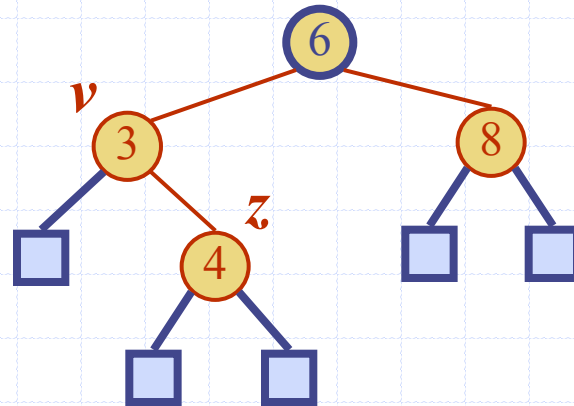
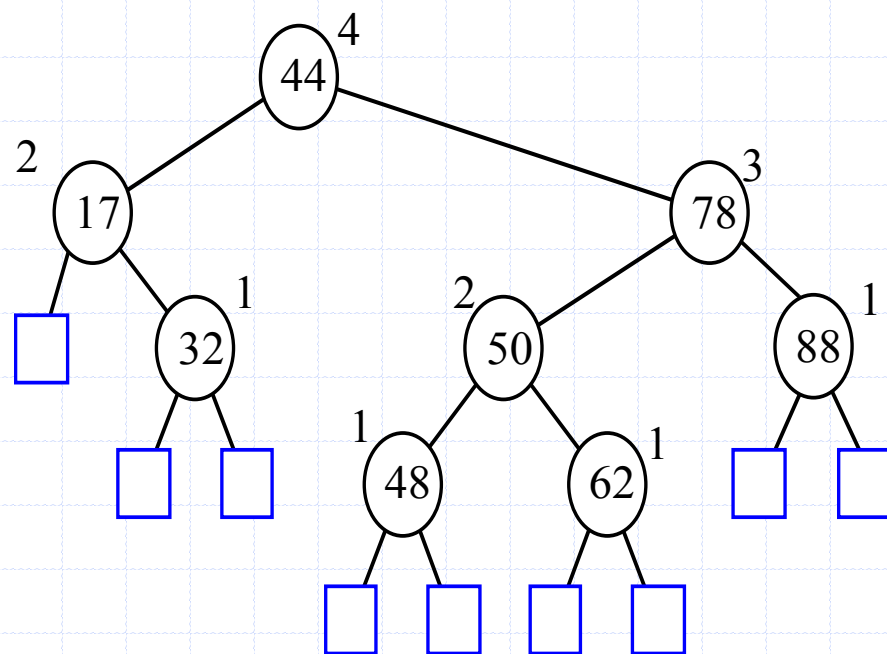


AVL Trees

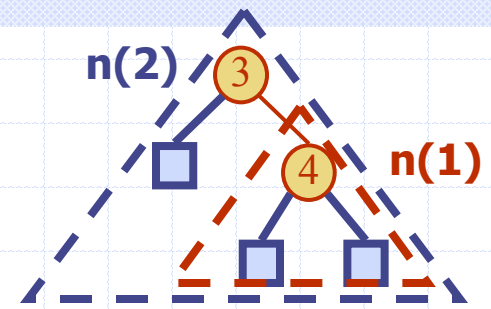


AVL Tree Definition (§ 9.2)

- ◆ **AVL trees are balanced.**
- ◆ An AVL Tree is a ***binary search tree*** such that for every internal node v of T , the *heights of the children of v can differ by at most 1.*



An example of an AVL tree where the heights are shown next to the nodes:

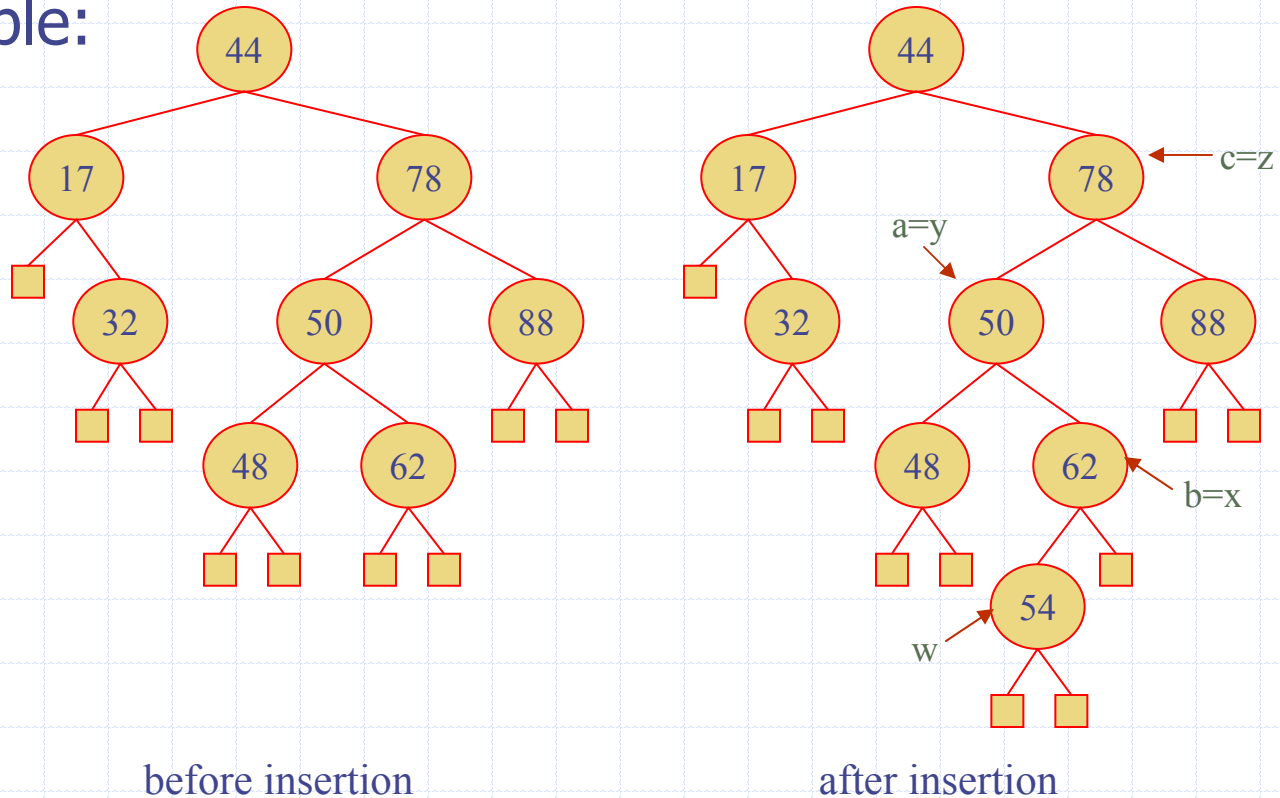


Height of an AVL Tree

- ◆ **Fact:** The *height* of an AVL tree storing n keys is $O(\log n)$.
- ◆ **Proof:** Let us bound $n(h)$: the minimum number of internal nodes of an AVL tree of height h .
- ◆ We easily see that $n(1) = 1$ and $n(2) = 2$
- ◆ For $n > 2$, an AVL tree of height h contains the root node, one AVL subtree of height $h-1$ and another of height $h-2$.
- ◆ That is, $n(h) = 1 + n(h-1) + n(h-2)$
- ◆ Knowing $n(h-1) > n(h-2)$, we get $n(h) > 2n(h-2)$. So
 $n(h) > 2n(h-2)$, $n(h) > 4n(h-4)$, $n(h) > 8n(h-6)$, ... (by induction),
 $n(h) > 2^i n(h-2i)$
- ◆ Solving the base case we get: $n(h) > 2^{h/2-1}$
- ◆ Taking logarithms: $h < 2\log n(h) + 2$
- ◆ Thus the height of an AVL tree is $O(\log n)$

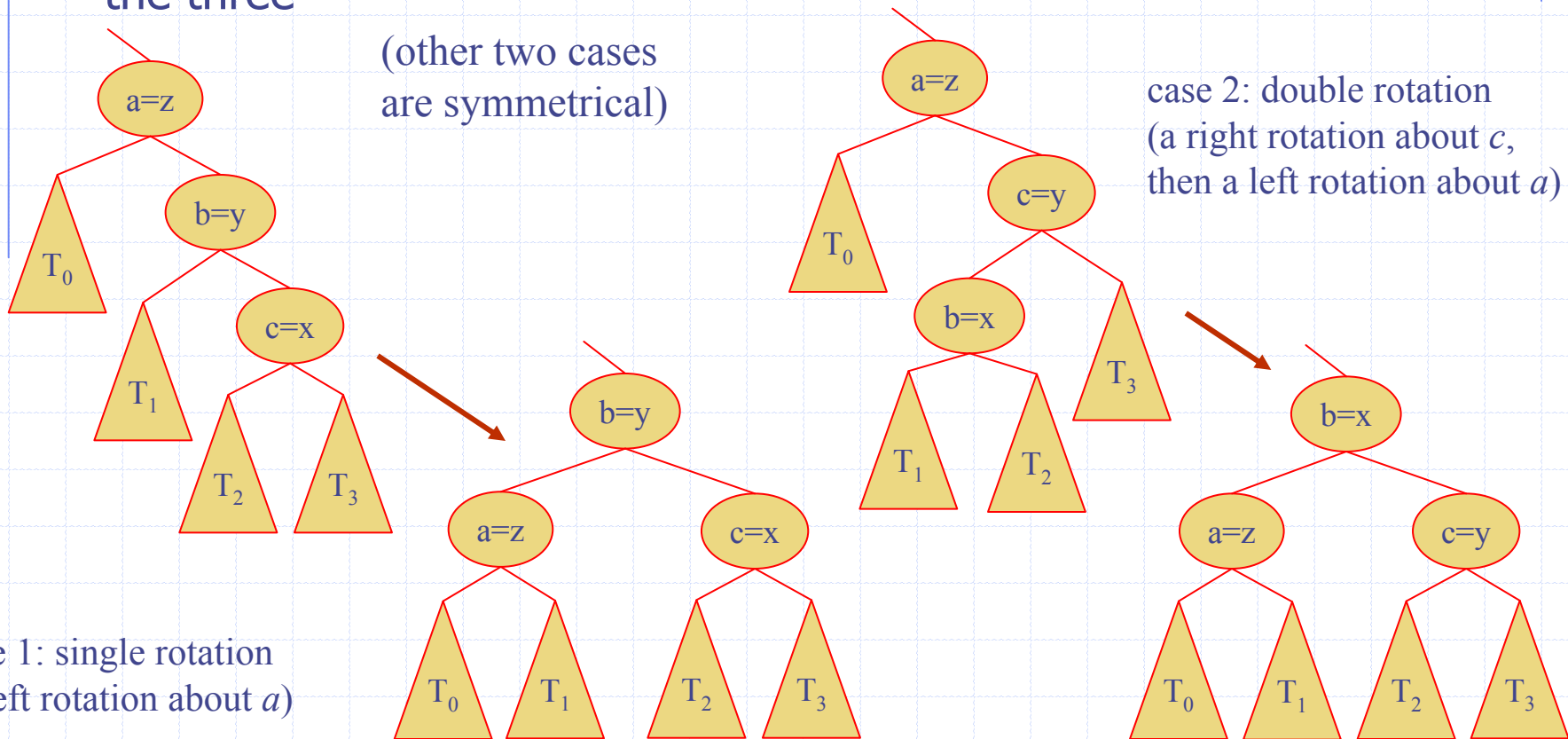
Insertion in an AVL Tree

- ◆ Insertion is as in a binary search tree
- ◆ Always done by expanding an external node.
- ◆ Example:

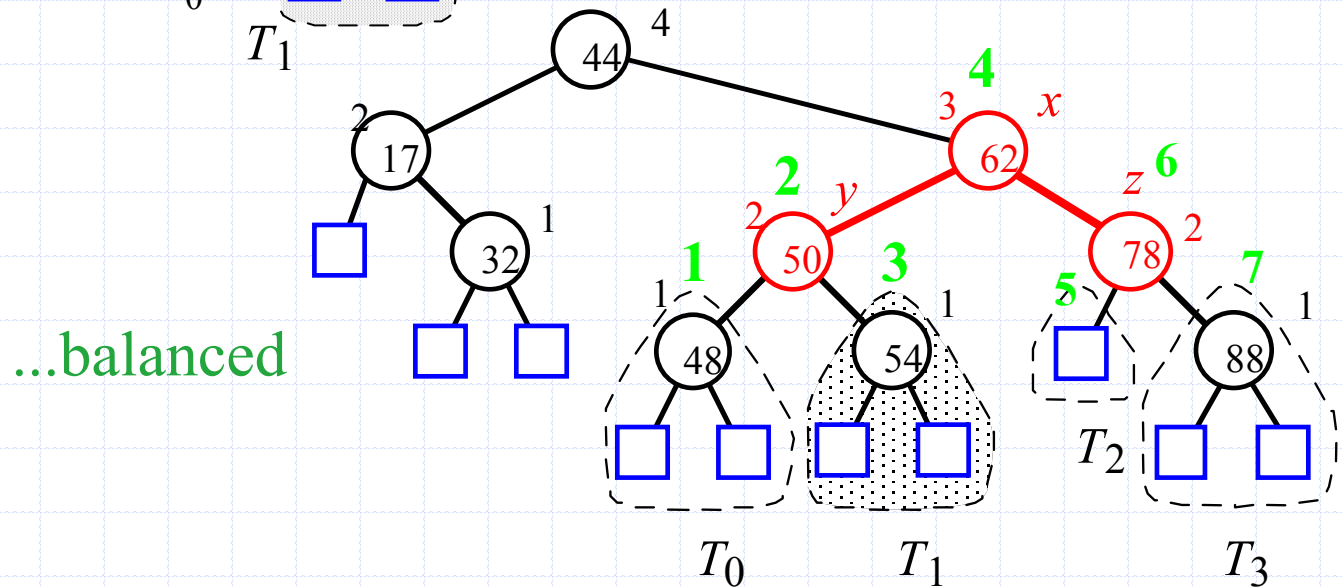
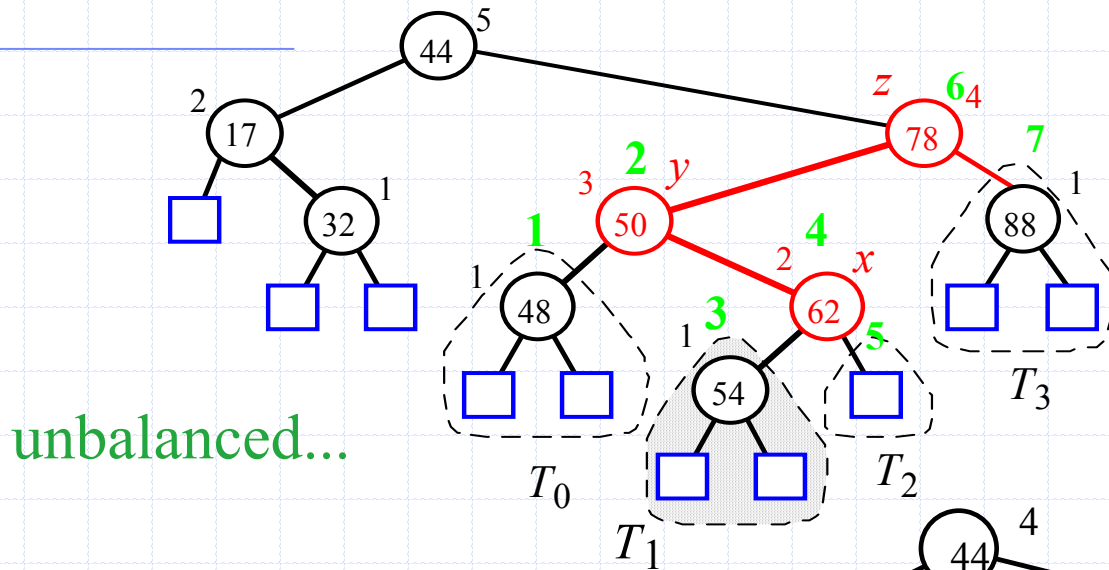


Trinode Restructuring

- ◆ let (a, b, c) be an inorder listing of x, y, z
- ◆ perform the rotations needed to make b the topmost node of the three

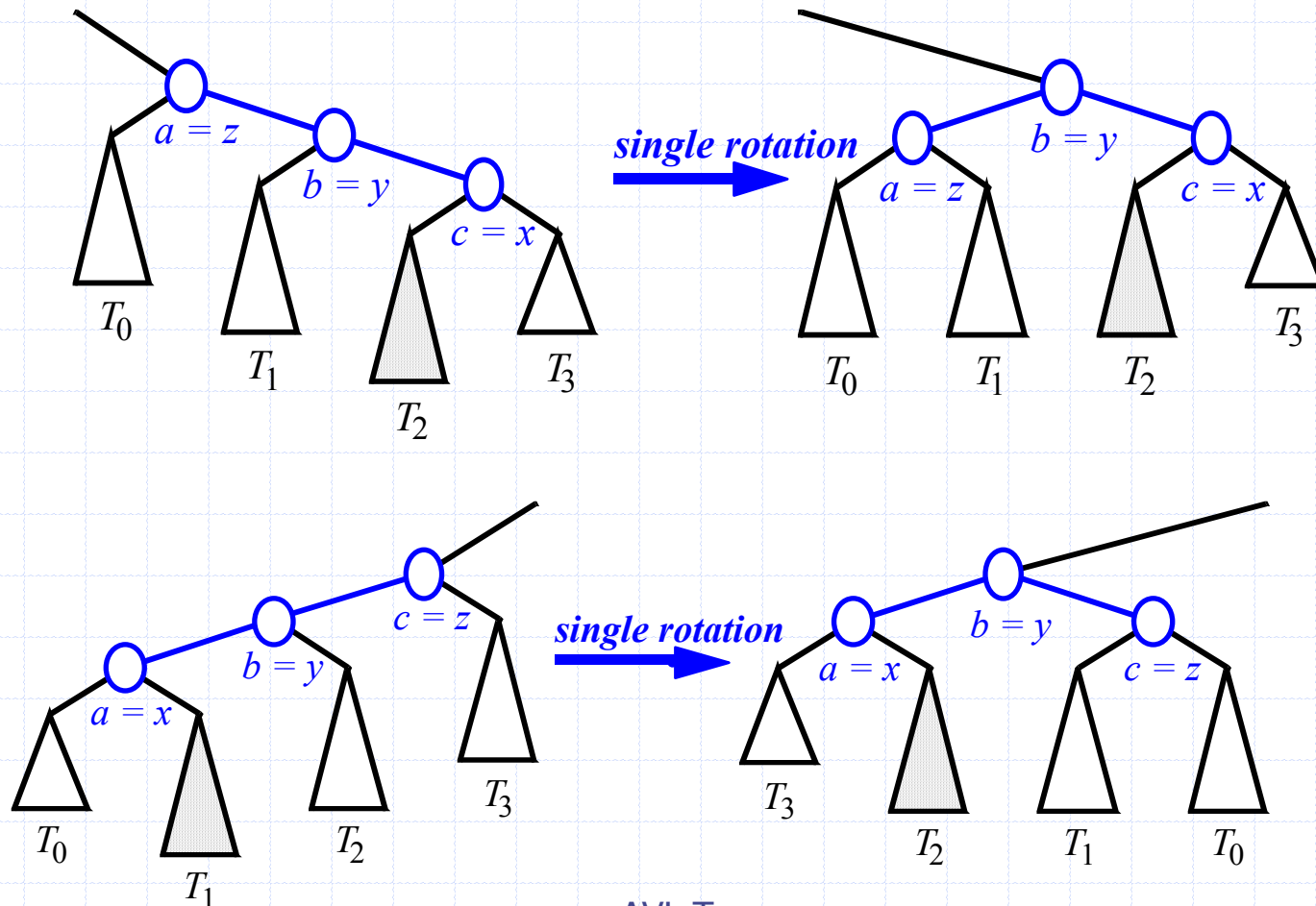


Insertion Example, continued



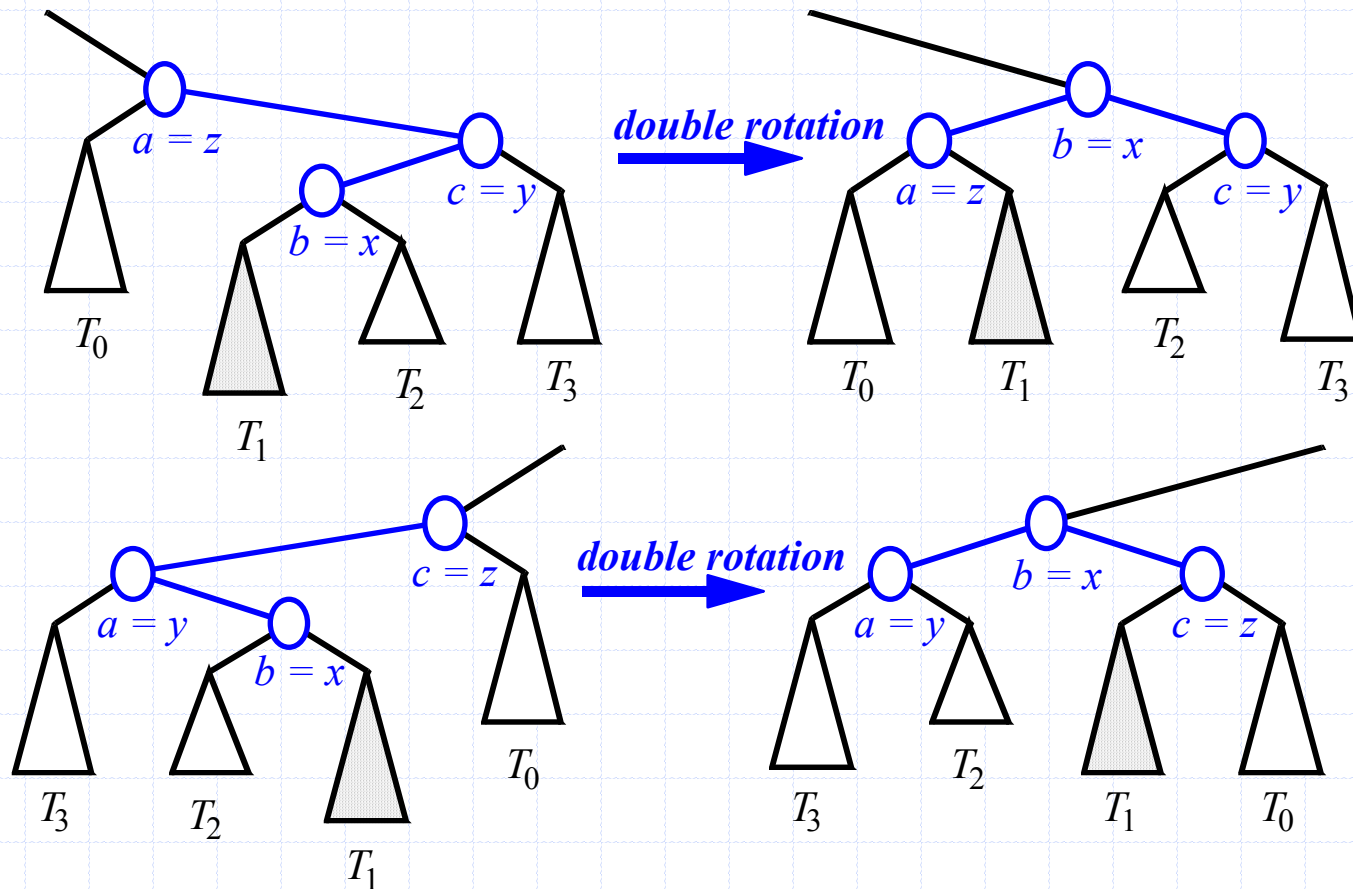
Restructuring (as Single Rotations)

◆ Single Rotations:



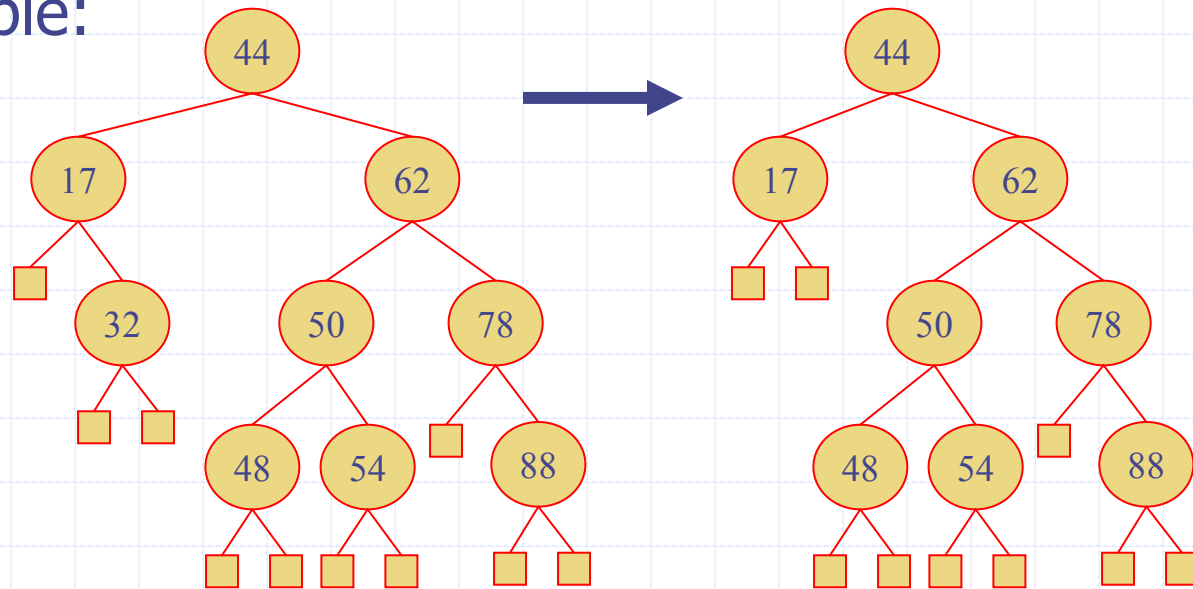
Restructuring (as Double Rotations)

◆ double rotations:



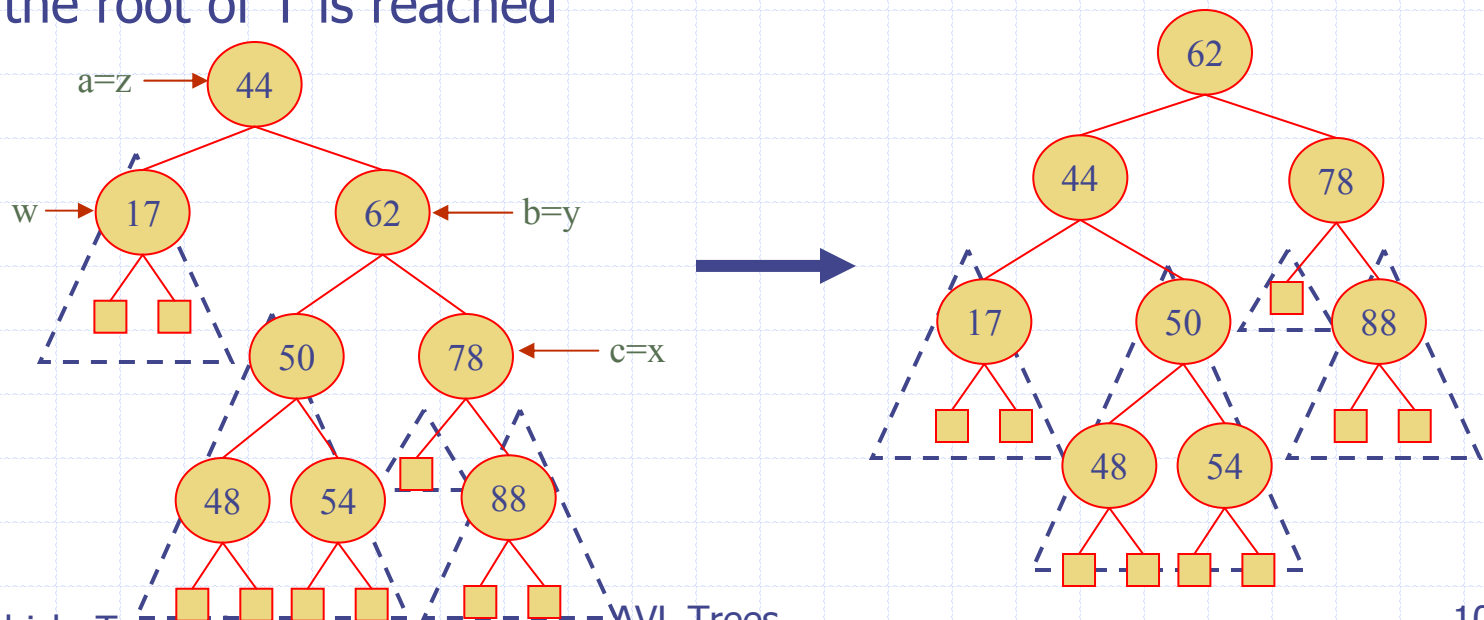
Removal in an AVL Tree

- ◆ Removal begins as in a binary search tree, which means the node removed will become an empty external node. Its parent, w , may cause an imbalance.
- ◆ Example:

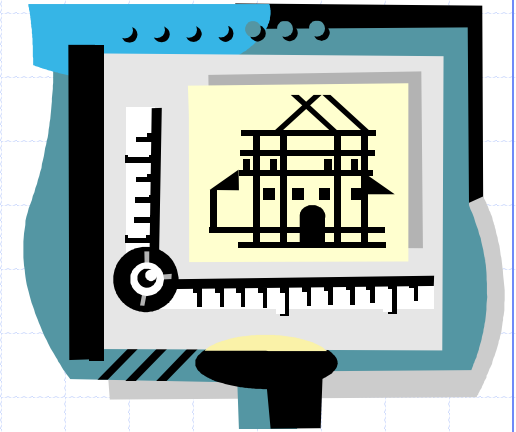


Rebalancing after a Removal

- ◆ Let z be the **first unbalanced** node encountered while travelling up the tree from w . Also, let y be the child of z with the larger height, and let x be the child of y with the larger height.
- ◆ We perform **restructure**(x) to restore balance at z .
- ◆ As this restructuring may upset the balance of another node higher in the tree, we must continue checking for balance until the root of T is reached



Running Times for AVL Trees



- ◆ a single restructure is $O(1)$
 - using a linked-structure binary tree
- ◆ find is $O(\log n)$
 - height of tree is $O(\log n)$, no restructures needed
- ◆ insert is $O(\log n)$
 - initial find is $O(\log n)$
 - Restructuring up the tree, maintaining heights is $O(\log n)$
- ◆ remove is $O(\log n)$
 - initial find is $O(\log n)$
 - Restructuring up the tree, maintaining heights is $O(\log n)$