Balanced Binary Search Trees (AVL Trees)

Slide Courtesy : Uwaterloo
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Background

So far …

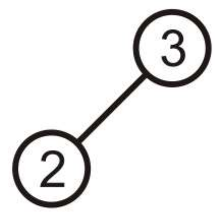
- Binary search trees store linearly ordered data
- Best case height: $\mathrm{O}(\log(n))$
- Worst case height: $\mathbf{O}(n)$

Requirement:

- Define and maintain a *balance* to ensure $\mathrm{O}(\log(\mathrm{n}))$ height

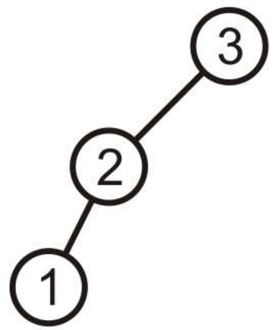
Prototypical Examples

These two examples demonstrate how we can correct for imbalances: starting with this tree, add 1:



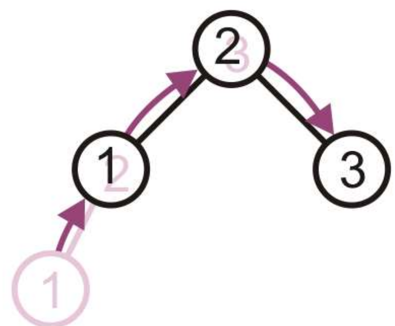
Prototypical Examples

This is more like a linked list; however, we can fix this…



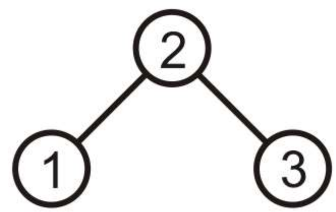
Prototypical Examples

Promote 2 to the root, demote 3 to be 2’s right child, and 1 remains the left child of 2



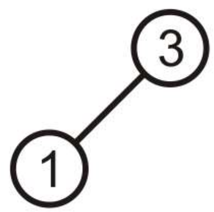
Prototypical Examples

The result is a perfect, though trivial tree



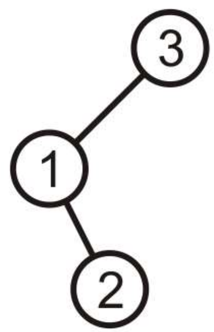
Prototypical Examples

Alternatively, given this tree, insert 2



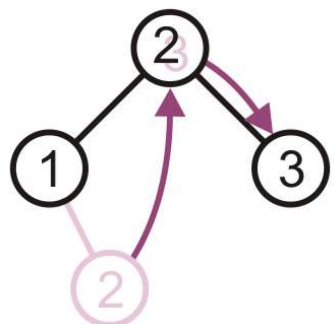
Prototypical Examples

Again, the product is a linked list; however, we can fix this, too



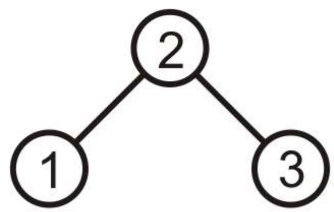
Prototypical Examples

Promote 2 to the root, and assign 1 and 3 to be its children



Prototypical Examples

The result is, again, a perfect tree



These examples may seem trivial, but they are the basis for the corrections in the next data structure we will see: AVL trees

AVL Trees

We will focus on the first strategy: AVL trees

– Named after Adelson-Velskii and Landis

Balance is defined by comparing the height of the two sub-trees

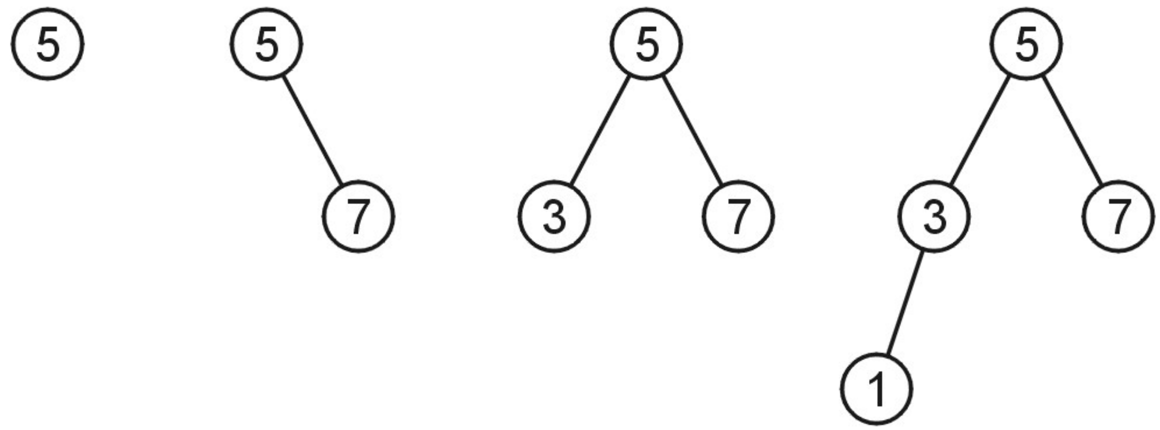
AVL Trees

A binary search tree is said to be AVL balanced if:

- The difference in the heights between the left and right sub-trees is at most one, and
- Both sub-trees are themselves AVL trees

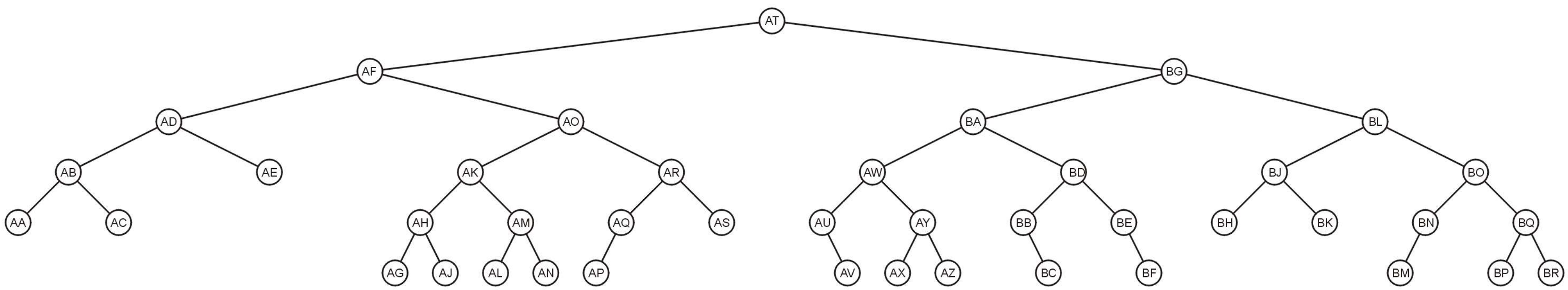
AVL Trees

AVL trees with 1, 2, 3, and 4 nodes:



AVL Trees

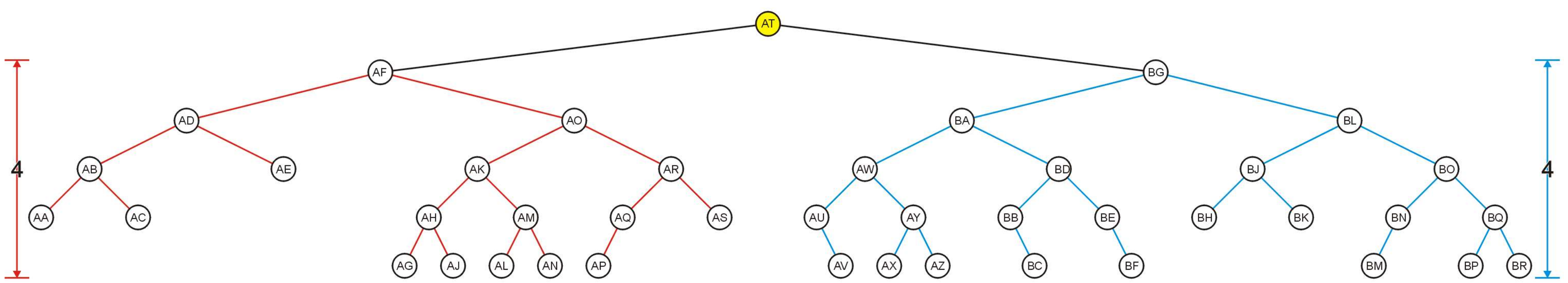
Here is a larger AVL tree (42 nodes):



AVL Trees

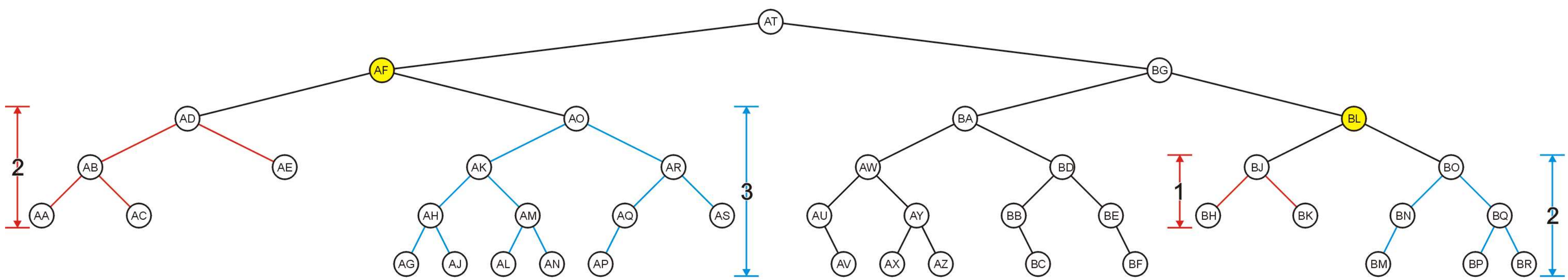
The root node is AVL-balanced:

– Both sub-trees are of height 4:



AVL Trees

- All other nodes are AVL balanced
  - The sub-trees differ in height by at most one

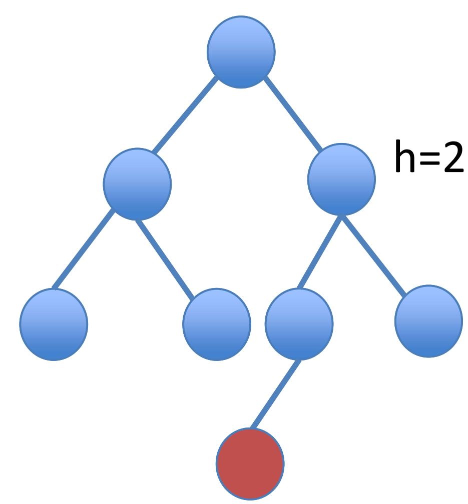


Height of an AVL Tree

By the definition of complete trees, any complete binary search tree is an AVL tree

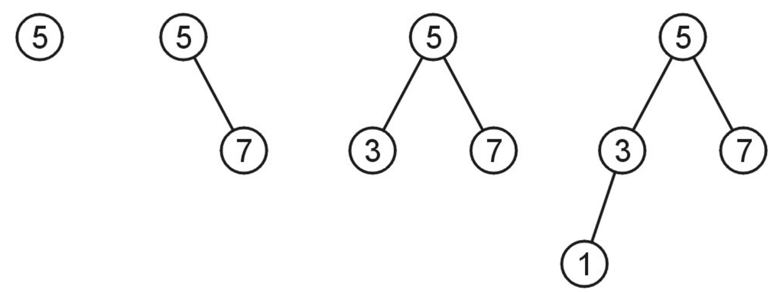
Thus an upper bound on the number of nodes in an AVL tree of height h a perfect binary tree with $2^{h+1} - 1$ nodes

– What is the lower bound?



Height of an AVL Tree

Let $\mathrm{F}(h)$ be the fewest number of nodes in a tree of height h



From a previous slide:

$$\mathrm{F}(0) = 1$$

$$\mathrm{F}(1) = 2$$

$$\mathrm{F}(2) = 4$$

Can we find $\mathrm{F}(h)$?

Height of an AVL Tree

The worst-case AVL tree of height h would have:

- A worst-case AVL tree of height $h - 1$ on one side,
- A worst-case AVL tree of height $h - 2$ on the other, and
- The root node

We get: $\mathrm{F}(h) = \mathrm{F}(h-1) + 1 + \mathrm{F}(h-2)$

Height of an AVL Tree

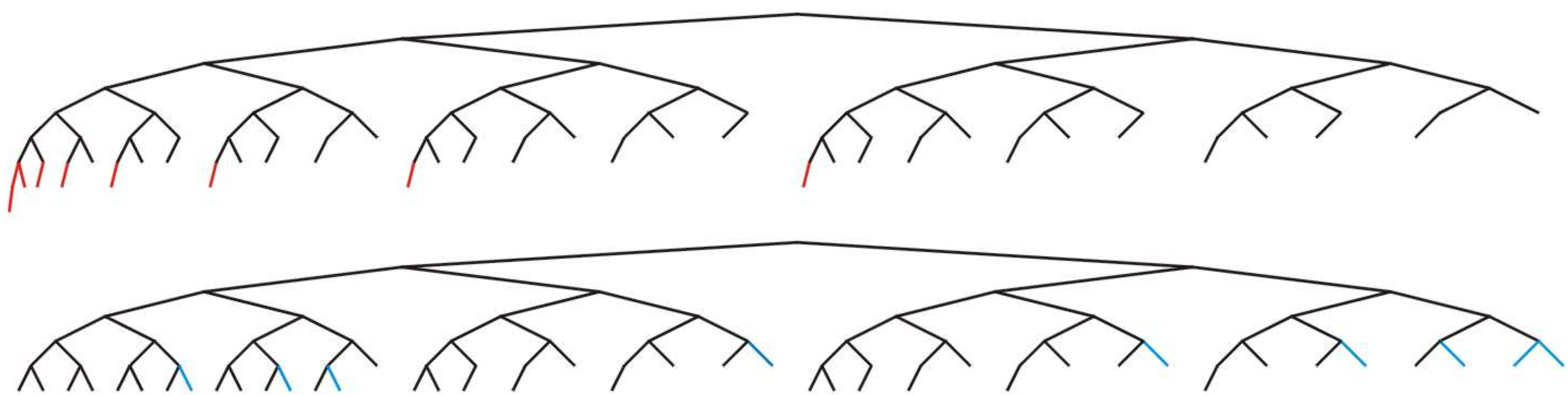
This is a recurrence relation:

$$\mathrm{F}(h) = \begin{cases} 1 & h = 0 \\ 2 & h = 1 \\ \mathrm{F}(h-1) + \mathrm{F}(h-2) + 1 & h > 1 \end{cases}$$

The solution?

Height of an AVL Tree

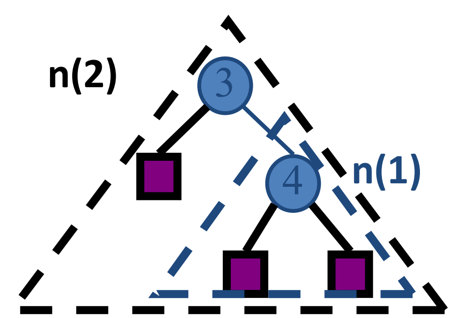
In this example, $n = 88$, the worst- and best-case scenarios differ in height by only 2



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(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)
- We can also solve this Fibonacci numbers:

  F(h) = F(h-1) + F(h-2)



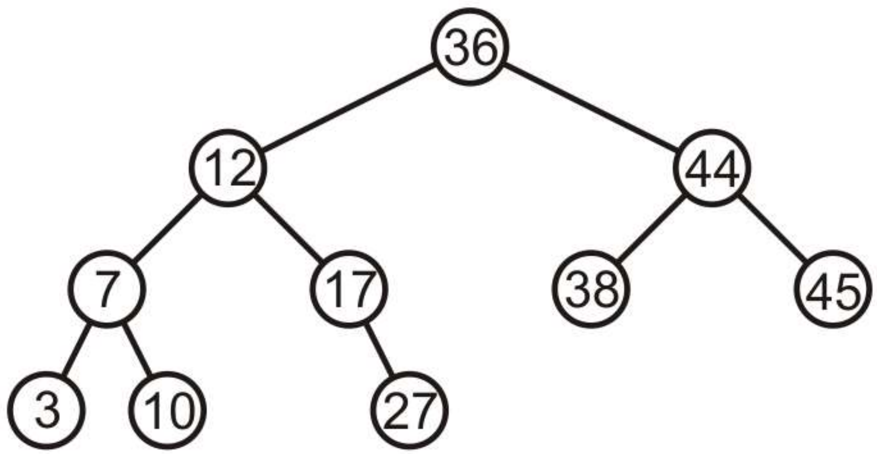
Maintaining Balance

To maintain AVL balance, observe that:

- Inserting a node can increase the height of a tree by at most 1
- Removing a node can decrease the height of a tree by at most 1

Maintaining Balance

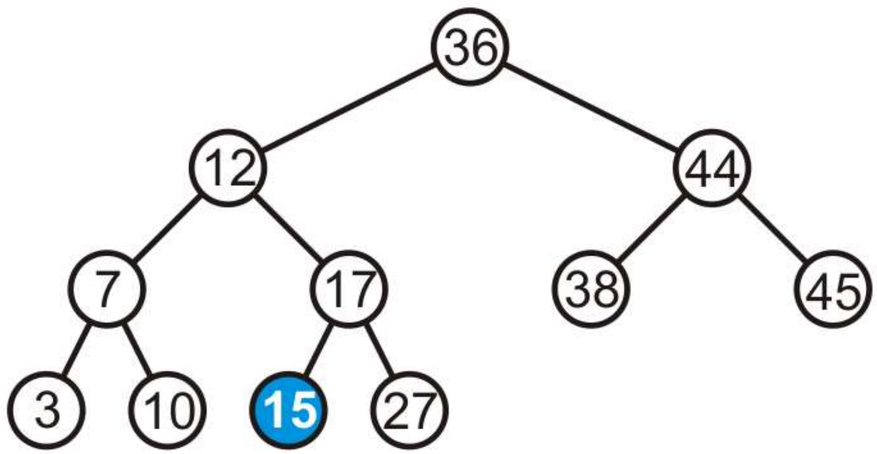
Consider this AVL tree



Maintaining Balance

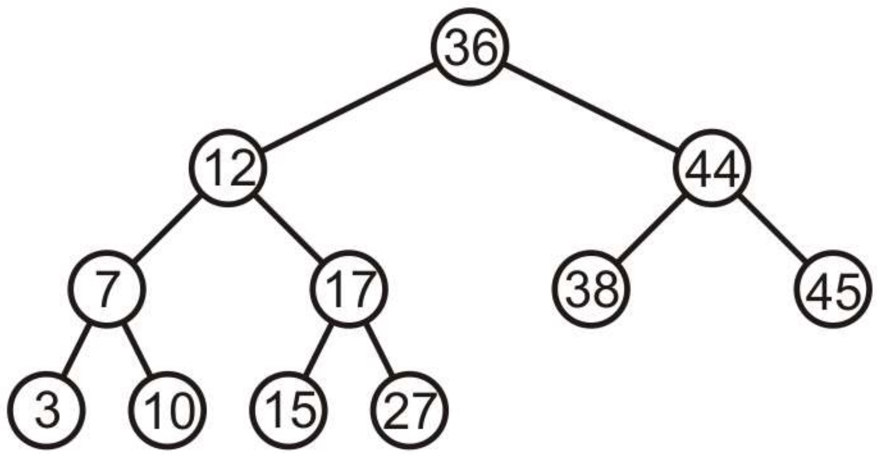
Consider inserting 15 into this tree

– In this case, the heights of none of the trees change



Maintaining Balance

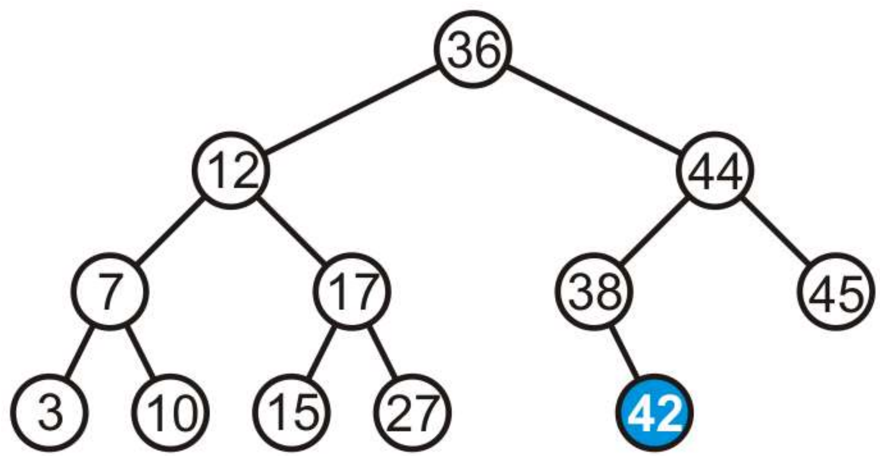
The tree remains balanced



Maintaining Balance

Consider inserting 42 into this tree

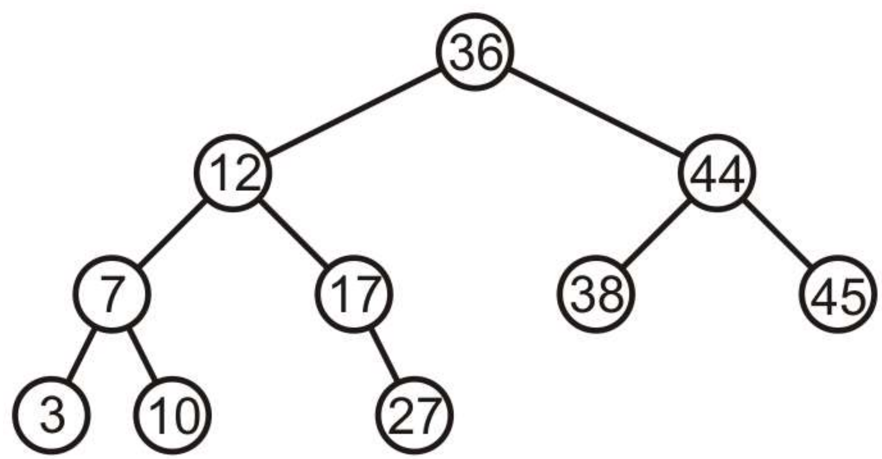
– In this case, the heights of none of the trees change



Maintaining Balance

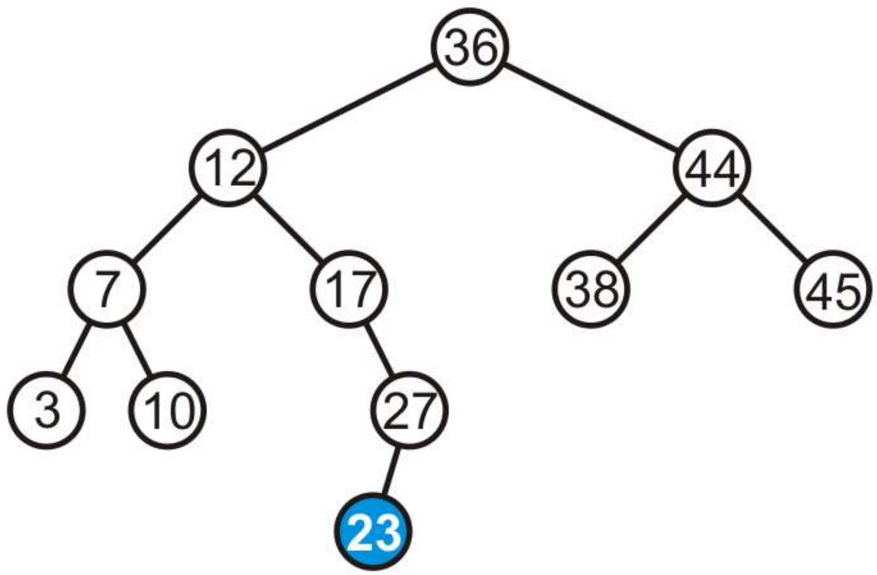
If a tree is AVL balanced, for an insertion to cause an imbalance:

- The heights of the sub-trees must differ by 1
- The insertion must increase the height of the deeper sub-tree by 1



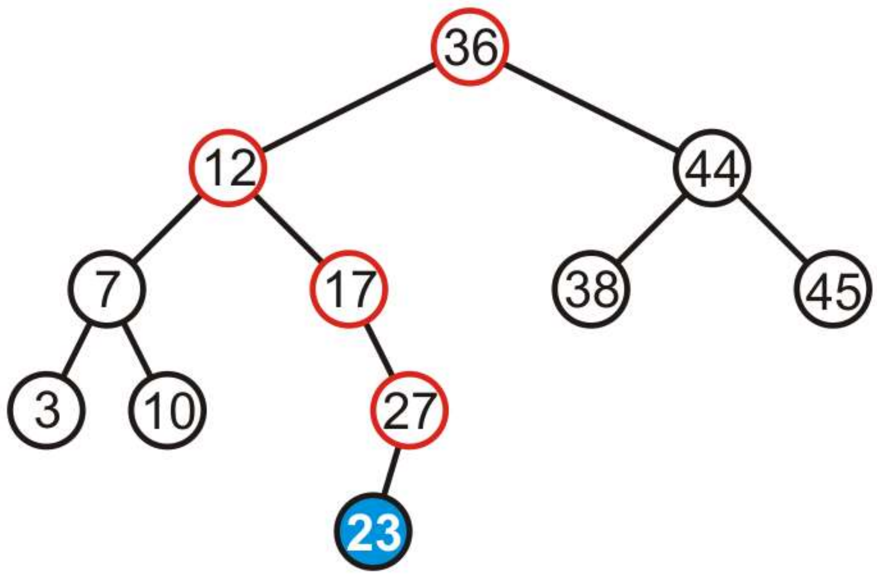
Maintaining Balance

Suppose we insert 23 into our initial tree



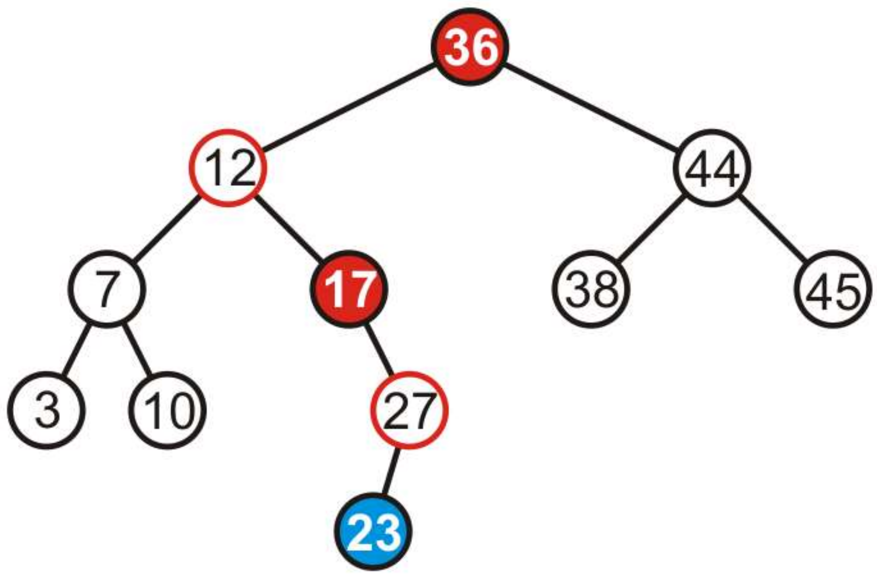
Maintaining Balance

The heights of each of the sub-trees from here to the root are increased by one



Maintaining Balance

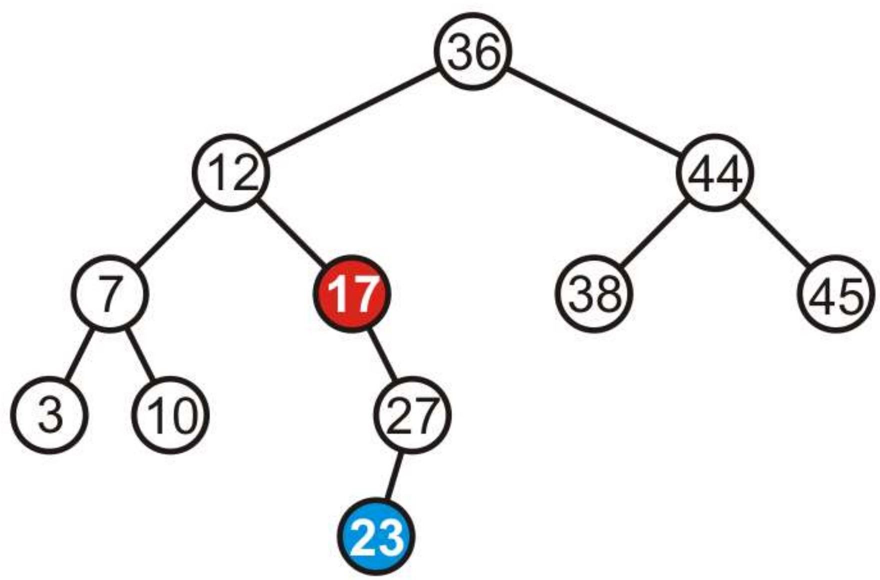
However, only two of the nodes are unbalanced: 17 and 36



Maintaining Balance

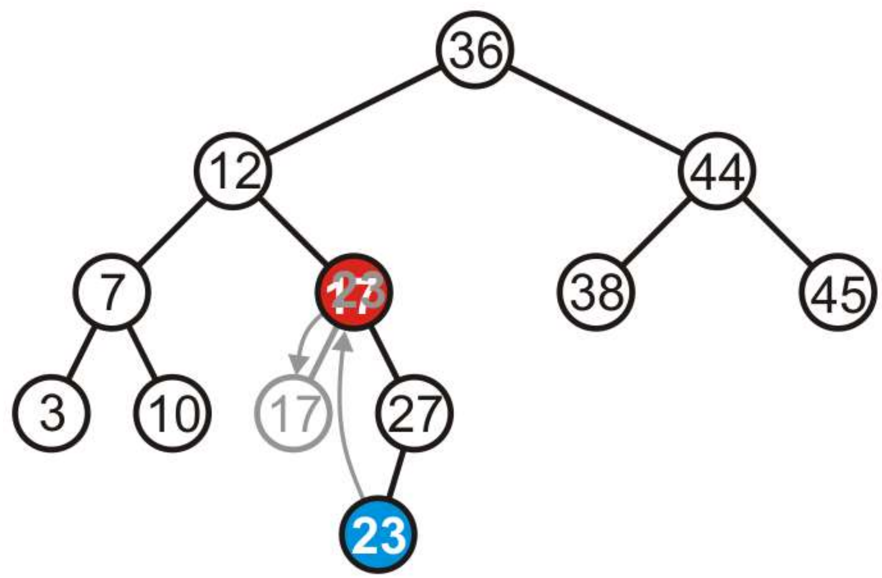
However, only two of the nodes are unbalanced: 17 and 36

– We only have to fix the imbalance at the lowest node



Maintaining Balance

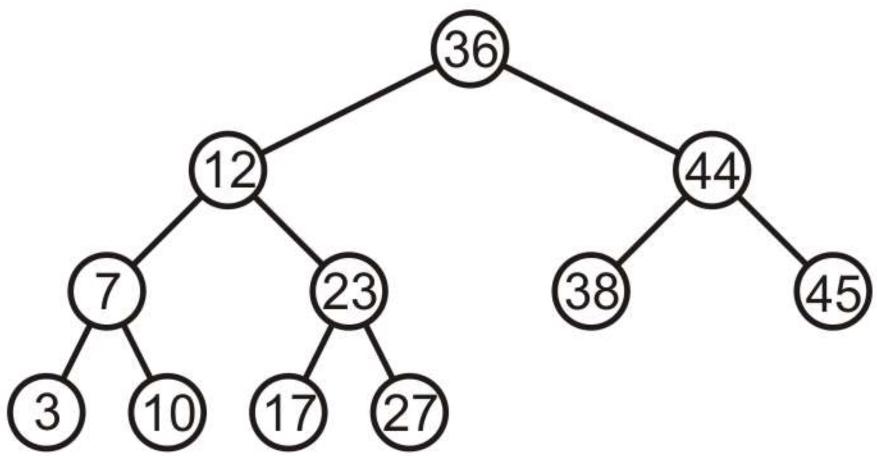
We can promote 23 to where 17 is, and make 17 the left child of 23



Maintaining Balance

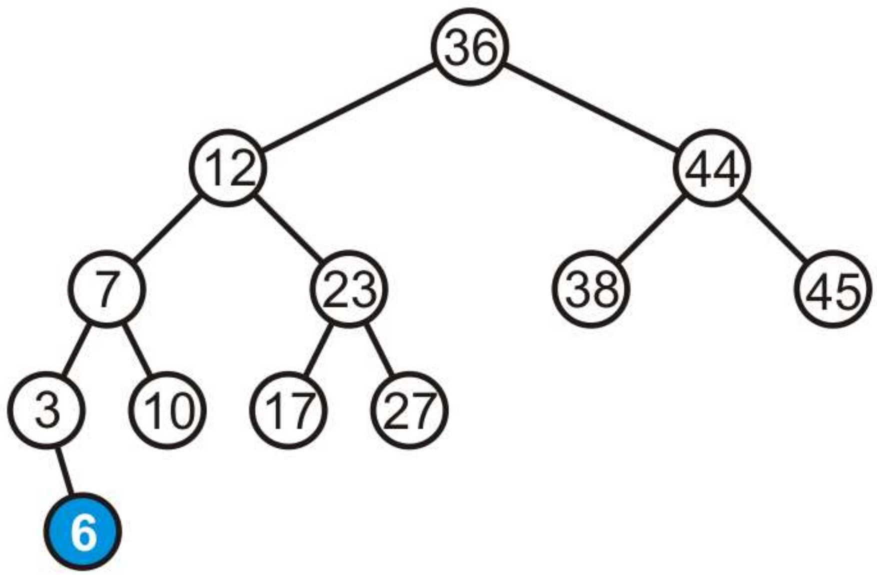
Thus, that node is no longer unbalanced

– Incidentally, neither is the root now balanced again, too



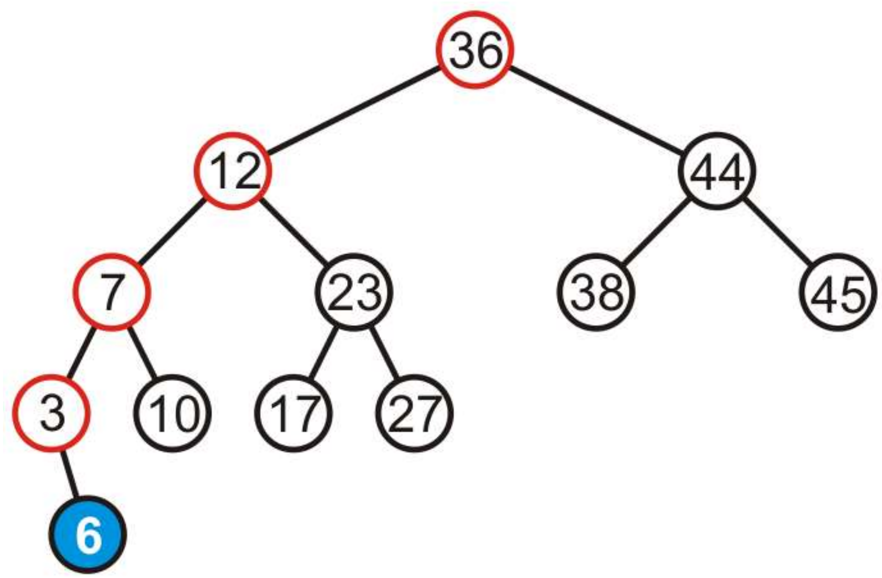
Maintaining Balance

Consider adding 6:



Maintaining Balance

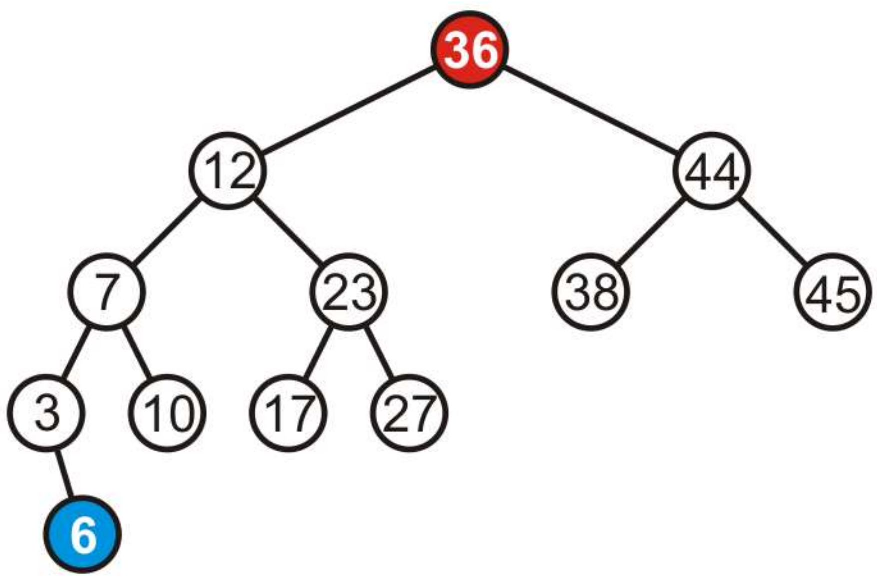
The height of each of the trees in the path back to the root are increased by one



Maintaining Balance

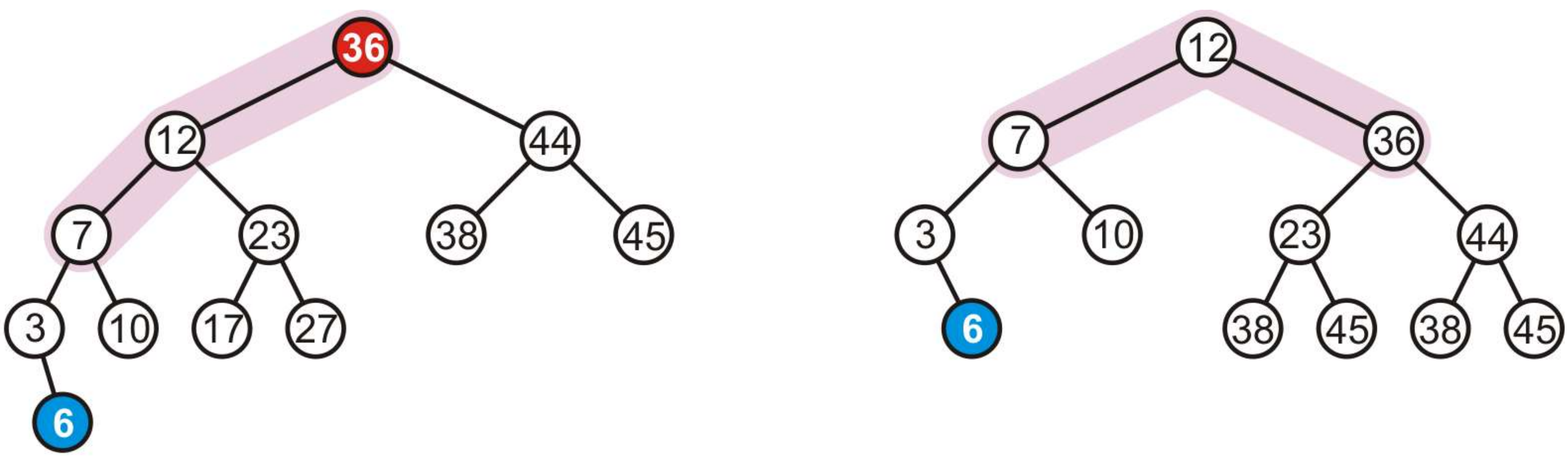
The height of each of the trees in the path back to the root are increased by one

– However, only the root node is now unbalanced



Maintaining Balance

We may fix this by rotating the root to the right

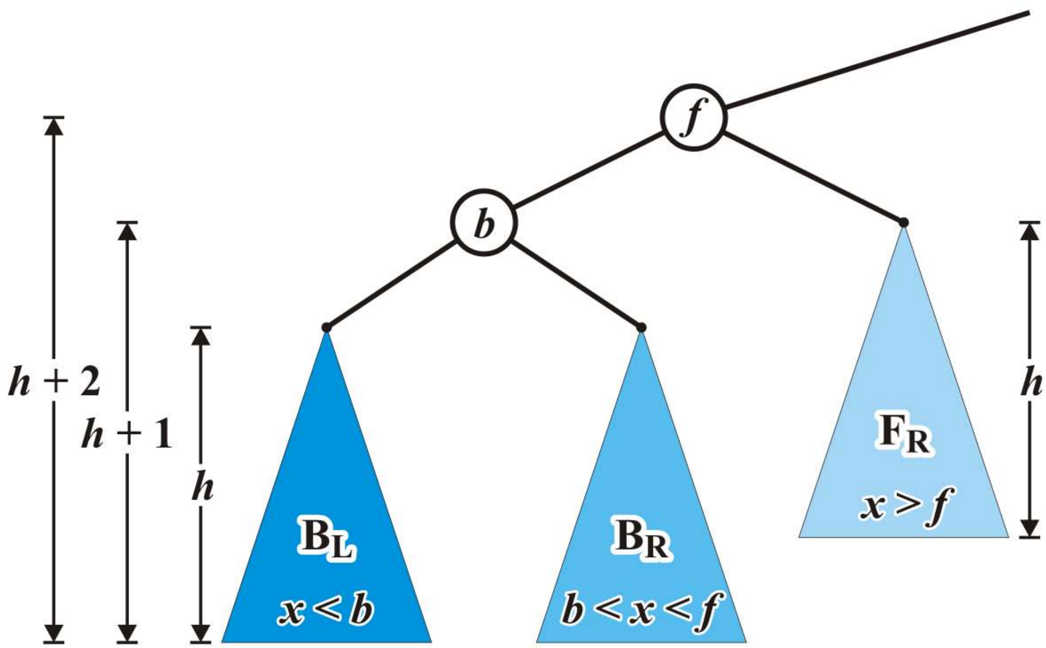


Note: the right subtree of 12 became the left subtree of 36

Case 1 setup

Consider the following setup

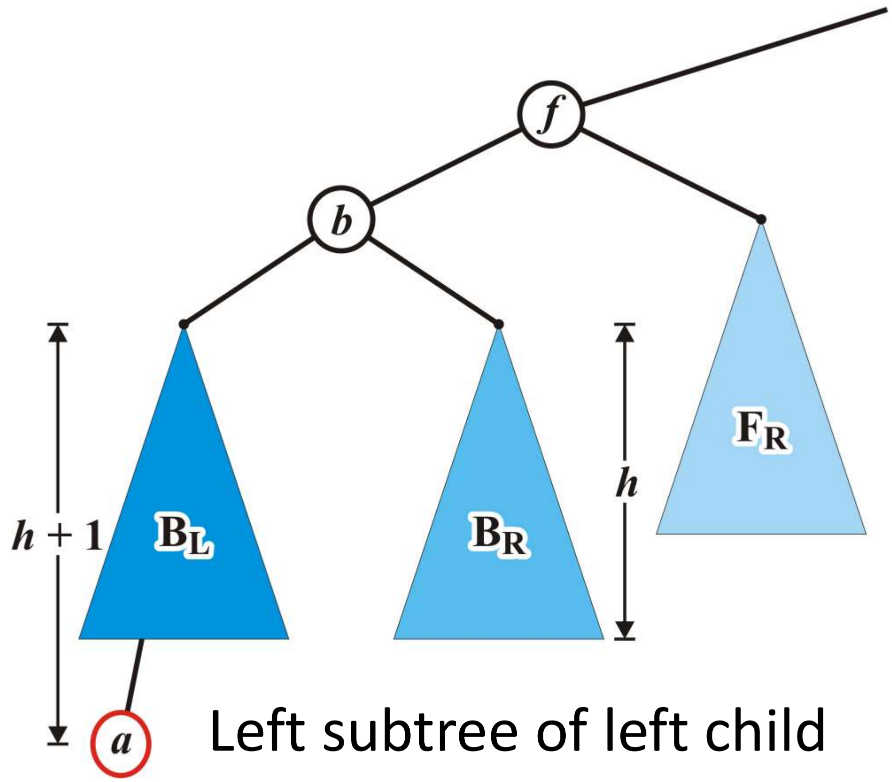
– Each blue triangle represents a tree of height h



Maintaining Balance: Case 1

Insert ***a*** into this tree: it falls into the left subtree $\mathbf{B_L}$ of ***b***

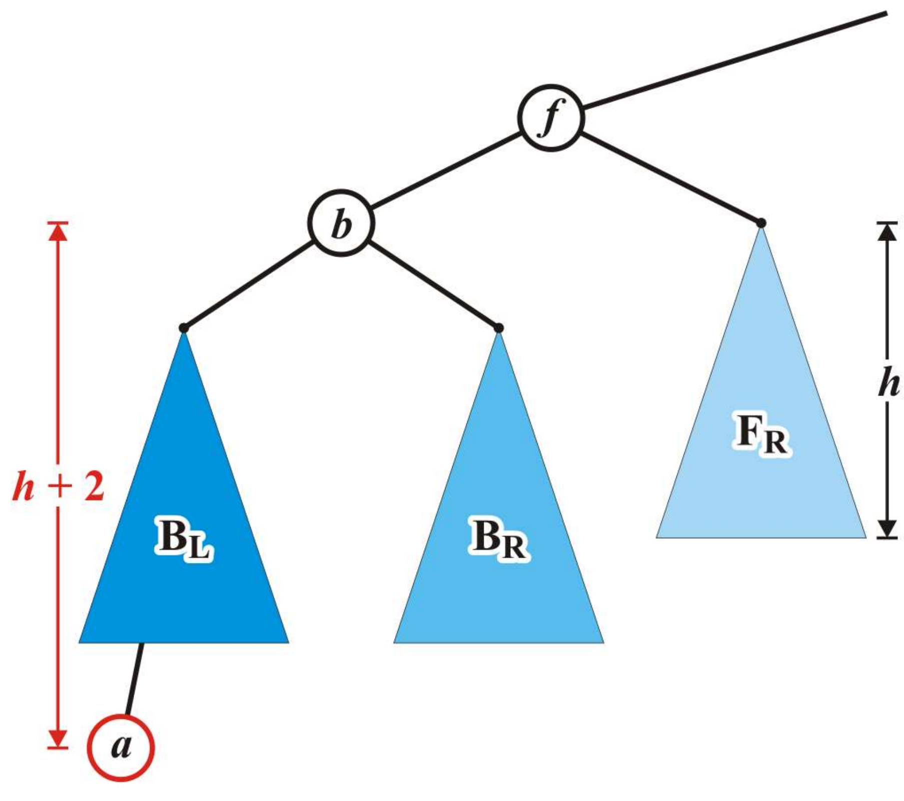
- Assume $\mathbf{B_L}$ remains balanced
- Thus, the tree rooted at ***b*** is also balanced



Maintaining Balance: Case 1

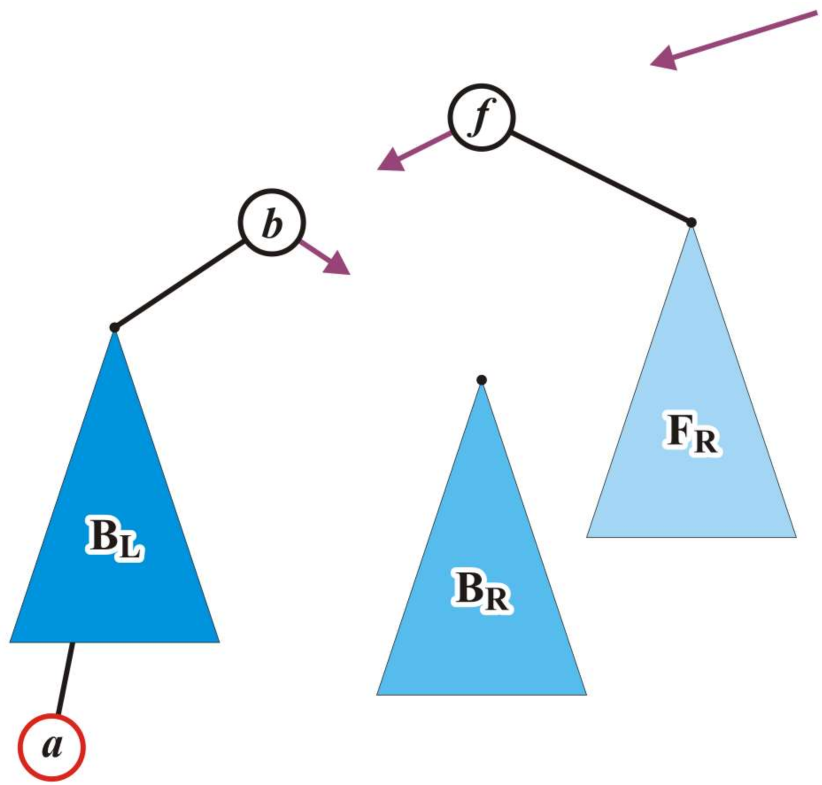
The tree rooted at node *f* is now unbalanced

– We will correct the imbalance at this node



Maintaining Balance: Case 1

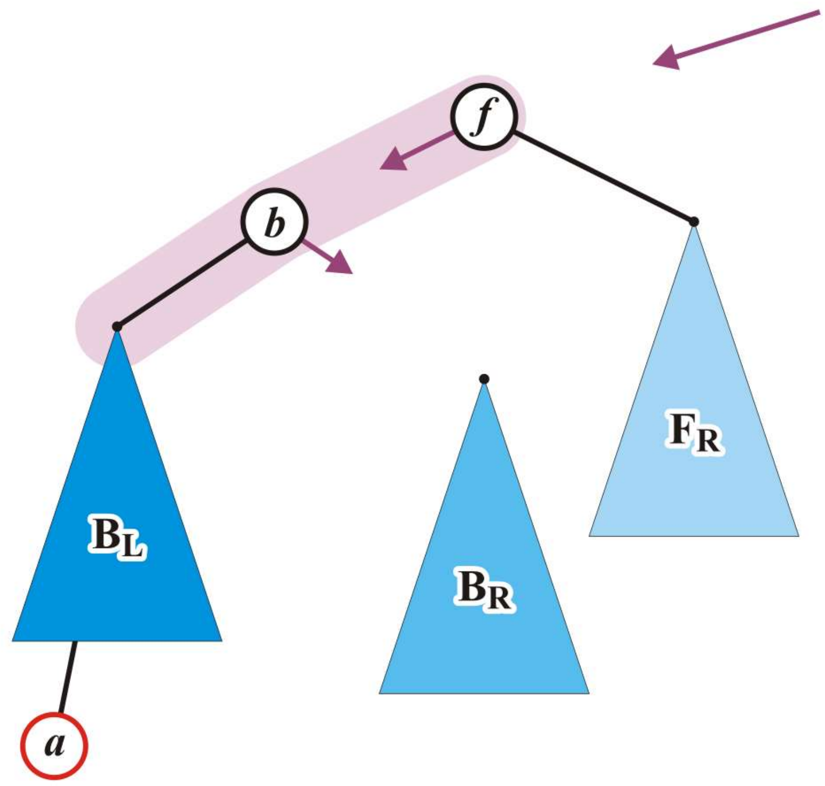
We will modify these three pointers:



Maintaining Balance: Case 1

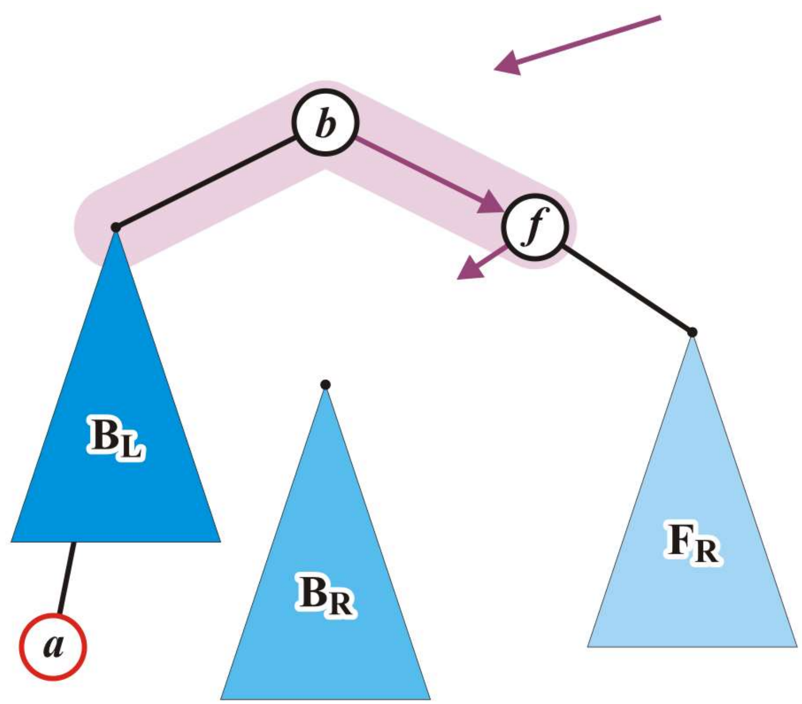
Specifically, we will rotate these two nodes around the root:

- Recall the first prototypical example
- Promote node ***b*** to the root and demote node ***f*** to be the right child of ***b***



Maintaining Balance: Case 1

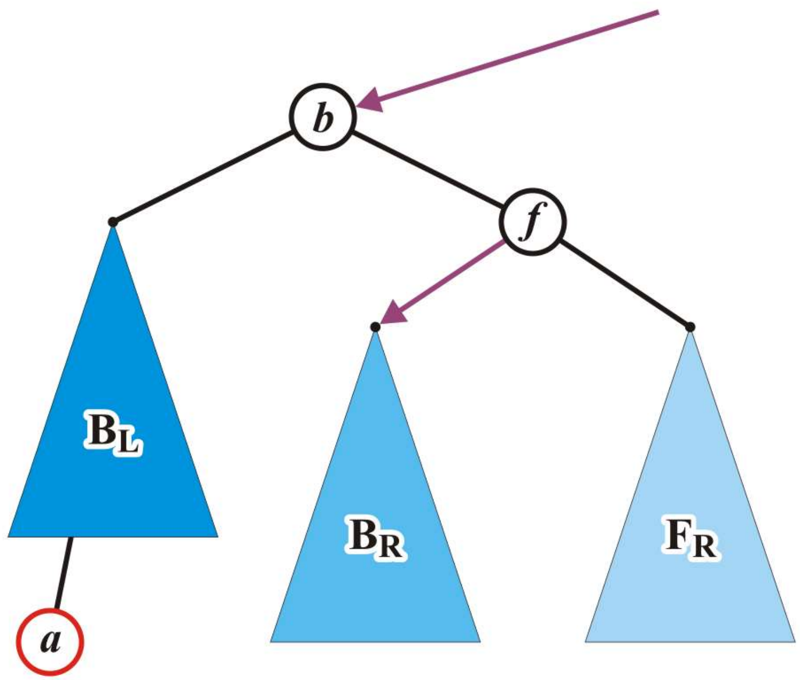
Make ***f*** the right child of ***b***



Maintaining Balance: Case 1

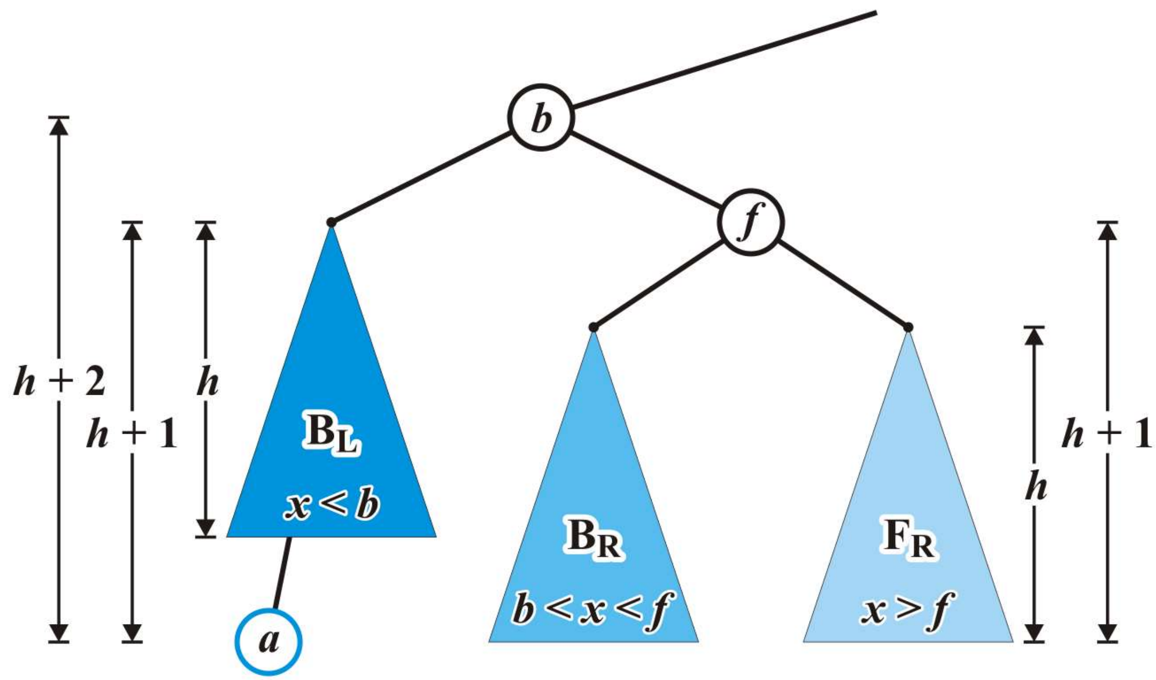
Assign former parent of node f to point to node b

Make $\mathbf{B_R}$ left child of node f



Maintaining Balance: Case 1

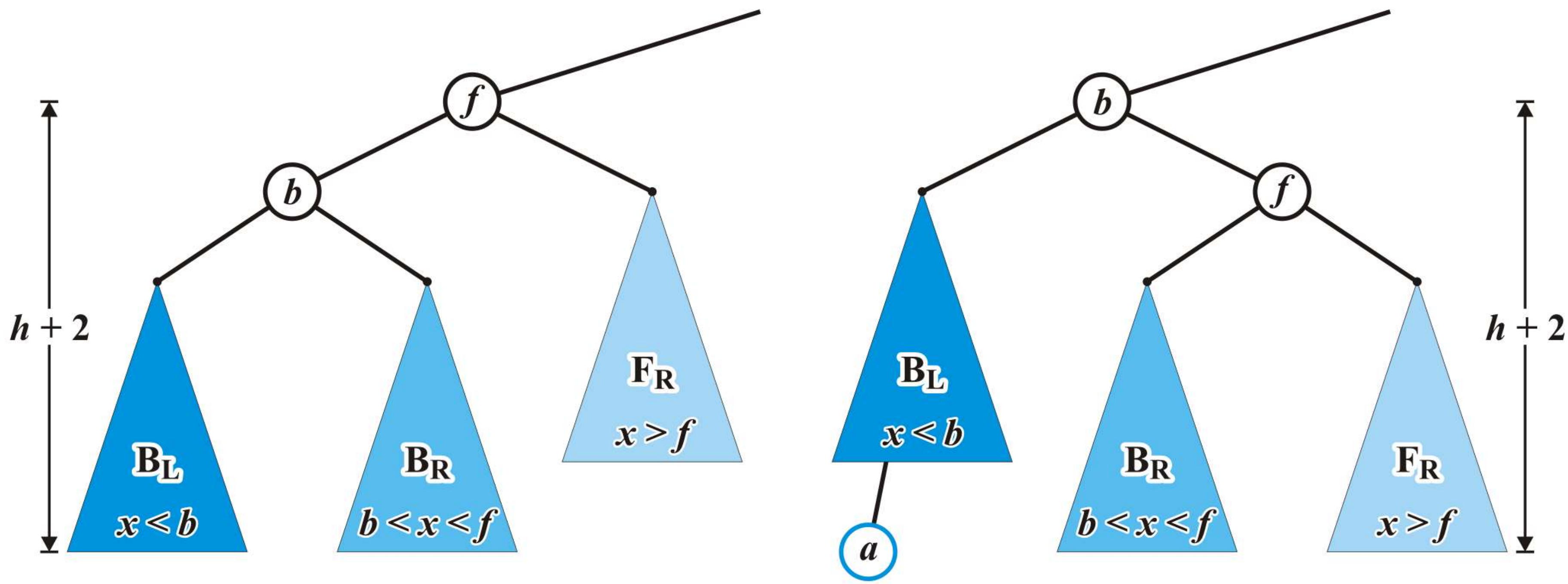
The nodes ***b*** and ***f*** are now balanced and all remaining nodes of the subtrees are in their correct positions



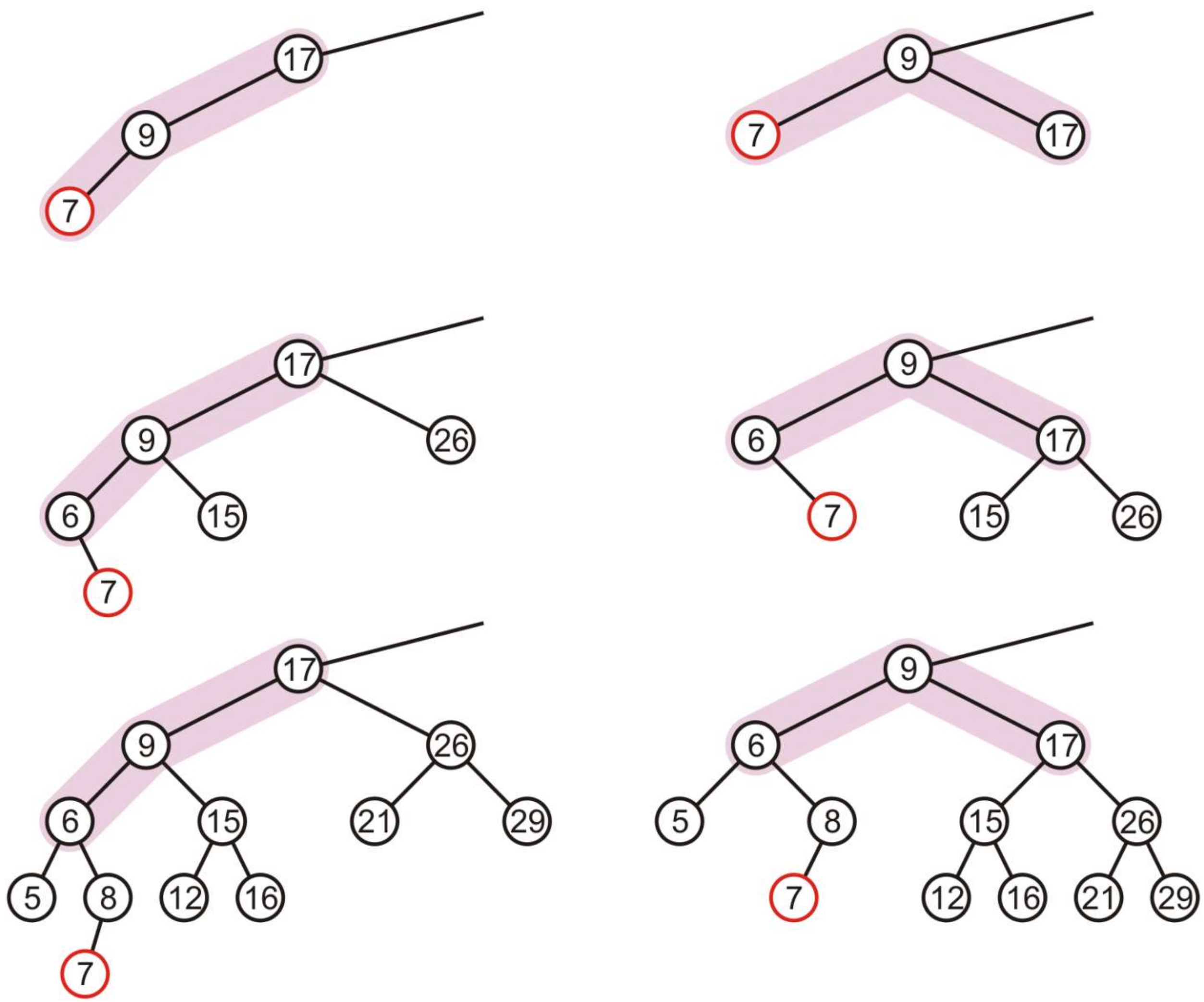
Maintaining Balance: Case 1

Additionally, height of the tree rooted at b equals the original height of the tree rooted at f

– Thus, this insertion will no longer affect the balance of any ancestors all the way back to the root

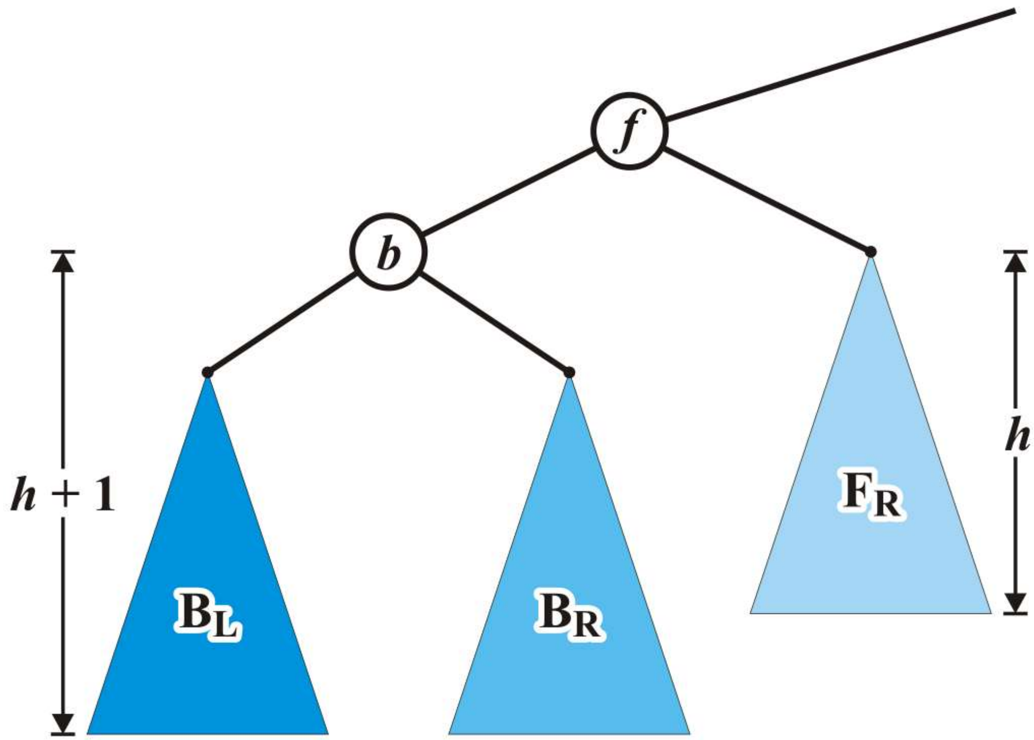


More Examples



Maintaining Balance: Case 2

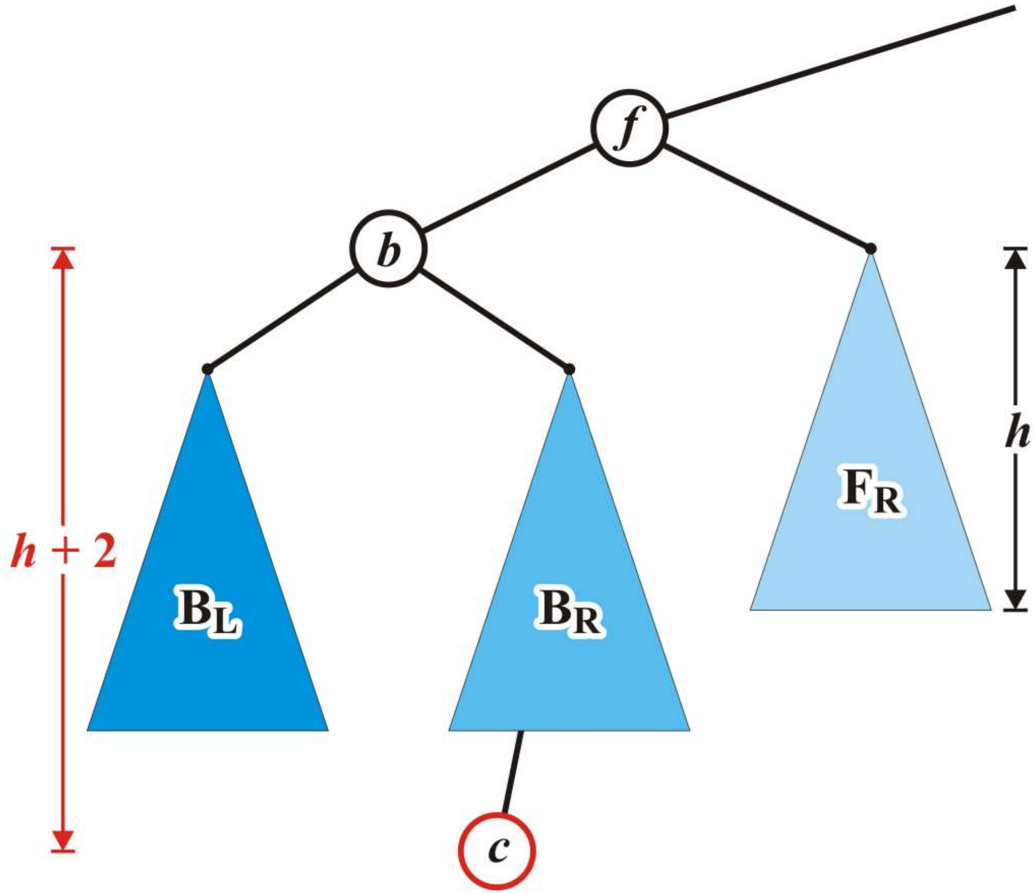
Alternatively, consider the insertion of c where $b < c < f$ into our original tree



Maintaining Balance: Case 2

Assume that the insertion of c increases the height of $\mathbf{B_R}$

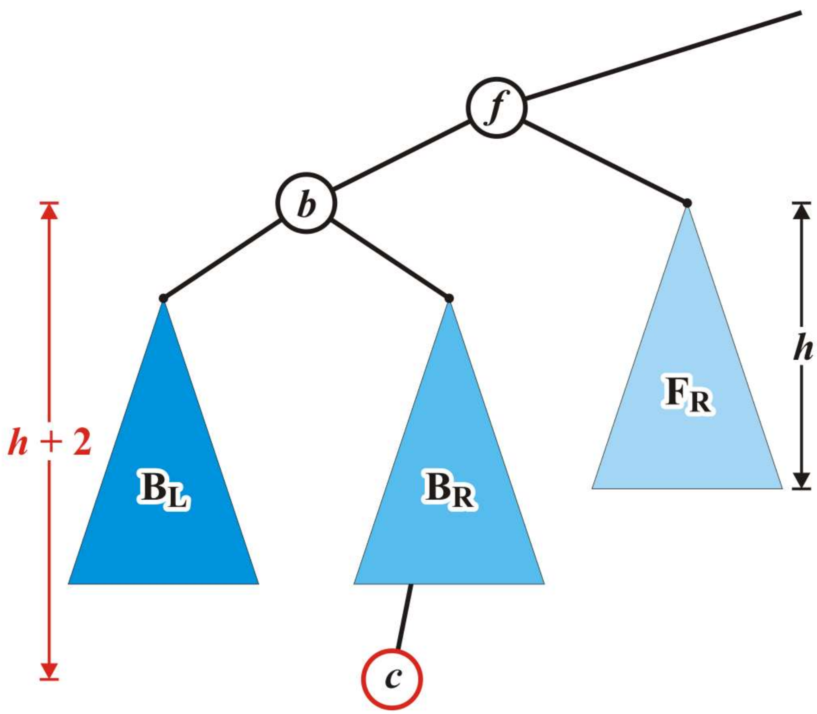
– Once again, f becomes unbalanced

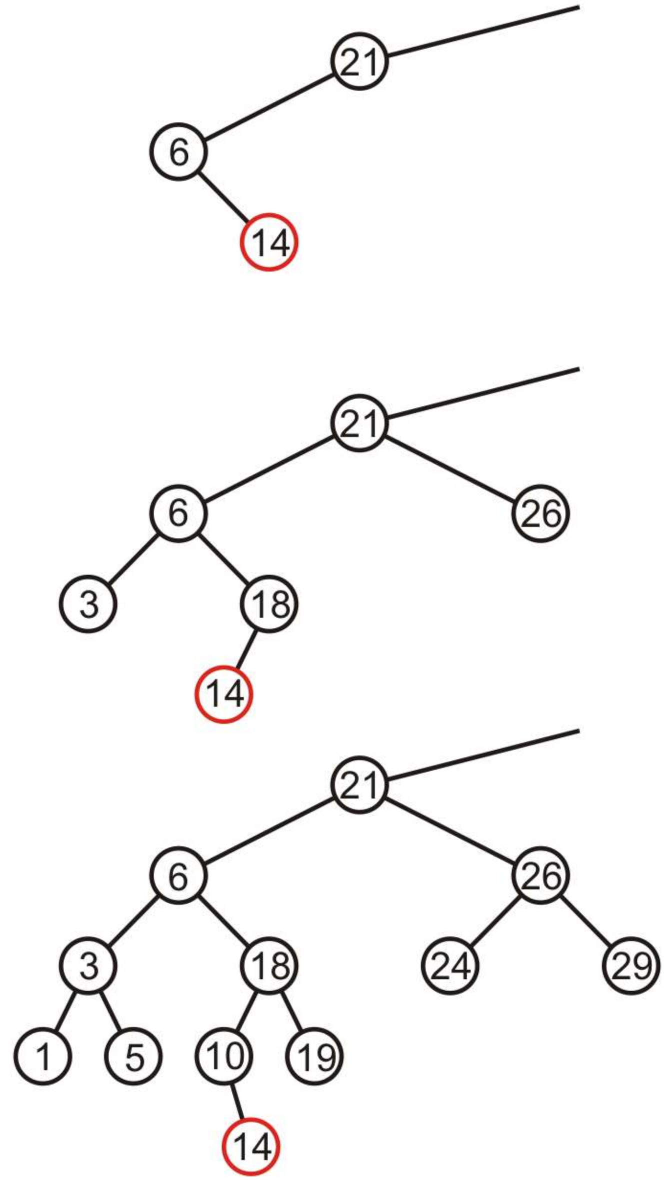


Right subtree of left child

Maintaining Balance: Case 2

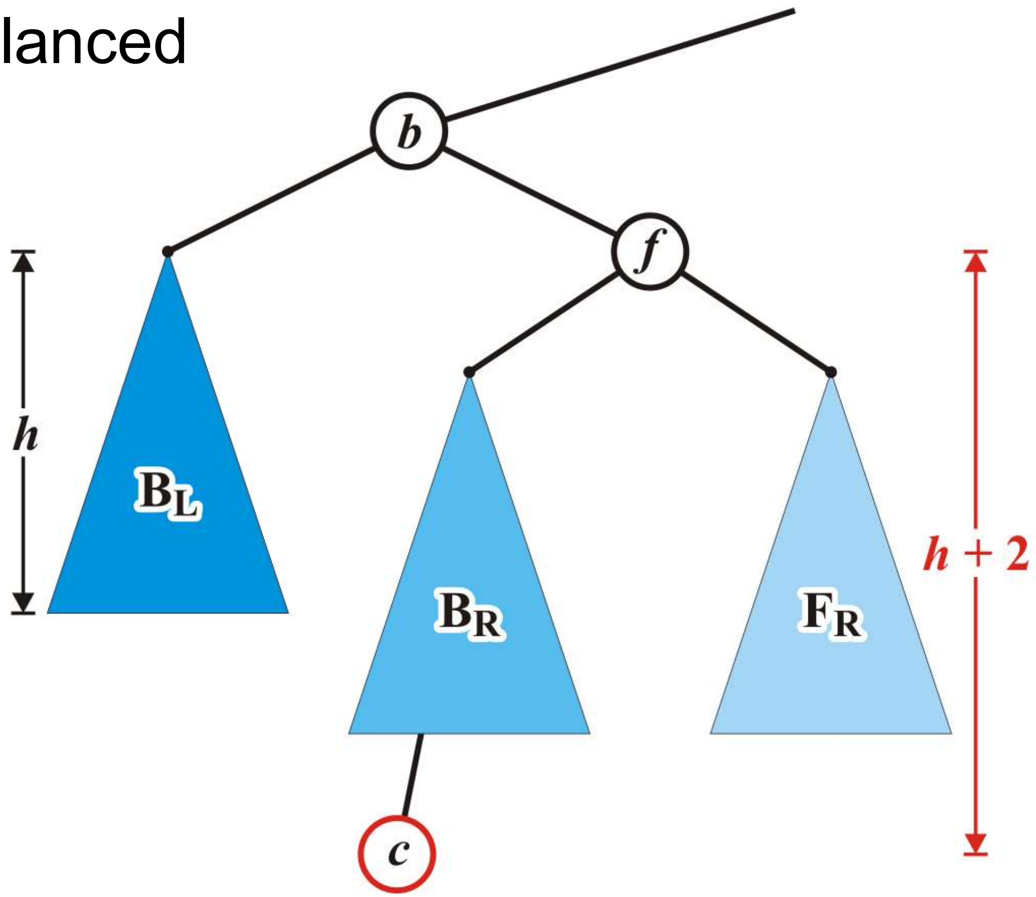
Here are examples of when the insertion of 14 may cause this situation when $h = -1$, 0, and 1





Maintaining Balance: Case 2

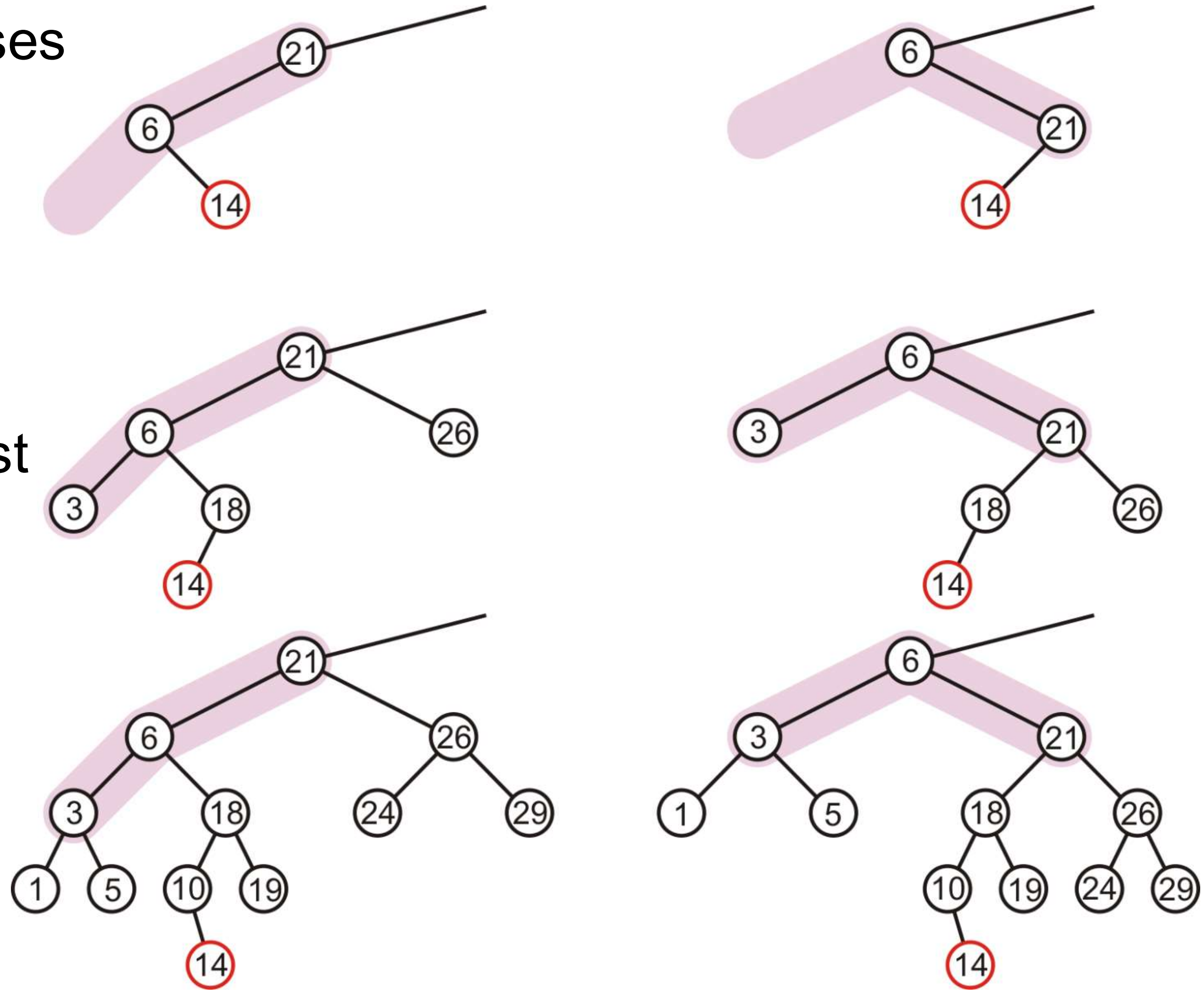
Unfortunately, the previous correction does not fix the imbalance at the root of this sub-tree: the new root, ***b***, remains unbalanced



Maintaining Balance: Case 2

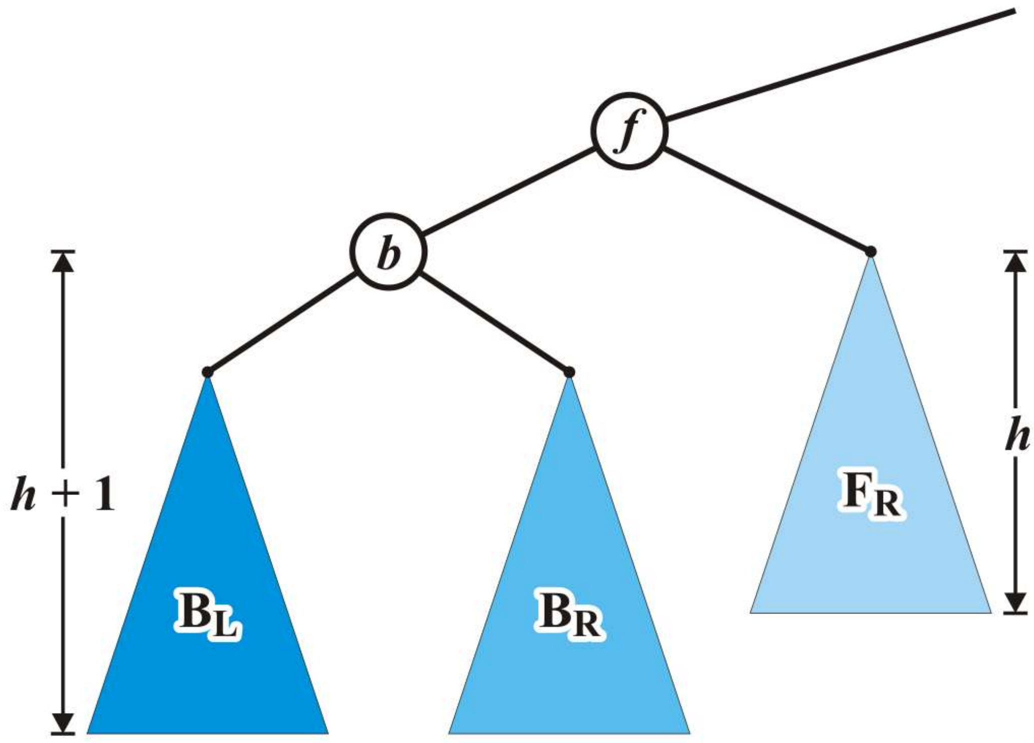
In our three sample cases with $h = -1$, 0, and 1, doing the same thing as before results in a tree that is still unbalanced…

- The imbalance is just shifted to the other side



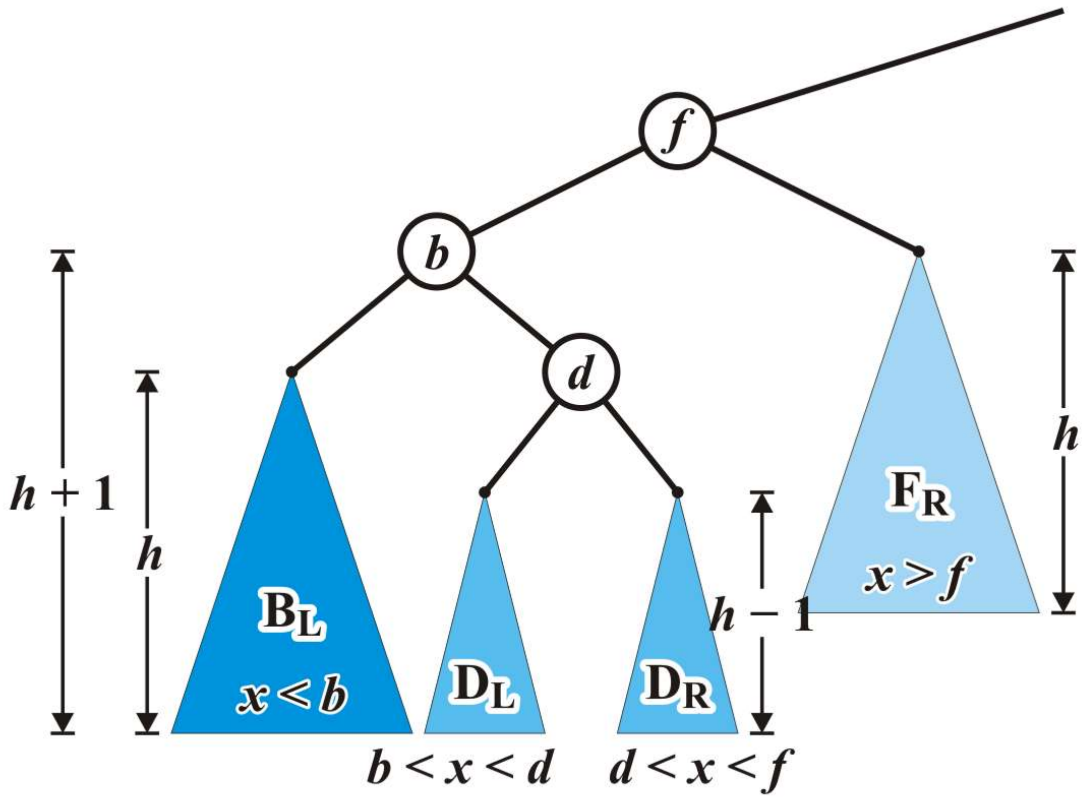
Maintaining Balance: Case 2

Lets start over …



Maintaining Balance: Case 2

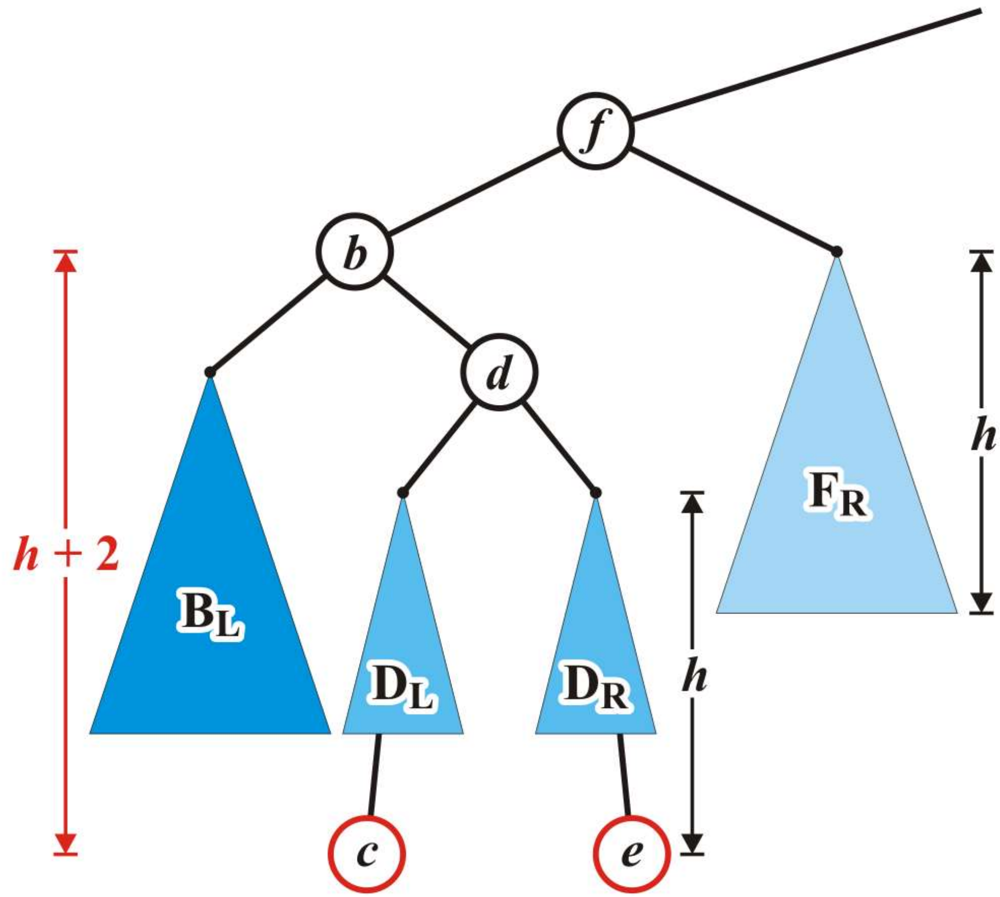
Re-label the tree by dividing the left subtree of f into a tree rooted at d with two subtrees of height $h - 1$



Maintaining Balance: Case 2

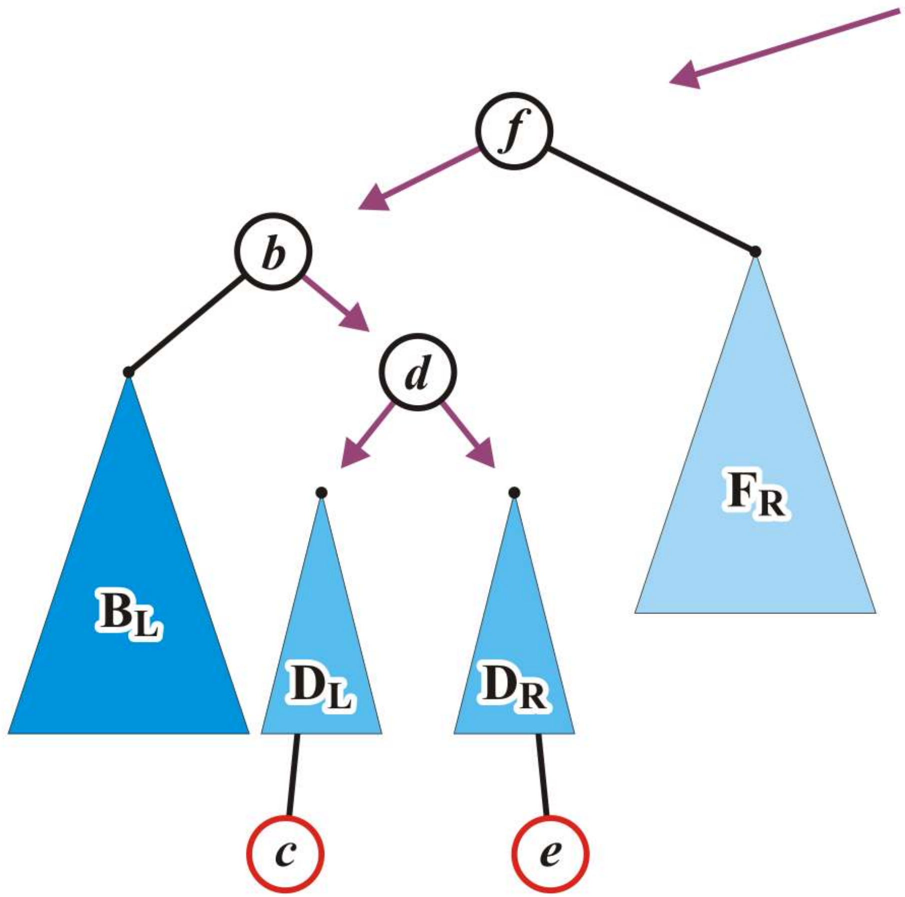
Now an insertion causes an imbalance at f

– The addition of either c or e will cause this



Maintaining Balance: Case 2

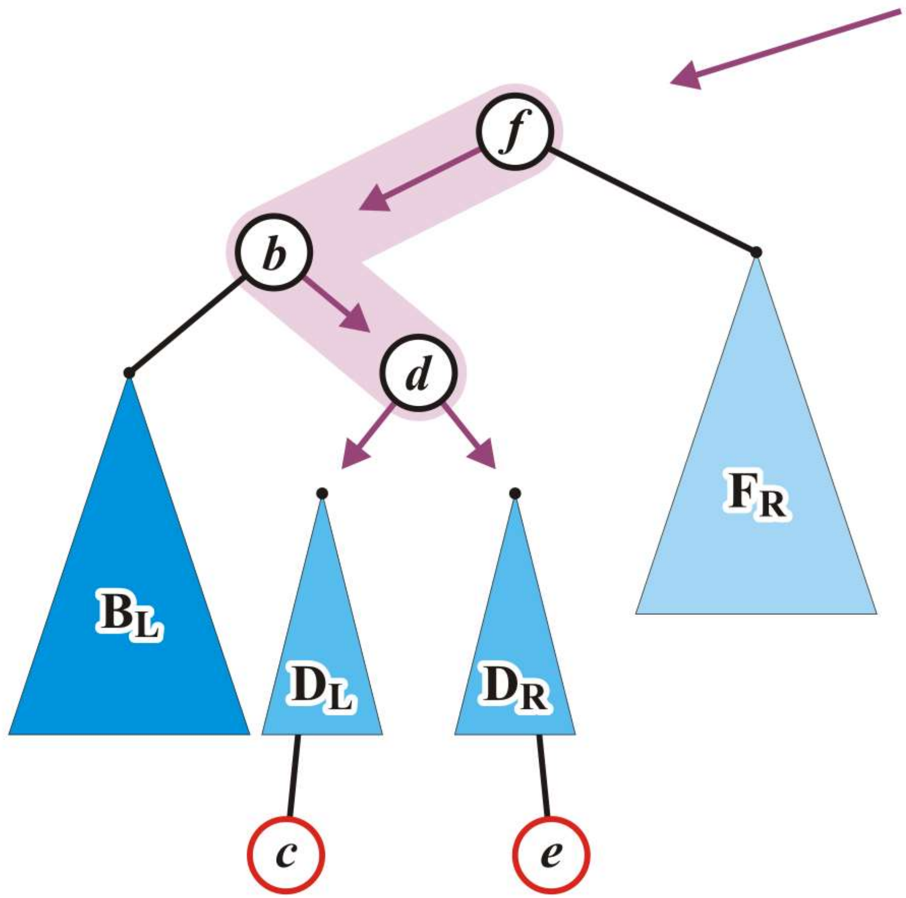
We will reassign the following pointers



Maintaining Balance: Case 2

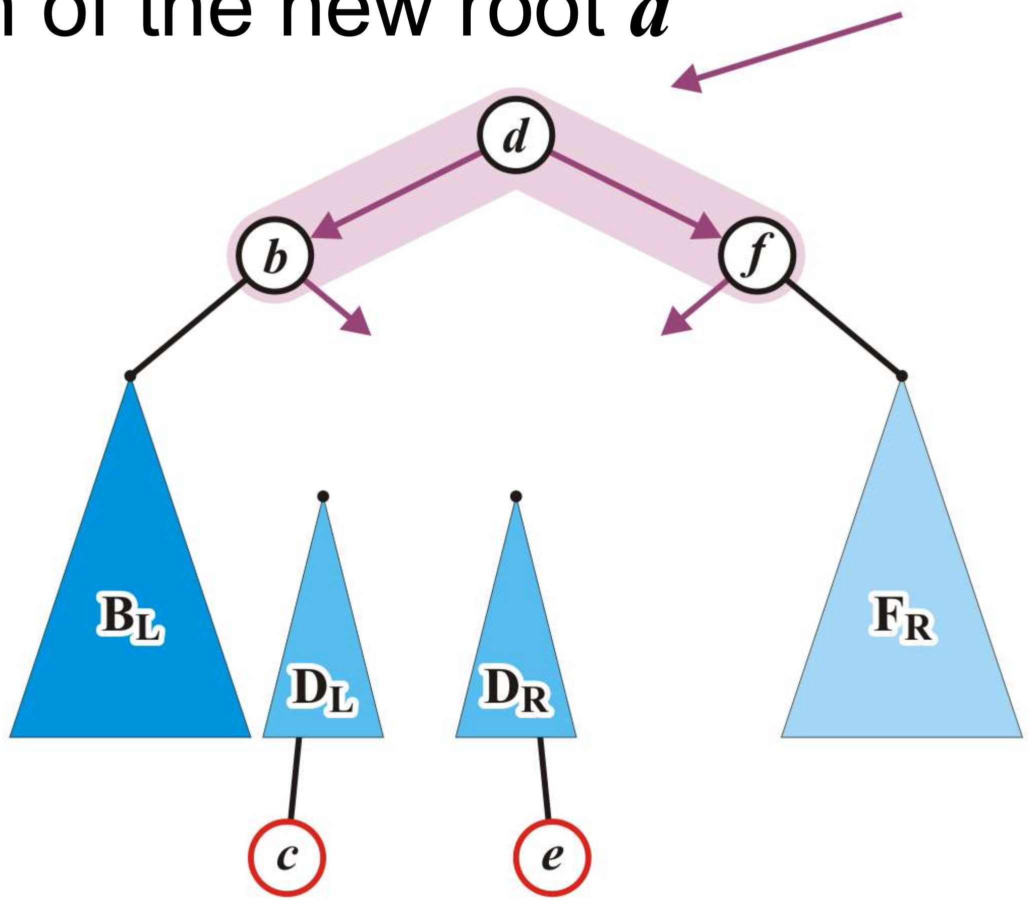
Specifically, we will order these three nodes as a perfect tree

– Recall the second prototypical example



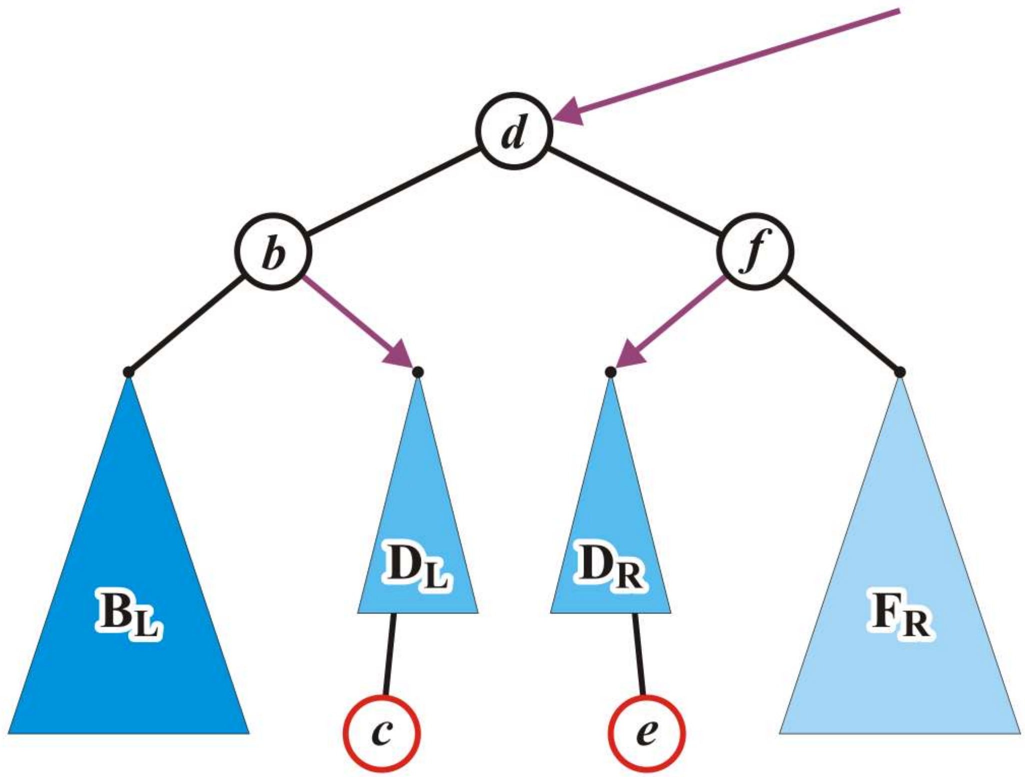
Maintaining Balance: Case 2

To achieve this, ***b*** and ***f*** will be assigned as children of the new root ***d***



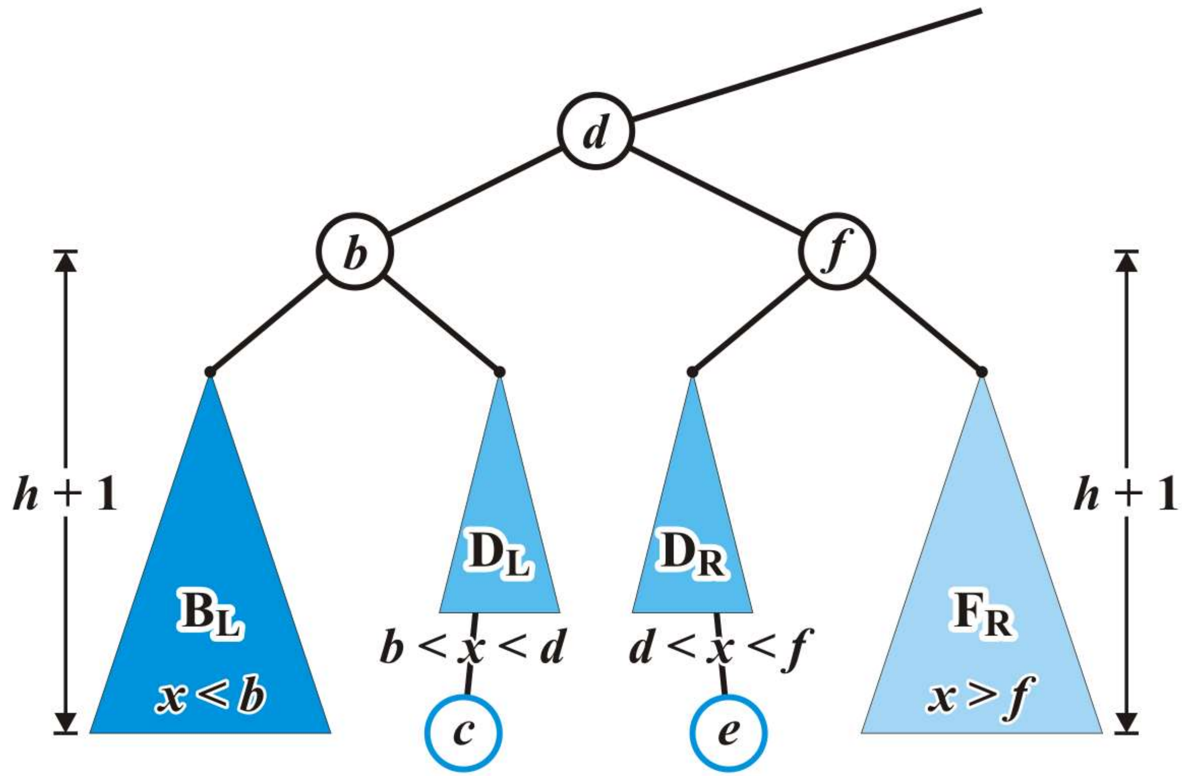
Maintaining Balance: Case 2

We also have to connect the two subtrees and original parent of f



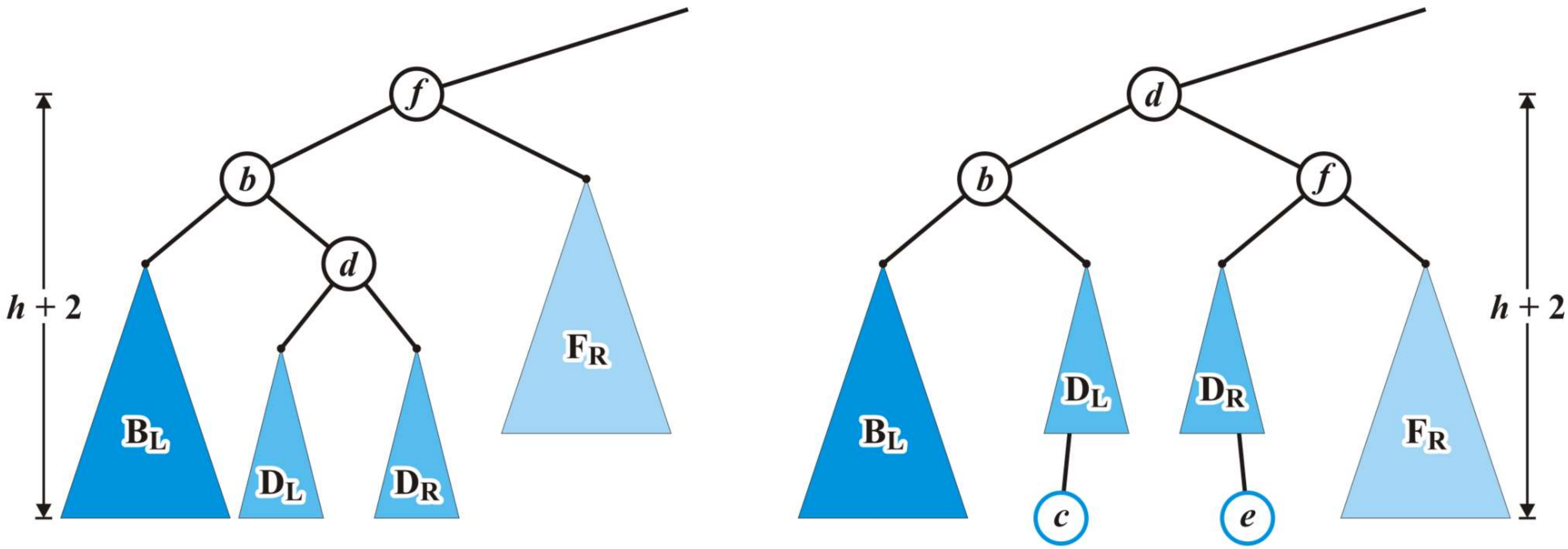
Maintaining Balance: Case 2

Now the tree rooted at ***d*** is balanced



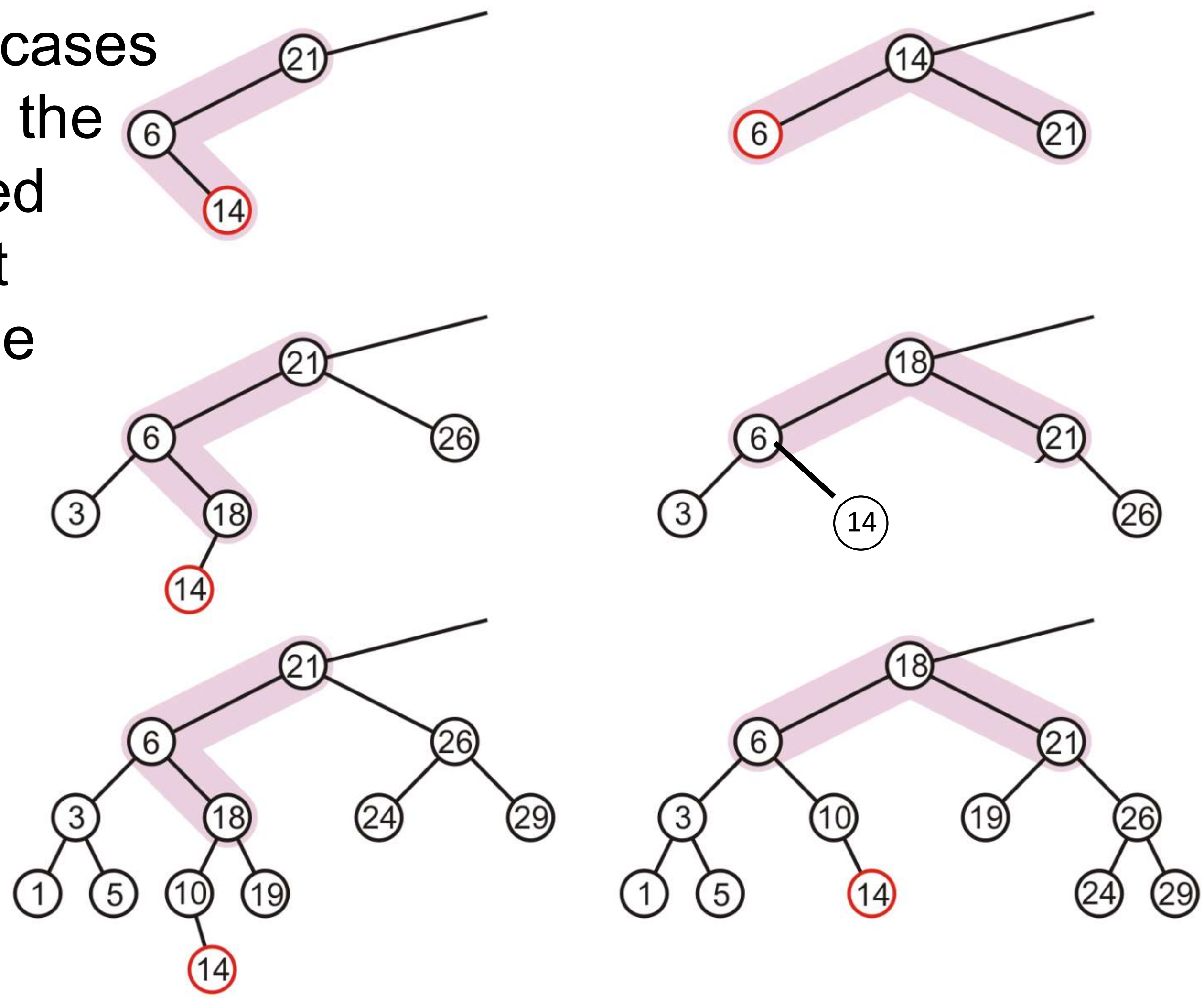
Maintaining Balance: Case 2

Again, the height of the root did not change



Maintaining Balance: Case 2

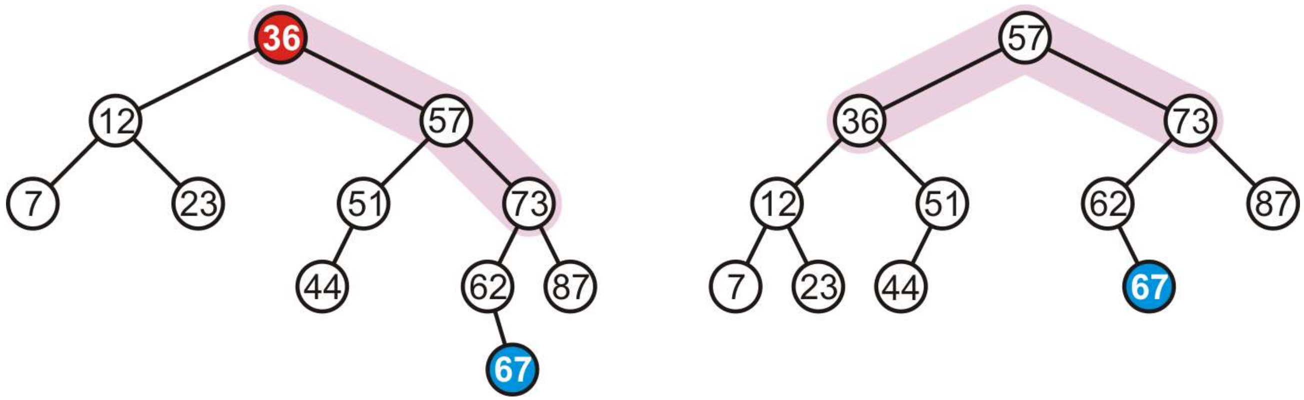
In our three sample cases with $h = -1$, 0, and 1, the node is now balanced and the same height as the tree before the insertion



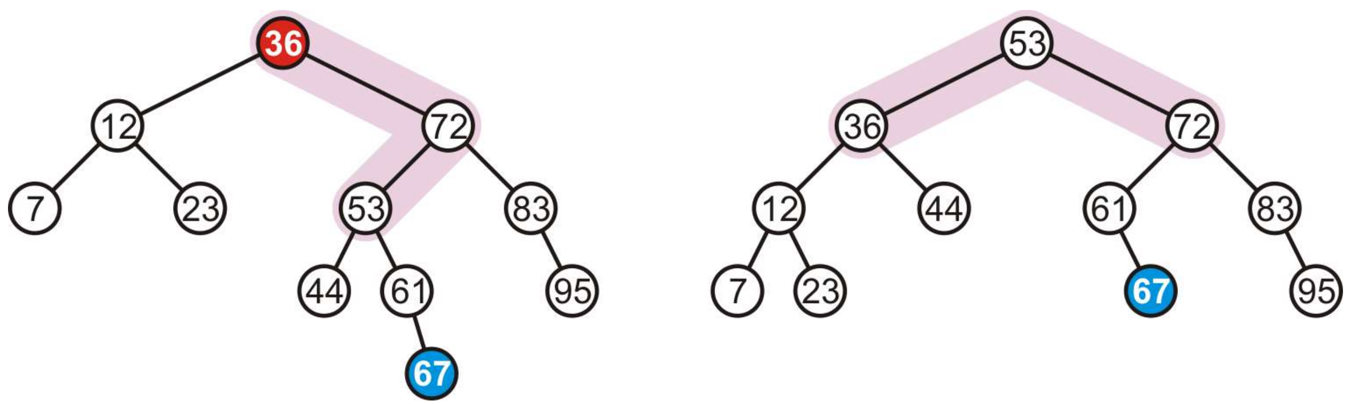
Maintaining balance: Summary

There are two symmetric cases to those we have examined:

– Insertions into the right-right sub-tree

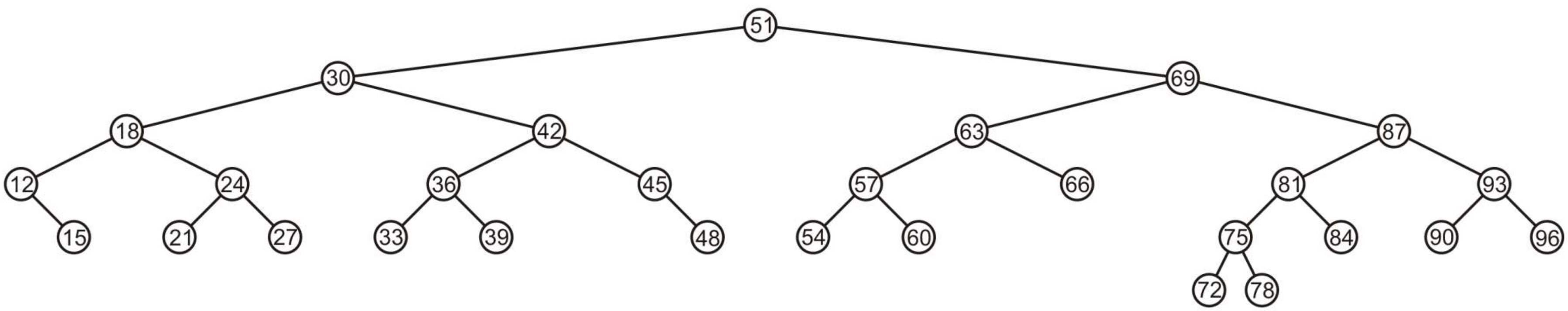


-- Insertions into either the right-left sub-tree



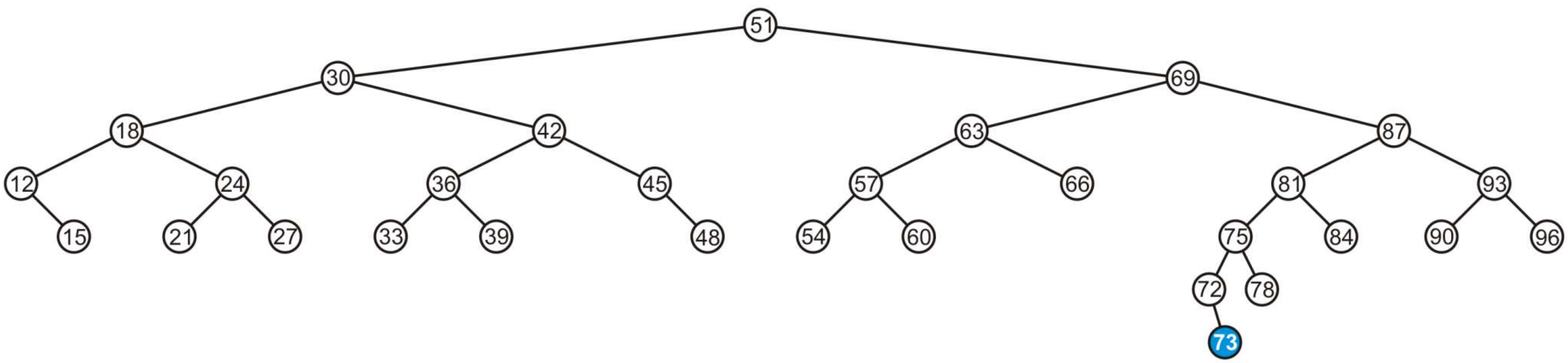
More examples : Insertion

Consider this AVL tree



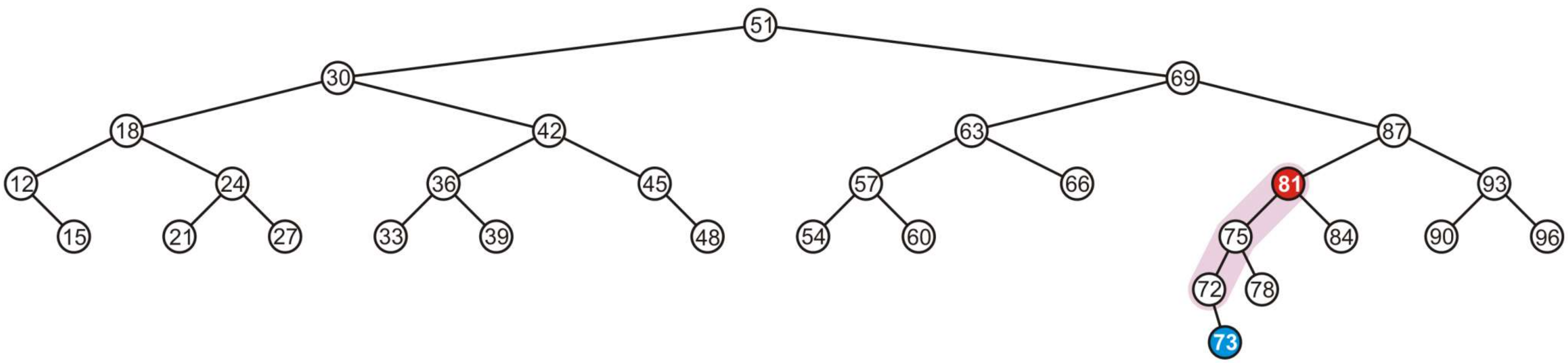
Insertion

Insert 73



Insertion

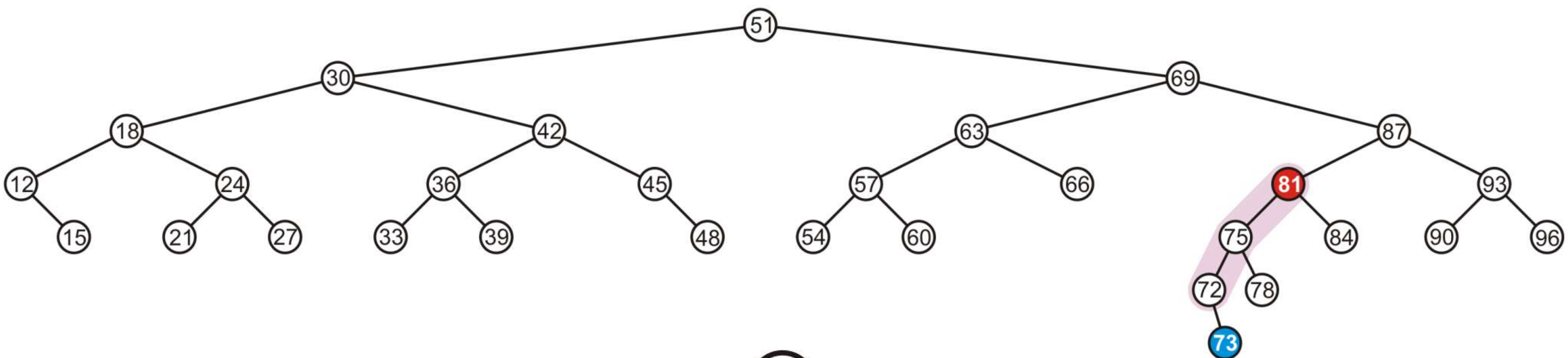
- The node 81 is unbalanced
  - A left-left imbalance

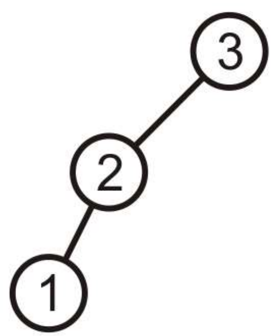


Insertion

The node 81 is unbalanced

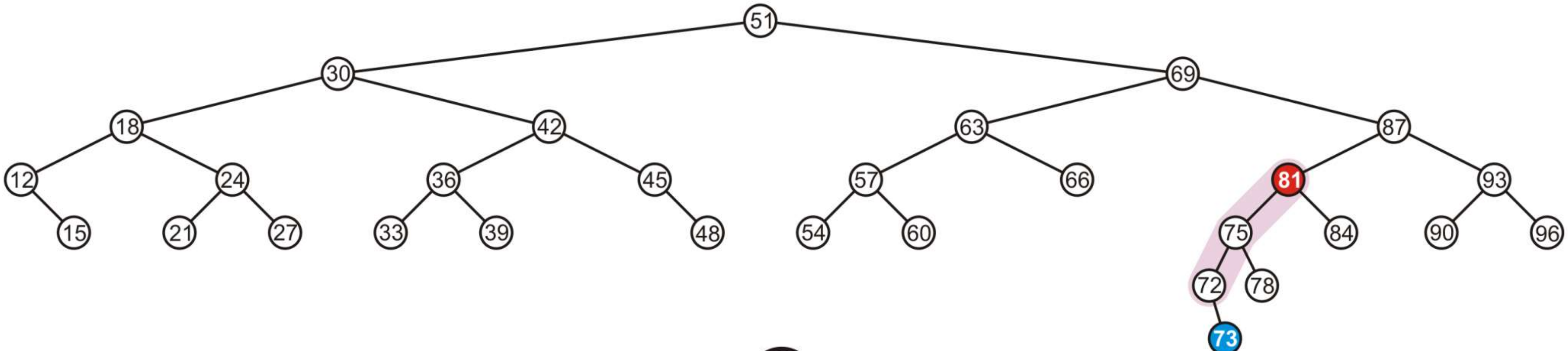
– A left-left imbalance

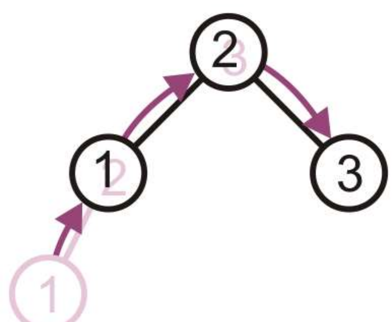




Insertion

- The node 81 is unbalanced
  - A left-left imbalance

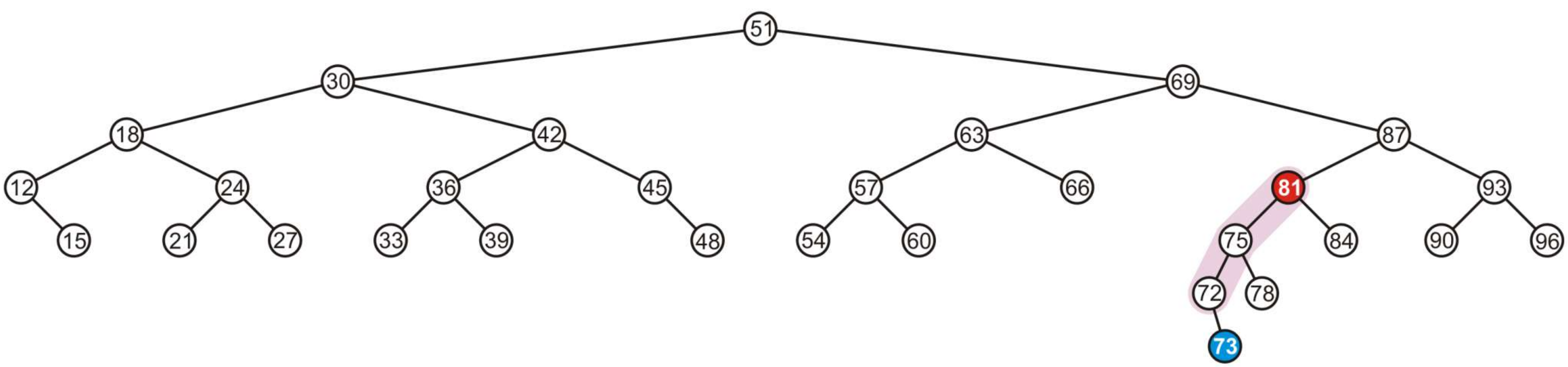




Insertion

The node 81 is unbalanced

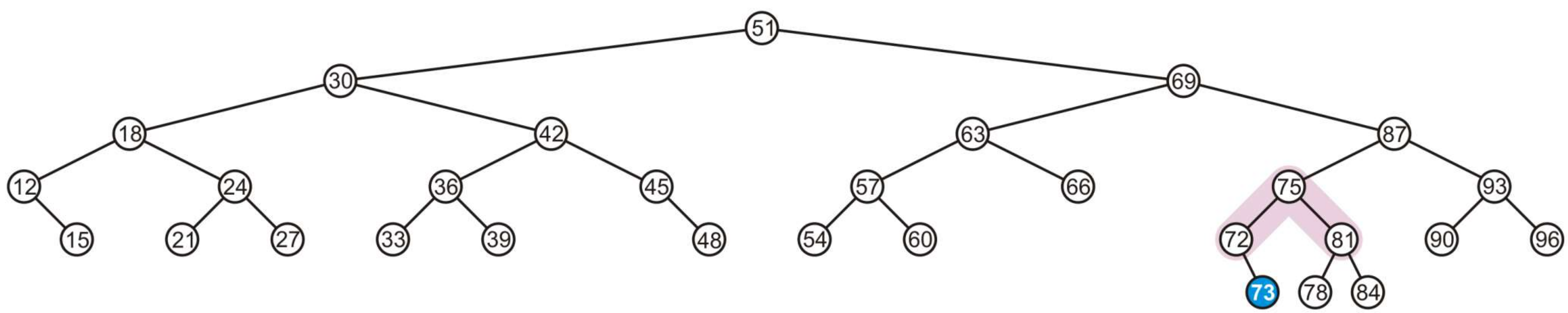
- A left-left imbalance
- Promote the intermediate node to the imbalanced node
- 75 is that node



Insertion

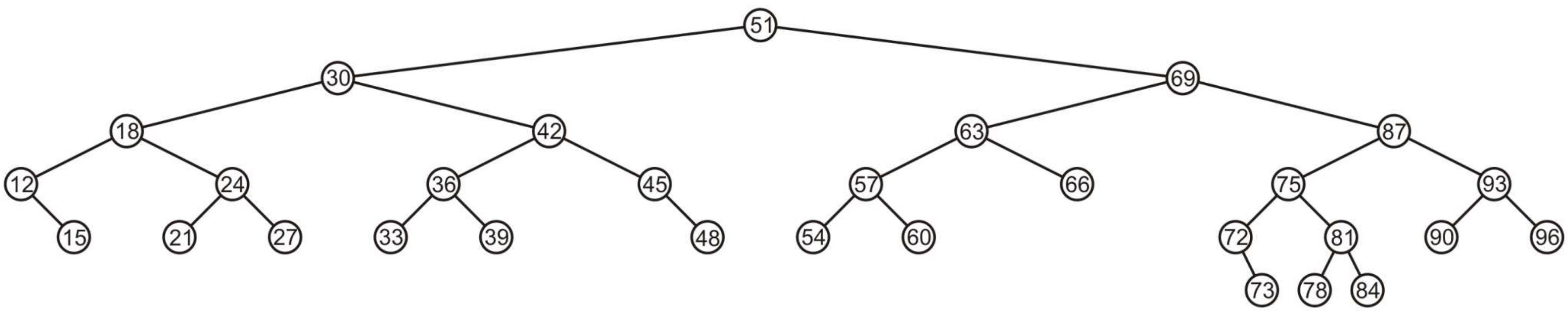
The node 81 is unbalanced

- A left-left imbalance
- Promote the intermediate node to the imbalanced node
- 75 is that node



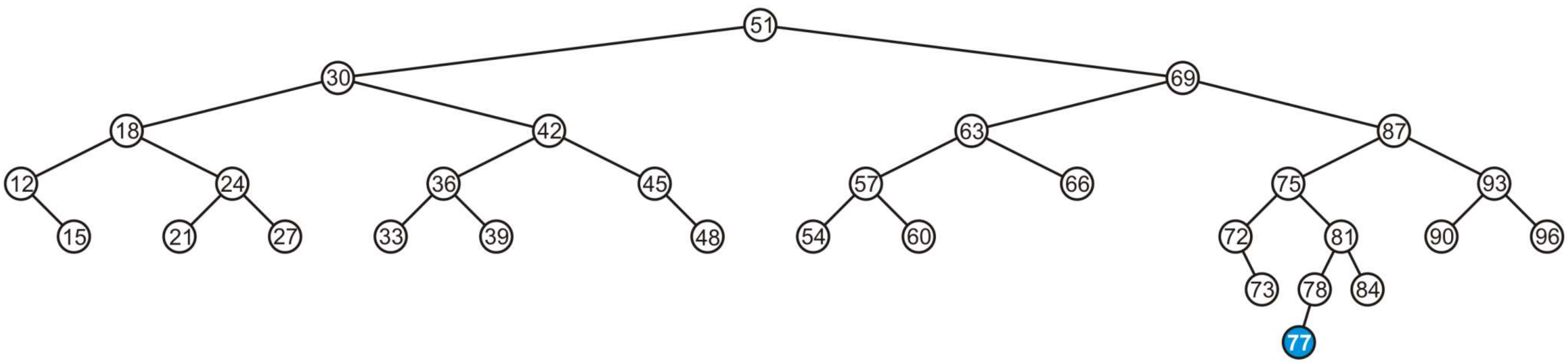
Insertion

The tree is AVL balanced



Insertion

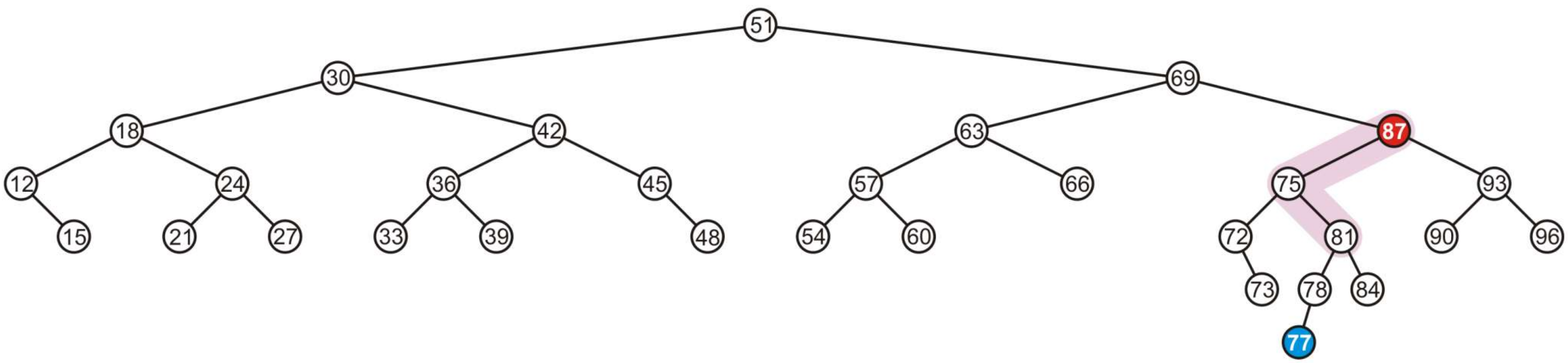
Insert 77



Insertion

The node 87 is unbalanced

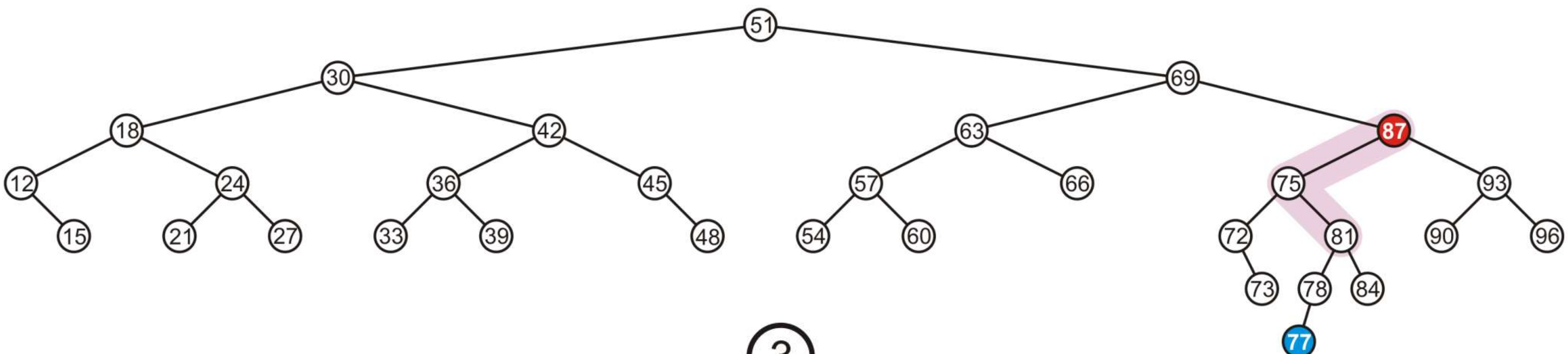
– A left-right imbalance

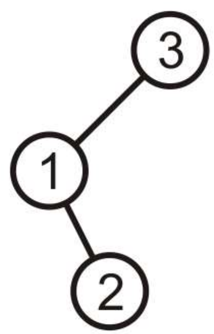


Insertion

The node 87 is unbalanced

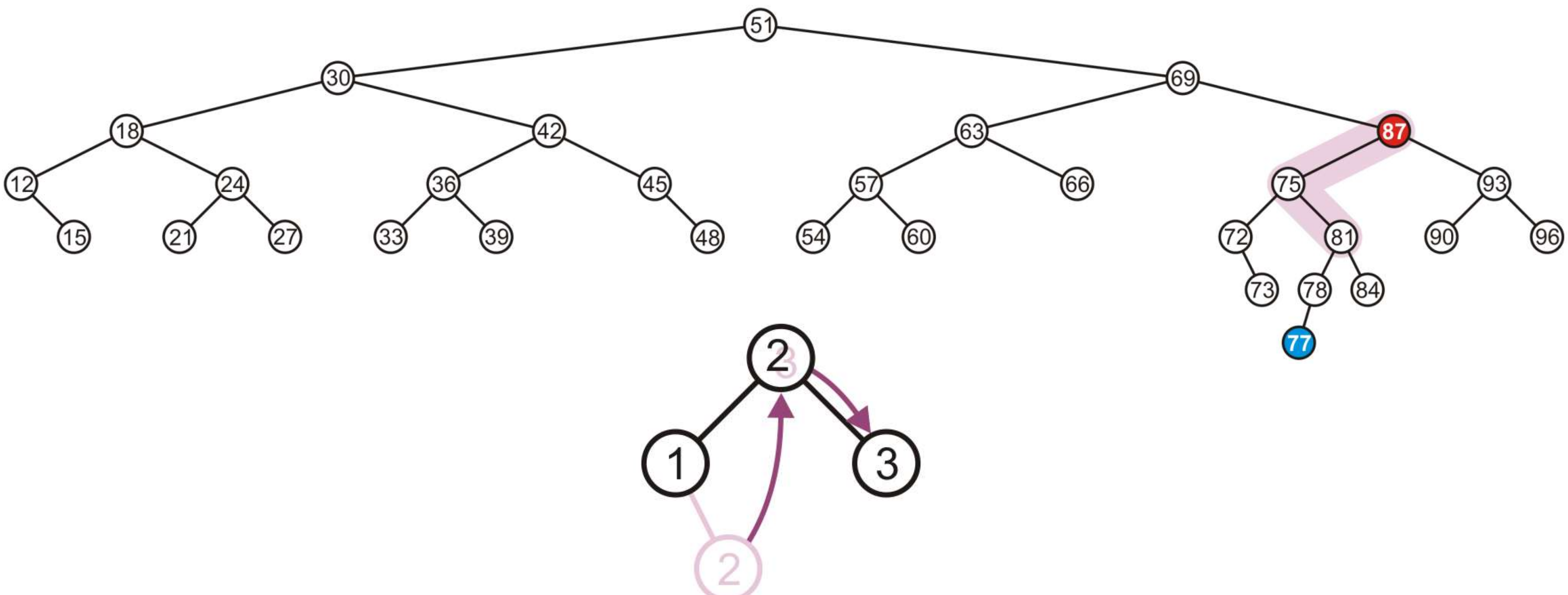
– A left-right imbalance





Insertion

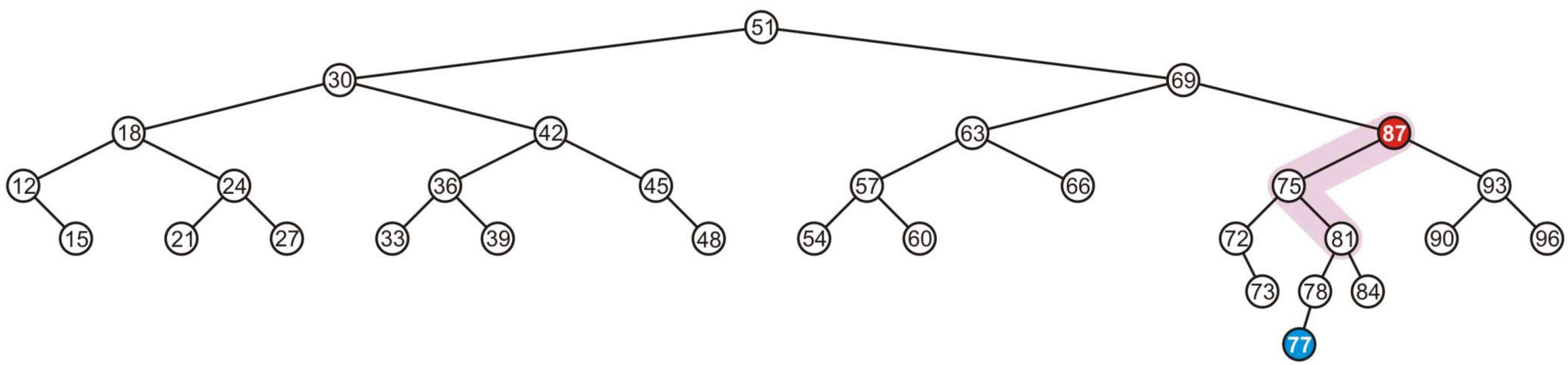
- The node 87 is unbalanced
  - A left-right imbalance



Insertion

The node 87 is unbalanced

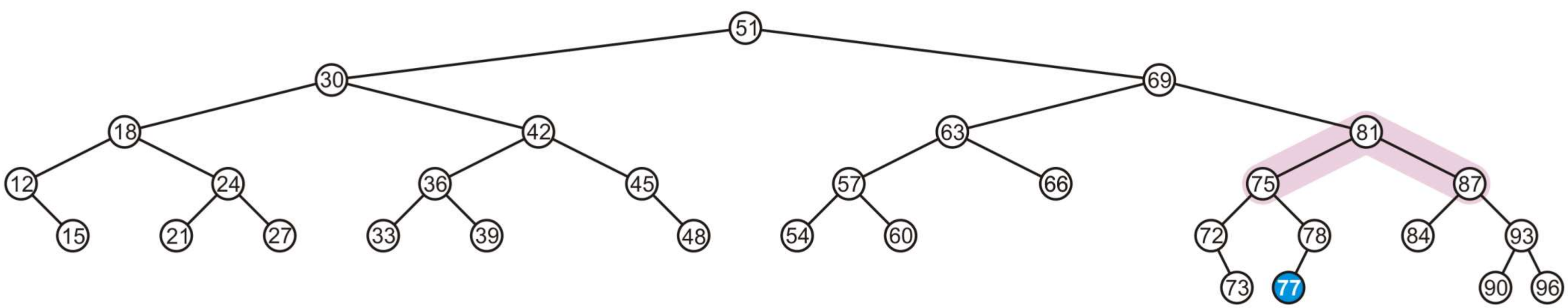
- A left-right imbalance
- Promote the intermediate node to the imbalanced node
- 81 is that value



Insertion

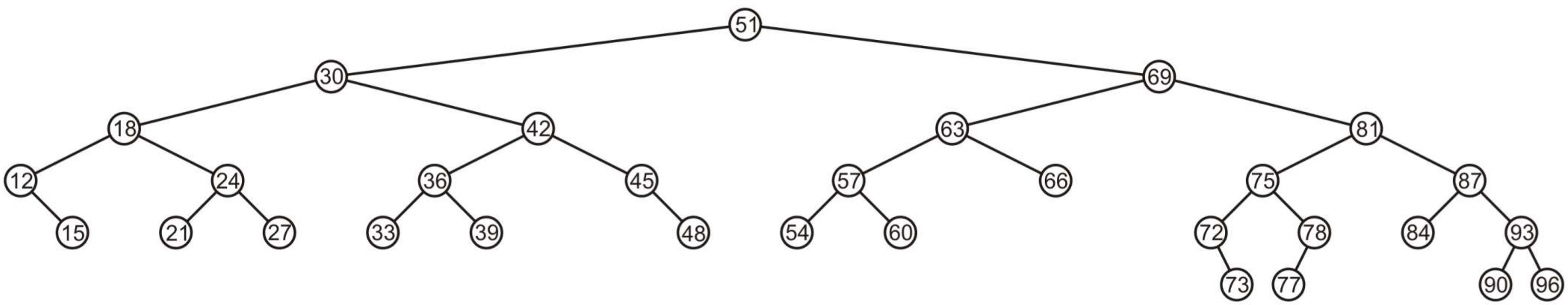
The node 87 is unbalanced

- A left-right imbalance
- Promote the intermediate node to the imbalanced node
- 81 is that value



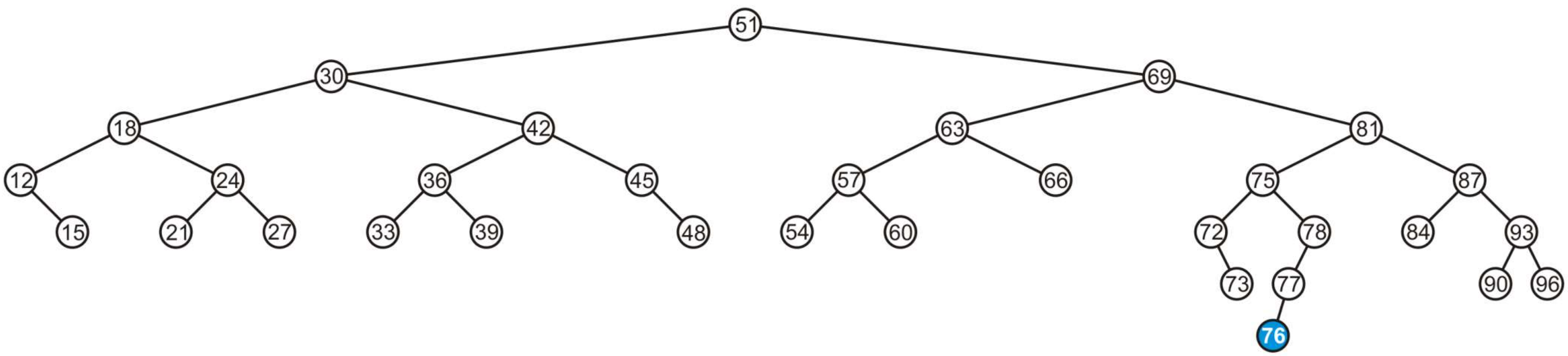
Insertion

The tree is balanced



Insertion

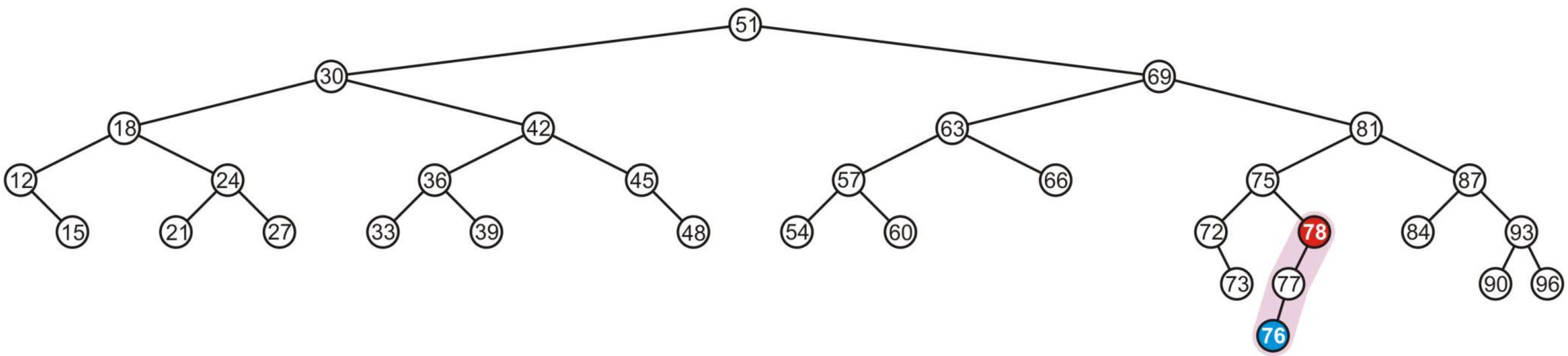
Insert 76



Insertion

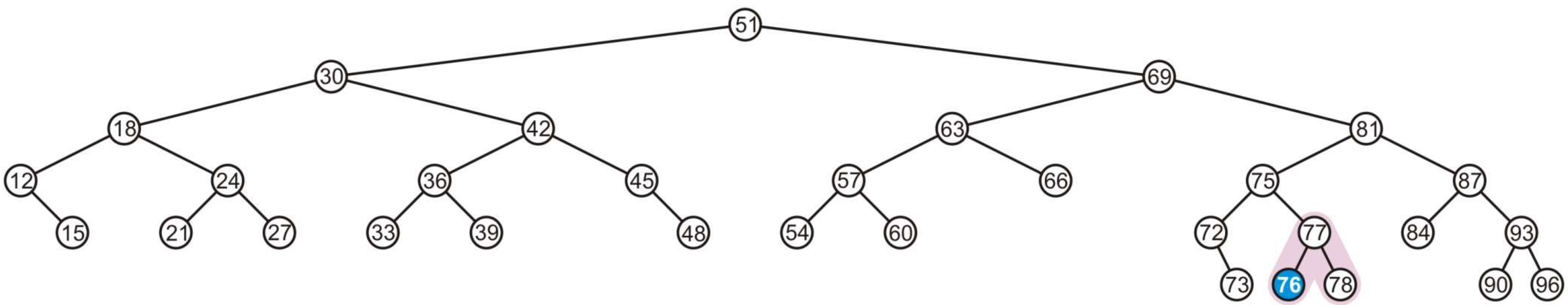
The node 78 is unbalanced

– A left-left imbalance



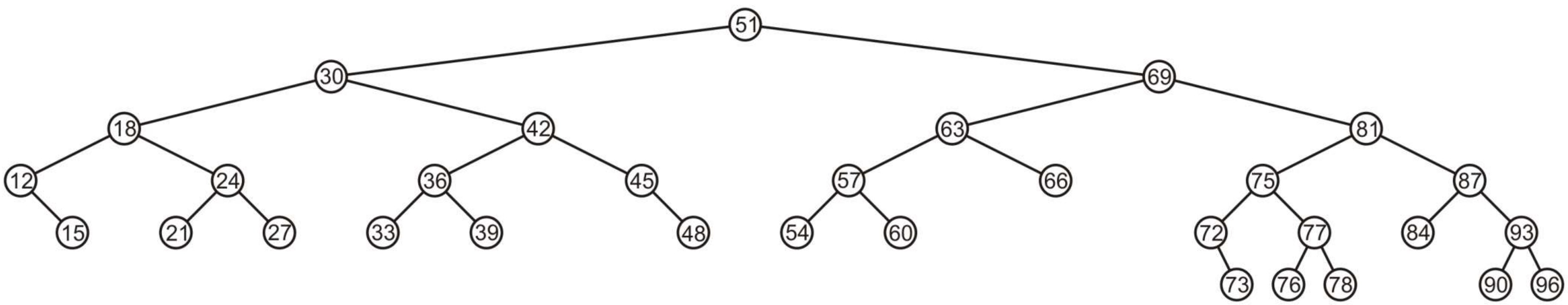
Insertion

- The node 78 is unbalanced
  – Promote 77



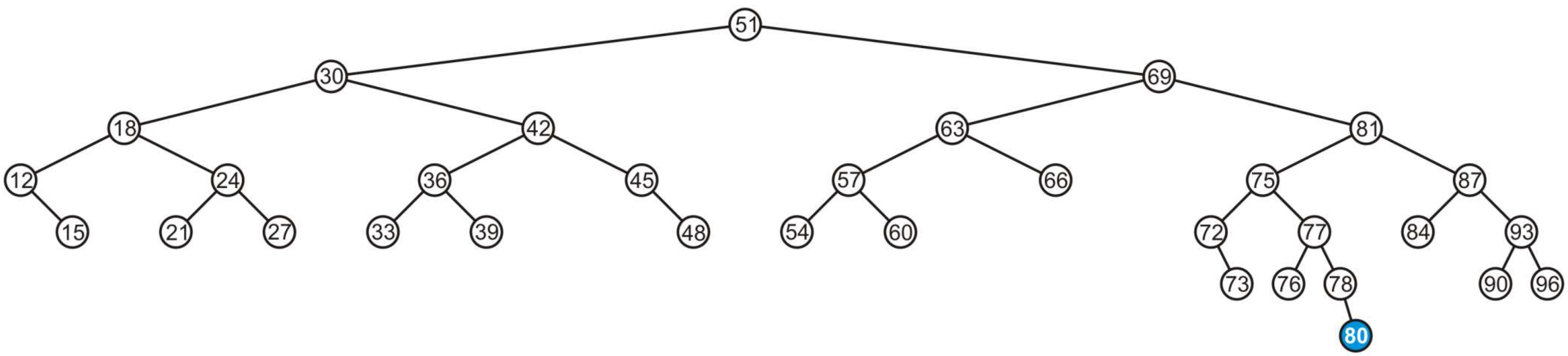
Insertion

Again, balanced



Insertion

Insert 80

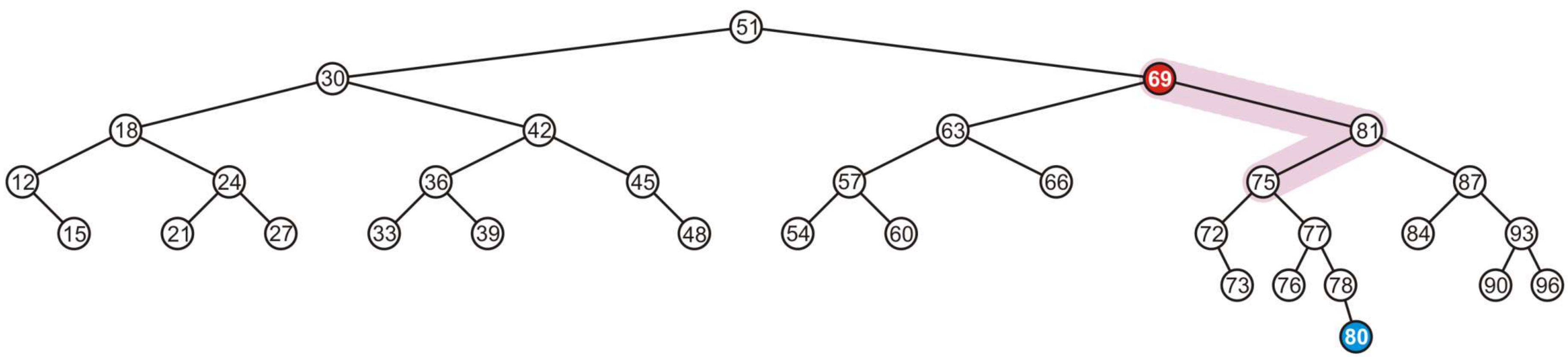


Insertion

The node 69 is unbalanced

– A right-left imbalance

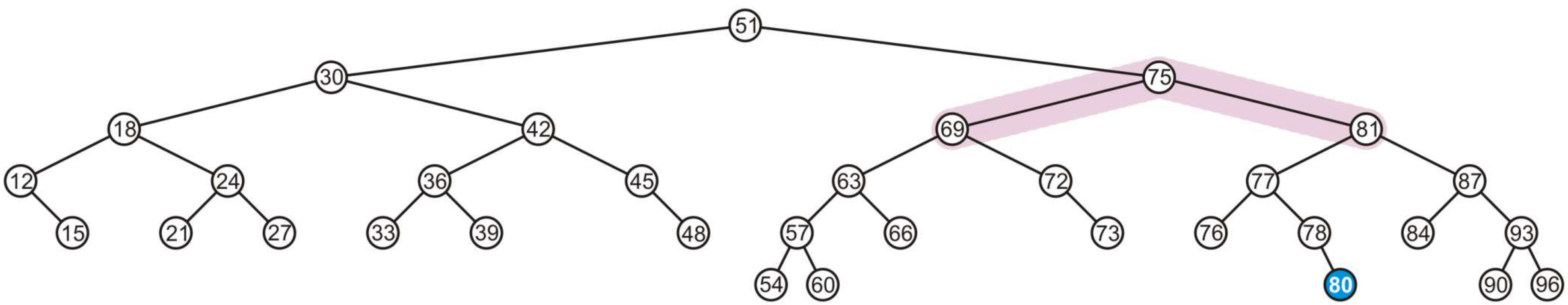
– Promote the intermediate node to the imbalanced node



Insertion

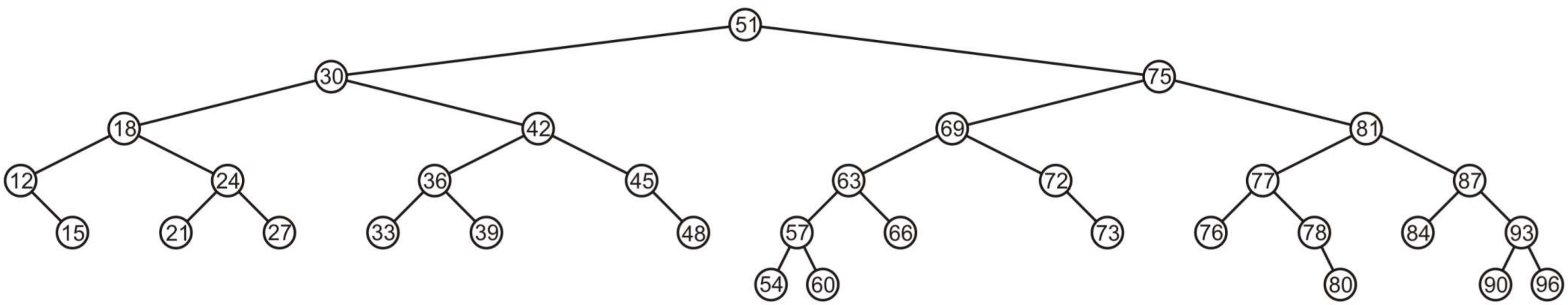
The node 69 is unbalanced

- A left-right imbalance
- Promote the intermediate node to the imbalanced node
- 75 is that value



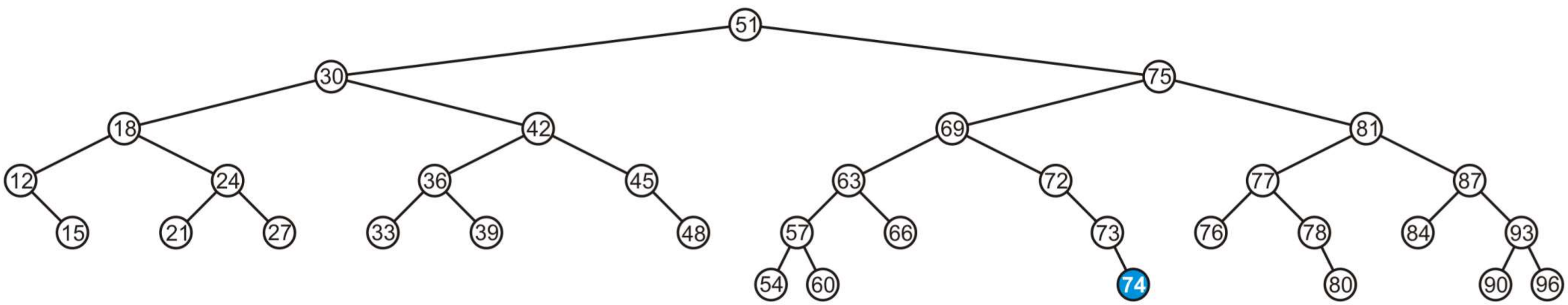
Insertion

Again, balanced



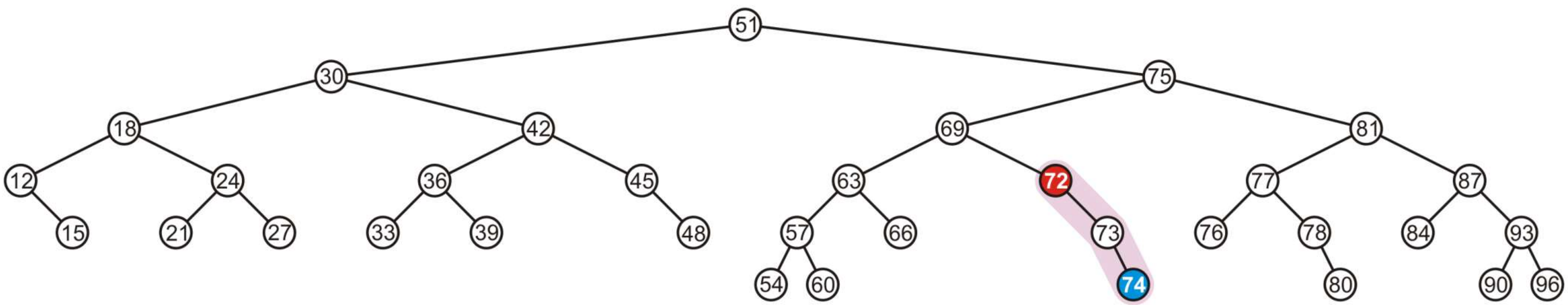
Insertion

Insert 74



Insertion

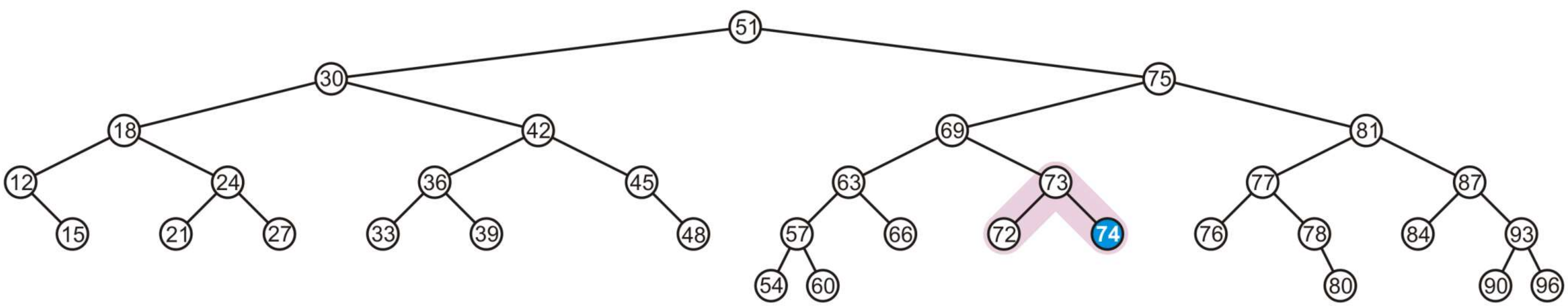
- The node 72 is unbalanced
  - A right-right imbalance



Insertion

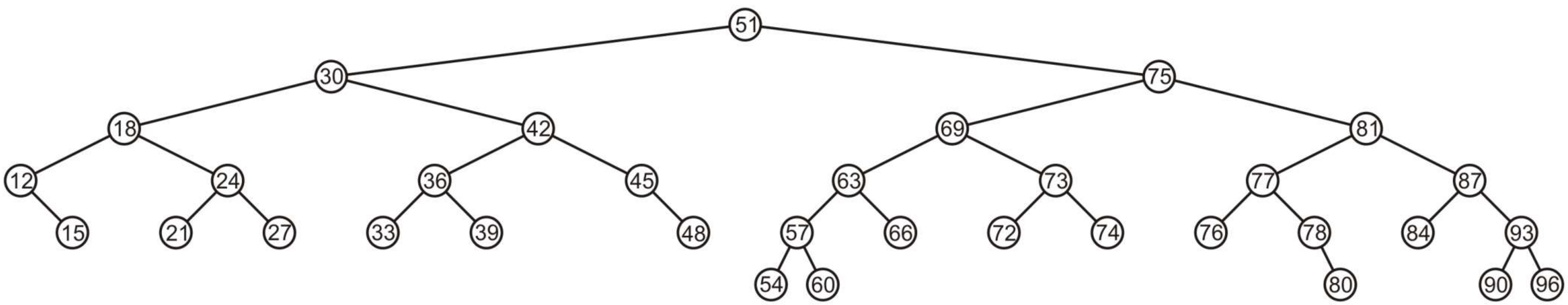
The node 72 is unbalanced

- A right-right imbalance
- Promote the intermediate node to the imbalanced node



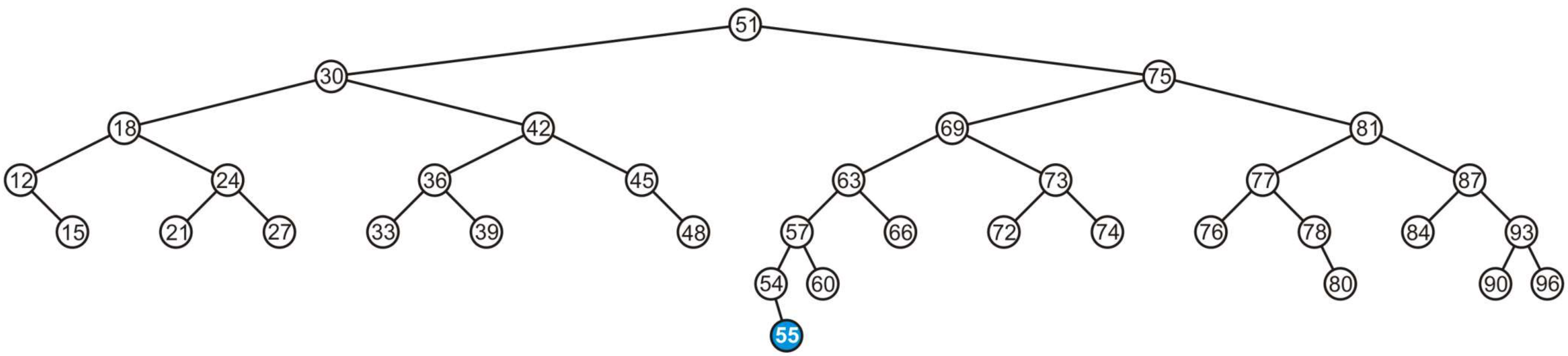
Insertion

Again, balanced



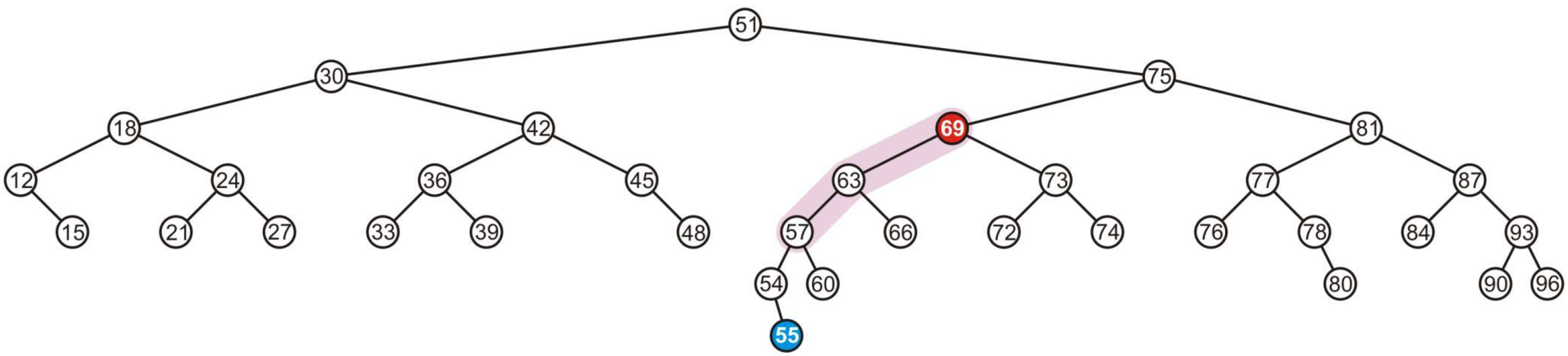
Insertion

Insert 55



Insertion

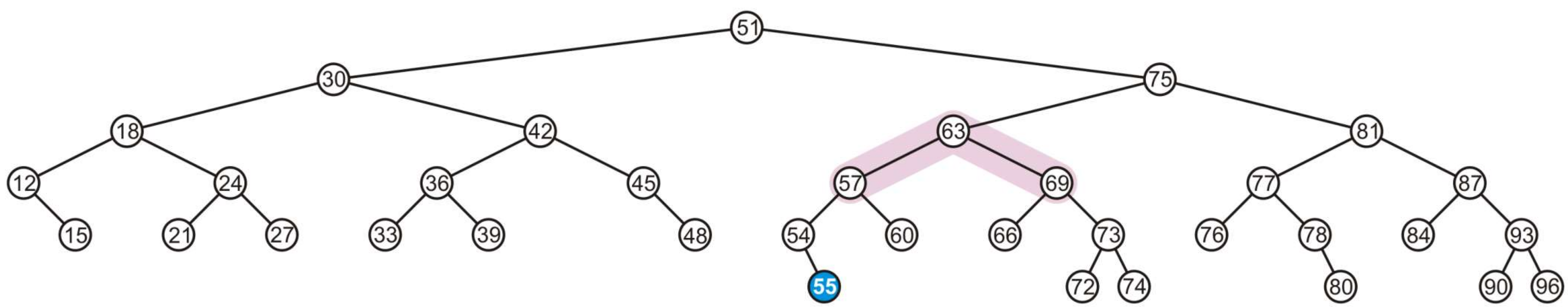
- The node 69 is imbalanced
  - A left-left imbalance



Insertion

The node 69 is imbalanced

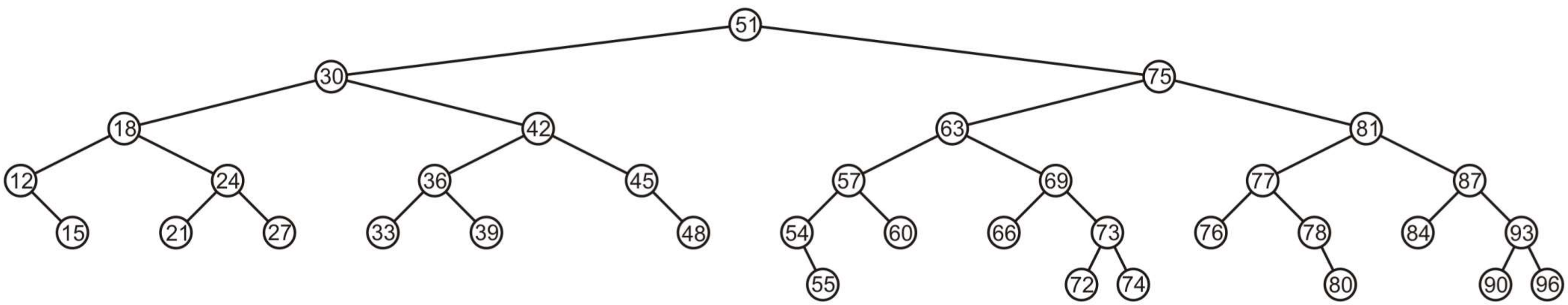
- A left-left imbalance
- Promote the intermediate node to the imbalanced node
- 63 is that value



Insertion

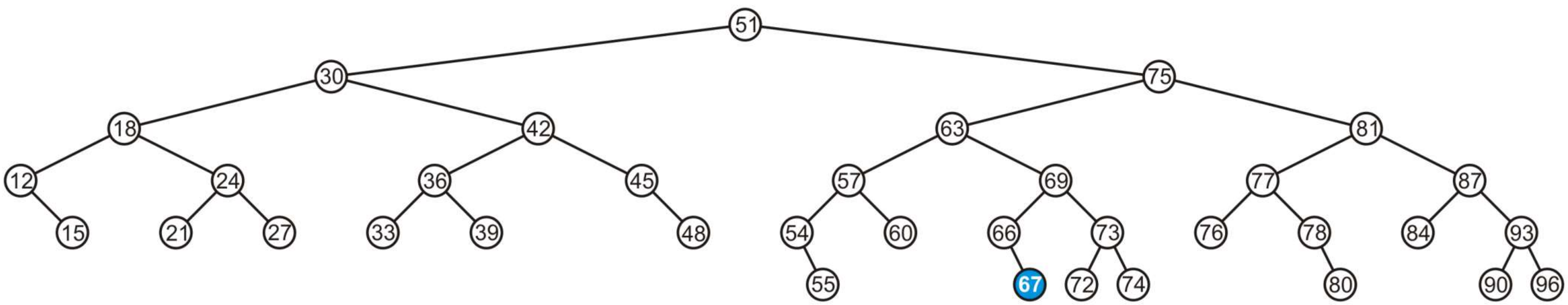
Insert 55

– No imbalances



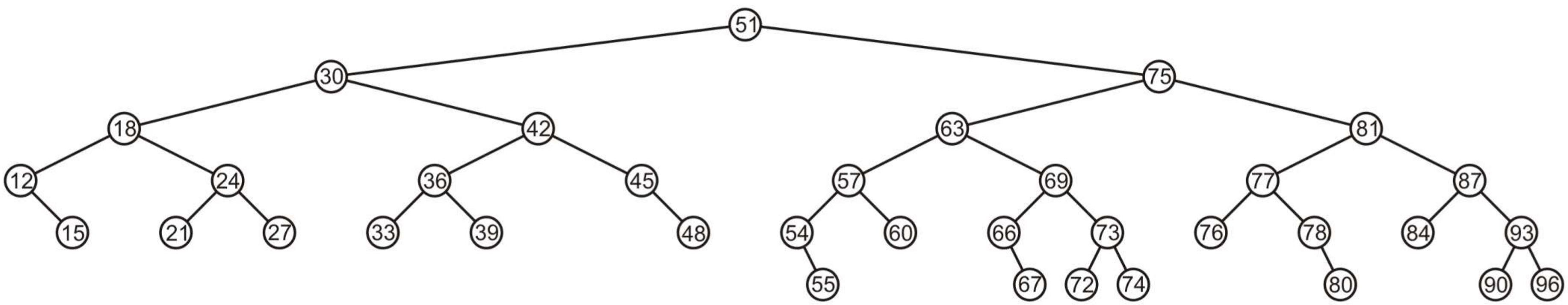
Insertion

Again, balanced



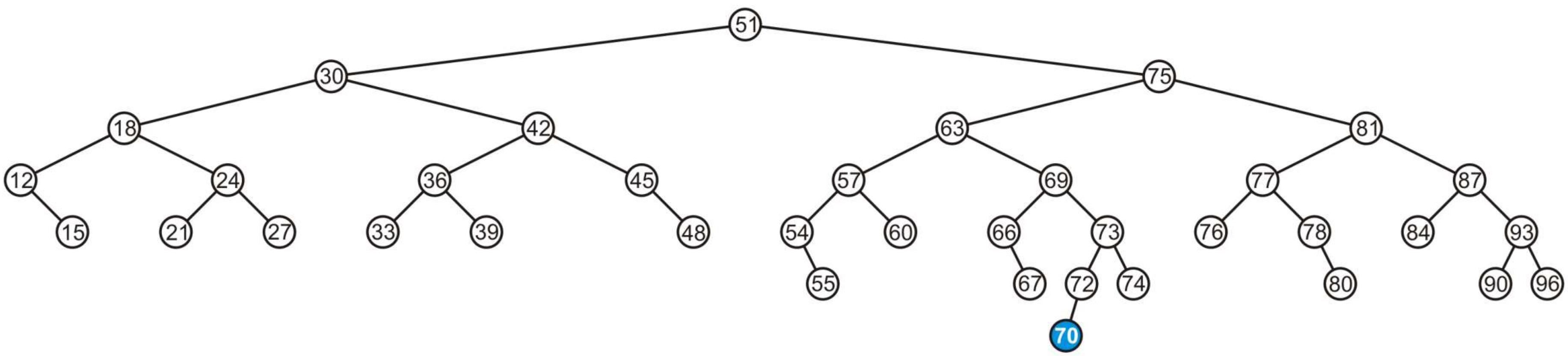
Insertion

Again, balanced



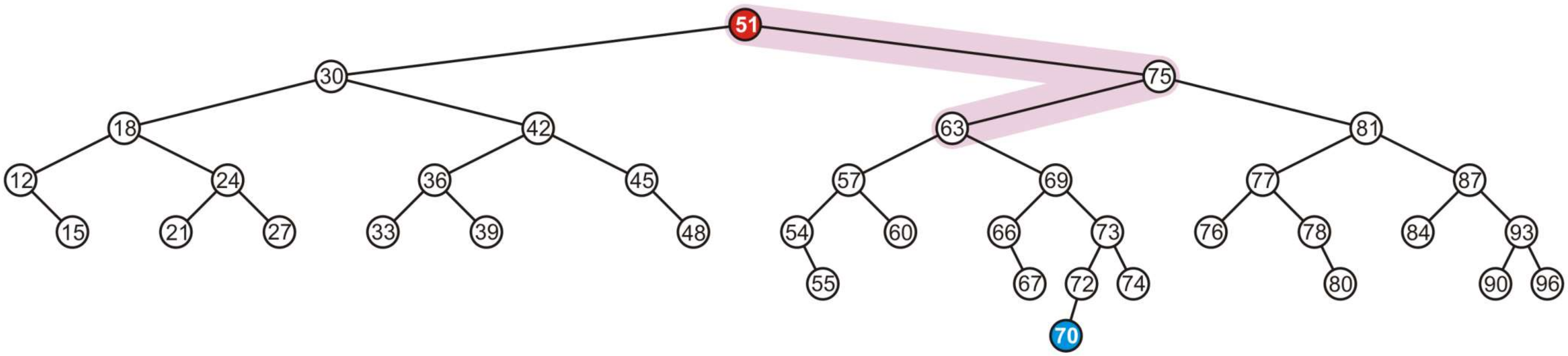
Insertion

Insert 70



Insertion

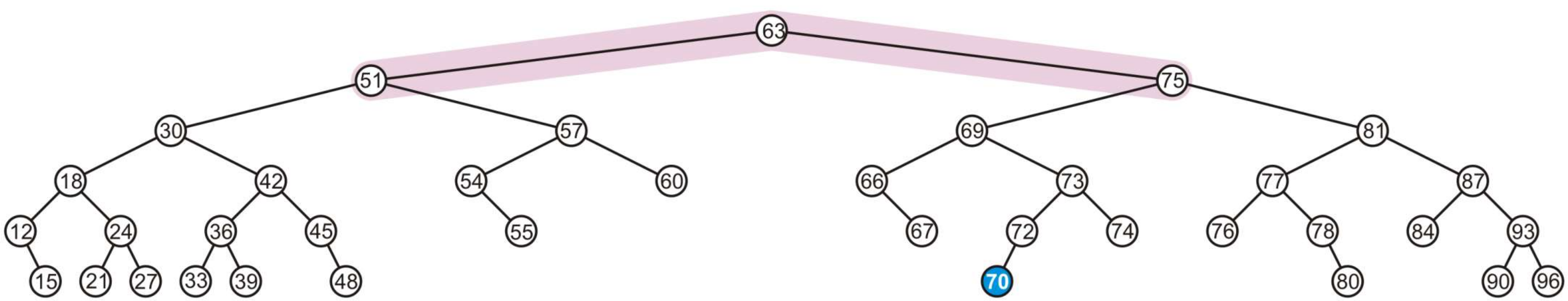
- The root node is now imbalanced
  - A right-left imbalance



Insertion

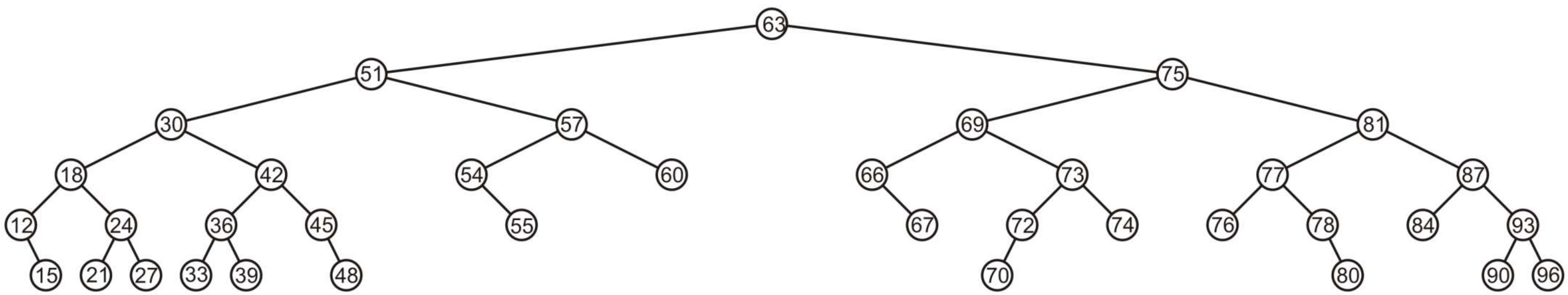
The root node is imbalanced

- A right-left imbalance
- Promote the intermediate node to the root
- 63 is that node



Insertion

The result is balanced



Summary : Insertions

Let the node that needs rebalancing be j.

There are 4 cases:

Outside Cases (require single rotation) :

1. Insertion into left subtree of left child of j.
2. Insertion into right subtree of right child of j.

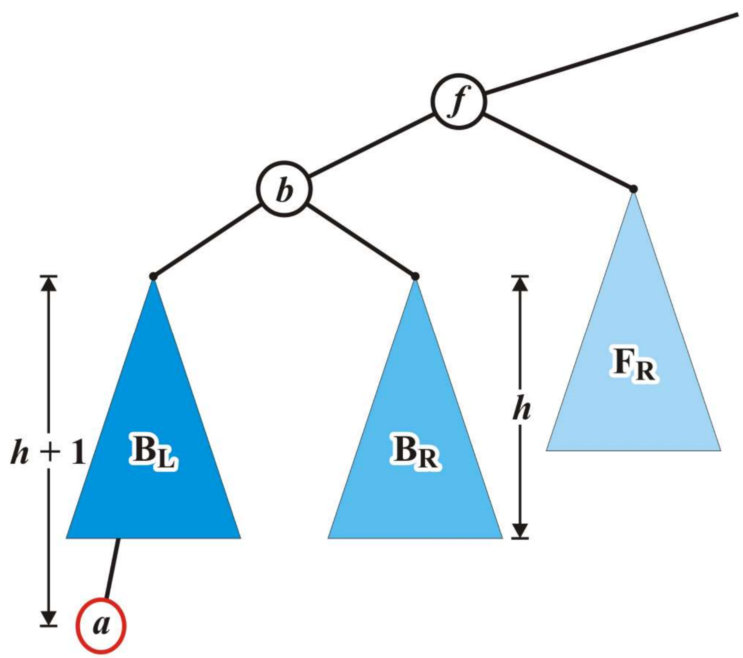
Inside Cases (require double rotation) :

3. Insertion into right subtree of left child of j.
4. Insertion into left subtree of right child of j.

The rebalancing is performed through four separate rotation algorithms.

Outside Case

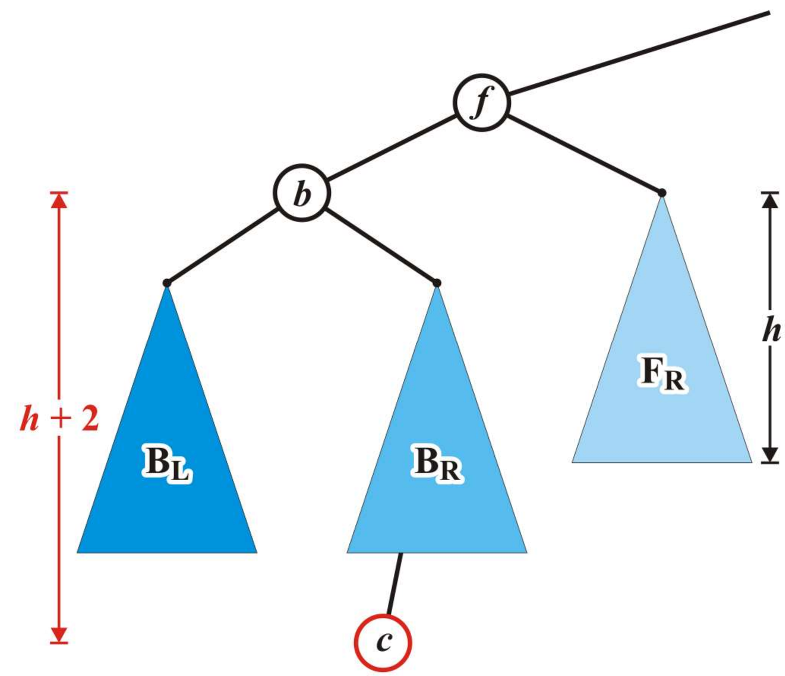
Left subtree of left child



Single "right" Rotation

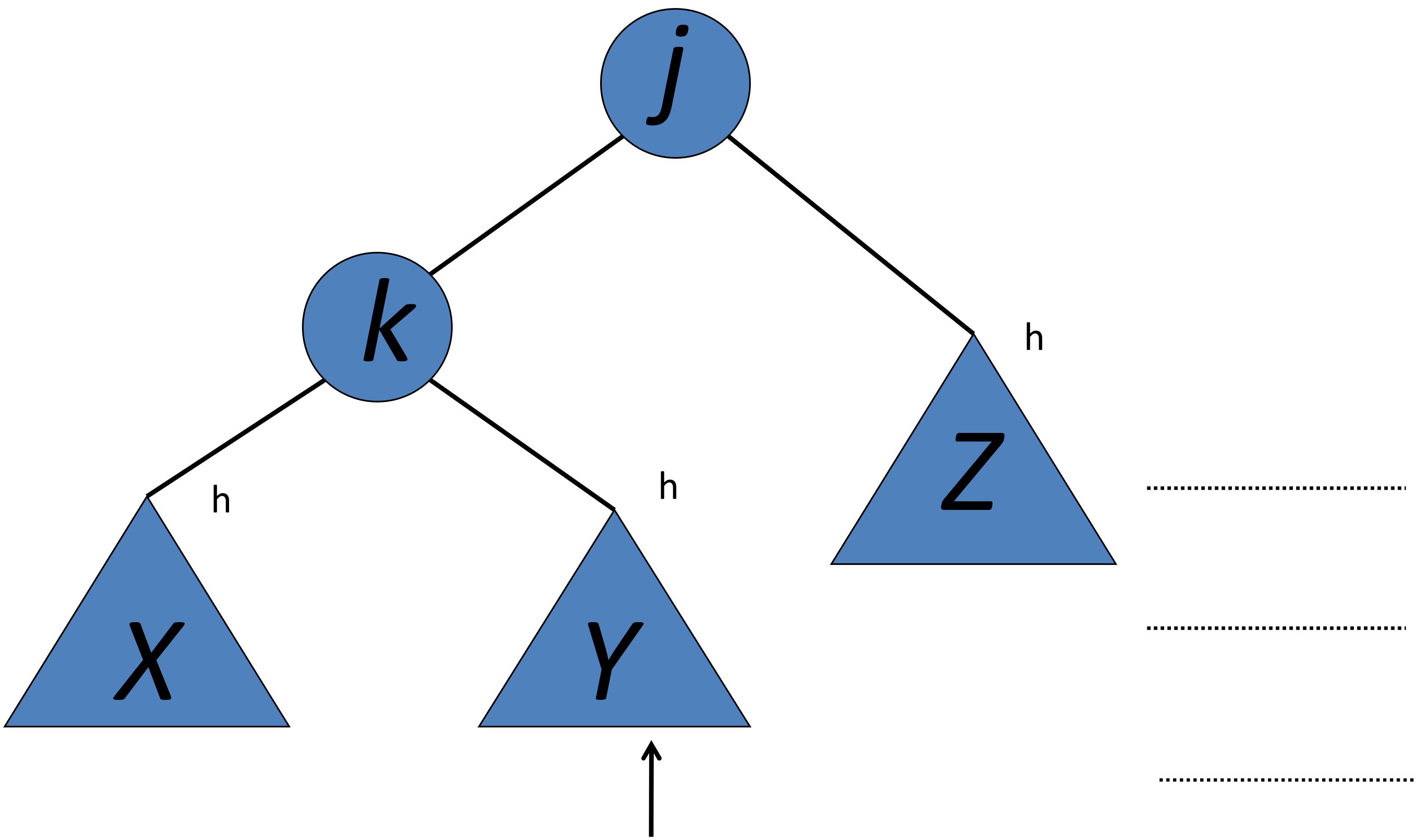
Inside Case

Right subtree of left child



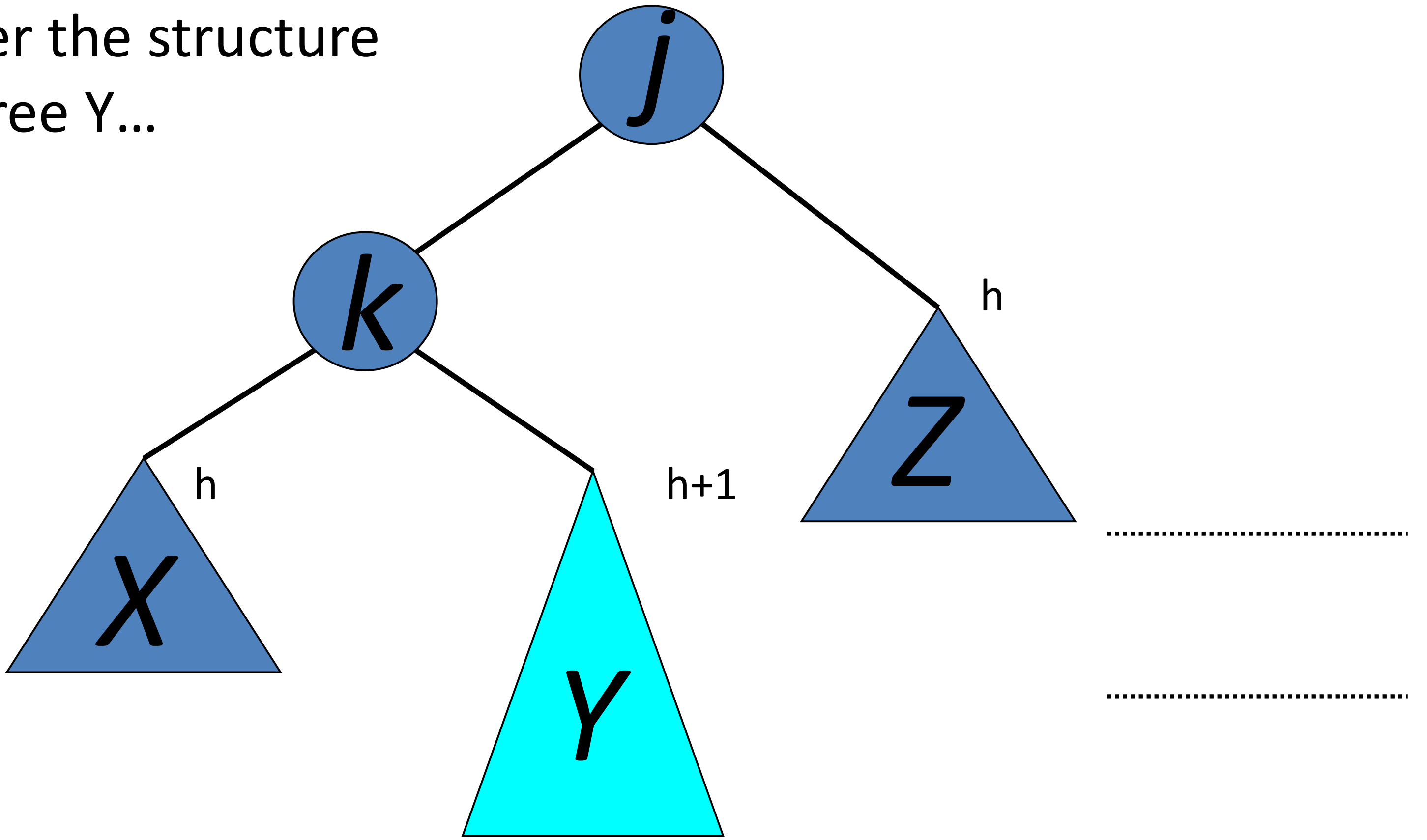
"left-right" Double Rotation

Inside Case Recap

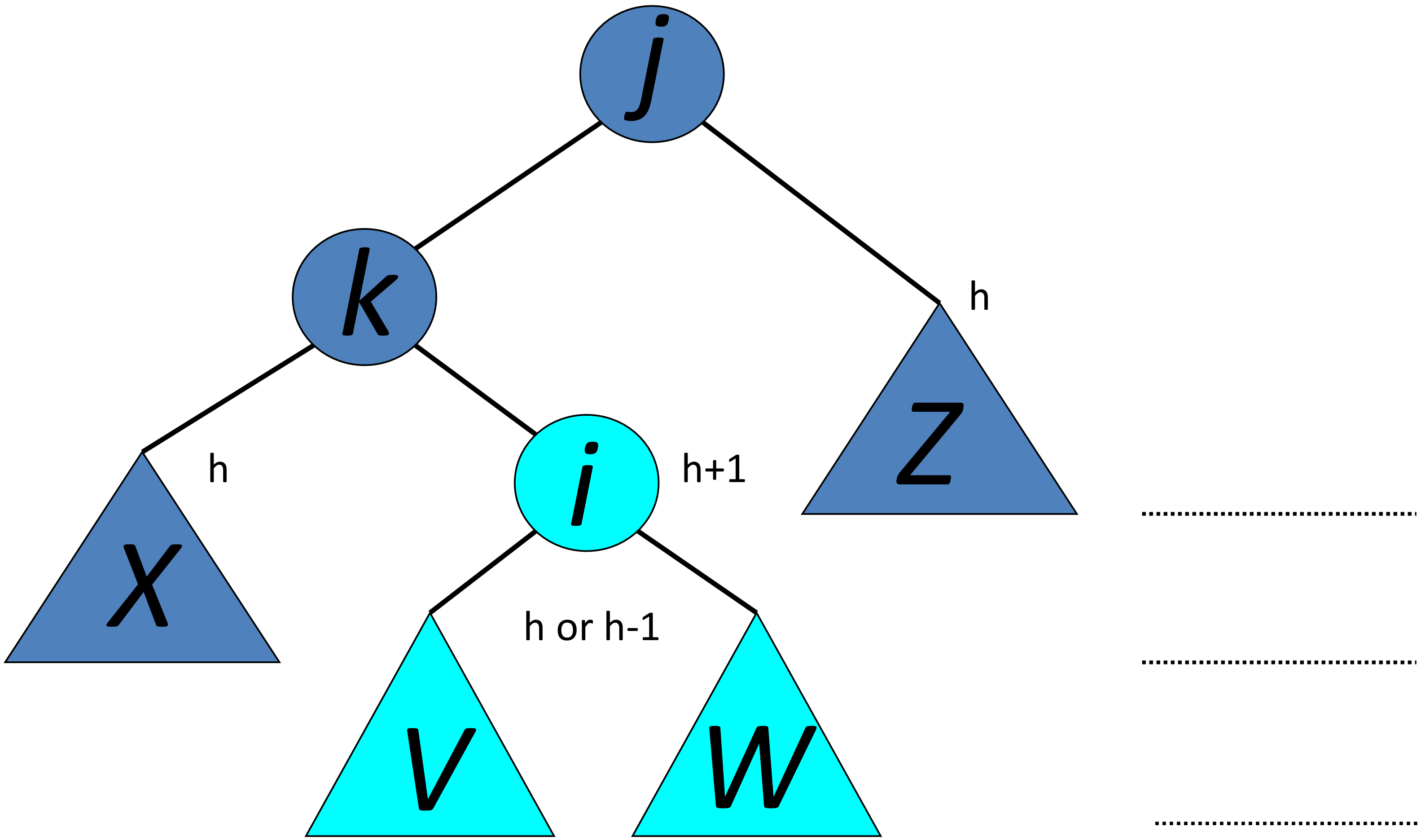


AVL Insertion: Inside Case

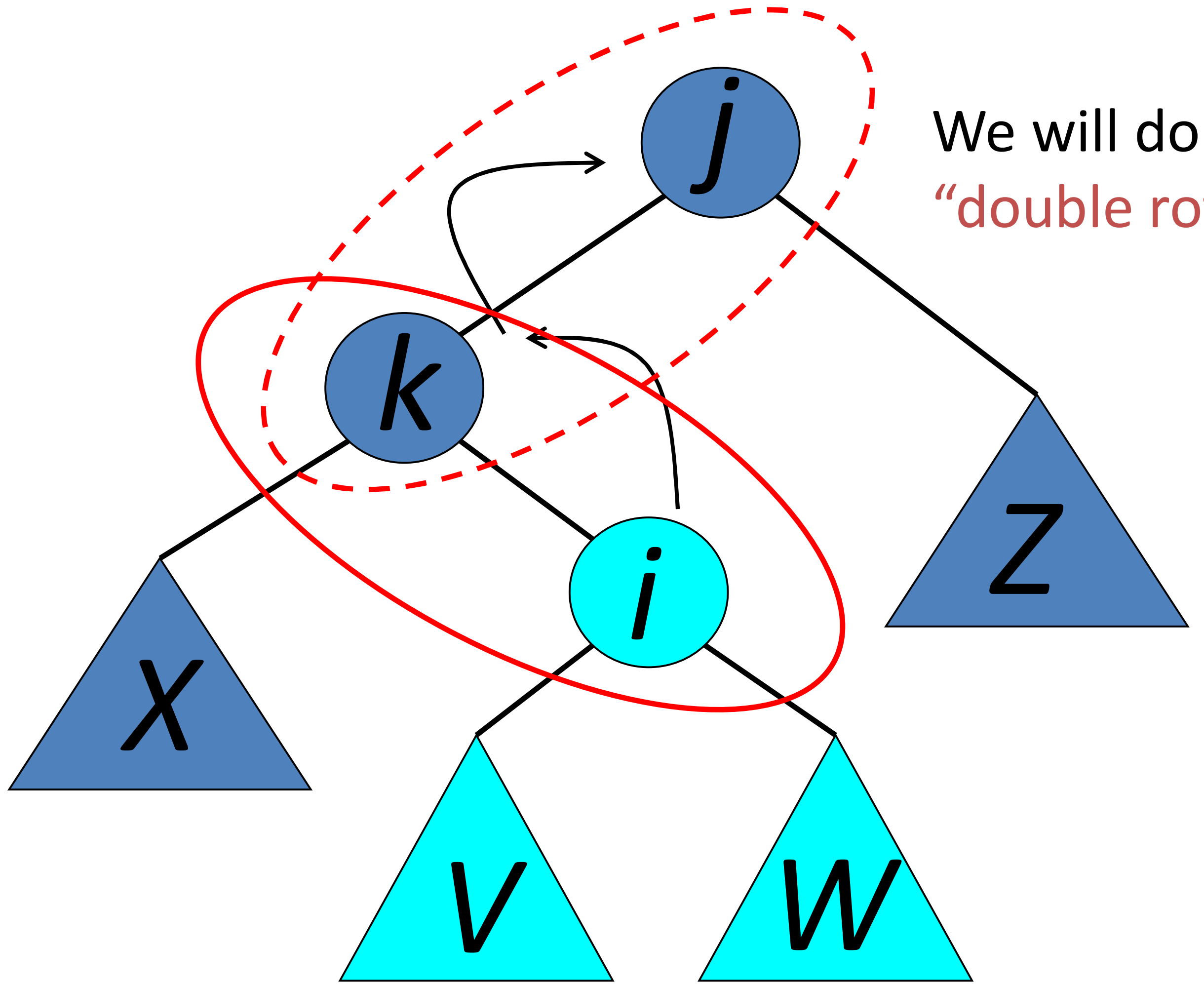
Consider the structure of subtree Y…



AVL Insertion: Inside Case



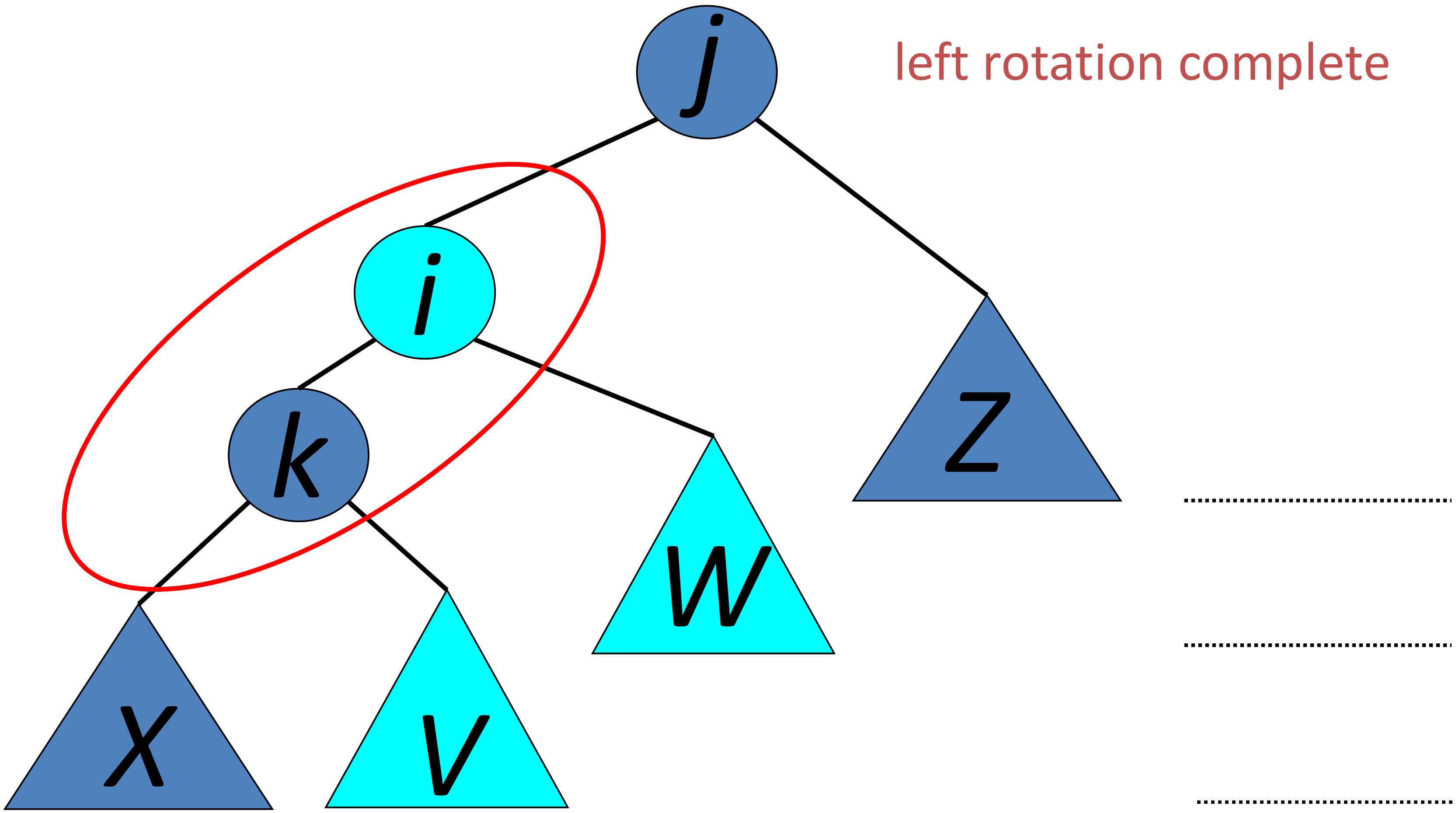
AVL Insertion: Inside Case



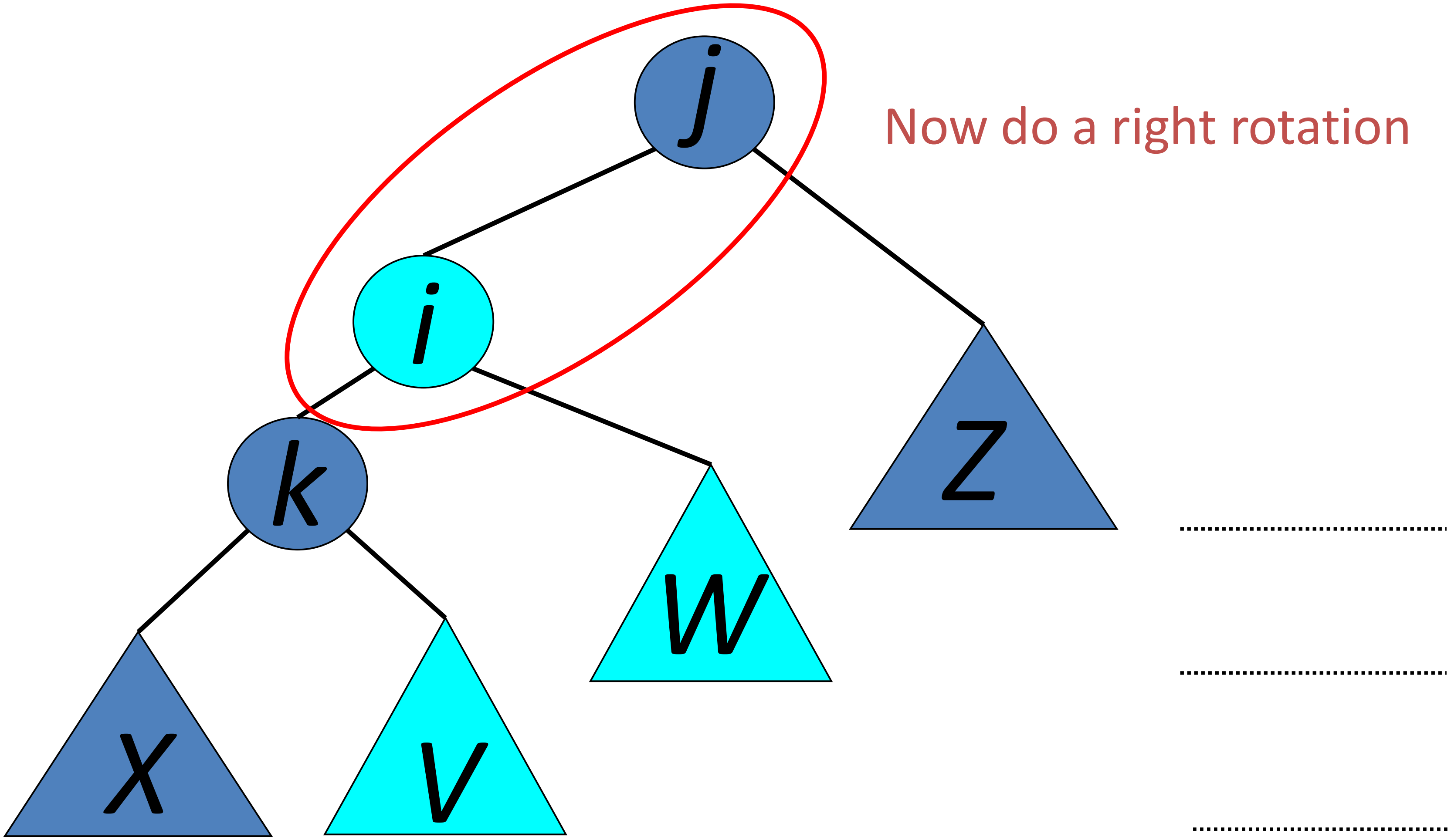
We will do a left-right "double rotation" . . .

Double rotation : first rotation

left rotation complete



Double rotation : second rotation

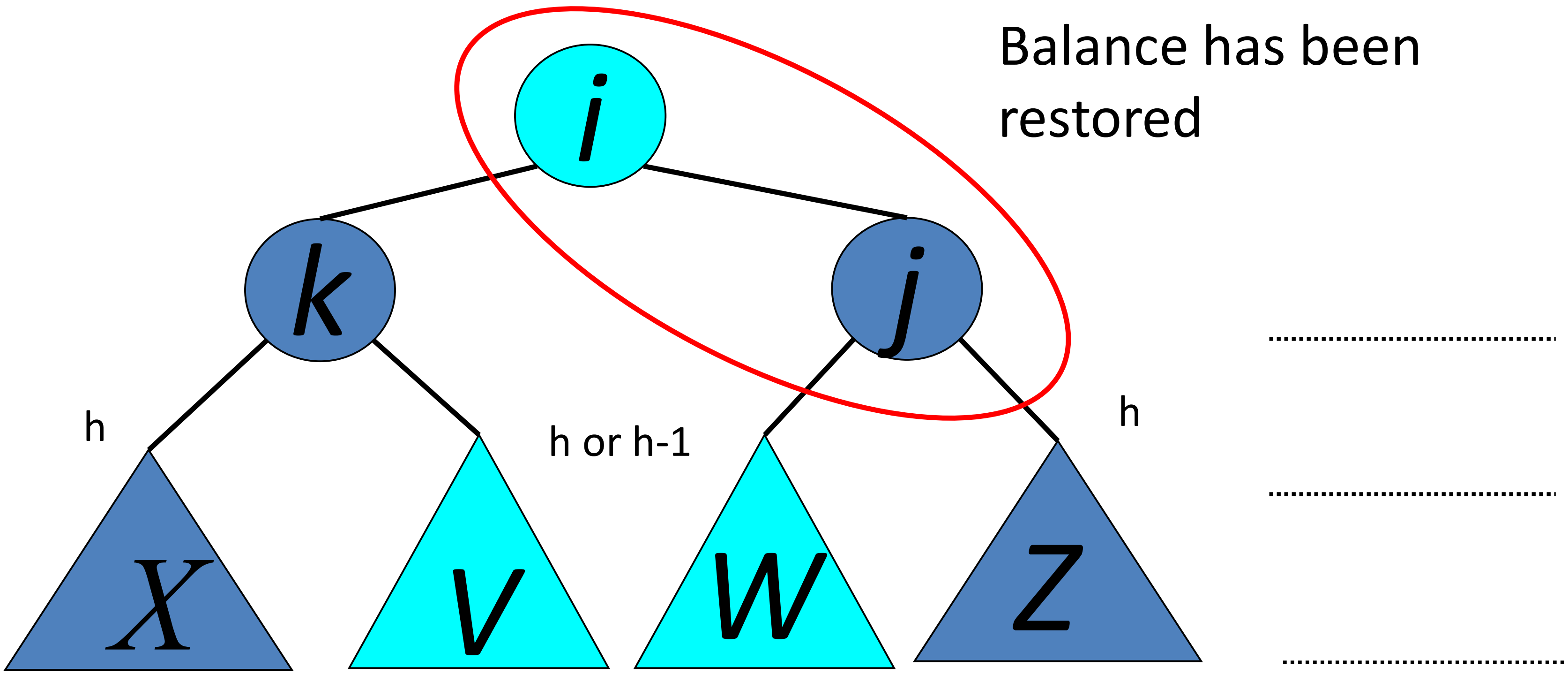


Now do a right rotation

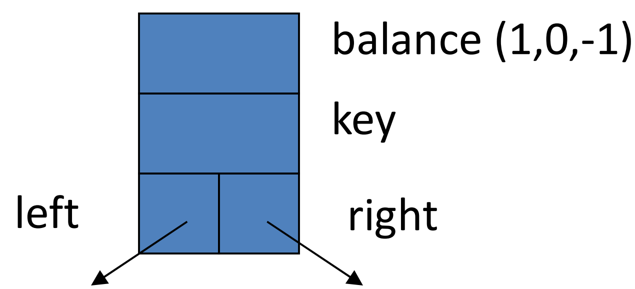
Double rotation : second rotation

right rotation complete

Balance has been restored



Implementation



No need to keep the height; just the difference in height, i.e. the balance factor; this has to be modified on the path of insertion even if you don't perform rotations

Once you have performed a rotation (single or double) you won't need to go back up the tree

Insertion in AVL Trees

- Insert at the leaf (as for all BST)
  - only nodes on the path from insertion point to root node have possibly changed in height
  - So after the Insert, go back up to the root node by node, updating heights
  - If a new balance factor (the difference h_{left}-h_{right}) is 2 or –2, adjust tree by *rotation* around the node

Correctness: Rotations preserve inorder traversal ordering

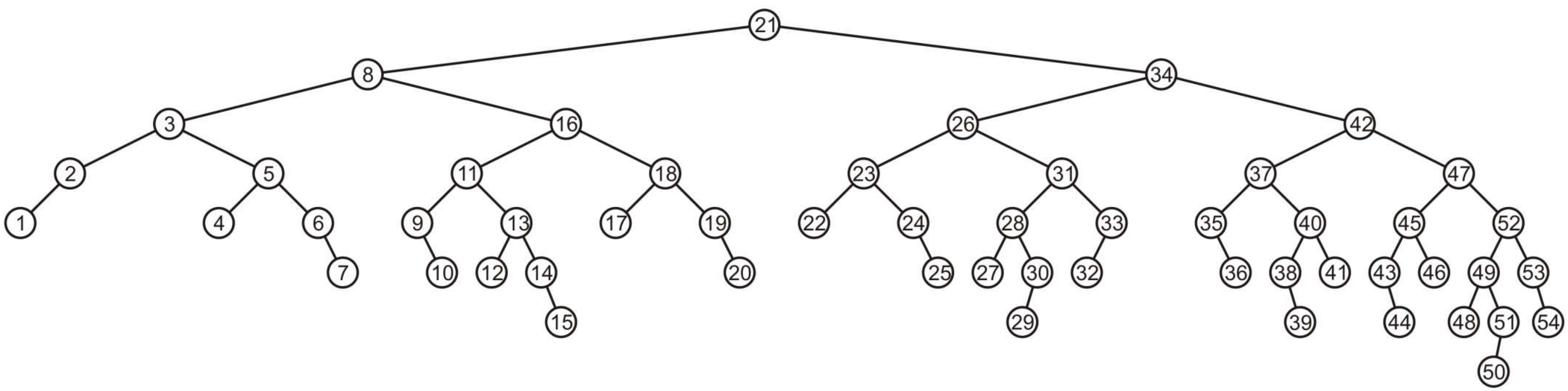
Delete

Removing a node from an AVL tree may cause more than one AVL imbalance

- Like insert, Delete must check after it has been successfully called on a child to see if it caused an imbalance
- Unfortunately, it may cause multiple imbalances that must be corrected
  - Insertions will only cause one imbalance that must be fixed

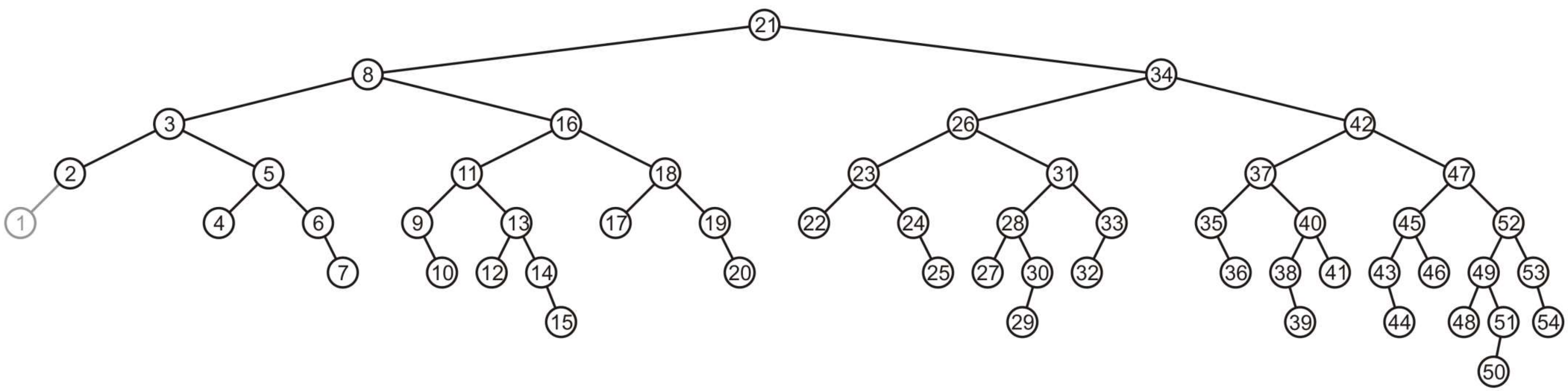
Delete

Consider the following AVL tree



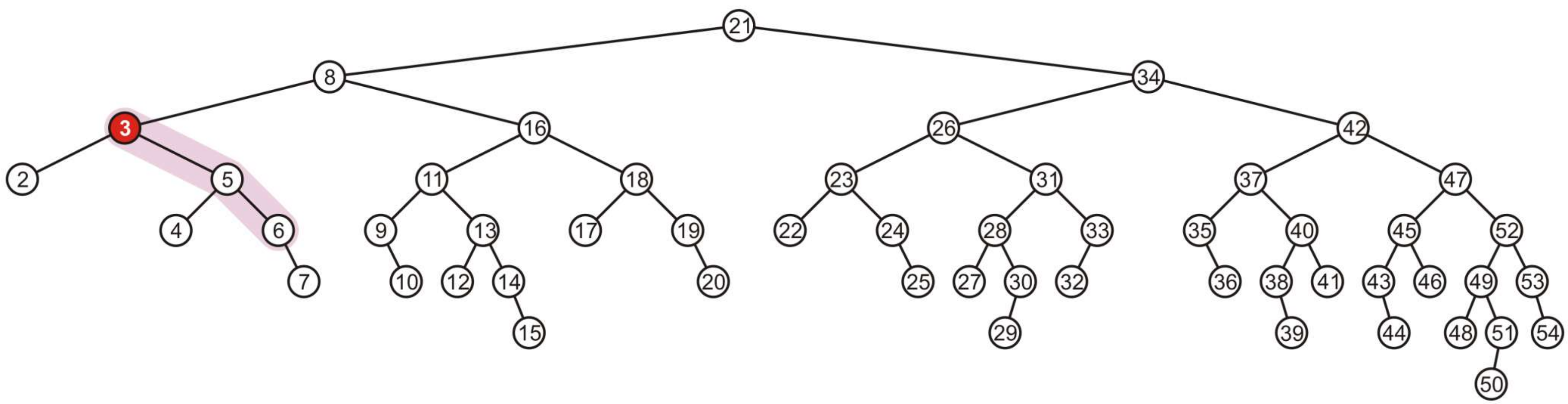
Delete

Suppose we Delete the front node: 1



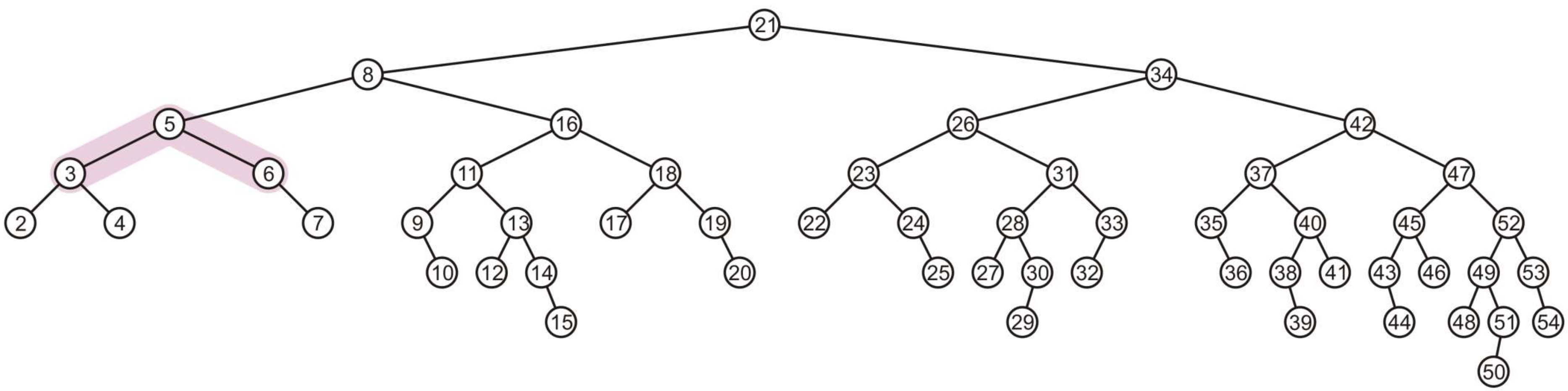
Delete

While its previous parent, 2, is not unbalanced, its grandparent 3 is



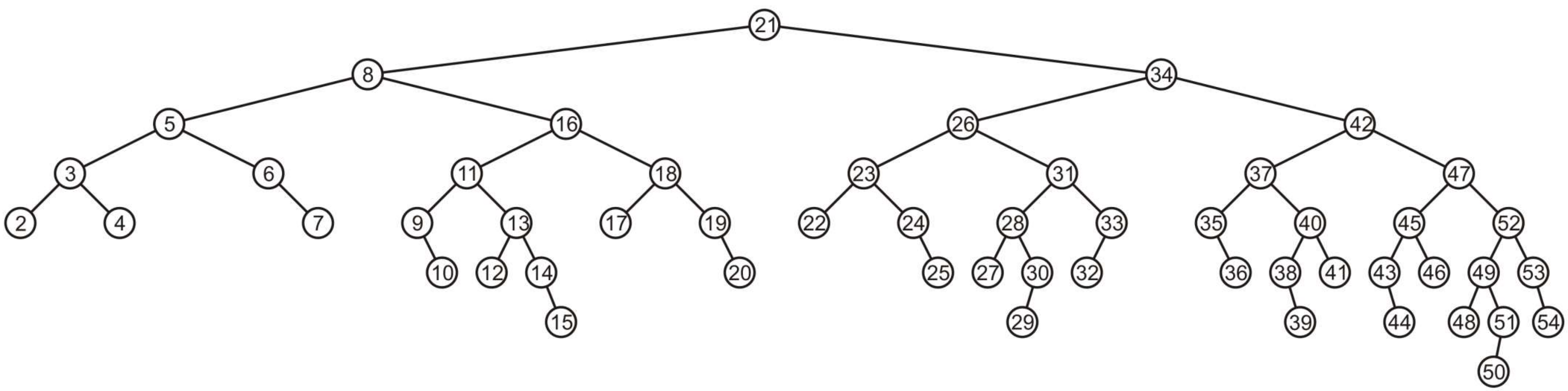
Delete

We can correct this with a simple balance



Delete

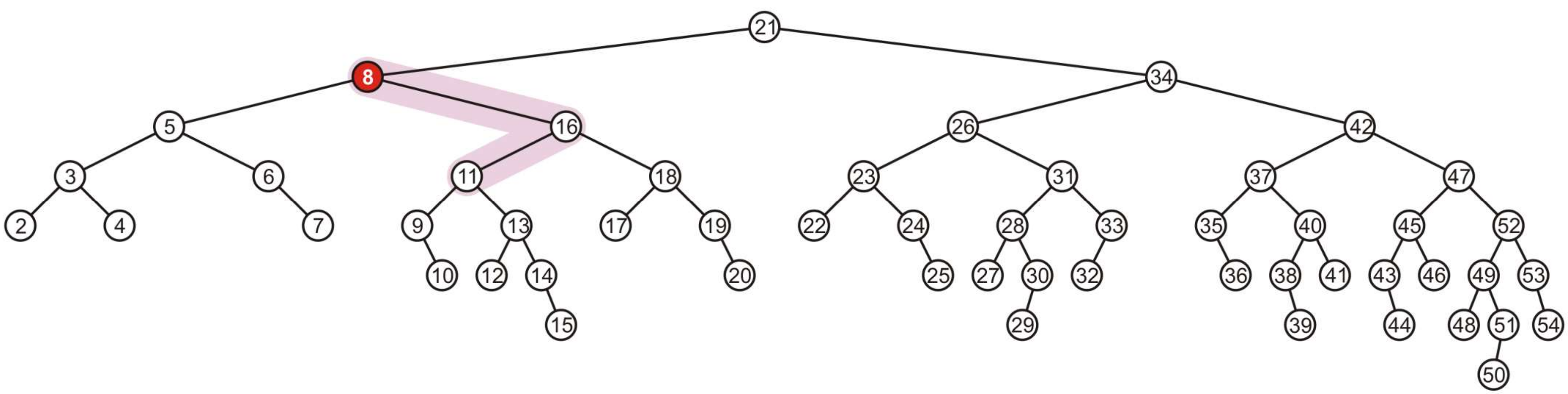
The node of that subtree, 5, is now balanced



Delete

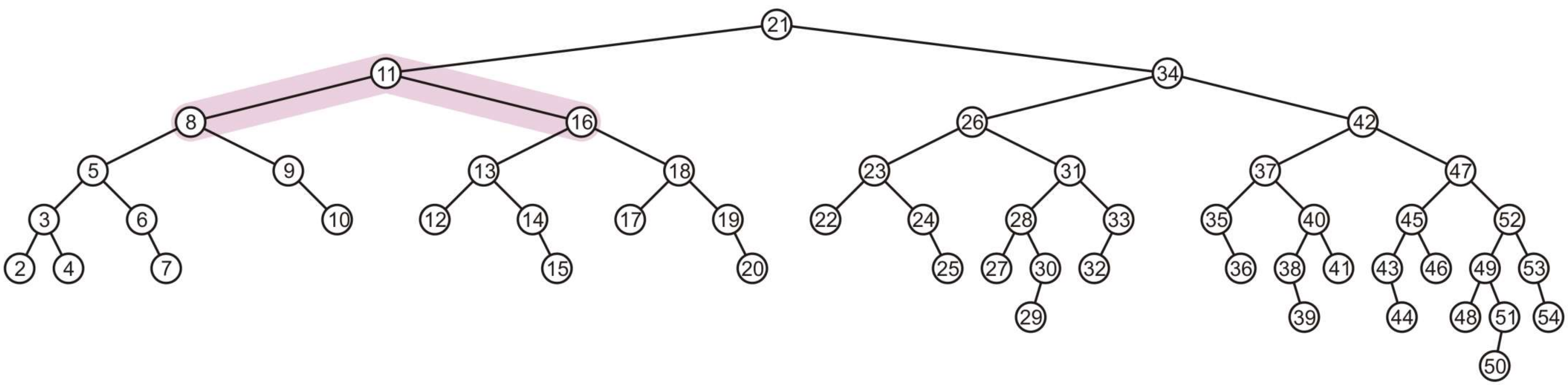
Recursing to the root, however, 8 is also unbalanced

– This is a right-left imbalance



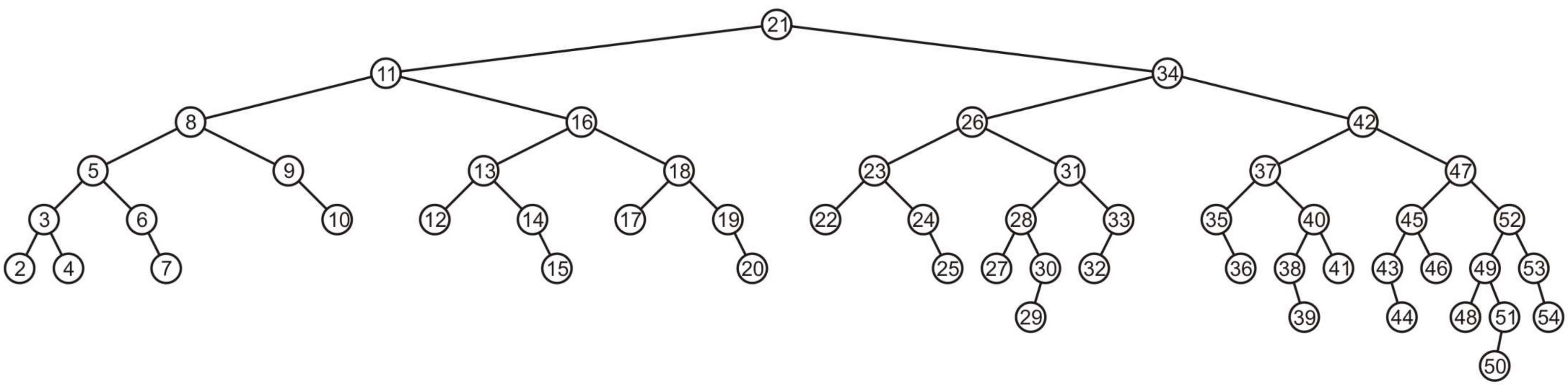
Delete

Promoting 11 to the root corrects the imbalance



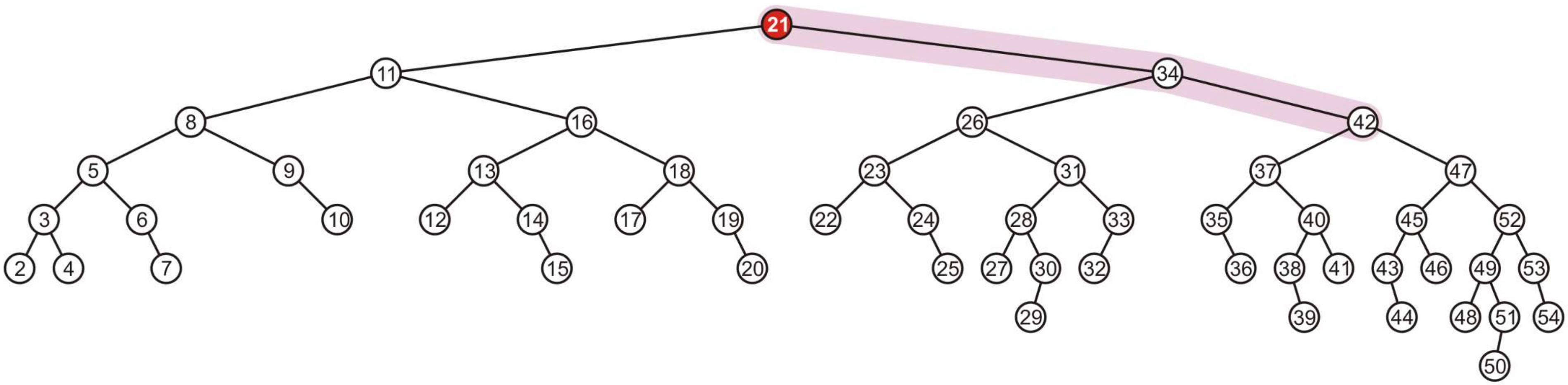
Delete

At this point, the node 11 is balanced



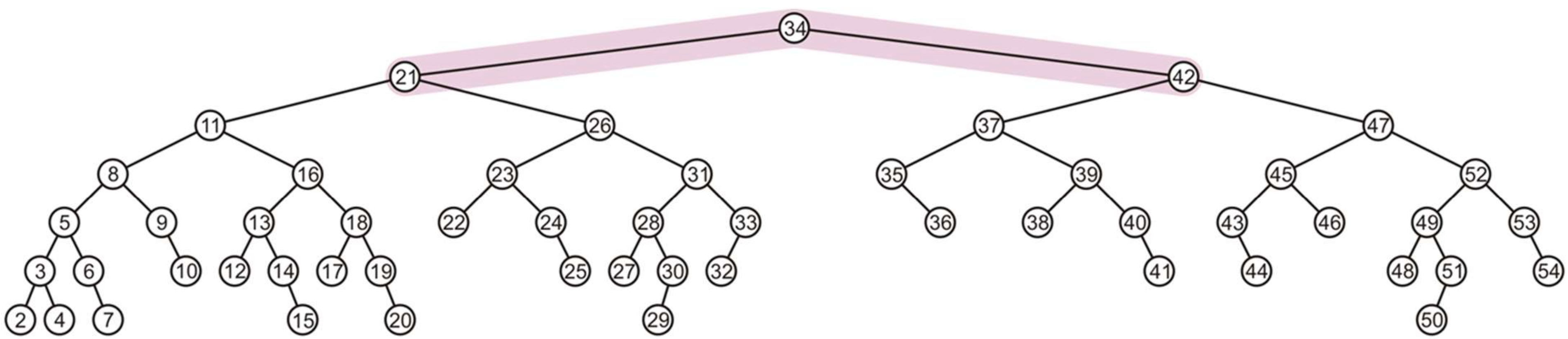
Delete

- Still, the root node is unbalanced
  – This is a right-right imbalance



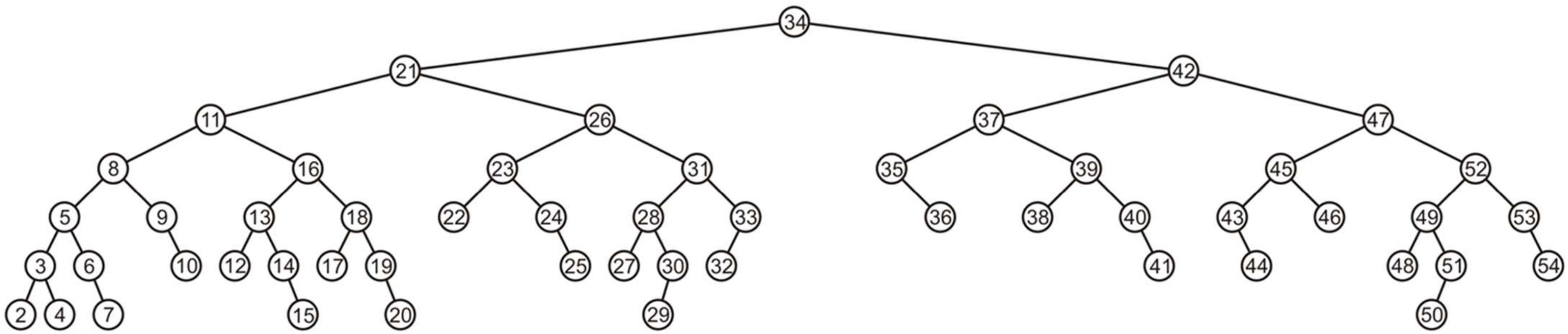
Delete

Again, a simple balance fixes the imbalance



Delete

The resulting tree is now AVL balanced



Pros and Cons of AVL Trees

Arguments for AVL trees:

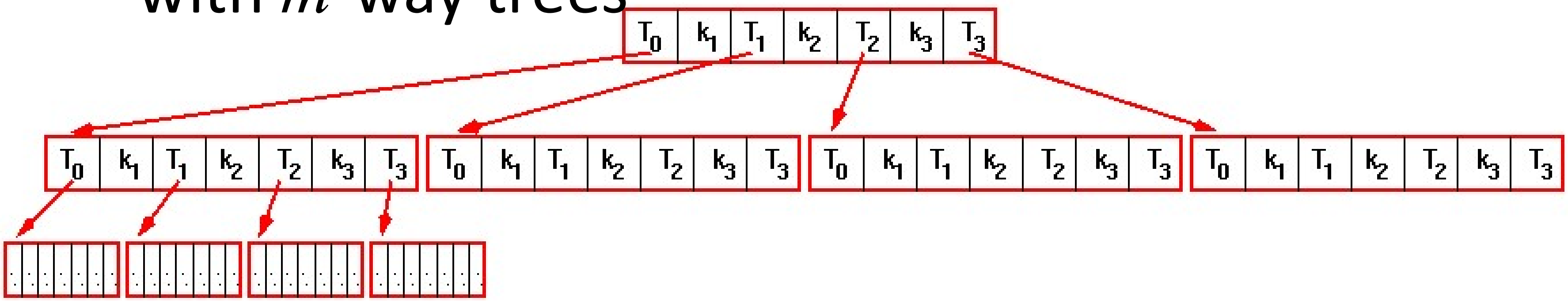
1. Search is O(log N) since AVL trees are always balanced.
2. Insertion and deletions are also O(logn)
3. The height balancing adds no more than a constant factor to the speed of insertion.

Arguments against using AVL trees:

1. Difficult to program & debug; more space for balance factor.
2. Asymptotically faster but rebalancing costs time.
3. Most large searches are done in database systems on disk and use other structures (e.g. B-trees).
4. May be OK to have O(N) for a single operation if total run time for many consecutive operations is fast (e.g. Splay trees).

m-way trees

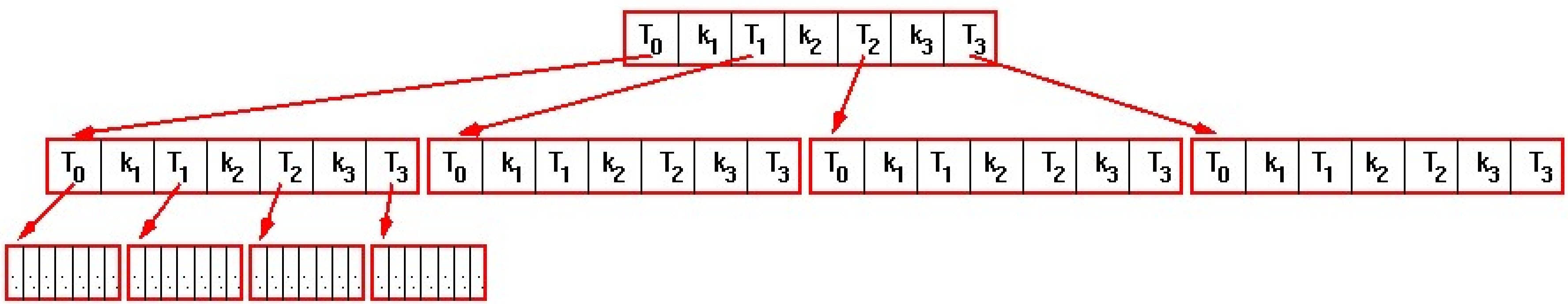
- Only two children per node?
- Reduce the depth of the tree to $O(\log_m n)$ with m-way trees



- m children, m-1 keys per node
- $m = 10$: 10^6 keys in 6 levels *vs* 20 for a binary tree
- *but* ....

m-way trees

- But you have to search through the m keys in each node!
- Reduces your gain from having fewer levels!



B-trees

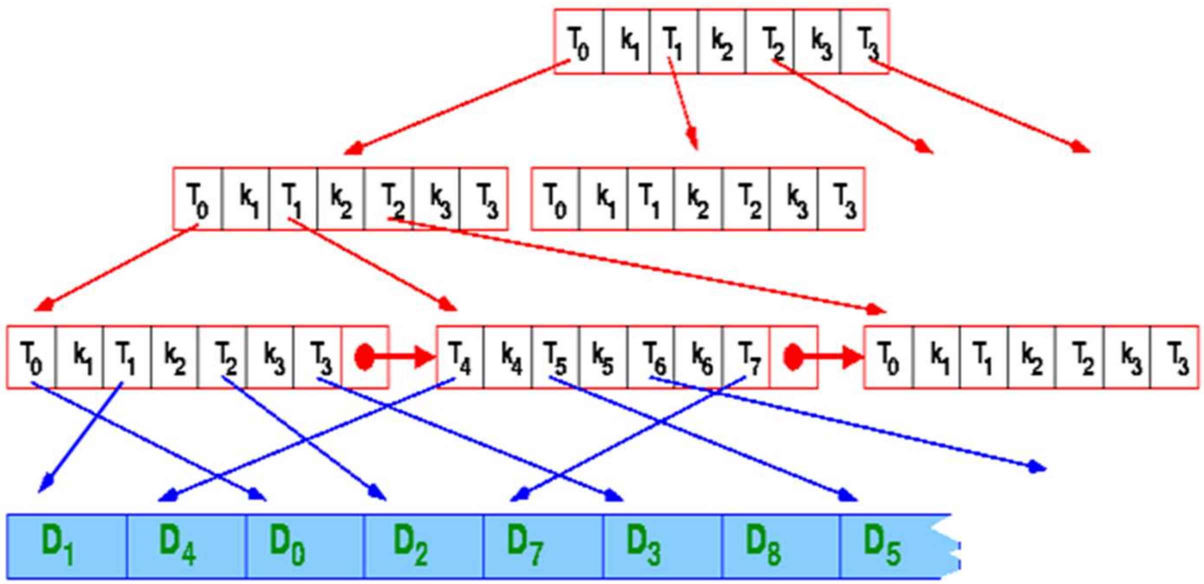
- All leaves are on the same level
- All nodes except for the root and the leaves have
  - at least $m/2$ children
  - at most m children

Each node is at least half full of keys

- B+ trees
  - All the keys in the nodes are dummies
  - Only the keys in the leaves point to “real” data
  - Linking the leaves
    - Ability to scan the collection *in order* without passing through the higher nodes

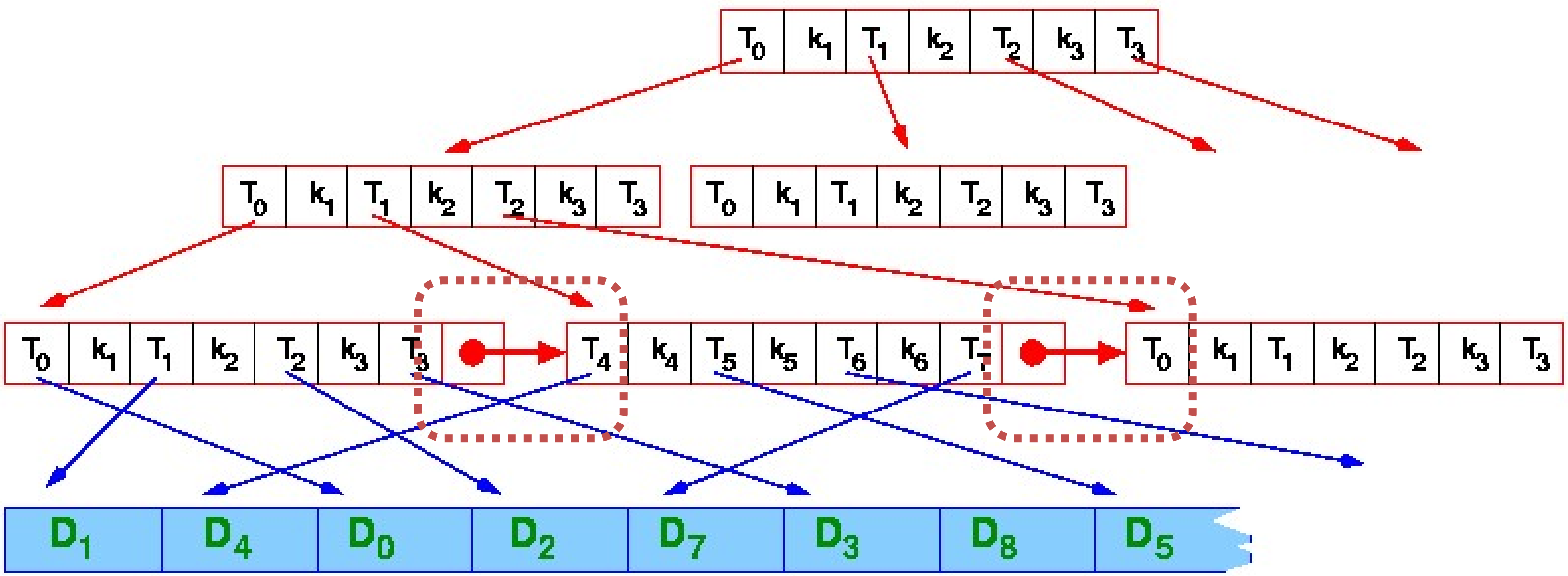
B+-trees

- B+ trees
  - All the keys in the nodes are dummies
  - Only the keys in the leaves point to “real” data
  - Data records kept in a separate area



B+-trees - Scanning in order

- B+ trees
  - – Linking the leaves
    - Ability to scan the collection *in order* without passing through the higher nodes



B+-trees - Use

- Use - Large Databases
  - Reading a disc block is *much* slower than reading memory (~ms *vs* ~ns)
  - Put each block of keys in one disc block