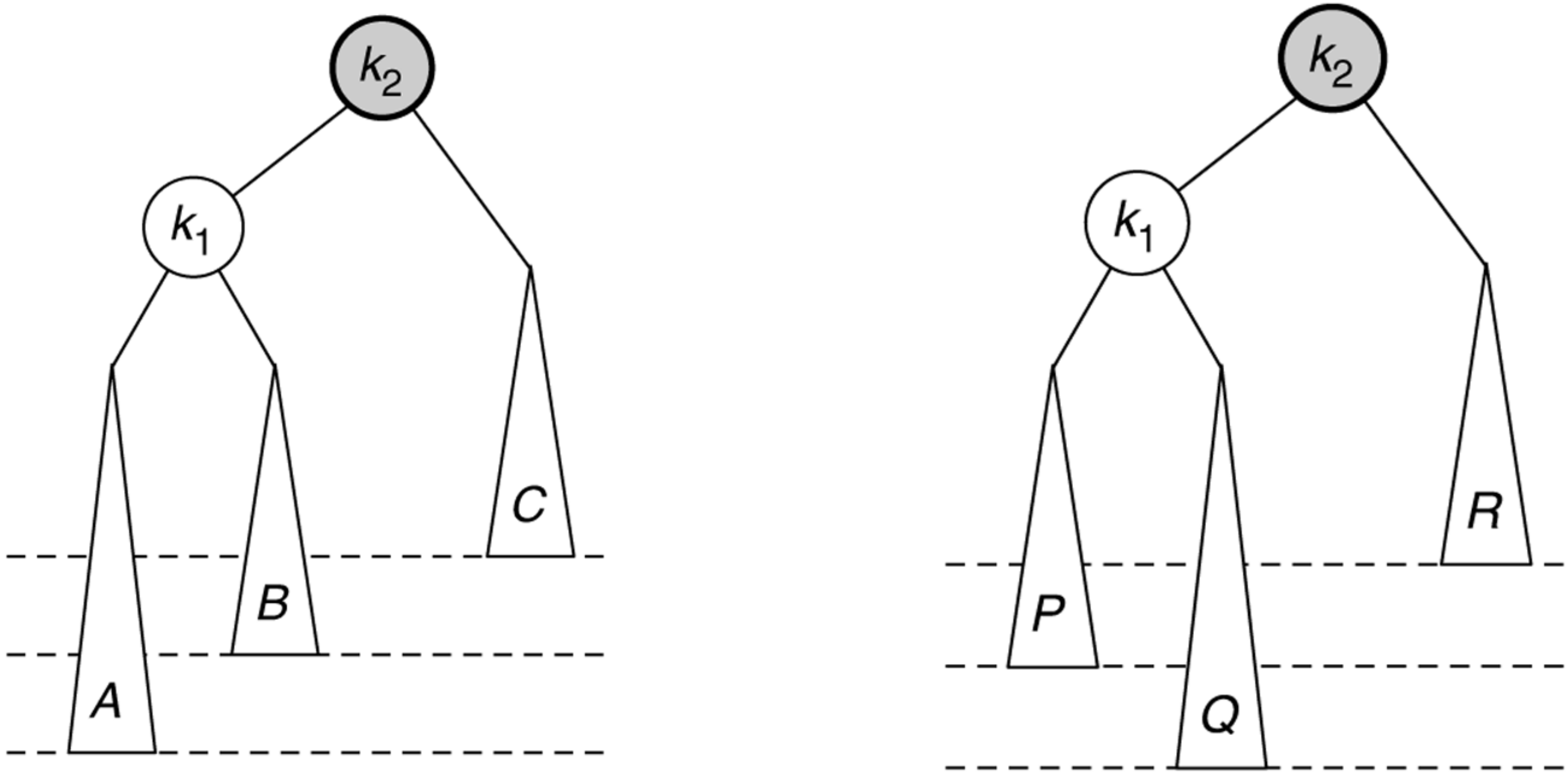
CSE 373
Data Structures and Algorithms

Lecture 12: Trees IV (AVL Trees)

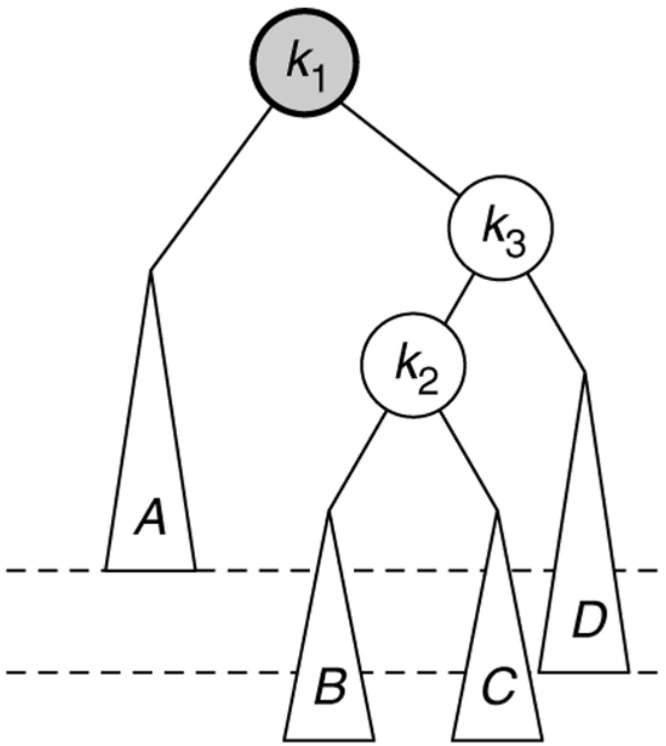
Problem Cases for AVL insert

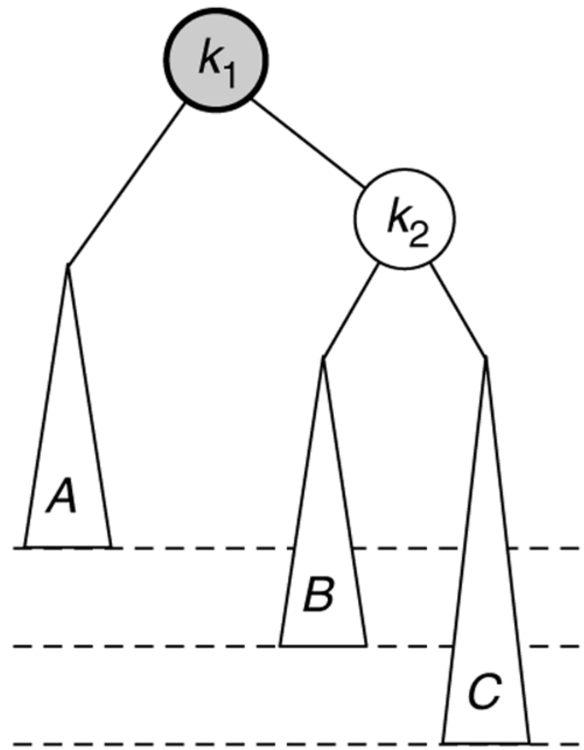
1. LL Case: insertion into left subtree of node's left child
2. LR Case: insertion into right subtree of node's left child



Problem Cases for AVL insert (cont'd)

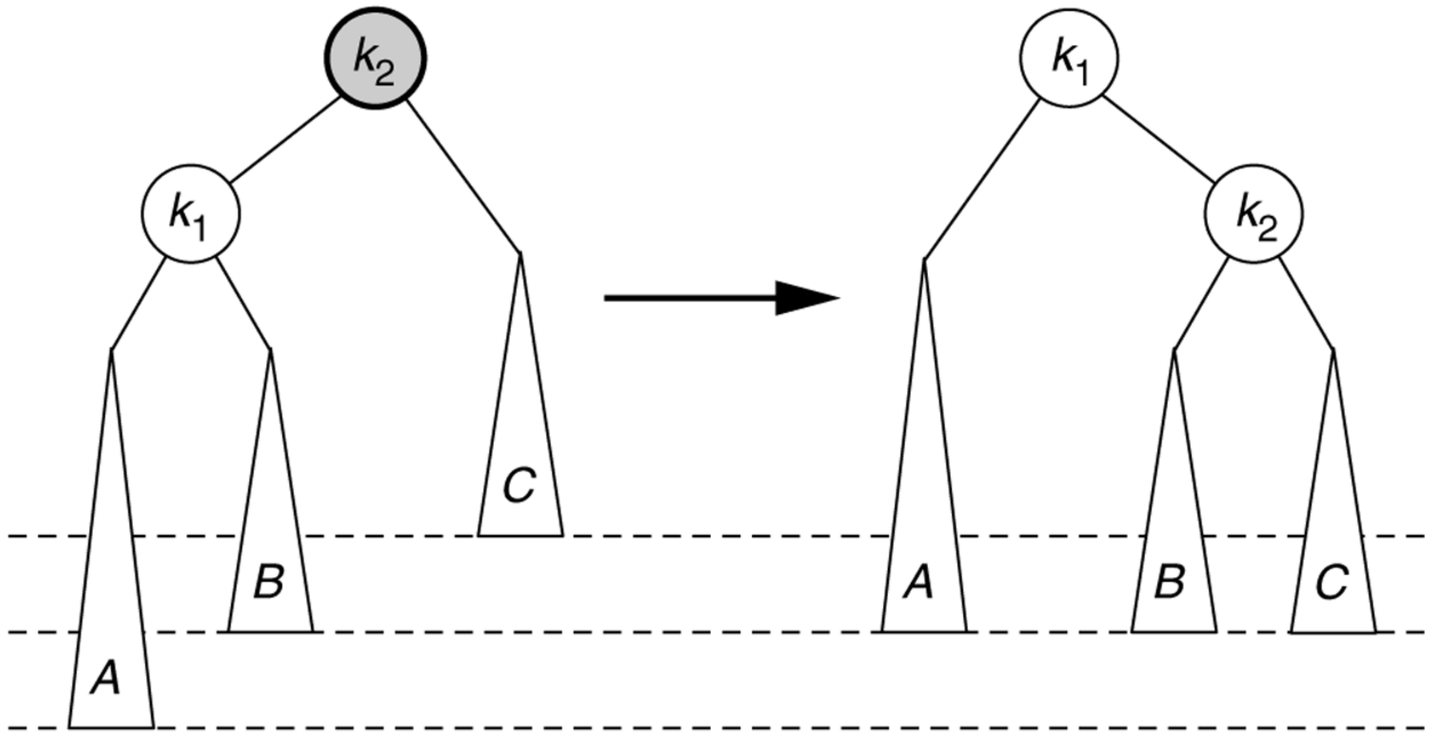
3. RL Case: insertion into left subtree of node's right child
4. RR Case: insertion into right subtree of node's right child





Right rotation to fix Case 1 (LL)

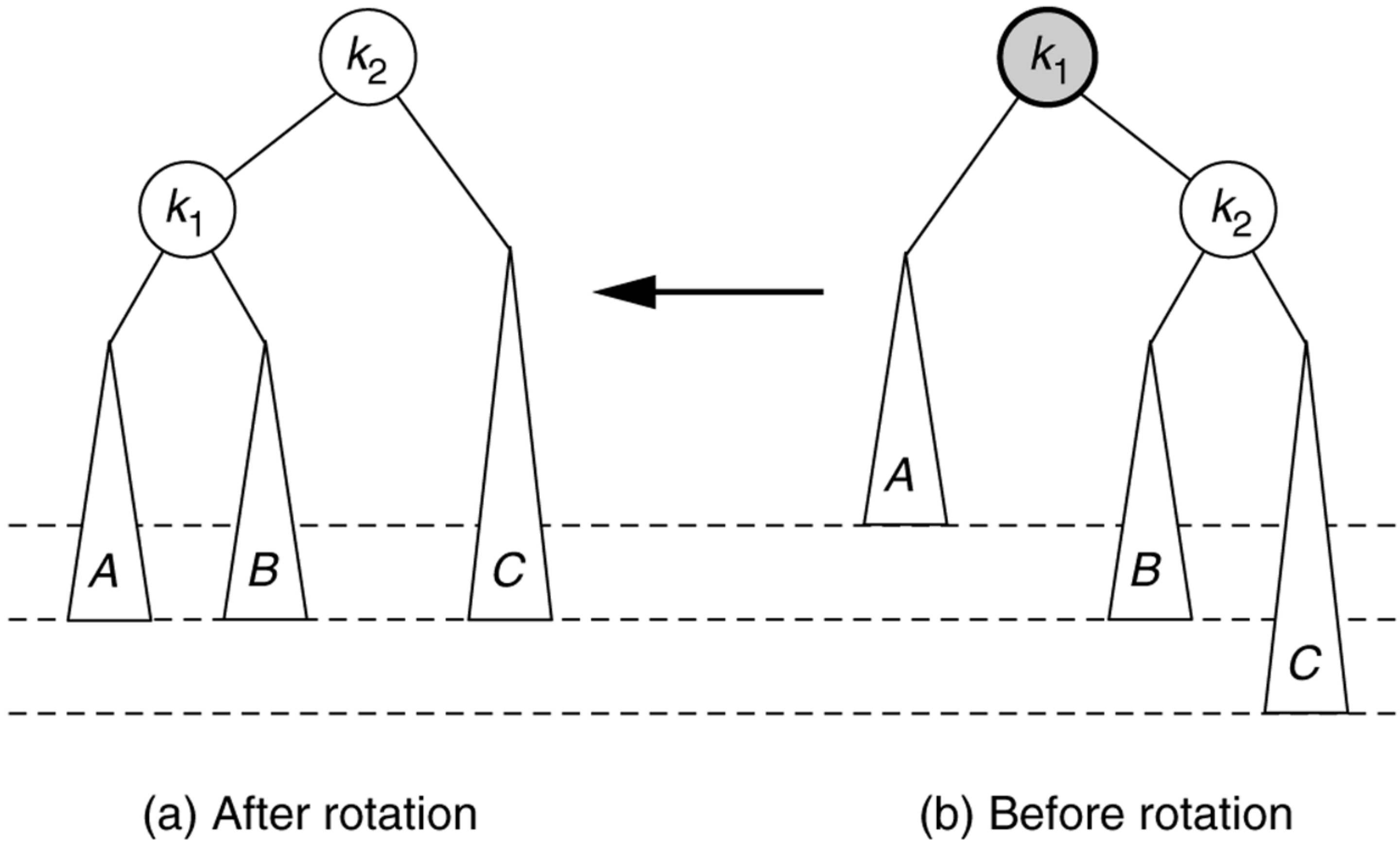
- **right rotation** (clockwise): left child becomes parent; original parent demoted to right



(a) Before rotation (b) After rotation

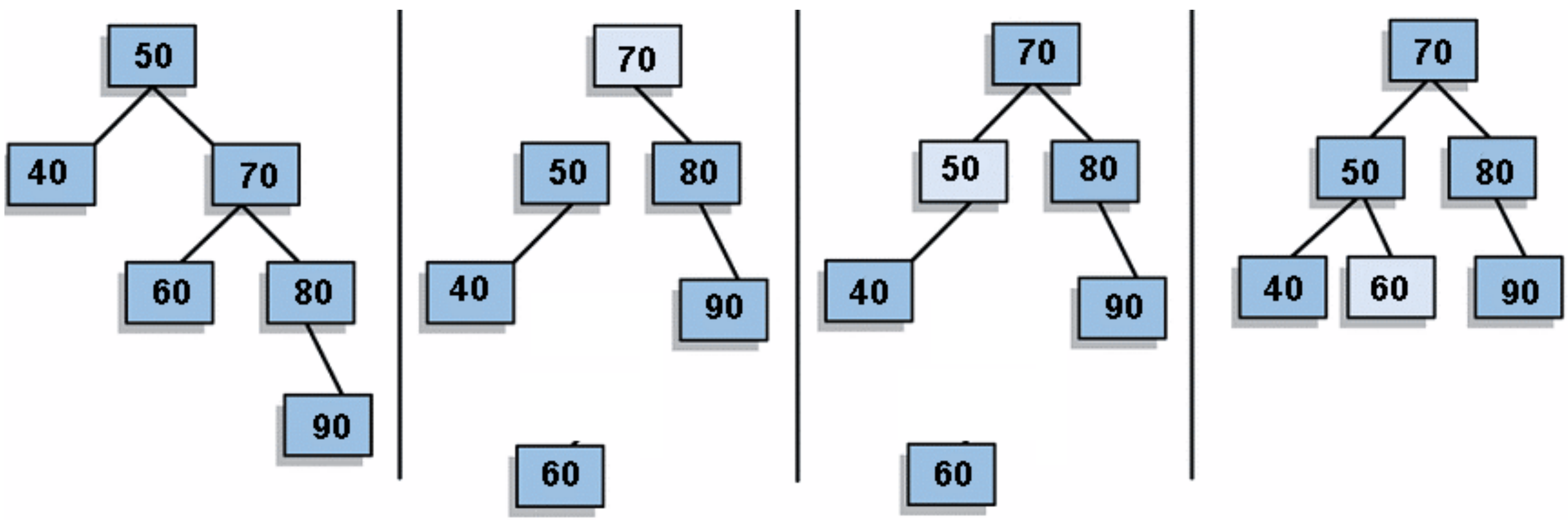
Left rotation to fix Case 4 (RR)

- **left rotation** (counter-clockwise): right child becomes parent; original parent demoted to left



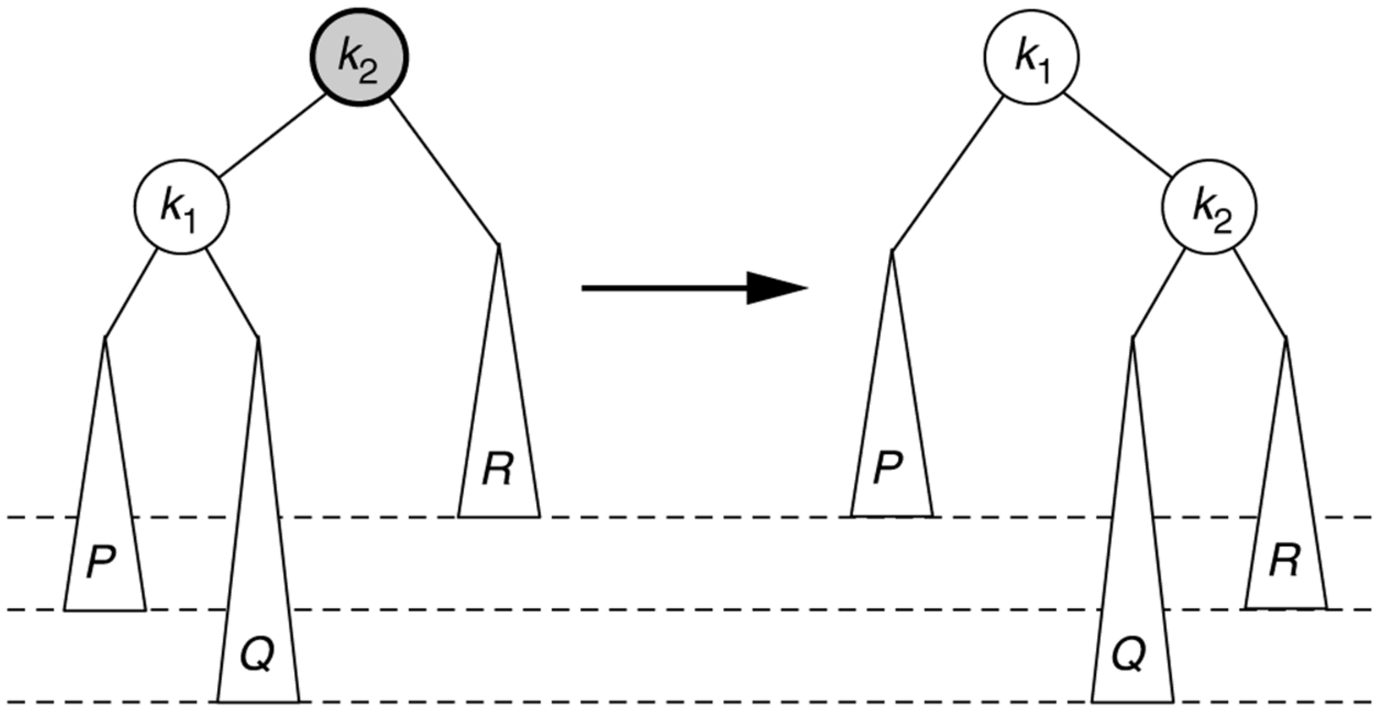
Left rotation, steps

1. detach right child (70)'s left subtree (60) (don't lose it!)
2. consider right child (70) be the new parent
3. attach old parent (50) onto left of new parent (70)
4. attach old right child (70)'s old left subtree (60) as right subtree of new left child (50)



Problem: Cases 2, 3

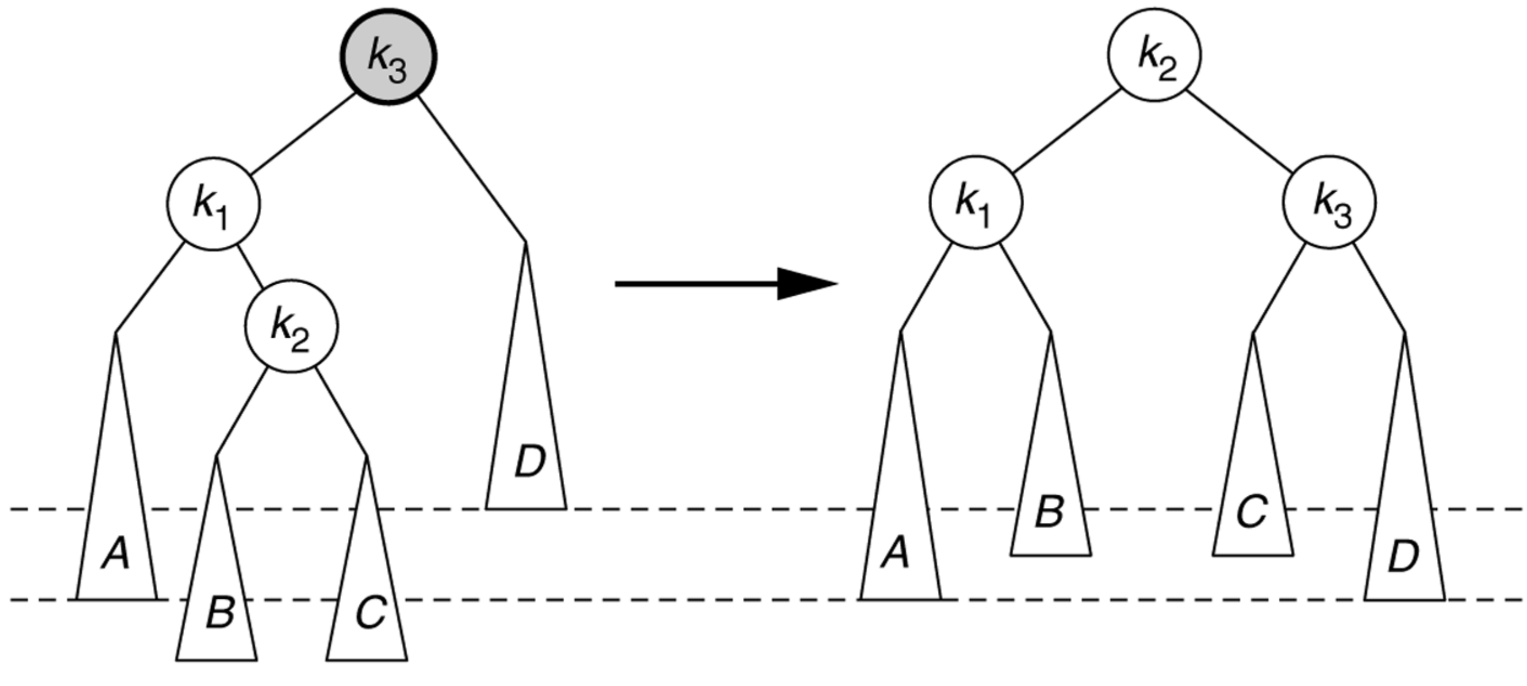
- A single right rotation does not fix Case 2!
- Similarly, a single left rotation does not fix Case 3!



(a) Before rotation (b) After rotation

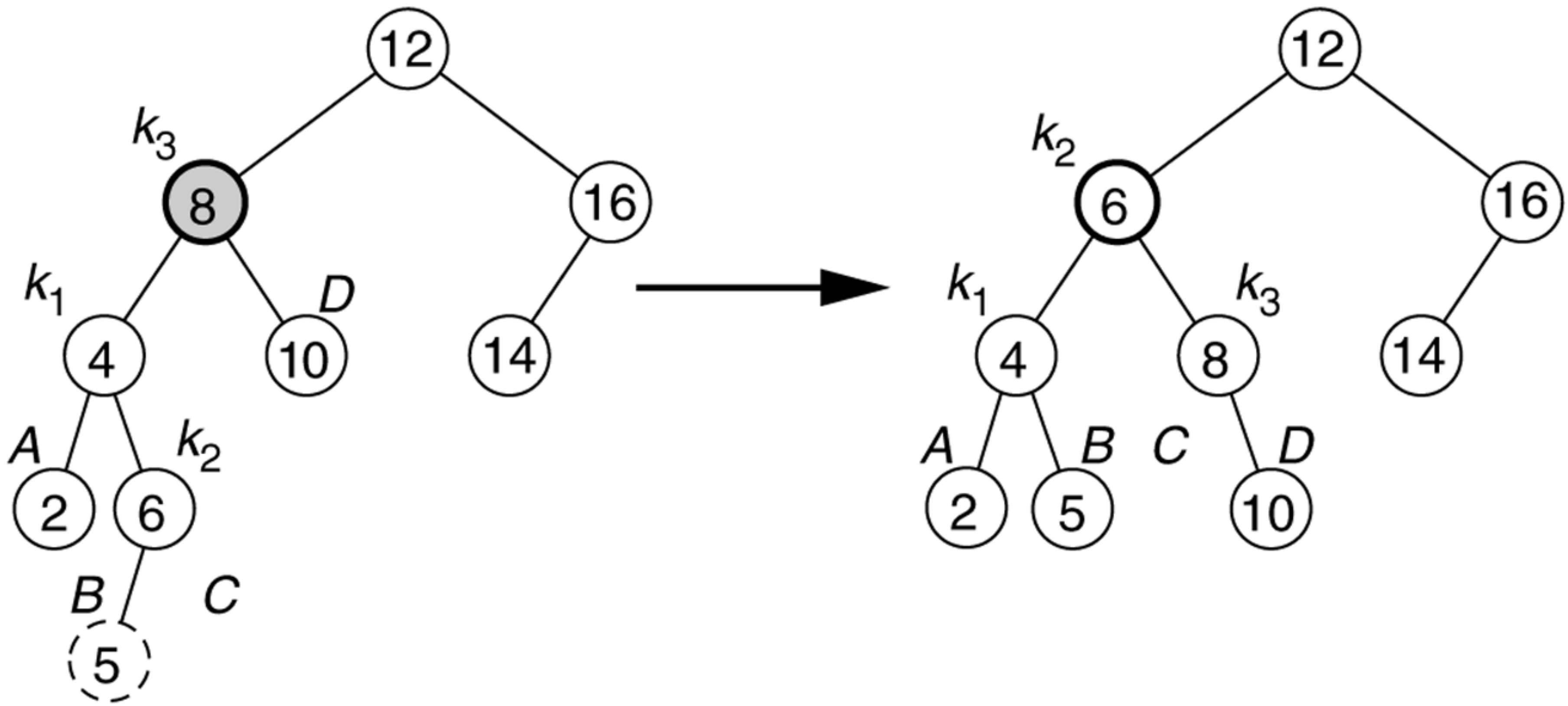
Left-right rotation for Case 2

- **left-right double rotation**: a left rotation of the left child, followed by a right rotation at the parent



(a) Before rotation (b) After rotation

Left-right rotation example

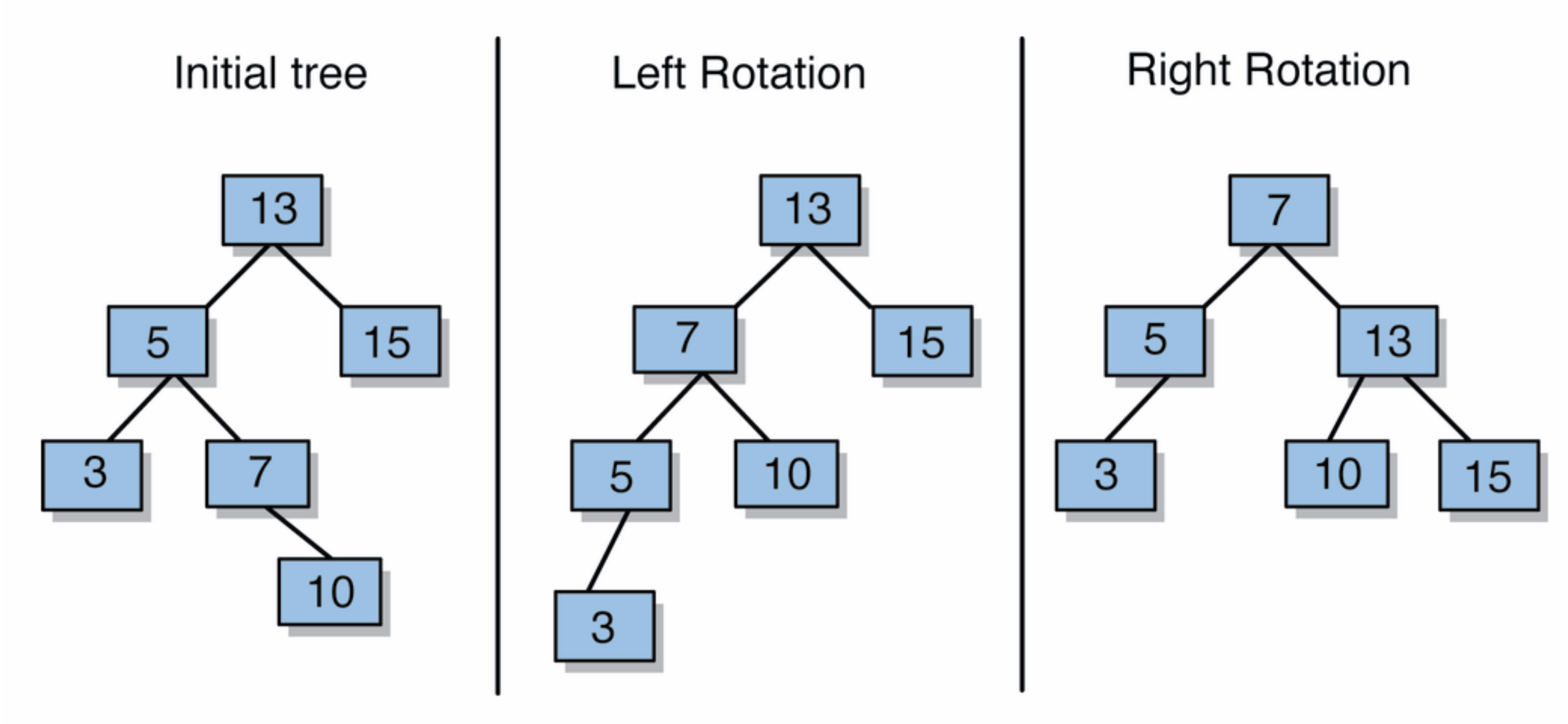


(a) Before rotation

(b) After rotation

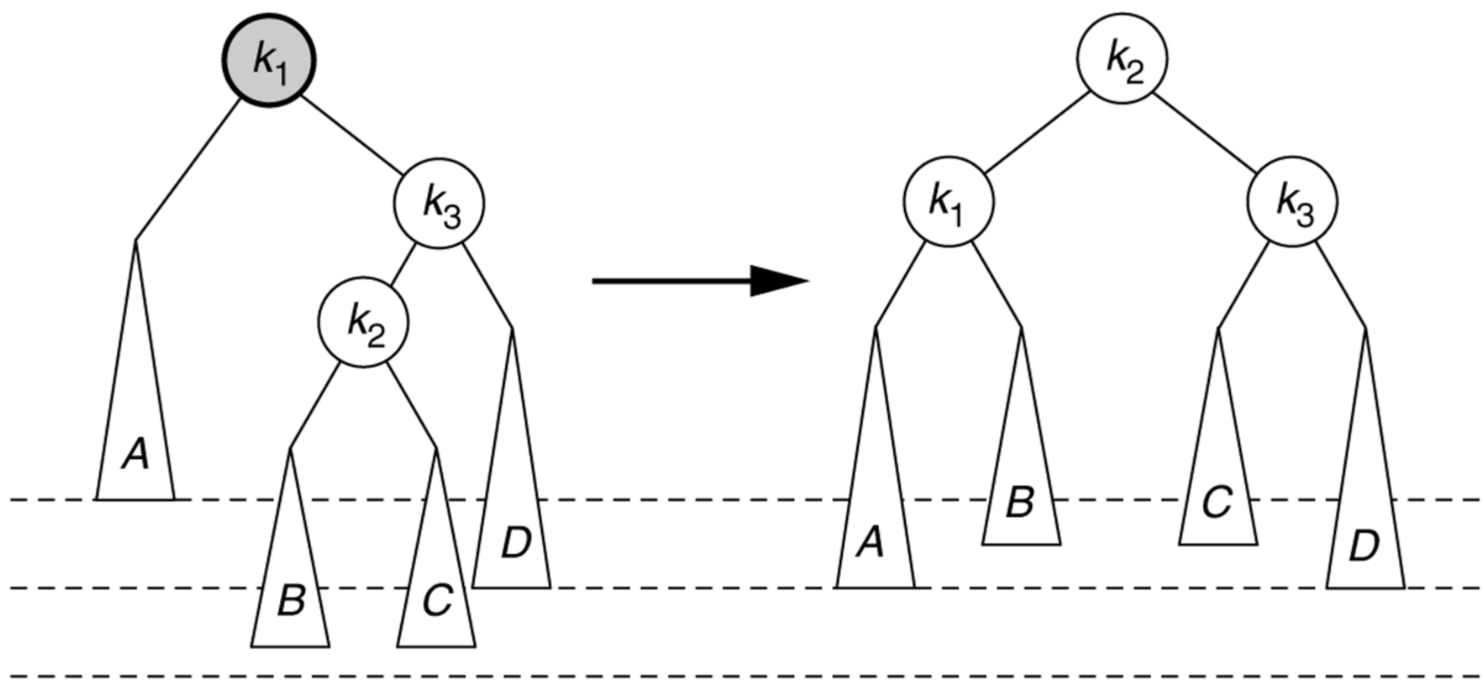
Left-right rotation, steps

1. perform left-rotate on left child
2. perform right-rotate on parent (current node)



Right-left rotation for Case 3

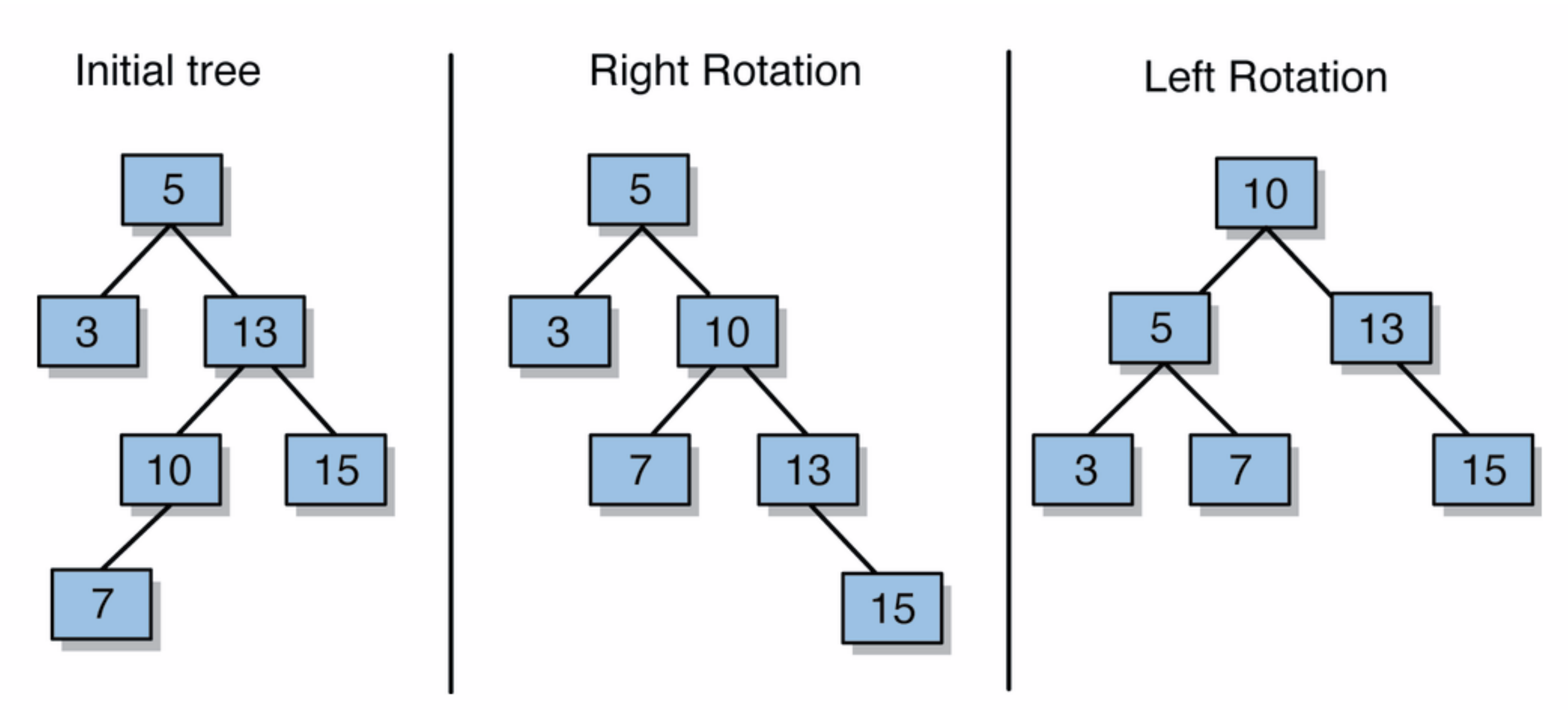
- **right-left double rotation**: a right rotation of the right child, followed by a left rotation at the parent



(a) Before rotation (b) After rotation

Right-left rotation, steps

1. perform right-rotate on right child
2. perform left-rotate on parent (current node)



AVL tree practice problem

- Draw the AVL tree that would result if the following numbers were added in this order to an initially empty tree:
  - 40, 70, 90, 80, 30, -50, 10, 60, 40, -70, 20, 35, 37, 32, 38, 39

- Then give the following information about the tree:
  - size
  - height
  - balance factor at each node

Implementing AVL add

- After normal BST add, update heights from new leaf up towards root
  - If balance factor changes to > +1 or < -1, then use rotation(s) to rebalance
- Let n be the first unbalanced node found
  - Case 1: *n* has balance factor -2 and *n*'s left child has balance factor of –1
    - fixed by performing **right-rotation** on *n*
  - Case 2: *n* has balance factor -2 and *n*'s left child has balance factor of 1
    - fixed by perform **left-rotation** on *n*'s left child, then **right-rotation** on *n* (left-right double rotation)

AVL add, cont'd

- <u>Case 3</u>: *n* has balance factor 2 and *n*'s right child has balance factor of −1
  - fixed by perform **right-rotation** on *n*'s right child, then **left-rotation** on *n* (right-left double rotation)
- <u>Case 4</u>: *n* has balance factor 2 and *n*'s right child has balance factor of 1
  - fixed by performing **left-rotation** on *n*

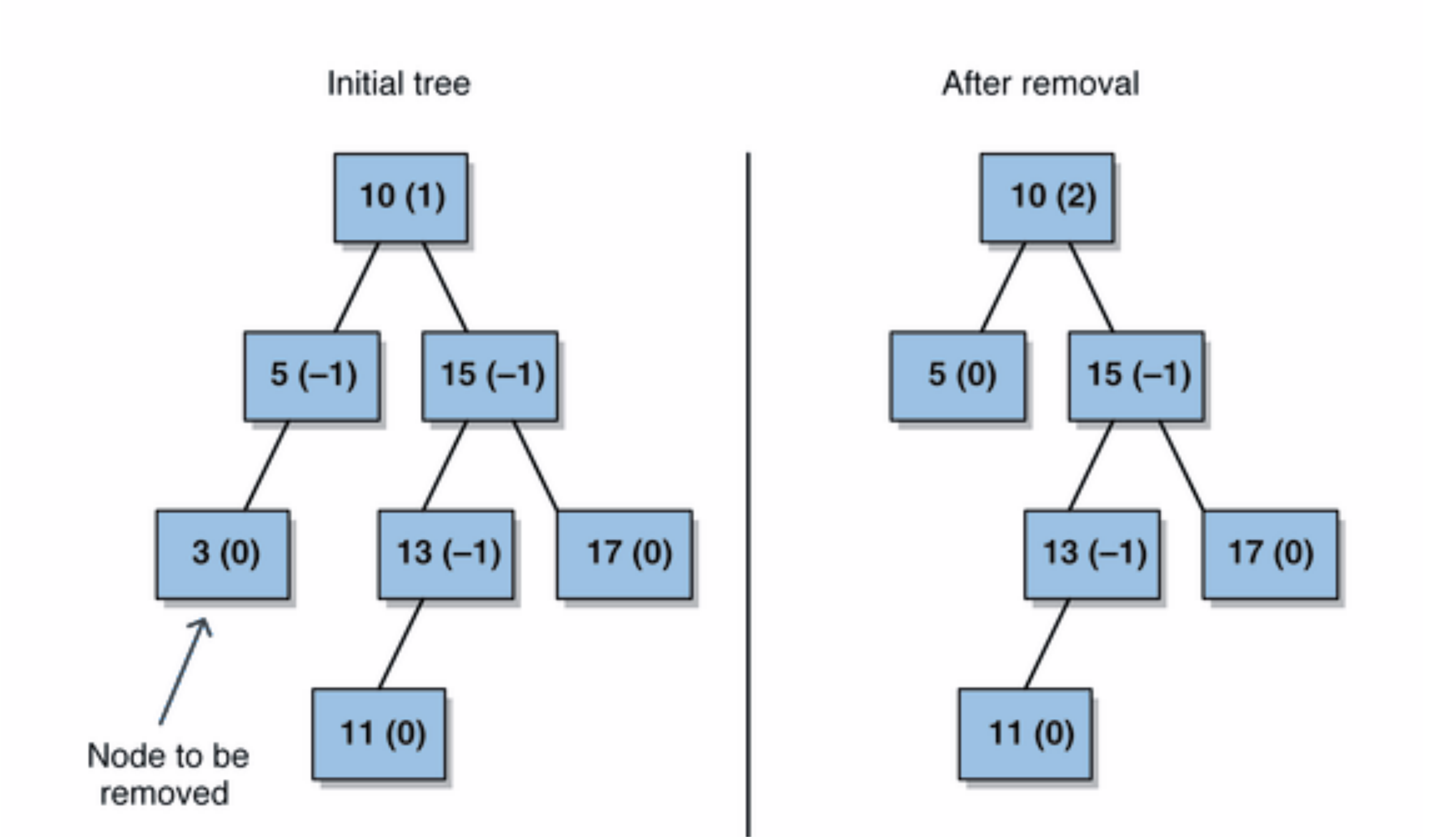
- After rebalancing, continue up the tree updating heights
  - What if *n*'s child has balance factor 0?
  - What if another imbalance occurs higher up?

AVL add outline

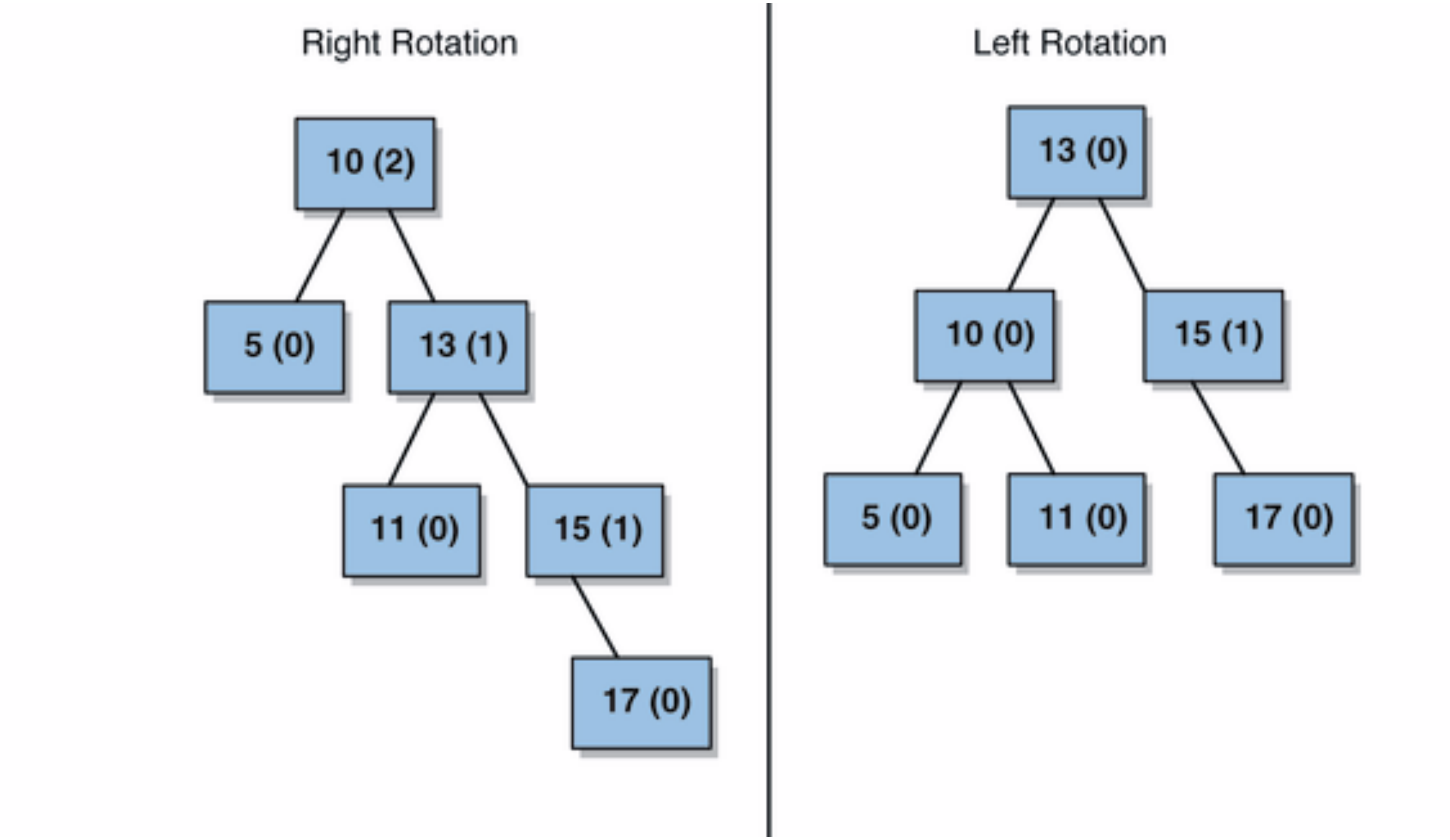
```
public class TrackingStreeSet extends StreeSet {

    protected StringTreeNode add(StringTreeNode node, String value) {
        // perform StreeSet add (i.e. regular BST add)

        // update node's height

        return node;
    }

    ...

}

public class AVLStreeSet extends TrackingStreeSet {

    protected StringTreeNode add(StringTreeNode node, String value) {
        // perform TrackingStreeSet add and update node's height

        // rebalance the node

        return node;
    }

    protected StringTreeNode rebalance(StringTreeNode node) {
        int bf = balanceFactor(node);
        if (bf < -1) {
             if (balanceFactor(node.left) < 0) {   // case 1 (LL insert)
                 node = rightRotate(node);
             } else {                              // case 2 (LR insert)
                 node.left = leftRotate(node.left);
                 node = rightRotate(node);
             }
         } else if (bf > 1) {
             // take care of symmetric cases
         }
    }
    ...
}
```

Problems for AVL remove

- Removal from AVL tree can unbalance the tree



Right-left rotation on remove



AVL remove, cont'd

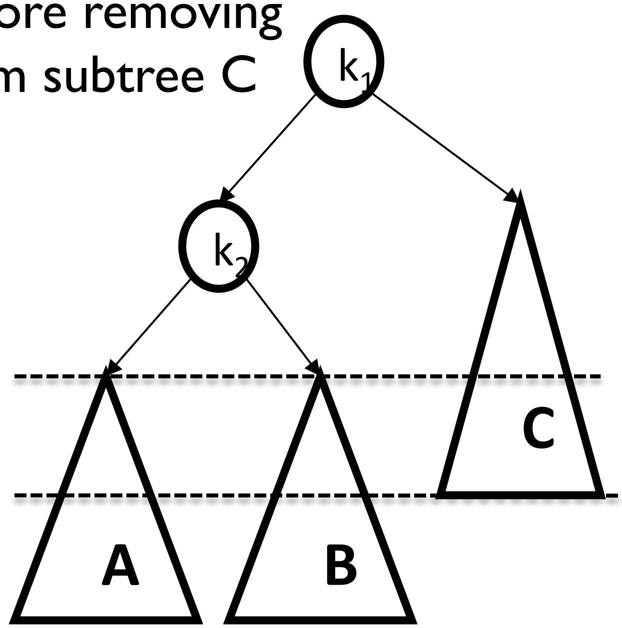
1. Perform normal BST remove (with replacement of node to be removed with its successor)
2. Update heights from successor node location upwards towards root
   - if balance factor changes to +2 or -2, then use rotation(s) to rebalance

- Are all cases handled?

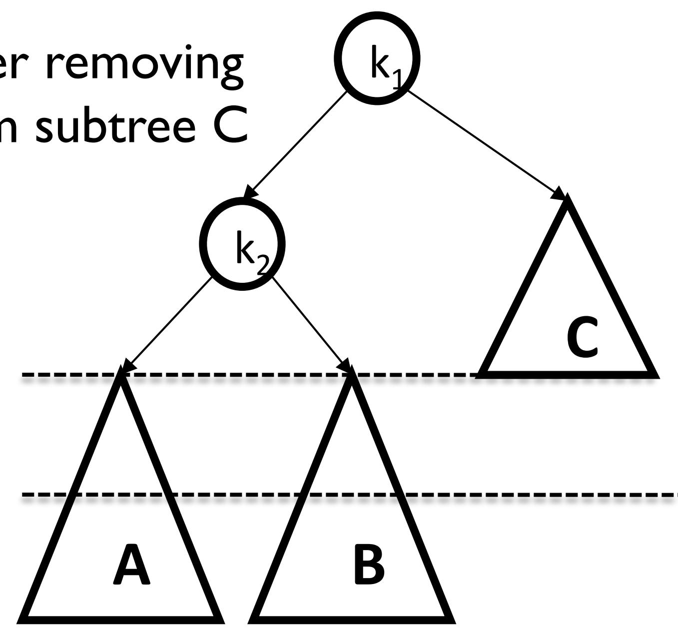
Additional AVL Remove Cases

- Why is this case not covered by insert?

Before removing from subtree C



After removing from subtree C



Two Additional AVL Remove Cases

- In these cases, a node (k_1 in previous slide) violates balance condition after removing from one of its subtrees when its other subtree has a balance factor of 0
  - These cases do not occur for insertion: when insertion causes a tree to have a balance factor of 2 or -2, the child containing the subtree where the insertion occurred either has a balance factor of -1 or 1

- Prior code snippet for rebalancing has to be modified to handle these cases.

Fixing AVL Remove Cases

- If deletion from right subtree of node creates imbalance and left subtree has balance factor of 0 we right rotate
  - The fix for symmetric case involves left rotation