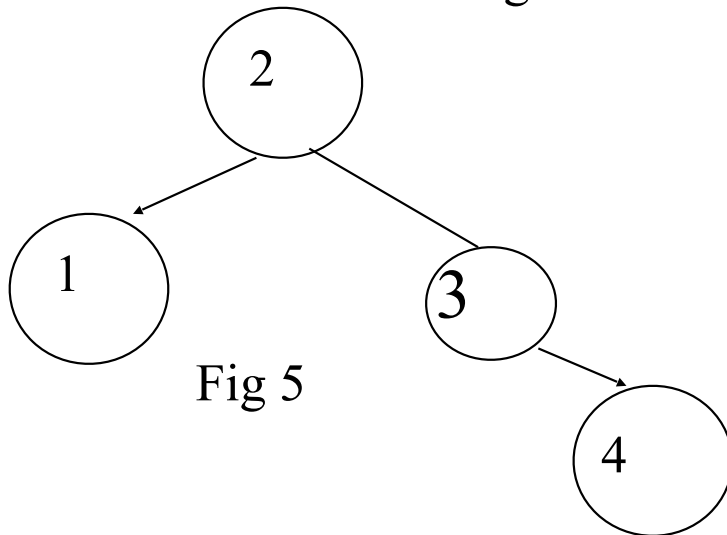


Fig 5

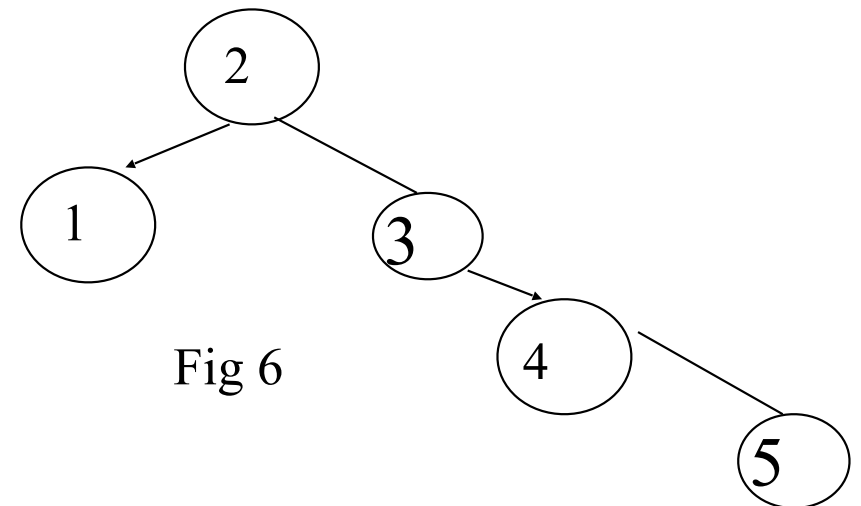


Fig 6

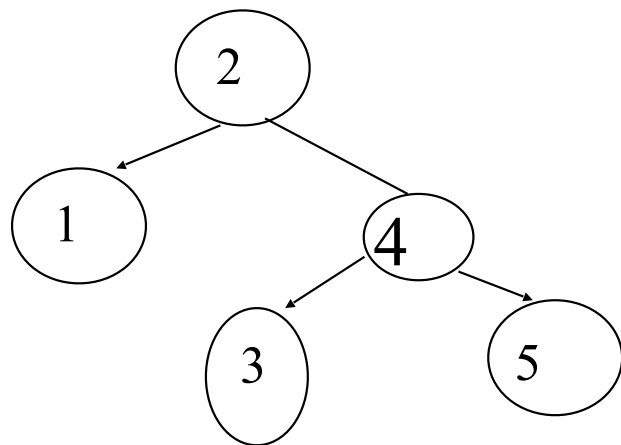


Fig 7

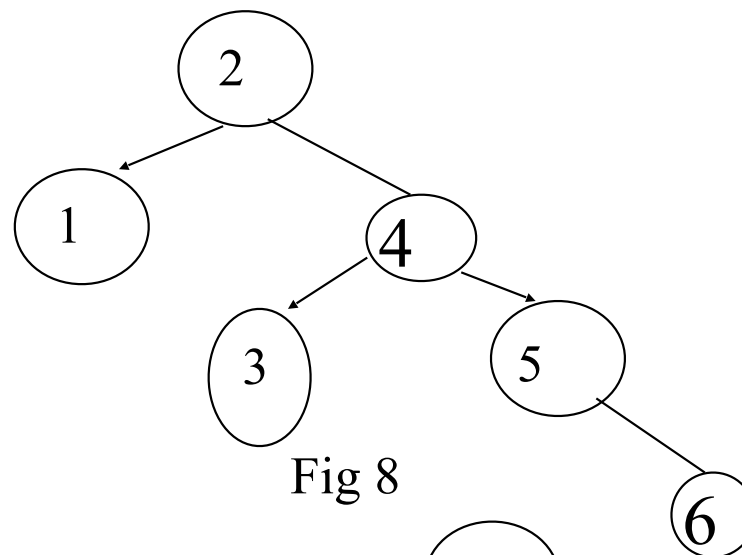


Fig 8

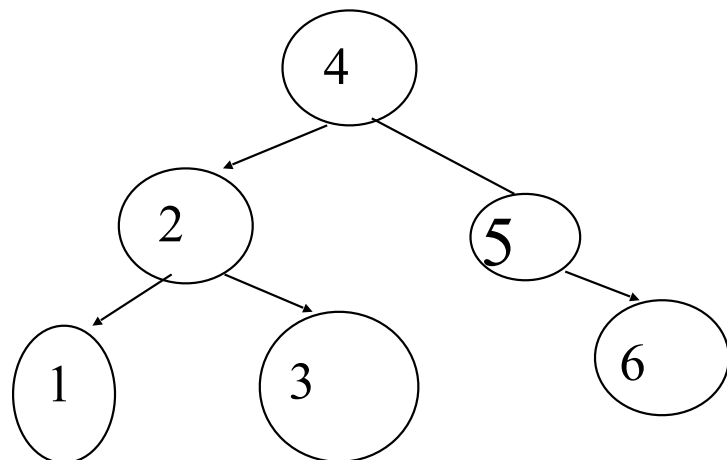


Fig 9

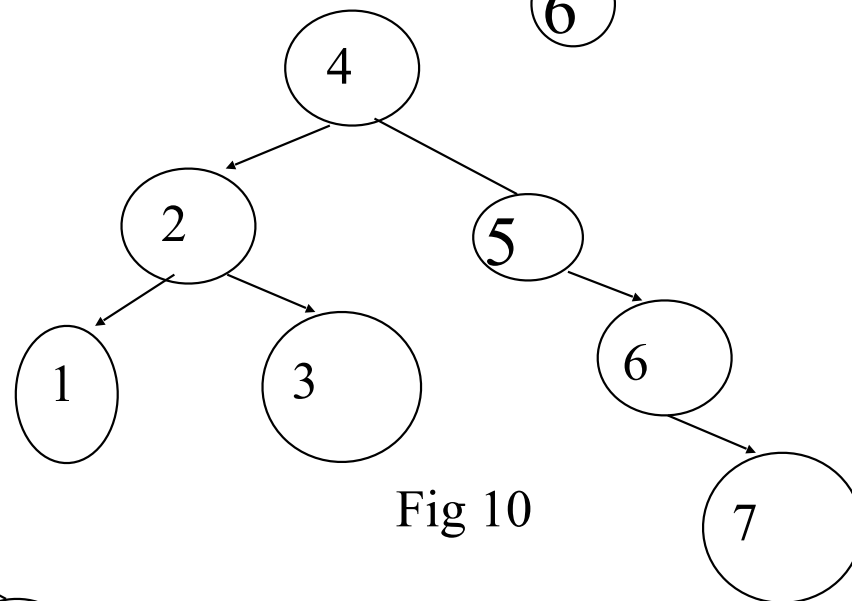


Fig 10

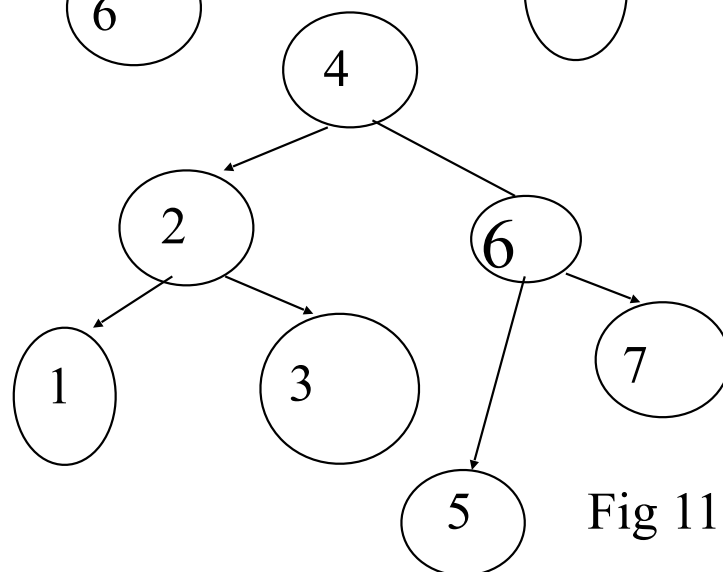


Fig 11

inside case:

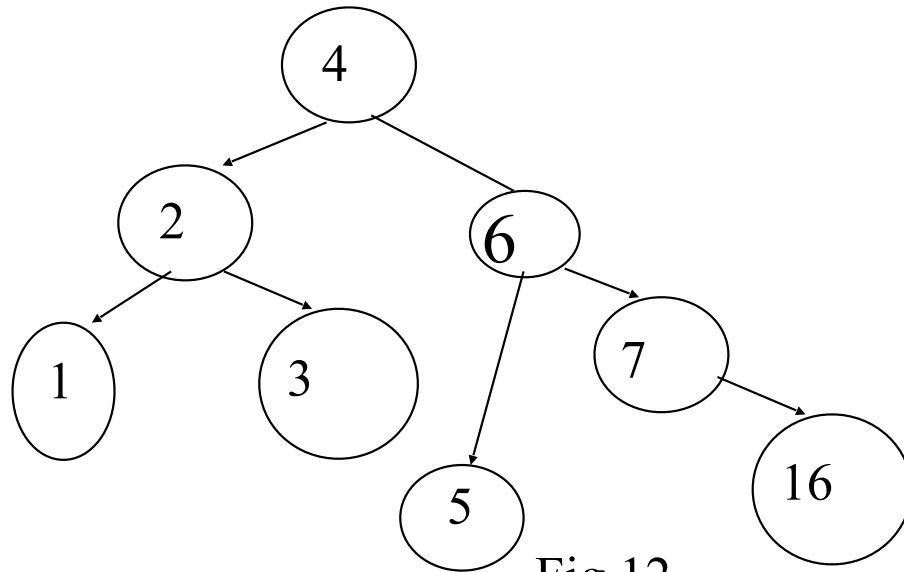


Fig 12

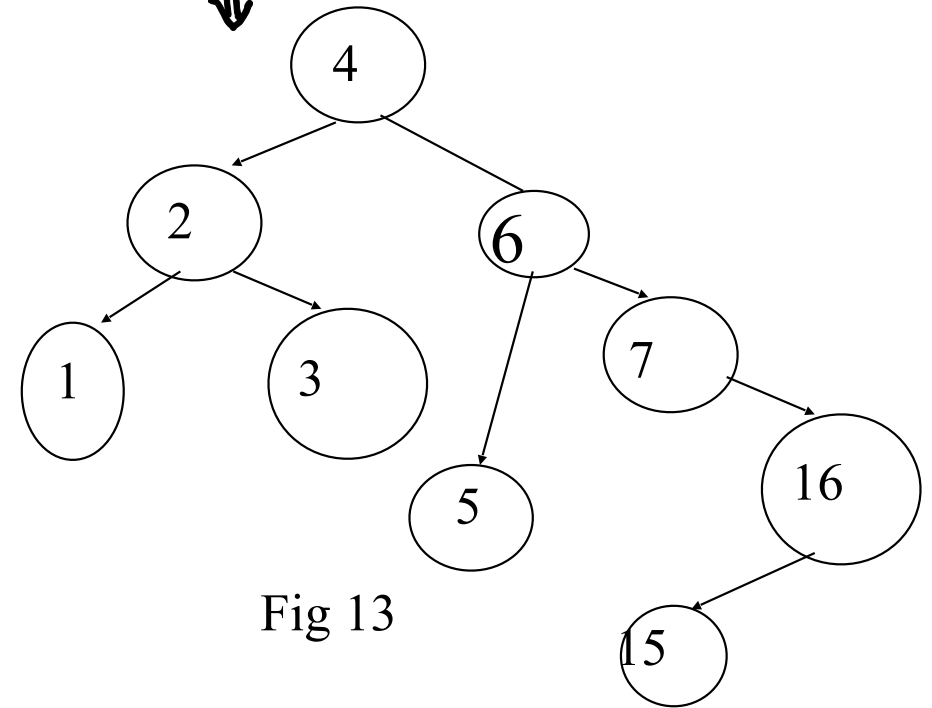


Fig 13

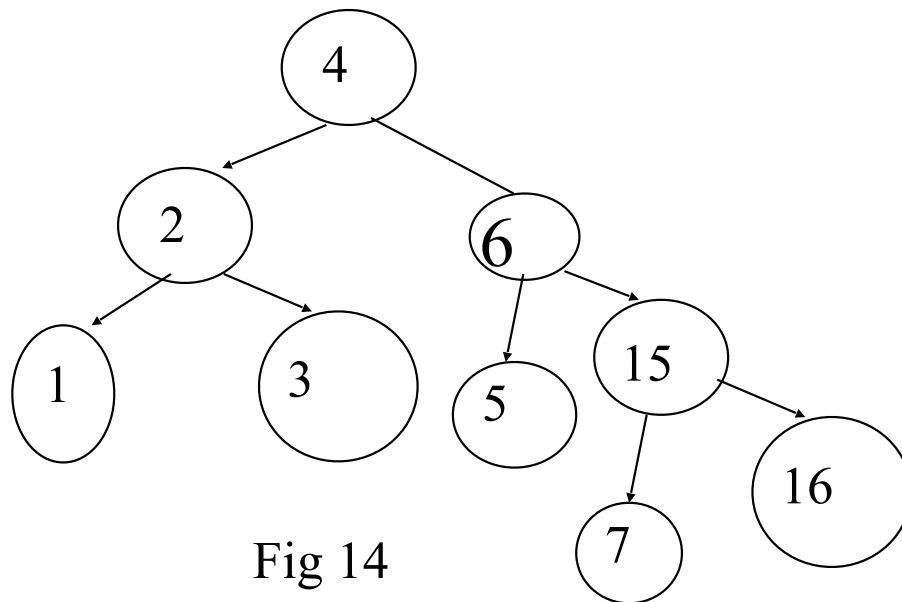
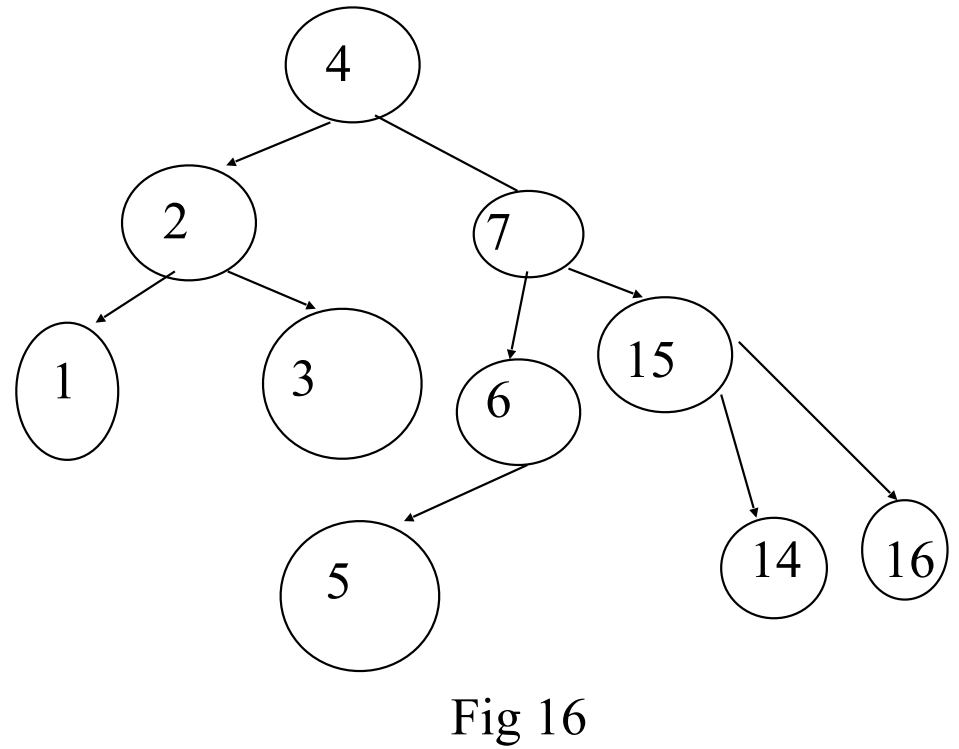
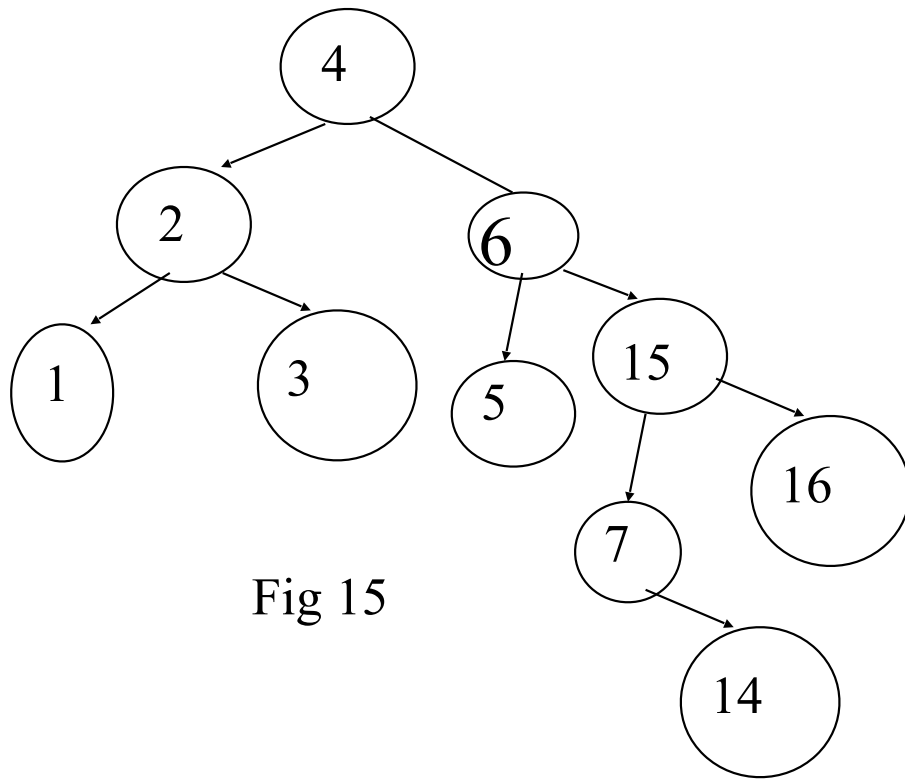


Fig 14



Deletions can be done with similar rotations

Running Times for AVL Trees

- ▶ A single restructure/rotation is $O(1)$
- ▶ Find/search is $O(\log n)$: *Search & Find the violation*
 - ▶ height of tree is $O(\log n)$, no restructures needed
- ▶ Insertion is $O(\log n)$
 - ▶ initial find is $O(\log n)$
 - ▶ Restructuring up the tree, maintaining heights is $O(\log n)$
- ▶ Deletion is $O(\log n)$
 - ▶ initial find is $O(\log n)$
 - ▶ Restructuring up the tree, maintaining heights is $O(\log n)$