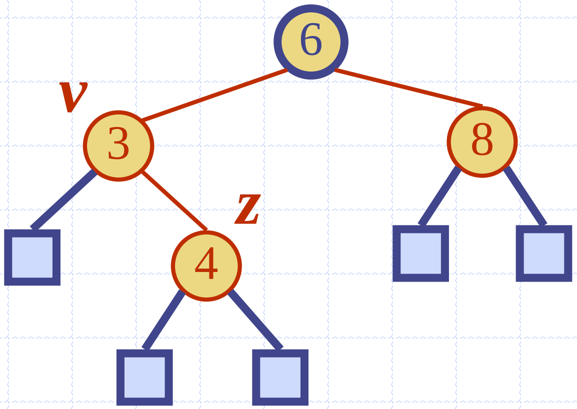
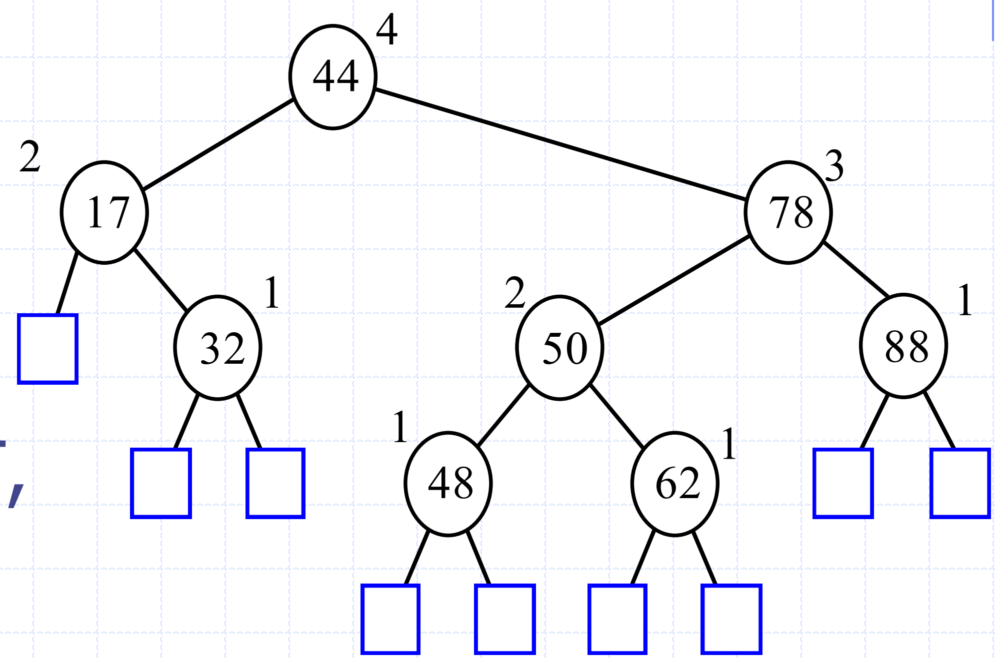
# AVL Trees



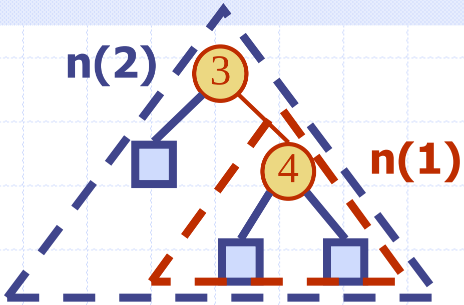
# AVL Tree Definition

- 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:

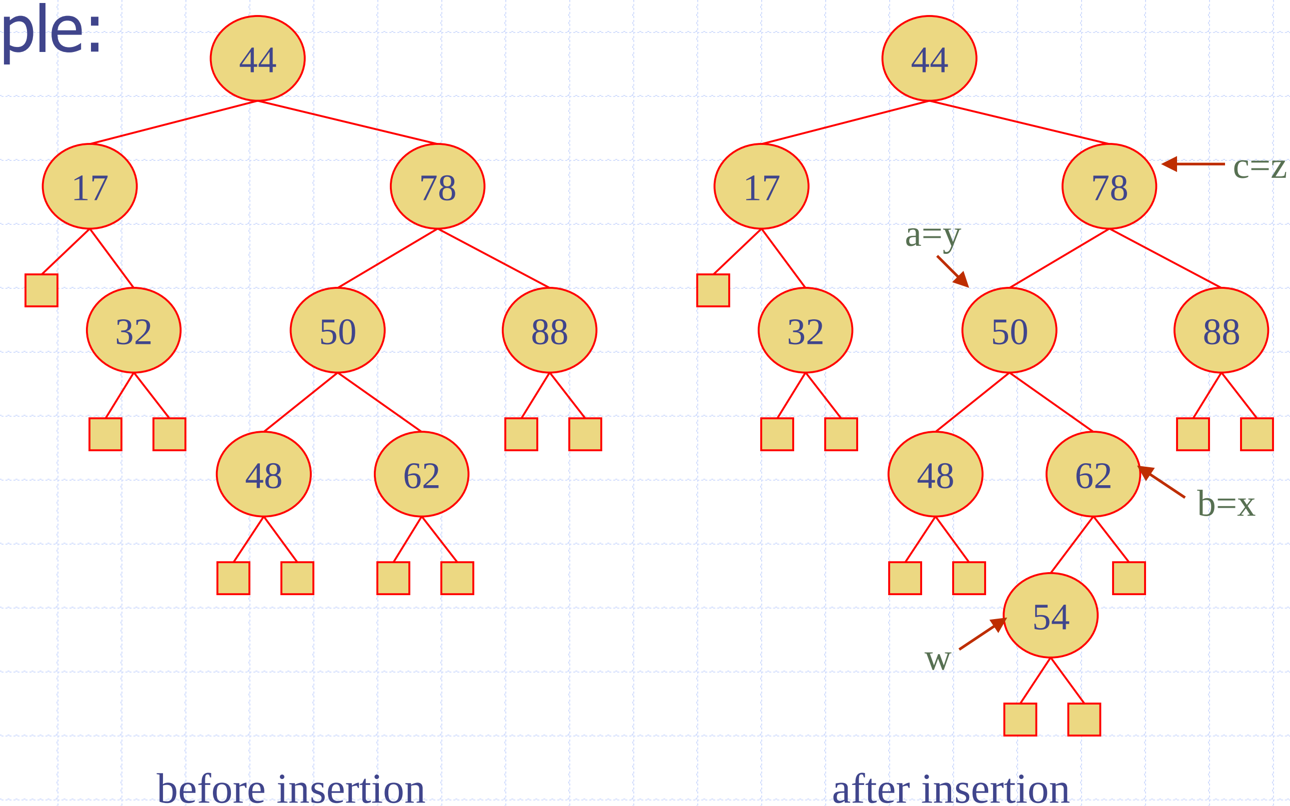
# Height of an AVL Tree




- 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 n-1 and another of height n-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(n-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 < 2log n(h) +2
- Thus the height of an AVL tree is O(log n)

# Insertion

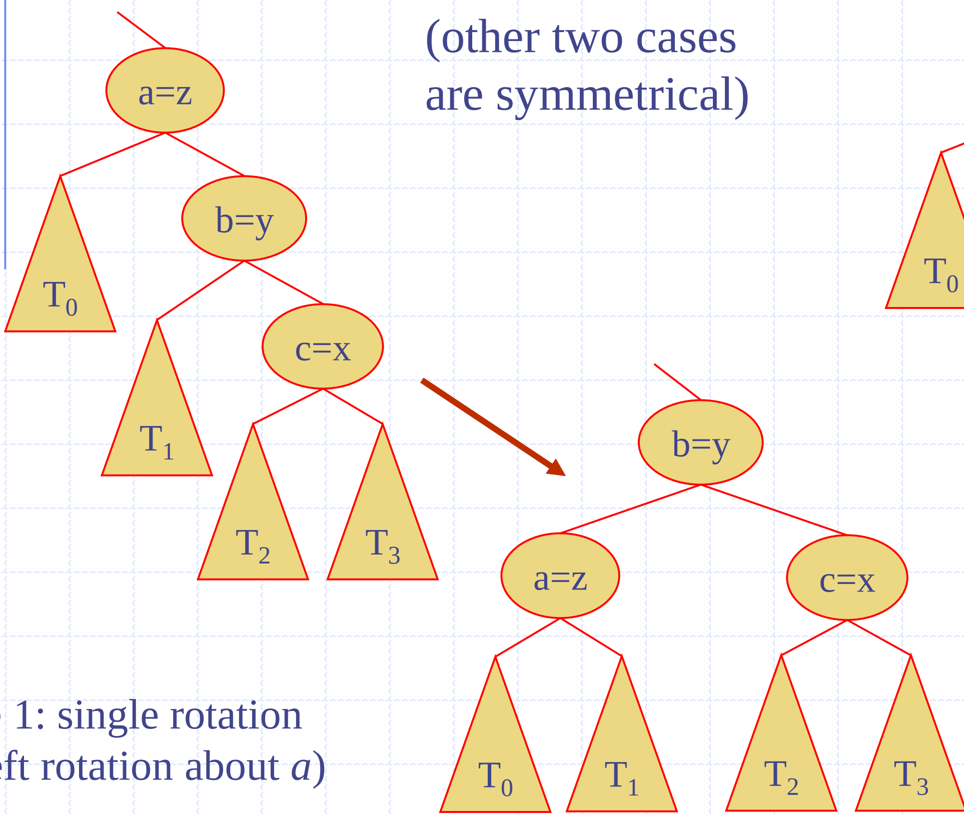
- Insertion is as in a binary search tree
- Always done by expanding an external node.
- Example:



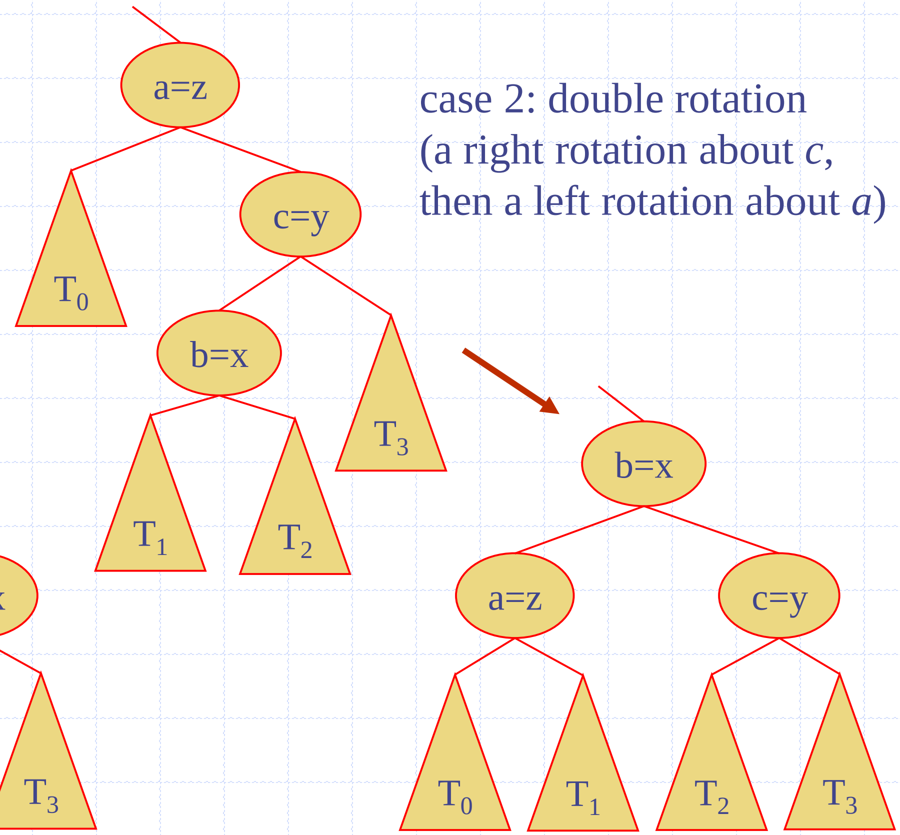
# Trinode Restructuring

- 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

(other two cases are symmetrical)

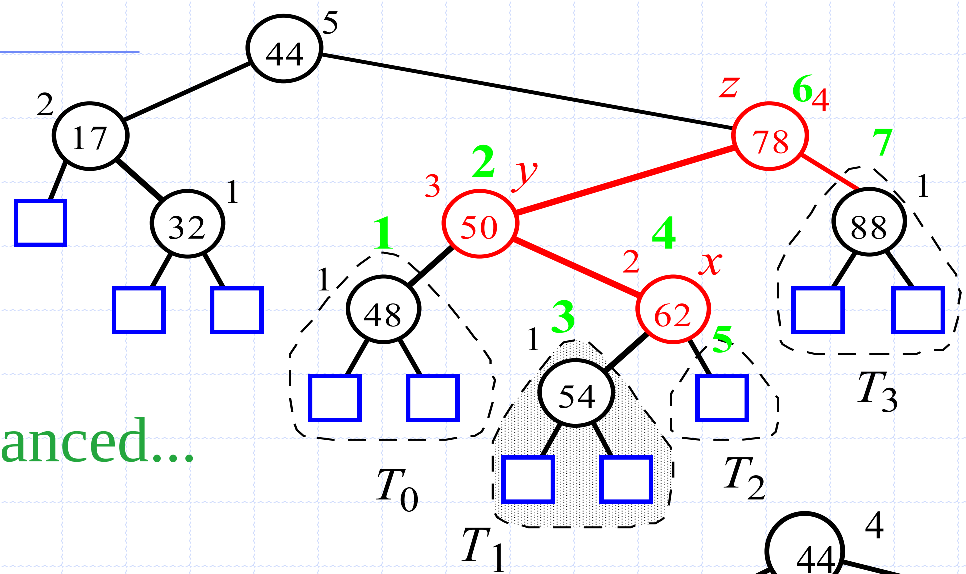



case 1: single rotation
(a left rotation about *a*)

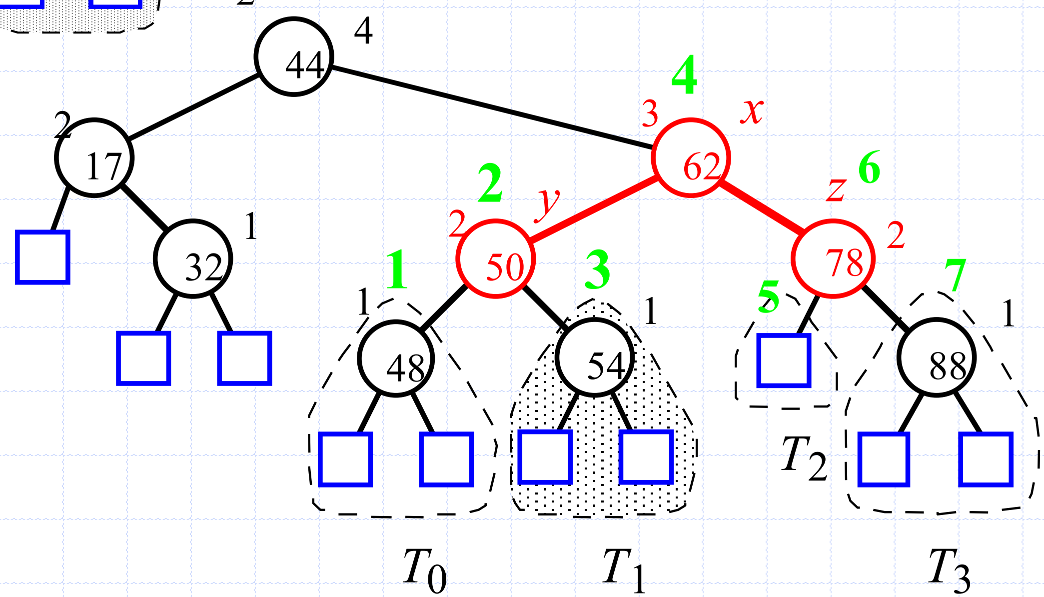



case 2: double rotation
(a right rotation about *c*,
then a left rotation about *a*)

# Insertion Example, continued



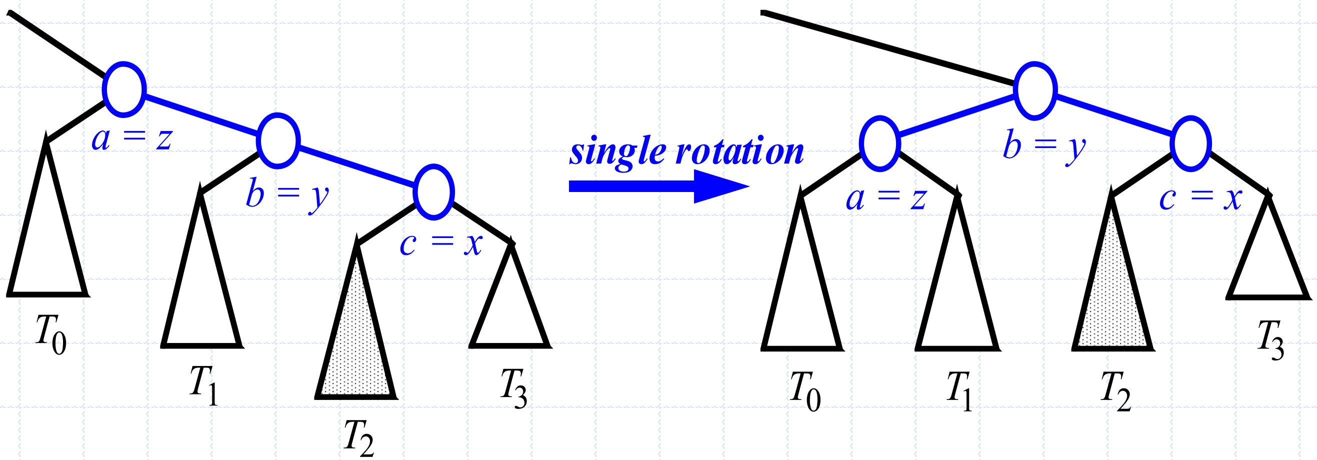

unbalanced...

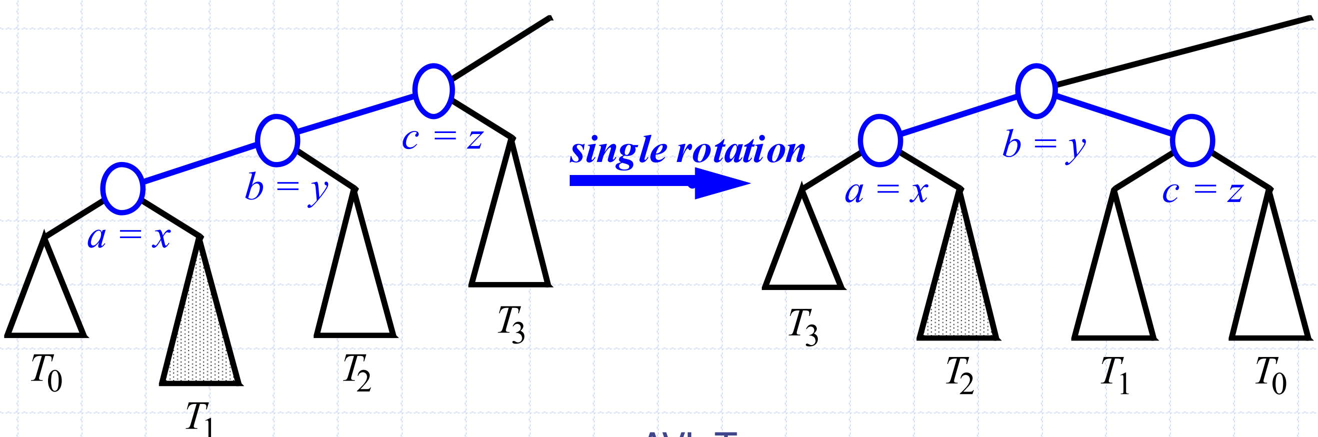



...balanced

# Restructuring (as Single Rotations)

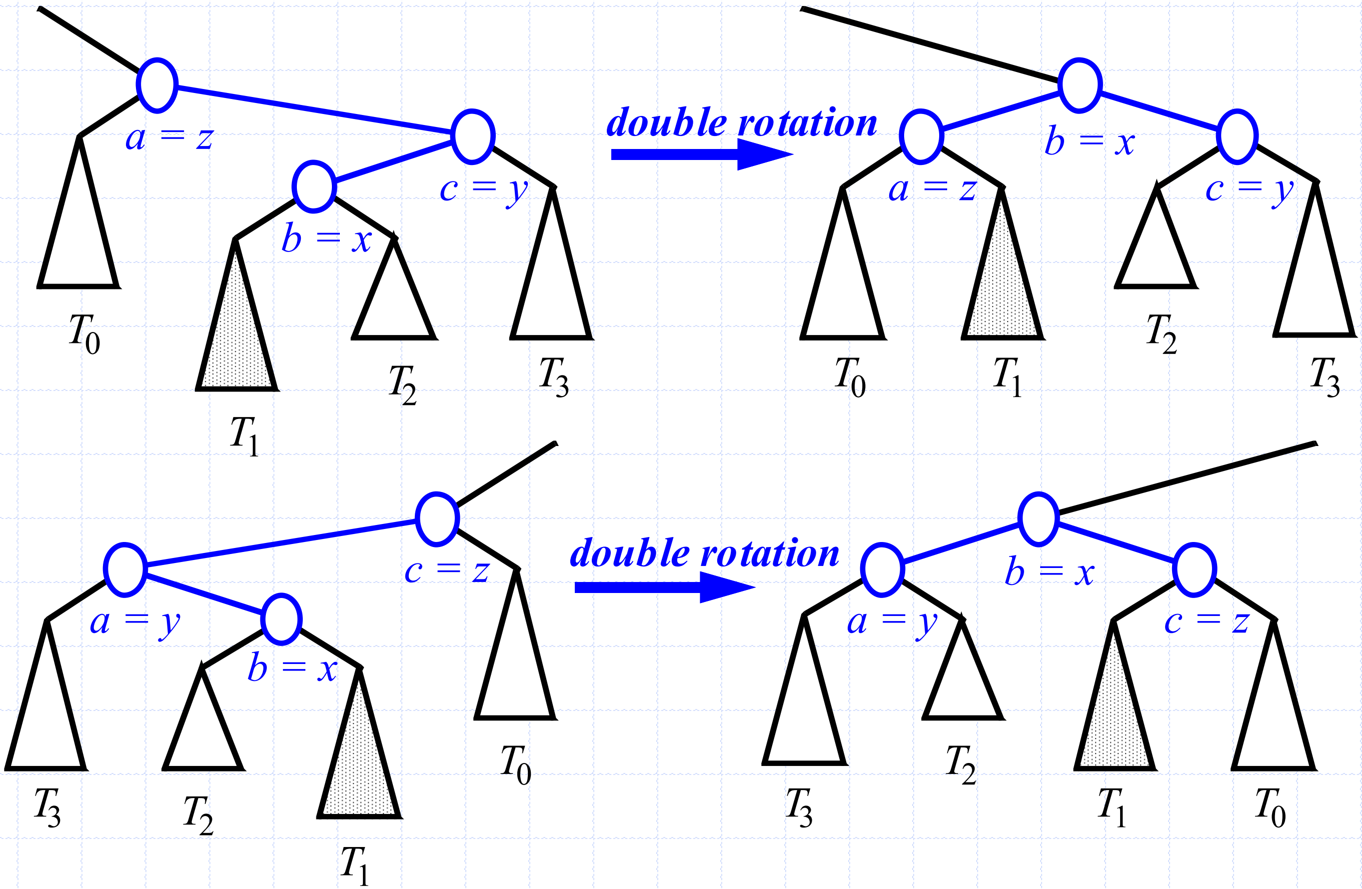
- Single Rotations:



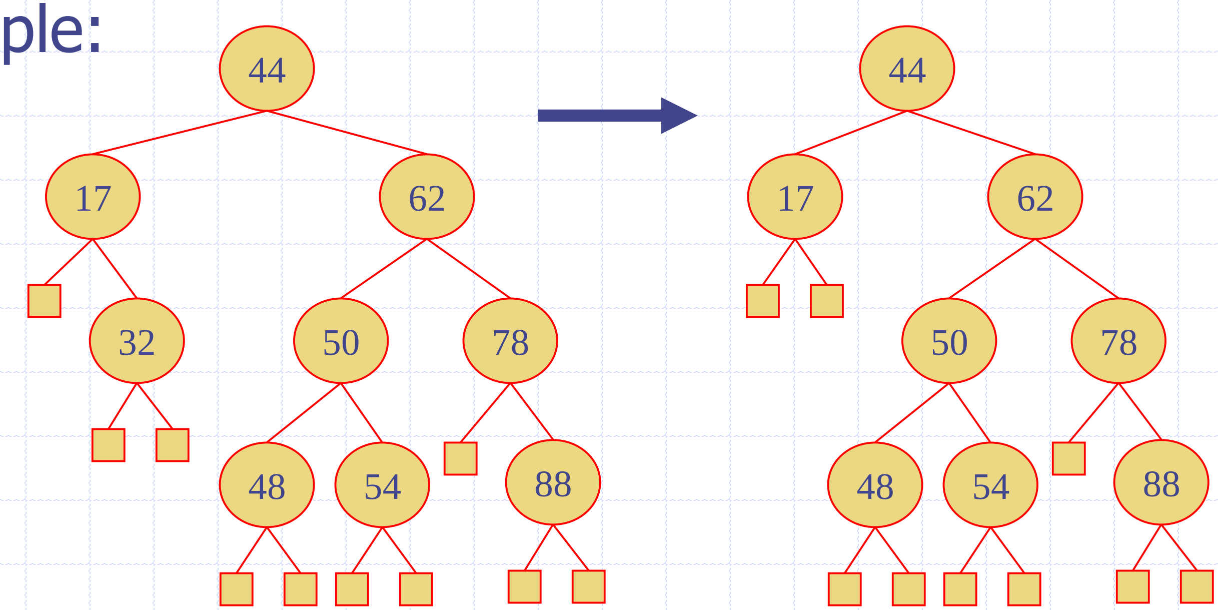
# Restructuring (as Double Rotations)

- double rotations:



# Removal

- 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:

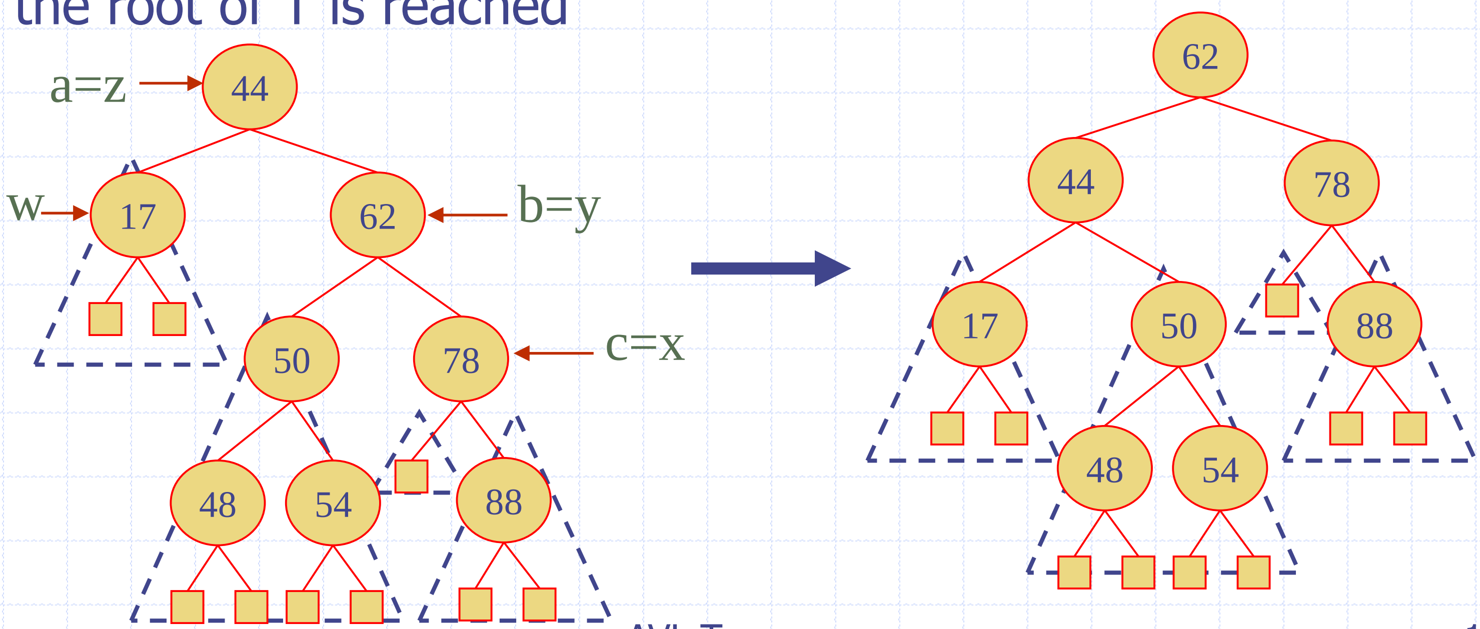



before deletion of 32

after deletion

# Rebalancing after a Removal

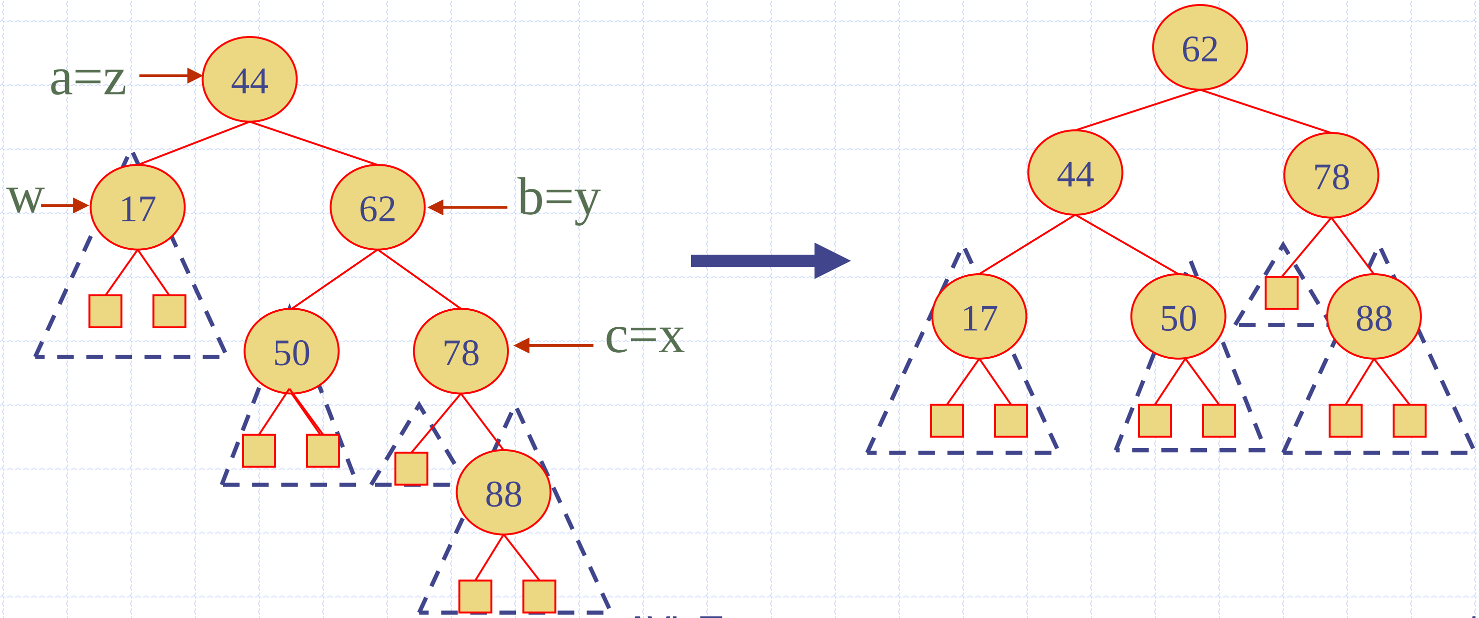
- Let z be the first unbalanced node encountered while travelling up the tree from w. Also, let y be the child of z with the larger height, and let x be the child of y with the larger height
- We perform restructure(x) to restore balance at z
- As this restructuring may upset the balance of another node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



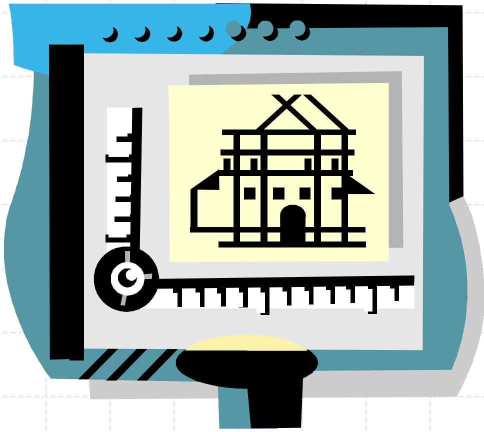
# Rebalancing after a Removal

[Slide added –jyp]

- In the case below, restructuring the subtree rooted at 44 created a new subtree (incidentally now rooted at 62) which is has height decreased by 1
- This might cause an unbalanced situation at an ancestor of this subtree



# AVL Tree Performance



- a single restructure takes O(1) time
  - using a linked-structure binary tree
- find takes O(log n) time
  - height of tree is O(log n), no restructures needed
- put takes O(log n) time
  - initial find is O(log n)
  - Restructuring up the tree, maintaining heights is O(log n)
- erase takes O(log n) time
  - initial find is O(log n)
  - Restructuring up the tree, maintaining heights is O(log n)