CS 240 – Data Structures and Data Management

Module 4: Dictionaries

A. Hunt A. Jamshidpey O. Veksler

Based on lecture notes by many previous cs240 instructors

David R. Cheriton School of Computer Science, University of Waterloo

Winter 2023

version *2023-01-31 14:59*

Outline

4 Dictionaries and Balanced Search Trees
- ADT Dictionary
- Review: Binary Search Trees
- AVL Trees
- Insertion in AVL Trees
- Restoring the AVL Property: Rotations

Outline

4 Dictionaries and Balanced Search Trees
- ADT Dictionary
- Review: Binary Search Trees
- AVL Trees
- Insertion in AVL Trees
- Restoring the AVL Property: Rotations

Dictionary ADT

Dictionary: An ADT consisting of a collection of items, each of which contains

- a *key*
- some *data* (the "value")

and is called a *key-value pair* (KVP). Keys can be compared and are (typically) unique.

Operations:

- *search*(k) (also called *findElement*(k))
- *insert*(k, v) (also called *insertItem*(k, v))
- *delete*(k) (also called *removeElement*(k)))
- optional: *closestKeyBefore*, *join*, *isEmpty*, *size*, *etc.*

Examples: symbol table, license plate database

Elementary Implementations

Common assumptions:

- Dictionary has n KVPs
- Each KVP uses constant space
  (if not, the "value" could be a pointer)
- Keys can be compared in constant time

Unordered array or linked list

search $\Theta(n)$

insert $\Theta(1)$ (except array occasionally needs to resize)

delete $\Theta(n)$ (need to search)

Ordered array

search $\Theta(\log n)$ (via binary search)

insert $\Theta(n)$

delete $\Theta(n)$

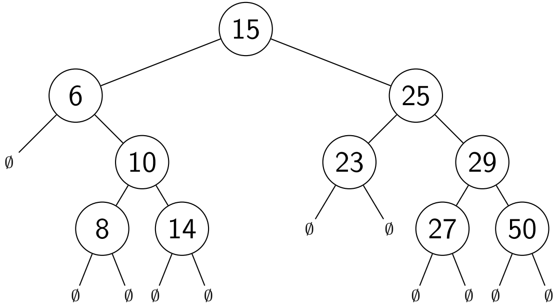
Outline

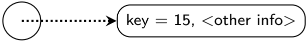
4. Dictionaries and Balanced Search Trees
   - ADT Dictionary
   - Review: Binary Search Trees
   - AVL Trees
   - Insertion in AVL Trees
   - Restoring the AVL Property: Rotations

Binary Search Trees (review)

Structure Binary tree: all nodes have two (possibly empty) subtrees
Every node stores a KVP
Empty subtrees usually not shown

Ordering Every key k in $T.left$ is less than the root key.
Every key k in $T.right$ is greater than the root key.

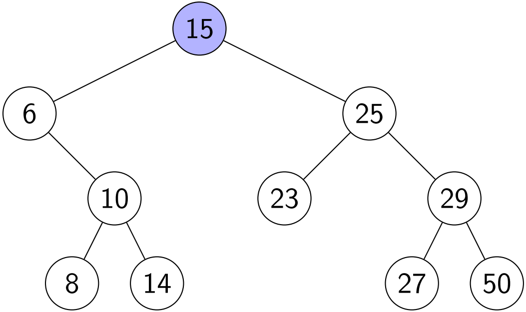


(In our examples we only show the keys, and we show them directly in the node. A more accurate picture would be )

BST as realization of ADT Dictionary

BST::search(k) Start at root, compare k to current node's key.
Stop if found or subtree is empty, else recurse at subtree.

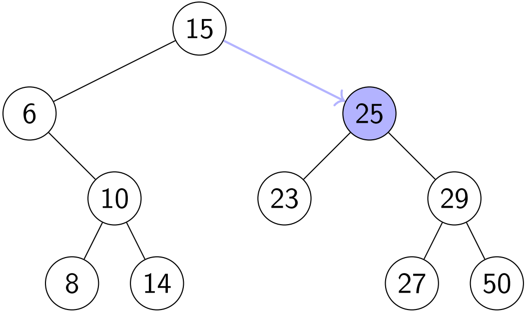
Example: *BST::search*(24)



BST as realization of ADT Dictionary

BST::search(k) Start at root, compare k to current node's key.
Stop if found or subtree is empty, else recurse at subtree.

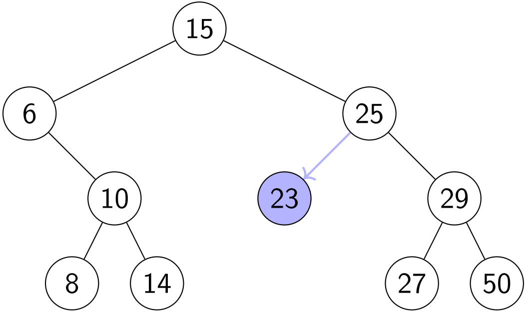
Example: *BST::search*(24)



BST as realization of ADT Dictionary

BST::search(k) Start at root, compare k to current node's key.
Stop if found or subtree is empty, else recurse at subtree.

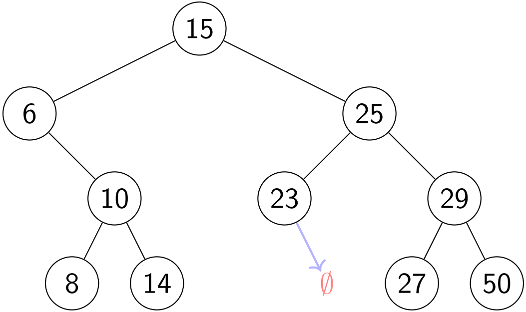
Example: *BST::search*(24)



BST as realization of ADT Dictionary

BST::search(k) Start at root, compare k to current node's key.
Stop if found or subtree is empty, else recurse at subtree.

Example: *BST::search*(24)

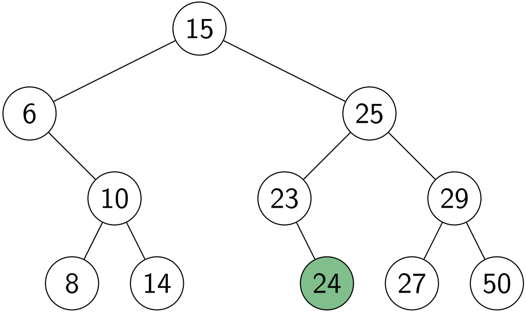


BST as realization of ADT Dictionary

BST::search(k) Start at root, compare k to current node's key.
Stop if found or subtree is empty, else recurse at subtree.

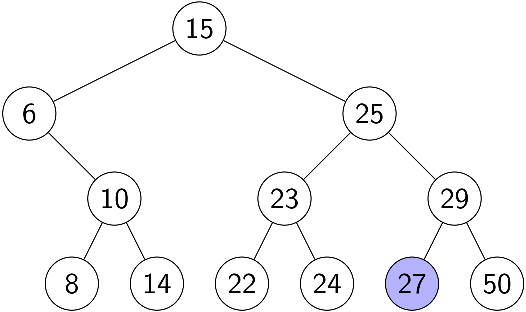
BST::insert(k, v) Search for k, then insert (k, v) as new node

Example: *BST::insert*$(24, v)$



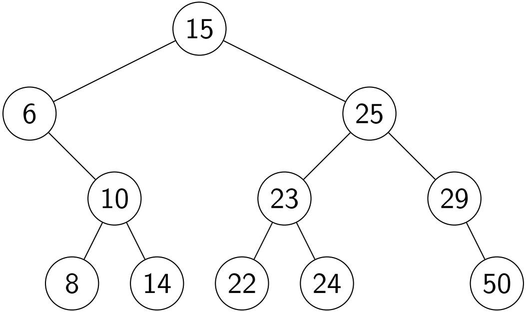
Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.



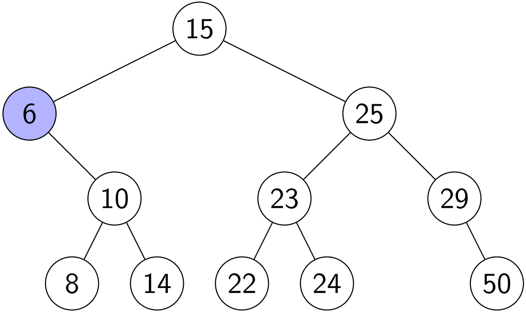
Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.



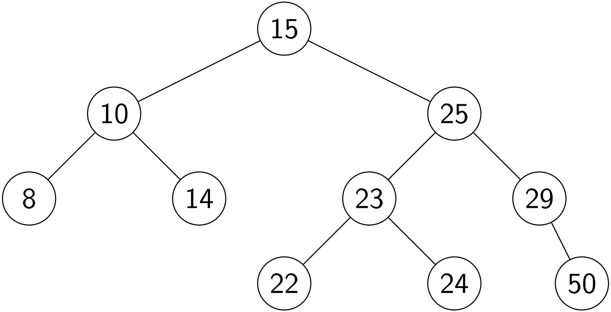
Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.
- If x has one non-empty subtree, move child up



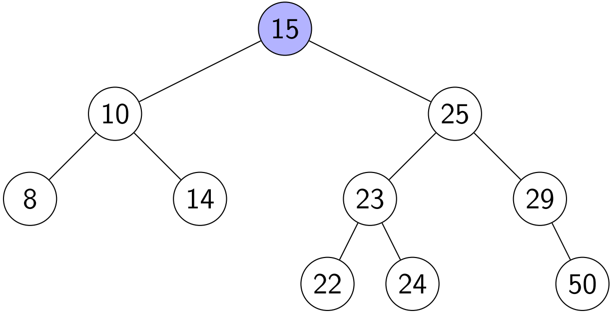
Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.
- If x has one non-empty subtree, move child up



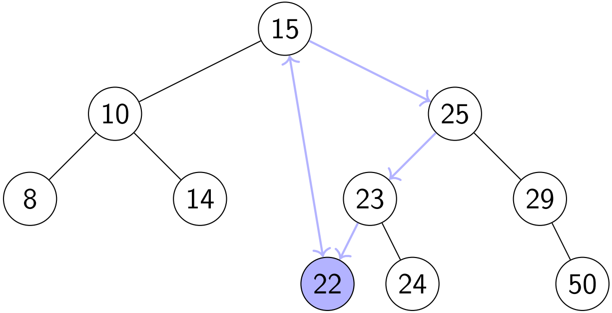
Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.
- If x has one non-empty subtree, move child up
- Else, swap key at x with key at **successor** or **predecessor** node and then delete that node



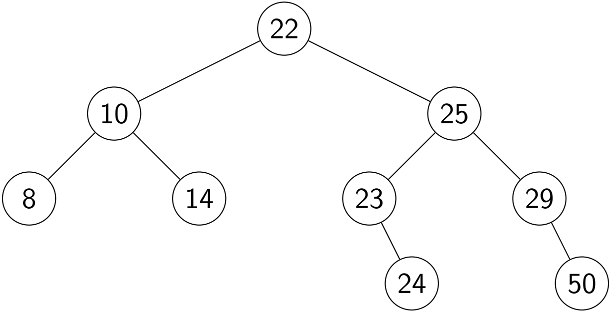
Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.
- If x has one non-empty subtree, move child up
- Else, swap key at x with key at **successor** or **predecessor** node and then delete that node



Deletion in a BST

- First search for the node x that contains the key.
- If x is a **leaf** (both subtrees are empty), delete it.
- If x has one non-empty subtree, move child up
- Else, swap key at x with key at **successor** or **predecessor** node and then delete that node



Height of a BST

BST::search, *BST::insert*, *BST::delete* all have cost $\Theta(h)$, where
$h =$ height of the tree $=$ max. path length from root to leaf

If n items are inserted one-at-a-time, how big is h?

- Worst-case:

Height of a BST

BST::search, *BST::insert*, *BST::delete* all have cost $\Theta(h)$, where
$h =$ height of the tree $=$ max. path length from root to leaf

If n items are inserted one-at-a-time, how big is h?

- Worst-case: $n - 1 = \Theta(n)$
- Best-case:

Height of a BST

BST::search, *BST::insert*, *BST::delete* all have cost $\Theta(h)$, where
$h =$ height of the tree $=$ max. path length from root to leaf

If n items are inserted one-at-a-time, how big is h?

- Worst-case: $n - 1 = \Theta(n)$
- Best-case: $\Theta(\log n)$.
  Any binary tree with n nodes has height $\geq \log(n+1) - 1$
- Average-case:

Height of a BST

BST::search, *BST::insert*, *BST::delete* all have cost $\Theta(h)$, where
h = height of the tree = max. path length from root to leaf

If n items are inserted one-at-a-time, how big is h?

- Worst-case: $n - 1 = \Theta(n)$
- Best-case: $\Theta(\log n)$.
  Any binary tree with n nodes has height $\geq \log(n+1) - 1$
- Average-case: Can show $\Theta(\log n)$

Outline

AVL Trees

Introduced by Adel'son-Vel'skiĭ and Landis in 1962, an **AVL Tree** is a BST with an additional **height-balance property** at every node:

The heights of the left and right subtree differ by at most 1.

(The height of an empty tree is defined to be -1.)

Rephrase: If node v has left subtree L and right subtree R, then

$$\textbf{balance}(v) := \mathit{height}(R) - \mathit{height}(L) \text{ must be in } \{-1, 0, 1\}$$

$\mathit{balance}(v) = -1$ means v is *left-heavy*

$\mathit{balance}(v) = +1$ means v is *right-heavy*

AVL Trees

Introduced by Adel'son-Vel'skiĭ and Landis in 1962, an **AVL Tree** is a BST with an additional **height-balance property** at every node:

The heights of the left and right subtree differ by at most 1.

(The height of an empty tree is defined to be -1.)

Rephrase: If node v has left subtree L and right subtree R, then

$$\textbf{balance}(v) := \mathit{height}(R) - \mathit{height}(L) \text{ must be in } \{-1, 0, 1\}$$

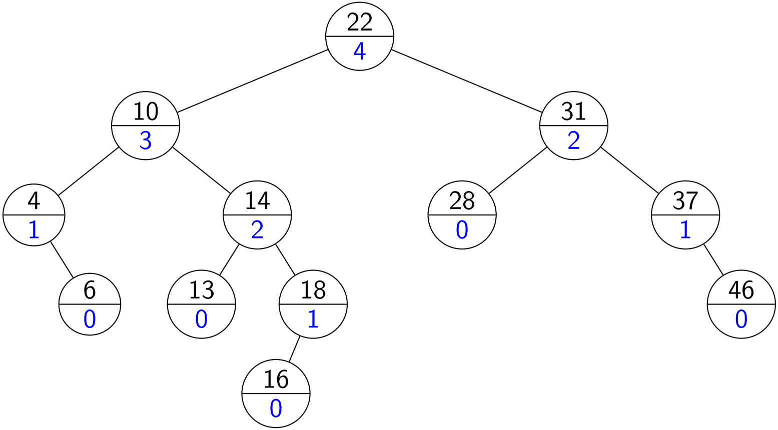
$\mathit{balance}(v) = -1$ means v is *left-heavy*

$\mathit{balance}(v) = +1$ means v is *right-heavy*

- Need to store at each node v the height of the subtree rooted at it
- Can show: It suffices to store $\mathit{balance}(v)$ instead
  - uses fewer bits, but code gets more complicated

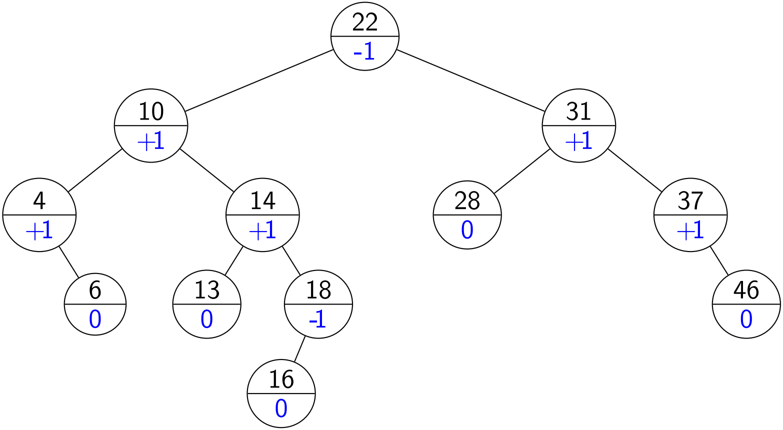
AVL tree example

(The lower numbers indicate the height of the subtree.)



AVL tree example

Alternative: store balance (instead of height) at each node.



Height of an AVL tree

Theorem: An AVL tree on n nodes has $\Theta(\log n)$ height.
$\Rightarrow$ *search*, *insert*, *delete* all cost $\Theta(\log n)$ in the *worst case!*

Proof:

- Define $N(h)$ to be the *least* number of nodes in a height-h AVL tree.
- What is a recurrence relation for $N(h)$?
- What does this recurrence relation resolve to?

Outline

4 Dictionaries and Balanced Search Trees
- ADT Dictionary
- Review: Binary Search Trees
- AVL Trees
- Insertion in AVL Trees
- Restoring the AVL Property: Rotations

AVL insertion

To perform *AVL::insert*(k, v):

- First, insert (k, v) with the usual BST insertion.
- We assume that this returns the new leaf z where the key was stored.
- Then, move up the tree from z, updating heights.
  - We assume for this that we have parent-links. This can be avoided if *BST::Insert* returns the full path to z.
- If the height difference becomes ± 2 at node z, then z is **unbalanced**. Must re-structure the tree to rebalance.

AVL insertion

AVL::insert(k, v)

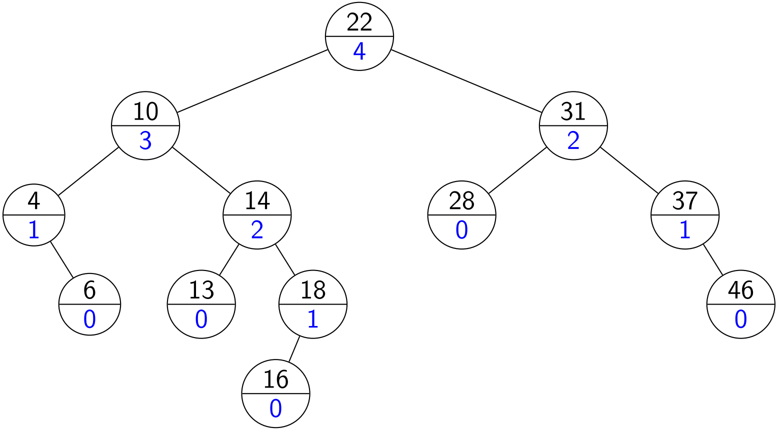
$z \leftarrow$ *BST::insert*(k, v) // leaf where k is now stored
while (z is not `NIL`)
  if $(|z.left.height - z.right.height| > 1)$ **then**
    Let y be taller child of z
    Let x be taller child of y
    $z \leftarrow$ *restructure*(x, y, z) // see later
    break // can argue that we are done
  setHeightFromSubtrees(z)
  $z \leftarrow z.parent$

setHeightFromSubtrees(u)

$u.height \leftarrow 1 + \max\{u.left.height, u.right.height\}$

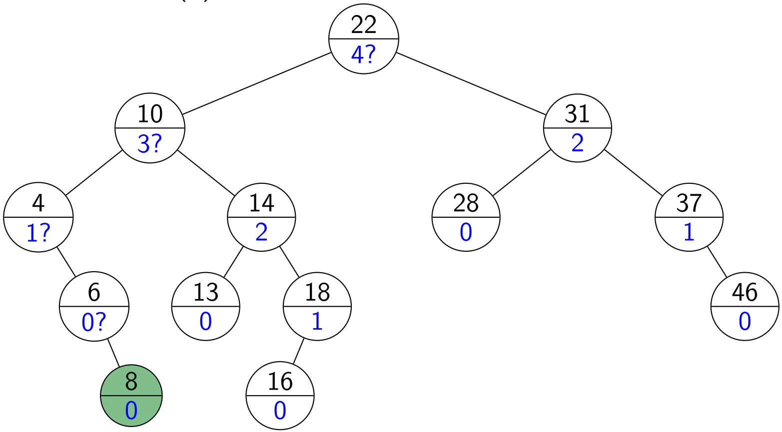
AVL Insertion Example

Example: *AVL::insert*(8)



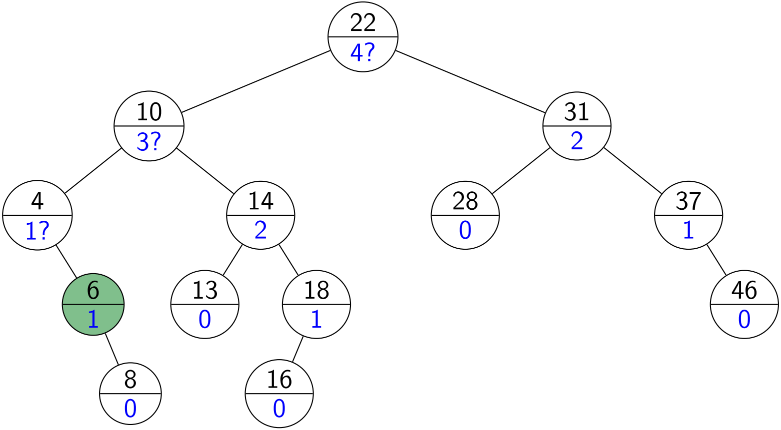
AVL Insertion Example

Example: *AVL::insert*(8)



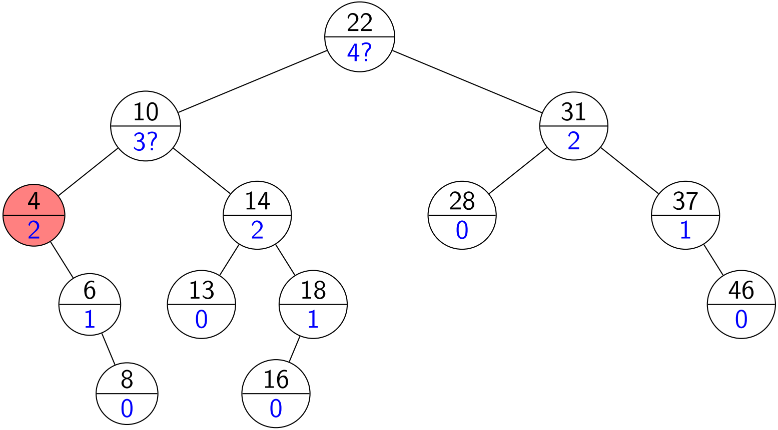
AVL Insertion Example

Example: *AVL::insert*(8)



AVL Insertion Example

Example: *AVL::insert*(8)

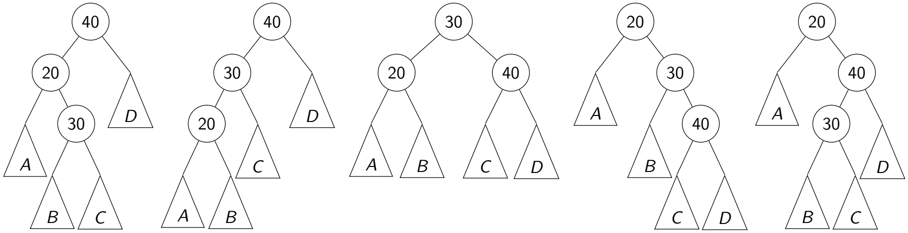


Outline

4. Dictionaries and Balanced Search Trees
   - ADT Dictionary
   - Review: Binary Search Trees
   - AVL Trees
   - Insertion in AVL Trees
   - Restoring the AVL Property: Rotations

How to "fix" an unbalanced AVL tree

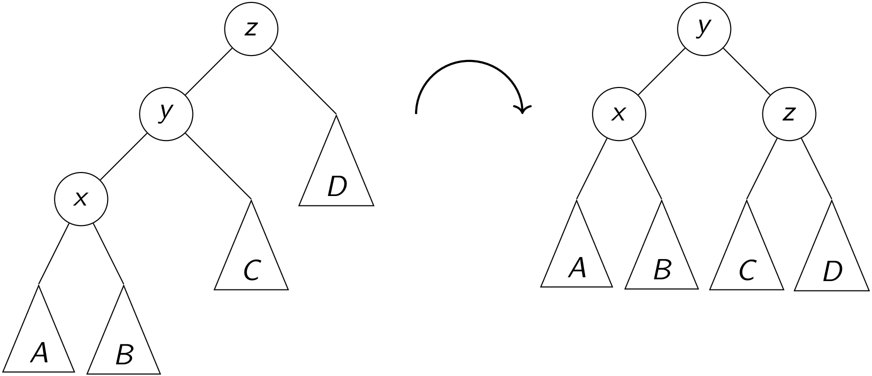
Note: there are many different BSTs with the same keys.



Goal: change the *structure* among three nodes without changing the *order* and such that the subtree becomes balanced.

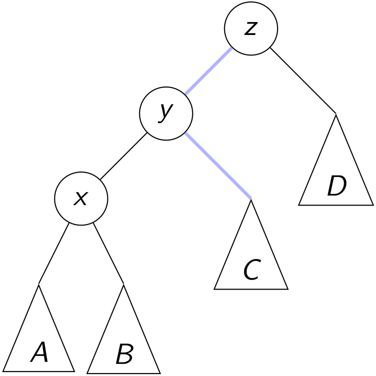
Right Rotation

This is a **right rotation** on node z:

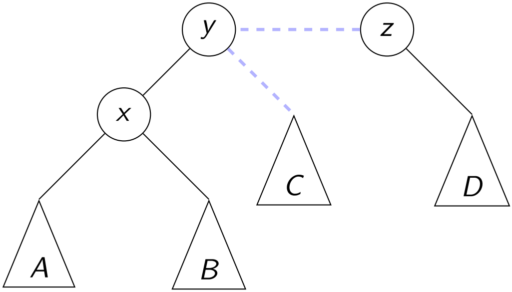


rotate-right(z)
1. $y \leftarrow z.left$, $z.left \leftarrow y.right$, $y.right \leftarrow z$
2. *setHeightFromSubtrees*(z), *setHeightFromSubtrees*(y)
3. **return** y // returns new root of subtree

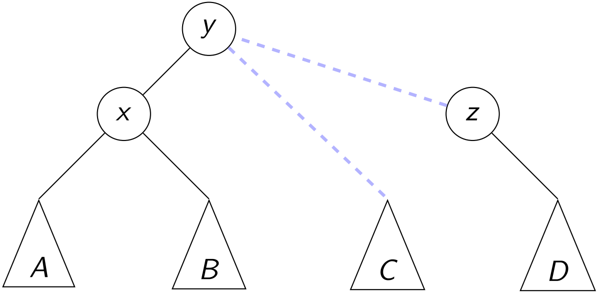
Why do we call this a rotation?



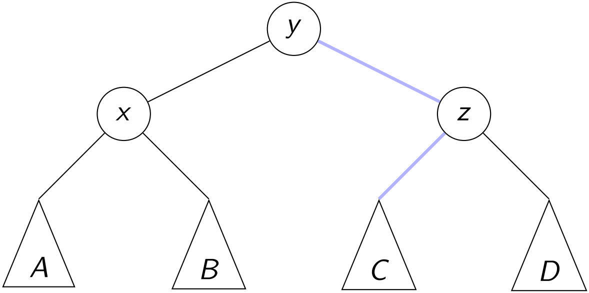
Why do we call this a rotation?



Why do we call this a rotation?

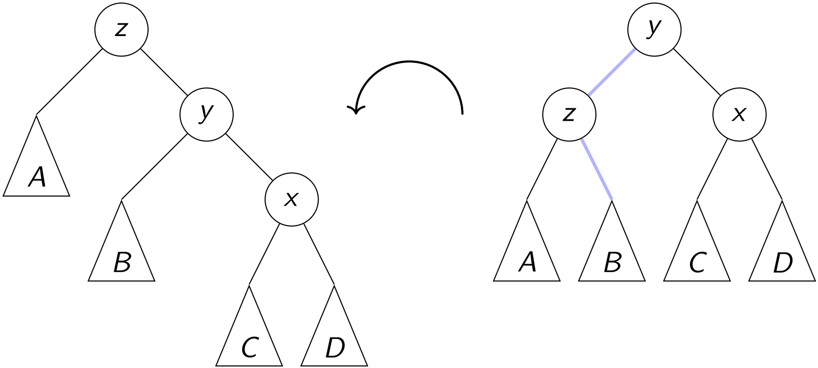


Why do we call this a rotation?



Left Rotation

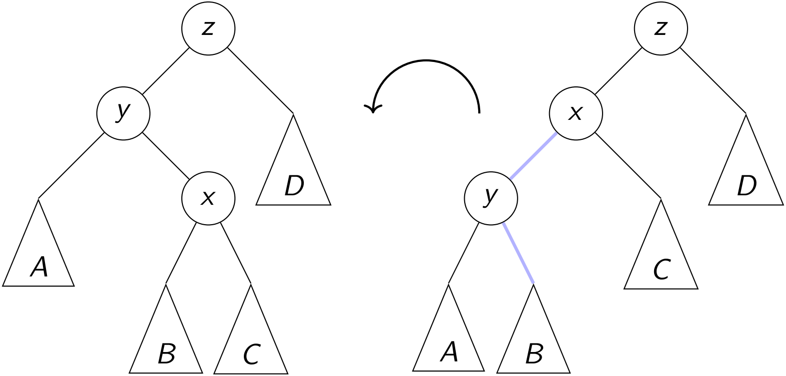
Symmetrically, this is a **left rotation** on node z:



Again, only two links need to be changed and two heights updated.
Useful to fix right-right imbalance.

Double Right Rotation

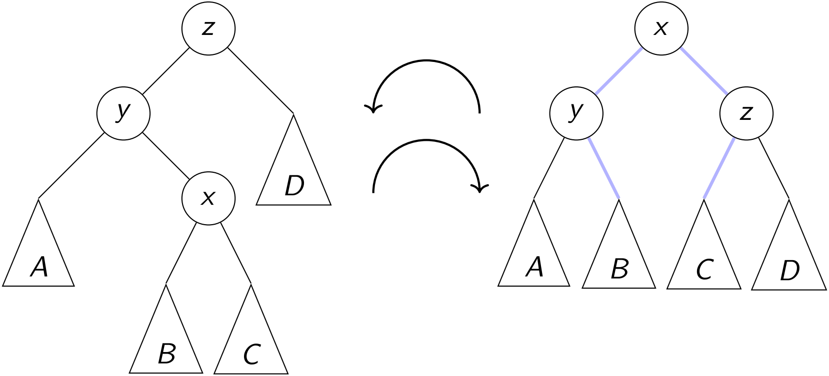
This is a **double right rotation** on node z:



First, a left rotation at y.

Double Right Rotation

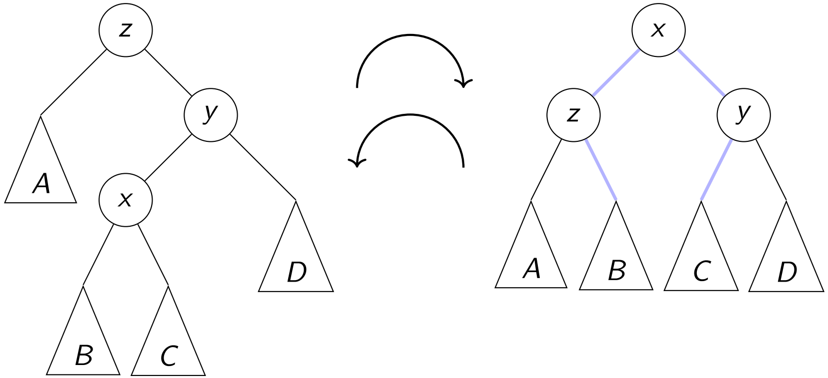
This is a **double right rotation** on node z:



First, a left rotation at y.
Second, a right rotation at z.

Double Left Rotation

Symmetrically, there is a **double left rotation** on node z:

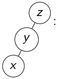


First, a right rotation at y.
Second, a left rotation at z.

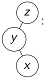
Fixing a slightly-unbalanced AVL tree

restructure(x, y, z)
node x has parent y and grandparent z

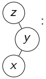
1. **case**



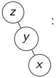
: // Right rotation
return *rotate-right*(z)



: // Double-right rotation
z.left ← *rotate-left*(y)
return *rotate-right*(z)



: // Double-left rotation
z.right ← *rotate-right*(y)
return *rotate-left*(z)

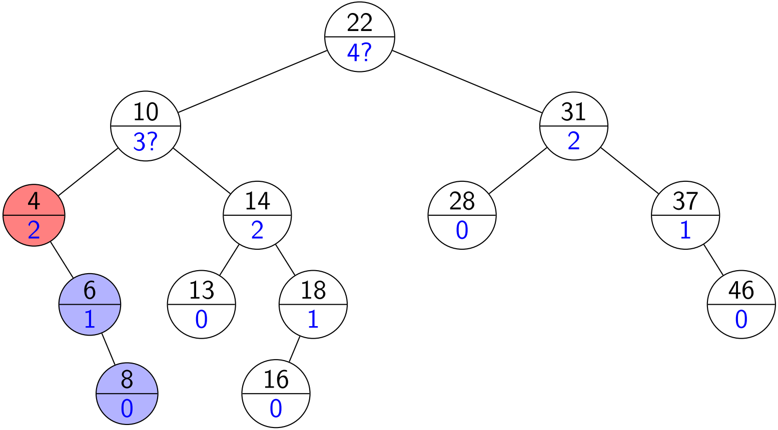


: // Left rotation
return *rotate-left*(z)

Rule: The middle key of x, y, z becomes the new root.

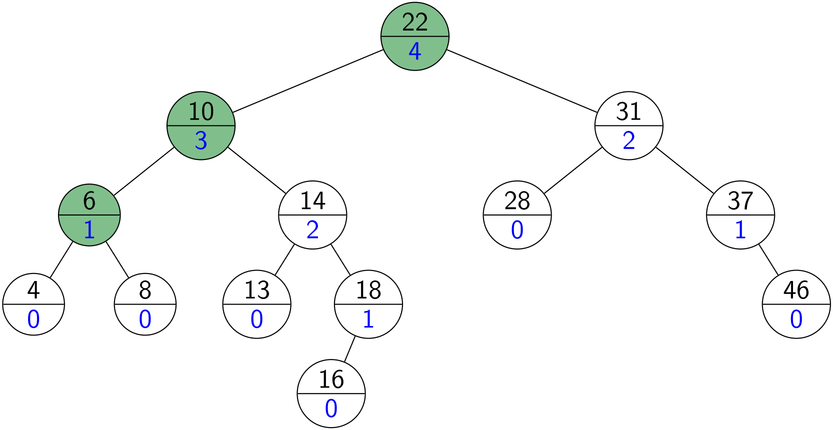
AVL Insertion Example revisited

Example: *AVL::insert*(8)



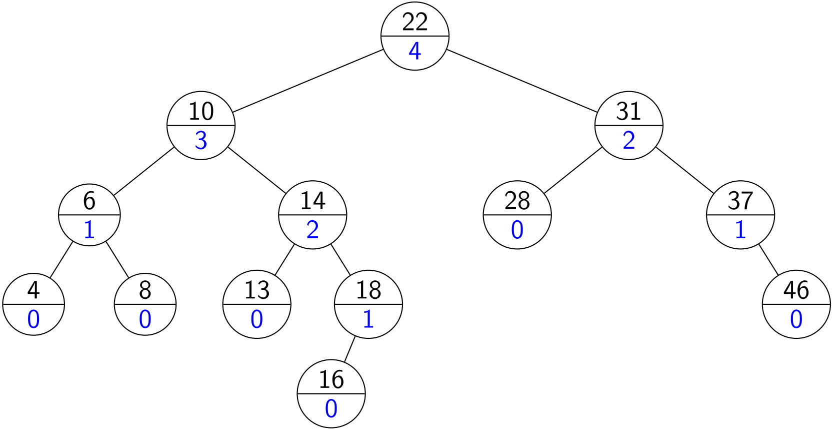
AVL Insertion Example revisited

Example: *AVL::insert*(8)



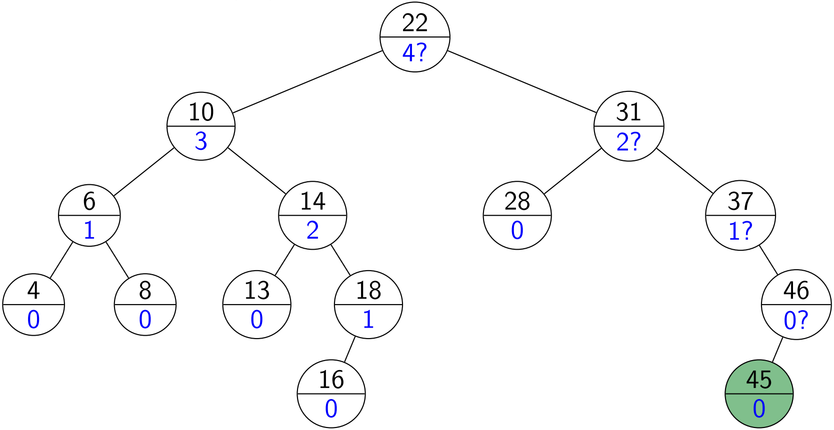
AVL Insertion: Second example

Example: *AVL::insert*(45)



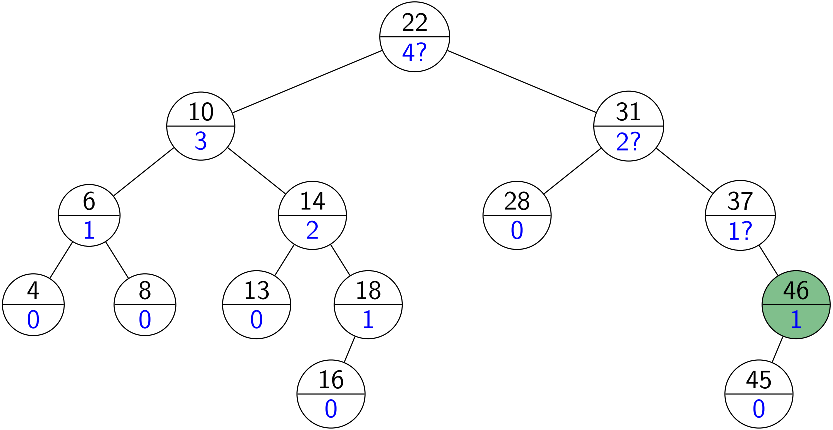
AVL Insertion: Second example

Example: *AVL::insert*(45)



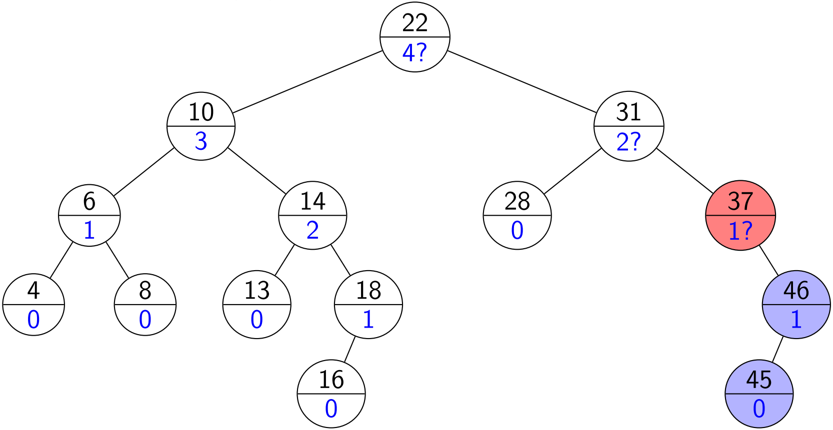
AVL Insertion: Second example

Example: *AVL::insert*(45)



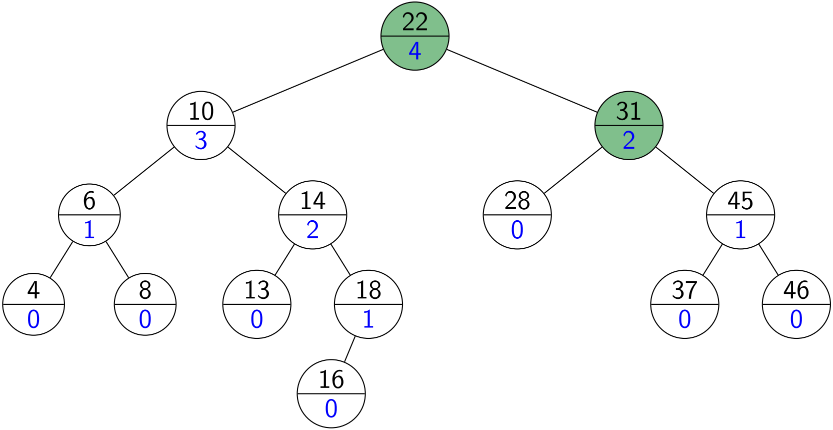
AVL Insertion: Second example

Example: *AVL::insert*(45)



AVL Insertion: Second example

Example: *AVL::insert*(45)



AVL Deletion

Remove the key k with *BST::delete*.

Find node where *structural* change happened.

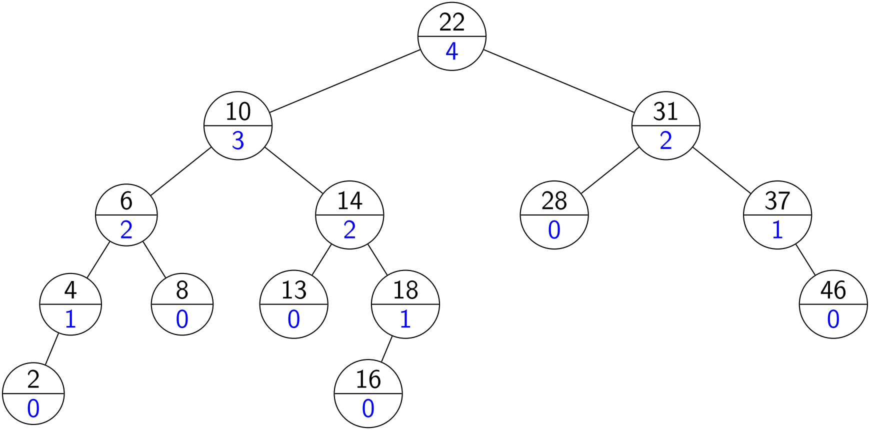
(This is not necessarily near the node that had k.)

Go back up to root, update heights, and rotate if needed.

```
AVL::delete(k)
    z ← BST::delete(k)
    // Assume z is the parent of the BST node that was removed
    while (z is not NIL)
        if (|z.left.height − z.right.height| > 1) then
            Let y be taller child of z
            Let x be taller child of y (break ties to prefer single rotation)
            z ← restructure(x, y, z)
        // Always continue up the path and fix if needed.
        setHeightFromSubtrees(z)
        z ← z.parent
```

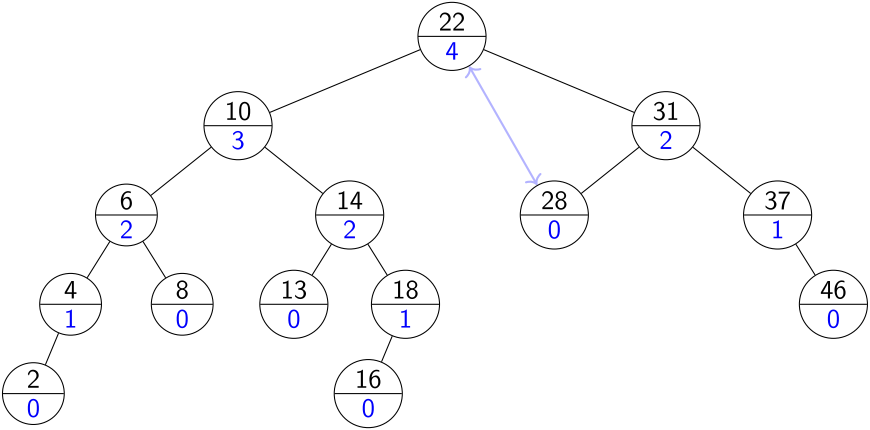
AVL Deletion Example

Example: *AVL::delete*(22)



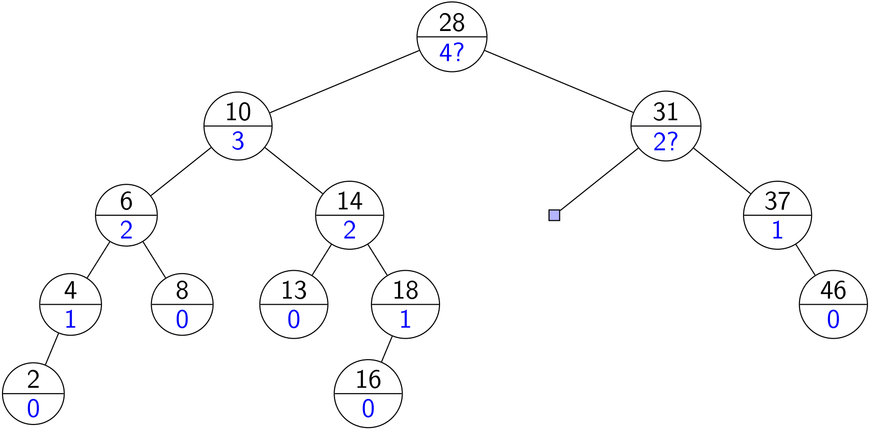
AVL Deletion Example

Example: *AVL::delete*(22)



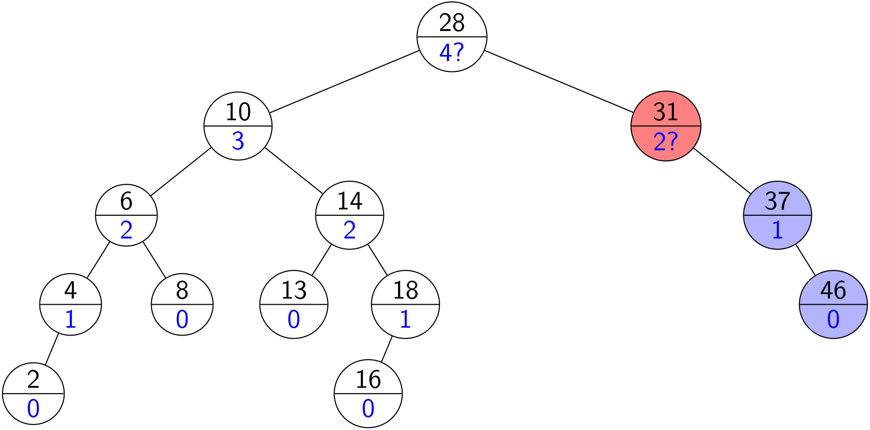
AVL Deletion Example

Example: *AVL::delete*(22)



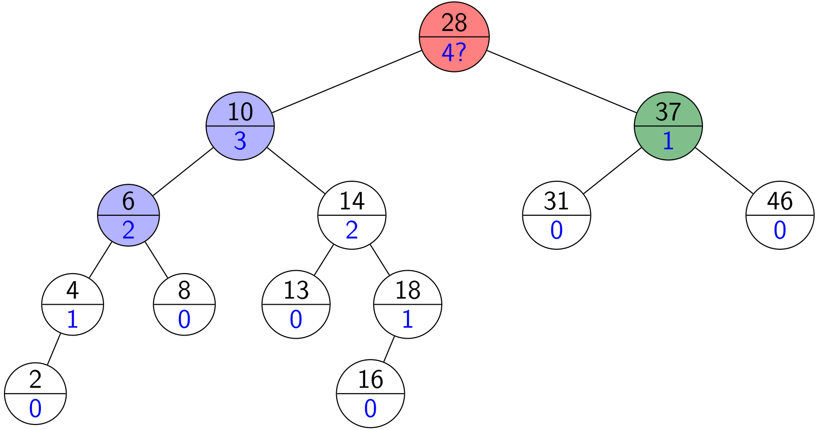
AVL Deletion Example

Example: *AVL::delete*(22)



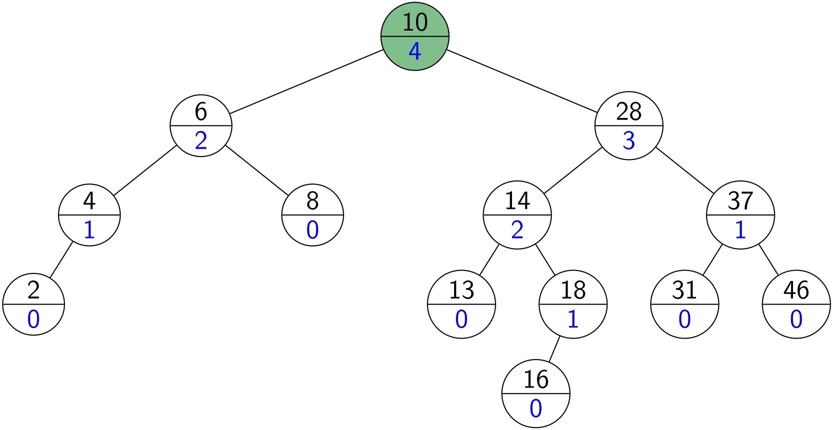
AVL Deletion Example

Example: *AVL::delete*(22)



AVL Deletion Example

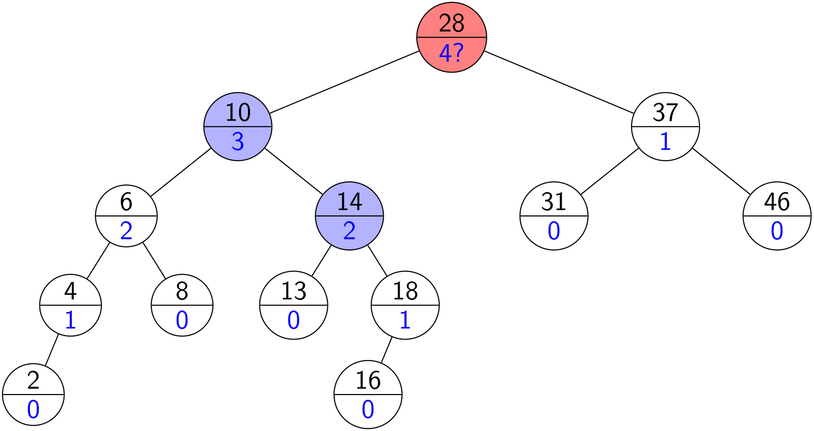
Example: *AVL::delete*(22)



AVL Deletion Example

Important: Ties *must* be broken to prefer single rotation.

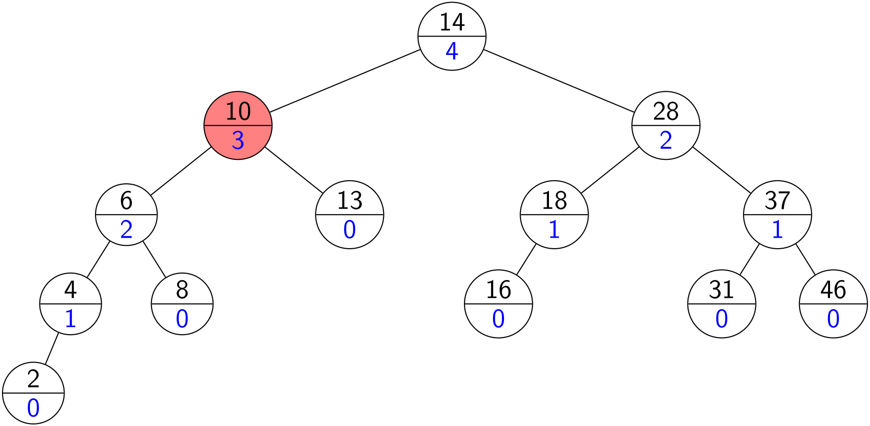
Consider again the above example. If we applied double-rotation:



AVL Deletion Example

Important: Ties *must* be broken to prefer single rotation.

Consider again the above example. If we applied double-rotation:



Resulting tree is *not* an AVL-tree.

AVL Tree Operations Runtime

search: Just like in BSTs, costs $\Theta(height)$

insert: *BST::insert*, then check & update along path to new leaf

- total cost $\Theta(height)$
- *restructure* restores the height of the subtree to what it was,
- so *restructure* will be called *at most once*.

delete: *BST::delete*, then check & update along path to deleted node

- total cost $\Theta(height)$
- *restructure* may be called $\Theta(height)$ times.

Worst-case cost for all operations is $\Theta(height) = \Theta(\log n)$.

But in practice, the constant is quite large.