Why care about advanced implementations?

Same entries, different insertion sequence:

→ Not good! Would like to keep tree balanced.
Balanced binary tree

- The disadvantage of a binary search tree is that its height can be as large as N-1.
- This means that the time needed to perform insertion and deletion and many other operations can be O(N) in the worst case.
- We want a tree with small height.
- A binary tree with N node has height at least $\Theta(\log N)$.
- Thus, our goal is to keep the height of a binary search tree O(log N).
- Such trees are called balanced binary search trees. Examples are AVL tree, and red-black tree.

Approaches to balancing trees

- Don't balance
  - May end up with some nodes very deep
- Strict balance
  - The tree must always be balanced perfectly
- Pretty good balance
  - Only allow a little out of balance
- Adjust on access
  - Self-adjusting
Balancing Search Trees

- Many algorithms exist for keeping search trees balanced
  - Adelson-Velskii and Landis (AVL) trees (height-balanced trees)
  - Red-black trees (black nodes balanced trees)
  - Splay trees and other self-adjusting trees
  - B-trees and other multiway search trees

Perfect Balance

- Want a complete tree after every operation
  - Each level of the tree is full except possibly in the bottom right
- This is expensive
  - For example, insert 2 and then rebuild as a complete tree
AVL - Good but not Perfect Balance

- AVL trees are height-balanced binary search trees
- **Balance factor** of a node
  - height(left subtree) - height(right subtree)
- An AVL tree has balance factor calculated at every node
  - For every node, heights of left and right subtree can differ by no more than 1
  - Store current heights in each node

Height of an AVL Tree

- \( N(h) = \text{minimum number of nodes in an AVL tree of height } h. \)
- **Basic case:**
  - \( N(0) = 1, N(1) = 2 \)
- **Inductive case:**
  - \( N(h) = N(h-1) + N(h-2) + 1 \)
- **Theorem** (from Fibonacci analysis)
  - \( N(h) \geq \phi^h \)
  - where \( \phi \approx 1.618 \), the golden ratio.
Height of an AVL Tree

- $N(h) > \phi^h$ ($\phi \approx 1.618$)
- Suppose we have $n$ nodes in an AVL tree of height $h$.
  - $n \geq N(h)$ (because $N(h)$ was the minimum)
  - $n \geq \phi^h$ hence $\log_\phi n > h$ (relatively well balanced tree!!)
  - $h < 1.44 \log_2 n$ (i.e., Find takes $O(\log n)$)

Node Heights

Tree A (AVL)
- height = 2
- BF = 1 - 0 = 1

Tree B (AVL)
- height = 2
- BF = 0 - 1 = -1

height of node = $h$
balance factor = $h_{\text{left}} - h_{\text{right}}$
empty height = -1
Insert and Rotation in AVL Trees

- Insert operation may cause balance factor to become 2 or -2 for some node
  - 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 $h_{\text{left}} - h_{\text{right}}$) is 2 or -2, adjust tree by rotation around the node

height of node = $h$
balance factor = $h_{\text{left}} - h_{\text{right}}$
empty height = -1

Node Heights after Insert 7

Tree A (AVL)

- height of node = $h$
- balance factor = $h_{\text{left}} - h_{\text{right}}$
- empty height = -1

Tree B (not AVL)

balance factor
$1 - (-1) = 2$

balance factor
$1 - (-1) = 2$

balance factor
$1 - (-1) = 2$

balance factor
$1 - (-1) = 2$
Let the node that needs rebalancing be $\alpha$.

There are 4 cases:

Outside Cases (require single rotation):
1. Insertion into left subtree of left child of $\alpha$. (left-left)
2. Insertion into right subtree of right child of $\alpha$. (right-right)

Inside Cases (require double rotation):
3. Insertion into right subtree of left child of $\alpha$. (left-right)
4. Insertion into left subtree of right child of $\alpha$. (right-left)

The rebalancing is performed through four separate rotation algorithms.
Consider a valid AVL subtree.

AVL Insertion: Outside Case

Inserting into X destroys the AVL property at node j.

Differ by 1
AVL Insertion: Outside Case

Do a “rotation to right”

Single right rotation

Do a “right rotation”
Outside Case Completed

"Right rotation" done! ("Left rotation" is mirror symmetric)

AVL property has been restored!

AVL Insertion: Inside Case

Consider a valid AVL subtree
AVL Insertion: Inside Case

Inserting into Y destroys the AVL property at node j

Does “right rotation” restore balance?

“One rotation” does not restore balance… now k is out of balance
AVL Insertion: Inside Case

Consider the structure of subtree Y...

Y = node i and subtrees V and W
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

right rotation complete

Balance has been restored
Implementation

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

Class BinaryNode

KeyType: Key
int: Height
BinaryNode: LeftChild
BinaryNode: RightChild

Constructor(KeyType: key)
Key = key
Height = 0
End Constructor
End Class

Java-like Pseudo-Code

rotateToRight(BinaryNode: x) {
BinaryNode y = x.LeftChild;
x.LeftChild = y.RightChild;
y.RightChild = x;
return y;
}

Rotate with left child
Java-like Pseudo-Code

rotateToLeft( BinaryNode: x ) {
    BinaryNode y = x.rightChild;
    x.rightChild = y.leftChild;
    y.leftChild = x;
    return y;
}

Double Rotation

- Implement Double Rotation in two lines.

DoubleRotateToLeft(n : binaryNode) {
    rotateToRight(n.rightChild);
    rotateToLeft(n);
}

DoubleRotateToRight(n : binaryNode) {
    rotateToLeft(n.leftChild);
    rotateToRight(n);
}
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 $h_{\text{left}} - h_{\text{right}}$) is 2 or –2, adjust tree by rotation around the node

Insert in ordinary BST

Algorithm `insert(k, v)`
- input: insert key $k$ into the tree rooted by $v$
- output: the tree root with $k$ adding to $v$. 
- if `isNull(v)`
  - return `newNode(k)`
- if $k \leq \text{key}(v)$ // duplicate keys are okay
  - `leftChild(v) ← insert(k, leftChild(v))`
- else if $k > \text{key}(v)$
  - `rightChild(v) ← insert(k, rightChild(v))`
- return $v$
Insert in AVL trees

Insert(v : binaryNode, x : element) : {
    if v = null then
        {v ← new node; v.data ← x; height ← 0;}
    else case
        v.data = x : ; //Duplicate do nothing
        v.data > x : v.leftChild ← Insert(v.leftChild, x); // handle left-right and left-left cases
            if ((height(v.leftChild) - height(v.rightChild)) = 2) then
                if (v.leftChild.data > x ) then //outside case
                    v = RotateToRight (v);
                else //inside case
                    v = DoubleRotateToRightt (v);
        v.data < x : v.rightChild ← Insert(v.rightChild, x); // handle right-right and right-left cases
        ... ...
    Endcase
    v.height ← max(height(v.left),height(v.right)) +1;
    return v;
}
Example of Insertions in an AVL Tree

Single rotation (outside case)

Now Insert 45

Now Insert 34
Double rotation (inside case)

In Class Exercises

- Build an AVL tree with the following values: 15, 20, 24, 10, 13, 7, 30, 36, 25
Possible Quiz Questions

- Build an AVL tree by inserting the following values in the given order:
  1, 2, 3, 4, 5, 6.
AVL Tree Deletion

- Similar but more complex than insertion
  - Rotations and double rotations needed to rebalance
  - Imbalance may propagate upward so that many rotations may be needed.

Deletion

- Removal begins as in a binary search tree, which means the node removed will become an empty external node. Its parent may have 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 a rotateToLeft 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.

Deletion in standard BST

Algorithm $remove(k, v)$

input: delete the node containing key $k$
output: the tree without $k$.

if $isNull(v)$
return $v$

if $k < key(v)$  // duplicate keys are okay
leftChild($v$) $\leftarrow$ $remove(k, leftChild(v))$
else if $k > key(v)$
rightChild($v$) $\leftarrow$ $remove(k, rightChild(v))$
else if $isNull(leftChild(v))$
return rightChild($v$)
else if $isNull(rightChild(v))$
return leftChild($v$)

node max $\leftarrow$ $treeMaximum(leftChild(v))$
key($v$) $\leftarrow$ key(min)
rightChild($v$) $\leftarrow$ $remove(key(min), rightChild(v))$
return $v$
Deletion in AVL Trees

**Algorithm** `remove(k, v)`

- **input**: delete the node containing key `k`
- **output**: the tree without `k`

```plaintext
if isNull(v)
    return v

if k < key(v) // duplicate keys are okay
    leftChild(v) ← remove(k, leftChild(v))
else if k > key(v)
    rightChild(v) ← remove(k, rightChild(v))
else if isNull(leftChild(v))
    return rightChild(v)
else if isNull(rightChild(v))
    return leftChild(v)

node max ← treeMaximum(leftChild(v))
key(v) ← key(max)
leftChild(v) ← remove(key(max), leftChild(v))

AVLbalance(v)
return v
```

**AVLbalance(v)**
Assume the height is updated in rotations.

```plaintext
if (v.left.height > v.right.height+1) {
    y = v.left
    if (y.right.height > y.left.height)
        DoubleRotateToRight(v)
    else
        rotateToRight(v)
}

if (v.right.height > v.left.height+1) {
    y = v.right
    if (y.left.height > y.right.height)
        DoubleRotateToLeft(v)
    else
        rotateToLeft(v)
}
```

**AVL Tree Example:**

- Now remove 53

```
8
/   \
4    53
/ \
2   8
/ \ \
1   3 12
```

```plaintext
49
```

```
50
```
AVL Tree Example:
• Now remove 53, unbalanced

AVL Tree Example:
• Balanced!

Now try Remove 11
AVL Tree Example:
- Remove 11, replace it with the largest, i.e., 8, in its left branch.

Now try Remove 8.

AVL Tree Example:
- Remove 8, unbalanced
AVL Tree Example:
• Remove 8, unbalanced

AVL Tree Example:
• Balanced!!
Deletion in AVL Trees

Algorithm \( \text{remove}(k, v) \)

input: delete the node containing key \( k \)
output: the tree without \( k \).

if isNull \( v \)
    return \( v \)
if \( k < \text{key}(v) \)  // duplicate keys are okay
    leftChild\( (v) \leftarrow \text{remove}(k, \text{leftChild}(v)) \)
else if \( k > \text{key}(v) \)
    rightChild\( (v) \leftarrow \text{remove}(k, \text{rightChild}(v)) \)
else if isNull(leftChild\( (v) \))
    return rightChild\( (v) \)
else if isNull(rightChild\( (v) \))
    return leftChild\( (v) \)
node max \( \leftarrow \text{treeMaximum}(\text{leftChild}(v)) \)
key\( (v) \leftarrow \text{key}(\text{max}) \)
leftChild\( (v) \leftarrow \text{remove} \left( \text{key}(\text{max}), \text{leftChild}(v) \right) \)
return \( \text{AVLbalance}(v) \)

AVLbalance\( (v) \) {
Assume the height is updated in rotations.
if (\( v \).left.height > \( v \).right.height + 1) {
    \( y \leftarrow v \).left
    if (\( y \).right.height > \( y \).left.height)
        \( v \leftarrow \text{DoubleRotateToRight}(v) \)
    else \( v \leftarrow \text{rotateToRight}(v) \)
}
if (\( v \).right.height > \( v \).left.height + 1) {
    \( y \leftarrow v \).right
    if (\( y \).left.height > \( y \).right.height)
        \( v \leftarrow \text{DoubleRotateToLeft}(v) \)
    else \( v \leftarrow \text{rotateToLeft}(v) \)
}
return \( v \)
}

Remove 24 and 20 from the AVL tree.
AVL Tree Performance

- AVL tree storing n items
  - The data structure uses $O(n)$ space
  - A single restructuring takes $O(1)$ time
    - using a linked-structure binary tree
  - Searching takes $O(\log n)$ time
    - height of tree is $O(\log n)$, no restructures needed
  - Insertion takes $O(\log n)$ time
    - initial find is $O(\log n)$
    - restructuring up the tree, maintaining heights is $O(\log n)$
  - Removal takes $O(\log n)$ time
    - initial find is $O(\log n)$
    - restructuring up the tree, maintaining heights is $O(\log n)$

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 $O(\log n)$
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 height.
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 the total run time for many consecutive operations is fast (e.g. Splay trees).
Red-Black Tree

- A ref-black tree is a binary search such that each node has a color of either red or black.
- The root is black.
- Empty (or null) nodes are assumed black.
- Every path from a node to a leaf contains the same number of black nodes.
- If a node is red then its parent must be black.

Class BinaryNode

| KeyType: Key |
| Boolean: isRed |
| BinaryNode: LeftChild |
| BinaryNode: RightChild |

Constructor(KeyType: key)

Key = key
isRed = true

End Constructor

End Class

Example

The root is black.
The parent of any red node must be black.
Theorem: Any red-black tree with root \( x \), has \( n \geq 2^{h/2} - 1 \) nodes, where \( h \) is the height of tree rooted by \( x \).

Proof: We repeatedly replace the subtree rooted by a red node by one of its children. Let the height of the new tree be \( h' \), then \( h' \geq h/2 \), because the number of red nodes in any path is no more than the number of black nodes.

The new tree is a perfect binary tree, because it has the same number of nodes from the root to any leaf. It must have \( 2^{h'} - 1 \) nodes.

So \( h \leq 2\log(n+1) \).

Maintain the Red Black Properties in a Tree

- **Insertions**
  - Must maintain rules of Red Black Tree.
  - New Node always added at leaf
  - can't be black or we will violate rule of the same # of blacks along any path
  - therefore the new node must be red
  - If parent is black, done (trivial case)
  - If parent red, things get interesting because a red node with a red parent violates no double red rule.
Algorithm: Insertion

A red-black tree is a particular binary search tree, so create a new node as red and insert it as in normal search tree.

What property is violated?

The parent of a red node must be black.

Solution: (1) Rotate; (2) Switch colors.

Example of Inserting Sorted Numbers

1 2 3 4 5 6 7 8 9 10

Insert 1. A leaf is red. Realize it is root so recolor to black.
Insert 2

make 2 red. Parent is black so done.

Insert 3

Insert 3. Parent is red. 2’s uncle, i.e., the sibling of the parent of 2, is black (null). 3 is outside relative to grandparent. Rotate parent and grandparent.
Insert 4

When adding 4
parent is **red**.

4 has a red uncle (1). So switch the great parent (2)’s color with parent and uncle.

```
2
/  \
1   3
   /  \
  2   4
```

2 is set to black if it’s the root.

```
2
/  \
1   3
   /  \
  2   4
```

Insert 5

5’s parent is red.
5’s uncle is black (null).
5 is outside relative to grandparent (3) so rotate parent and grandparent then recolor.

```
2
/  \
1   3
   /  \
  2   4
```

```
2
/  \
1   3
   /  \
  2   4
```

5
Finish insert of 5

6 has a red uncle (3).
So switch the grandparent (4)’s color with parent (5) and uncle (3).
Finishing insert of 6

4's parent is black so done.

Insert 7

7's parent is red. Parent's sibling is black (null). 7 is outside relative to grandparent (5) so rotate parent and grandparent then recolor
Finish insert of 7

Insert 8

8’s parent is red and its uncle (5) is also red. Switching the color of 6 with 5 and 7 creates a problem because 6’s parent, 4, is also red. Must handle the red-red violation at 6.
Still Inserting 8

8’s parent is red and its uncle (5) is also red. Switching the color of 6 with 5 and 7 creates a problem because 6’s parent, 4, is also red. Must handle the red-red violation at 6.

6’s uncle (1) is black. So rotate and recolor.

Finish inserting 8
Insert 9

Finish Inserting 9

After rotations and recoloring
10 has a red uncle. Grandparent (8) switch colors with parent (9) and uncle (7).

8 has a red uncle (2). Grandparent (4) switch colors with parent (2) and uncle (6). 4 is recolored black as root.
Algorithm: Insertion

We have detected a need for balance when $X$ is red and its parent, too.

- If $X$ has a red uncle: colour the parent and uncle black, and grandparent red. Then replace $X$ by grandparent to see if new $X$’s parent is red.
Algorithm: Insertion

We have detected a need for balance when $X$ is red and its parent, too.

- If $X$ has a red uncle: colour the parent and uncle black, and grandparent red. Then replace $X$ by grandparent to see if new $X$’s parent is red.

- If $X$ has a red uncle: colour the parent and uncle black, and grandparent red. Then replace $X$ by grandparent to see if new $X$’s parent is red.

- If $X$ is a left child and has a black uncle: colour the parent black and the grandparent red, then rotateToRight($X$.parent.parent)
Algorithm: Insertion

We have detected a need for balance when X is red and his parent too.

• If X has a red uncle: colour the parent and uncle black, and grandparent red. Then replace X by grandparent to see if X’s parent is red.
• If X is a left child and has a black uncle: colour the parent black and the grandparent red, then rotateRight(X.parent.parent)
• If X is a right child and has a black uncle, then rotateLeft(X.parent)
Algorithm: Insertion

We have detected a need for balance when X is red and his parent too.

- If X has a red uncle: colour the parent and uncle black, and grandparent red. Then replace X by grandparent to see if X’s parent is red.
- If X is a right child and has a black uncle, then rotateToLeft(X.parent) and
- If X is a left child and has a black uncle: colour the parent black and the grandparent red, then rotateToRight(X.parent.parent)
Double Rotation

- What if X is at left right relative to G?
  - a single rotation will not work
- Must perform a double rotation
  - rotate X and P
  - rotate X and G

After Double Rotation

Double rotation is also needed when X is at right left position relative to G.
Properties of Red Black Trees

- If a Red node has any children, it must have two children and they must be black. (Why?)
- If a black node has only one child, that child must be a Red leaf. (Why?)
- Due to the rules there are limits on how unbalanced a Red Black tree may become.

Red Black Trees vs AVL Trees

- AVL trees provide faster lookups than Red Black Trees because they are more strictly balanced.
- Red Black Trees provide faster insertion and removal operations than AVL trees as fewer rotations are done due to relatively relaxed balancing.
- AVL trees store balance factors or heights with each node, thus requires storage for an integer per node whereas Red Black Tree requires only 1 bit of information per node.
Motivation for Splay Trees

Problems with AVL Trees
- extra storage/complexity for height fields
- ugly delete code

Solution: splay trees
- blind adjusting version of AVL trees
- amortized time for all operations is $O(\log n)$
- worst case time is $O(n)$
- insert/find always rotates node to the root!
Splay Tree Idea

You’re forced to make a really deep access:

Since you’re down there anyway, fix up a lot of deep nodes!

Splaying Cases

Node n being accessed is:
- Root
- Child of root
- Has both parent (p) and grandparent (g)

Zig-zig pattern: g → p → n is left-left or right-right (outside nodes)
Zig-zag pattern: g → p → n is left-right or right-left (inside nodes)
Access root:
Do nothing (that was easy!)

Access child of root:
Zig (AVL single rotation)
Access (LR, RL) grandchild:
Zig-Zag (AVL double rotation)

Access (LL, RR) grandchild:
Zig-Zig

Rotate top-down – why?
Splaying Example:

Find(6)

Splaying Example:

Find(6)

zig-zig

... still splaying ...

zig-zig
... 6 splayed out!

Splay it Again!

Find (4)

zig-zag
A splay tree is a binary search tree where a node is splayed after it is accessed (for a search or update):

- deepest internal node accessed is splayed
- splaying costs $O(h)$, where $h$ is height of the tree – which is still $O(n)$ worst-case
  - $O(h)$ rotations, each of which is $O(1)$
Splay Trees do Rotations after Every Operation (Even Search)

- new operation: **splay**
  - splaying moves a node to the root using rotations
- right rotation
  - makes the left child $x$ of a node $y$ into $y$’s parent; $y$ becomes the right child of $x$
- left rotation
  - makes the right child $y$ of a node $x$ into $x$’s parent; $x$ becomes the left child of $y$

(structure of tree above $y$ is not modified)

Visualizing the Splaying Cases

- zig-zag
- zig-zig
- zig
Splaying:

- “x is a left-left grandchild” means x is a left child of its parent, which is itself a left child of its parent
- p is x’s parent; g is p’s parent

- is x the root?
  - yes: stop
  - no: is x a child of the root?
    - no: is x the left child of the root?
      - yes: right-rotate about the root
      - no: Zig-Zig
    - yes: Zig-Zig

- is x a left-left grandchild?
  - yes: right-rotate about g, right-rotate about p
  - no: Zig-Zig

- is x a right-right grandchild?
  - yes: right-rotate about p, right-rotate about g
  - no: Zig-Zag

- is x a left-right grandchild?
  - yes: left-rotate about p, left-rotate about g
  - no: Zig-Zag

- Zig-Zag

Splay Tree Operations

- Which nodes are splayed after each operation?

<table>
<thead>
<tr>
<th>method</th>
<th>splay node</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for k</td>
<td>if key found, use that node</td>
</tr>
<tr>
<td></td>
<td>if key not found, use parent of ending external node</td>
</tr>
<tr>
<td>Insert (k,v)</td>
<td>use the new node containing the entry inserted</td>
</tr>
<tr>
<td>Remove item with key k</td>
<td>use the predecessor of the node to be removed</td>
</tr>
</tbody>
</table>
Why Splaying Helps

- If a node \( n \) on the access path is at depth \( d \) before the splay, it's at about depth \( d/2 \) after the splay
  - Exceptions are the root, the child of the root, and the node splayed

- Overall, nodes which are below nodes on the access path tend to move closer to the root

- Splaying gets amortized \( O(\log n) \) performance. (Maybe not now, but soon, and for the rest of the operations.)

Splay Operations: Find

- Find the node in normal BST manner
- Splay the node to the root
Splay Operations: Insert

- Ideas?
- Can we just do BST insert?

Digression: Splitting

- Split(T, x) creates two BSTs L and R:
  - all elements of T are in either L or R \((T = L \cup R)\)
  - all elements in L are \(\leq x\)
  - all elements in R are \(\geq x\)
  - L and R share no elements \((L \cap R = \emptyset)\)
Splitting in Splay Trees

How can we split?

- We have the splay operation.
- We can find x or the parent of where x should be.
- We can splay it to the root.
- Now, what’s true about the left subtree of the root?
- And the right?

Split

\[ \text{split}(x) \]

T

splay

L

R

\[ \leq x \quad > x \quad < x \quad \geq x \]
void insert(Node root, Object x)
{
    <left, right> = split(root, x);
    root = newNode(x, left, right);
}

Splay Operations: Delete

Now what?
Join

Join(L, R): given two trees such that L < R, merge them

Splay on the maximum element in L, then attach R

Delete Completed

find(x) delete x

Join(L, R)
Splay Tree Summary

Can be shown that any \( m \) consecutive operations starting from an empty tree take at most \( O(m \log(n)) \), where \( n \) is the total number of elements in the tree.

All splay tree operations run in amortized \( O(\log n) \) time.

\( O(N) \) operations can occur, but splaying makes them infrequent.

Implements most-recently used (MRU) logic
- Splay tree structure is self-tuning

Splay Tree Summary (cont.)

Splaying can be done top-down; better because:
- only one pass
- no recursion or parent pointers necessary

There are alternatives to split/insert and join/delete

Splay trees are \textit{very} effective search trees
- relatively simple: no extra fields required
- excellent \textit{locality} properties:
  - frequently accessed keys are cheap to find (near top of tree)
  - infrequently accessed keys stay out of the way (near bottom of tree)
Amortized Analysis of Splay Trees

- Running time of each operation is proportional to time for splaying.
- Define rank(v) as the logarithm (base 2) of the number of nodes in subtree rooted at v:
  - rank(v) = log n(v) if null for external nodes
  - rank(v) = log (2n(v)+1) if empty nodes for externals.
- Costs: zig = $1, zig-zig = $2, zig-zag = $2.
- Thus, cost for splaying a node at depth d = $d.
- Imagine that we store rank(v) cyber-dollars at each node v of the splay tree (just for the sake of analysis).
- The total counter values is rank(T) = sum of rank(v) for any node v in T.