

Red-Black Trees (A Balanced BST)

<https://cs.pomona.edu/classes/cs140/>

Some notes taken from
<http://www.geeksforgeeks.org/>

Outline


Topics and Learning Objectives

- Discuss tree balancing (rotations, insertions, deletions)
- Prove the balancing characteristic of red-black trees
- Discuss the running time of red-black tree operations

Assessments Exercise

- Red-black tree activity ★

Extra Resources

- Introduction to Algorithms, 3rd, chapter 13
- <https://www.cs.usfca.edu/~galles/visualization/RedBlack.html> 

Implementations

Although Red-Black trees are not the most modern choice, they do appear in

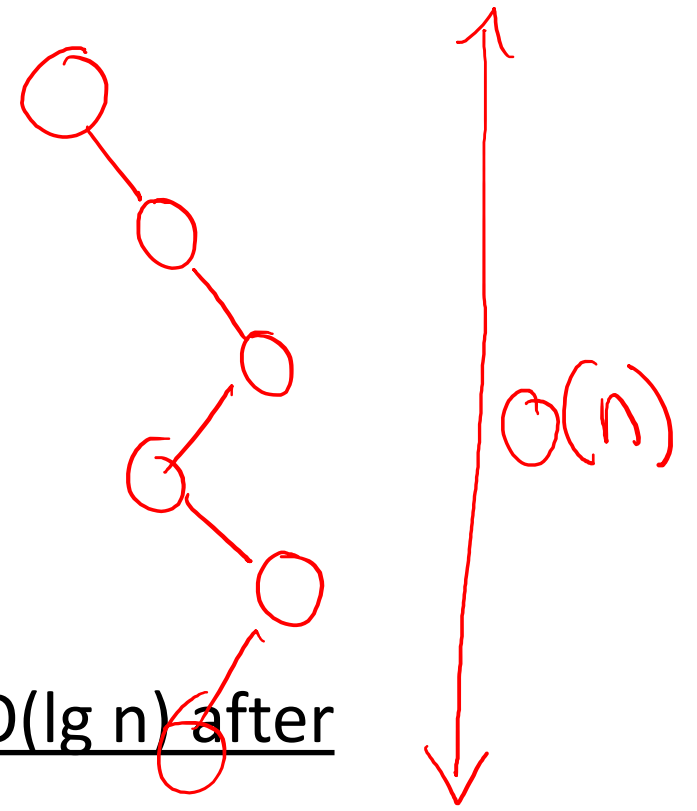
- Java: TreeMap<K,V>

- C++: std::map

Not something you
should use in
practice.

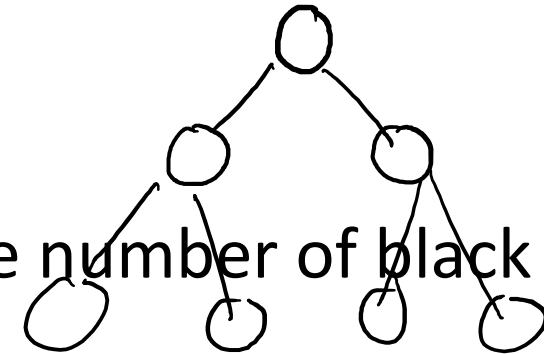
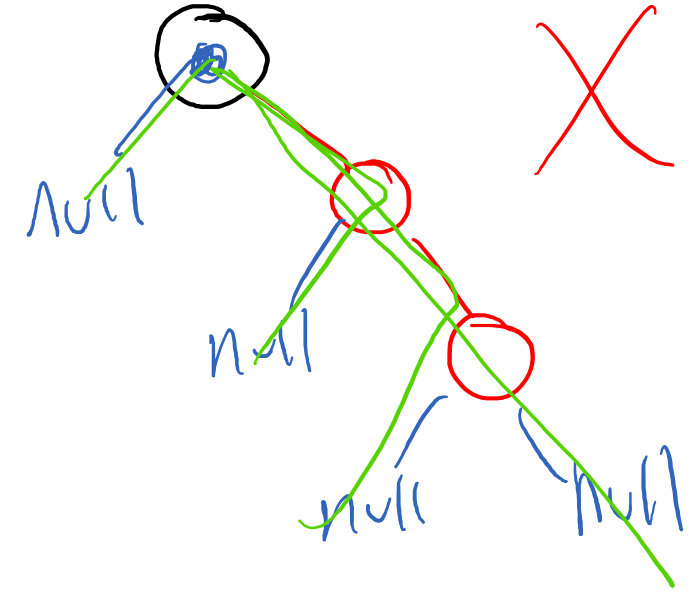
Balanced Binary Search Trees

- Why is balancing important?
- What is the worst case for a binary tree?
- Balanced tree: the height of a balanced tree stays $O(\lg n)$ after insertions and deletions
- Many different types of balanced search trees:
 - AVL Tree, Splay Tree, B Tree, Red-Black Tree



Red-Black Trees Invariants

1. Each node must be labeled either **red** or black
2. The root must be labeled black
3. The tree cannot have two **red** nodes in a row (for any **red** node its parent, left, and right must be black)
4. Every root-NULL path must include the same number of black nodes

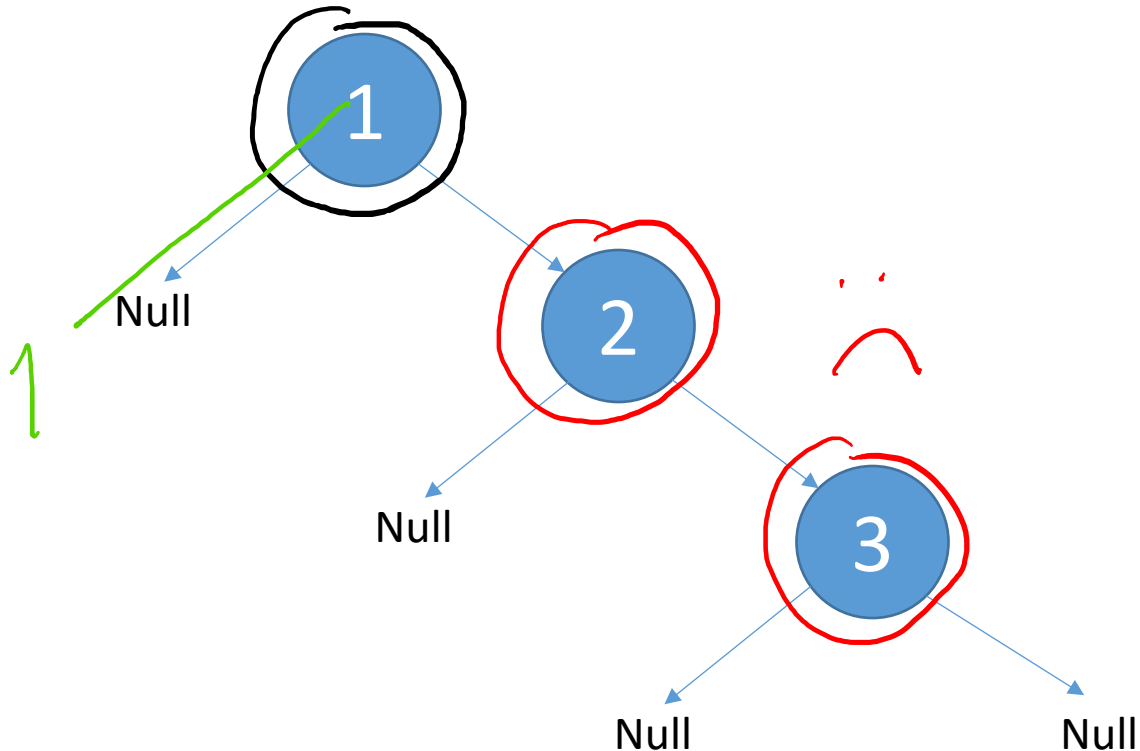


Can a **Red**-Black tree of any height have only black nodes?

Yes

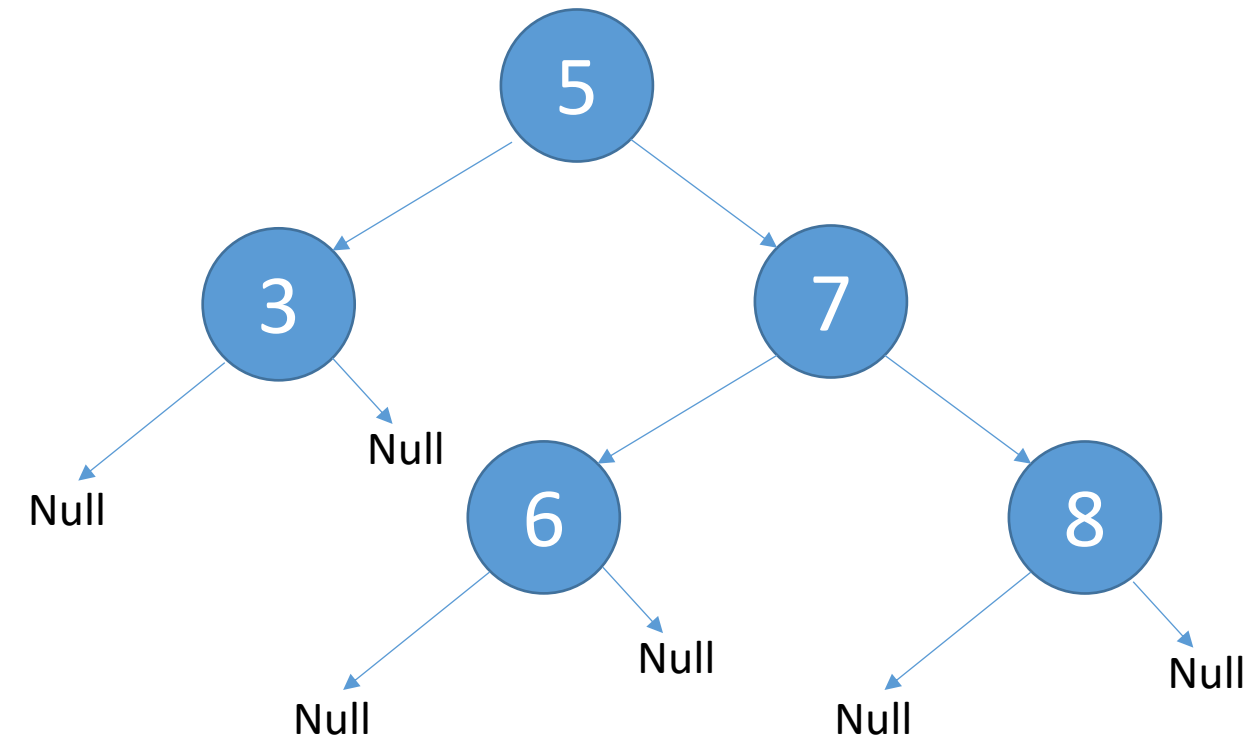
Red-Black Trees

Can a “chain” be a red-black tree?



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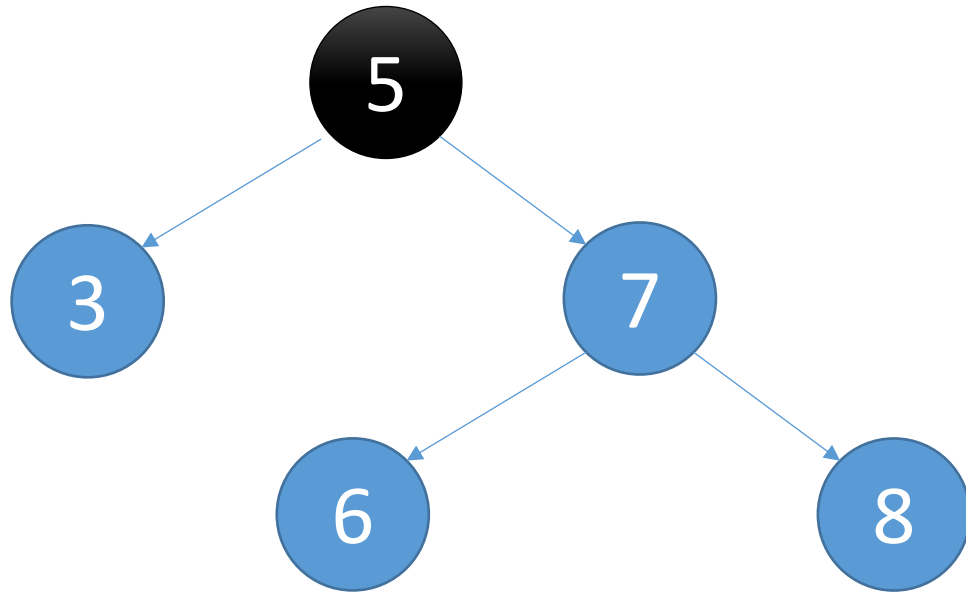
Red-Black Trees



Color this as a Red-Black Tree

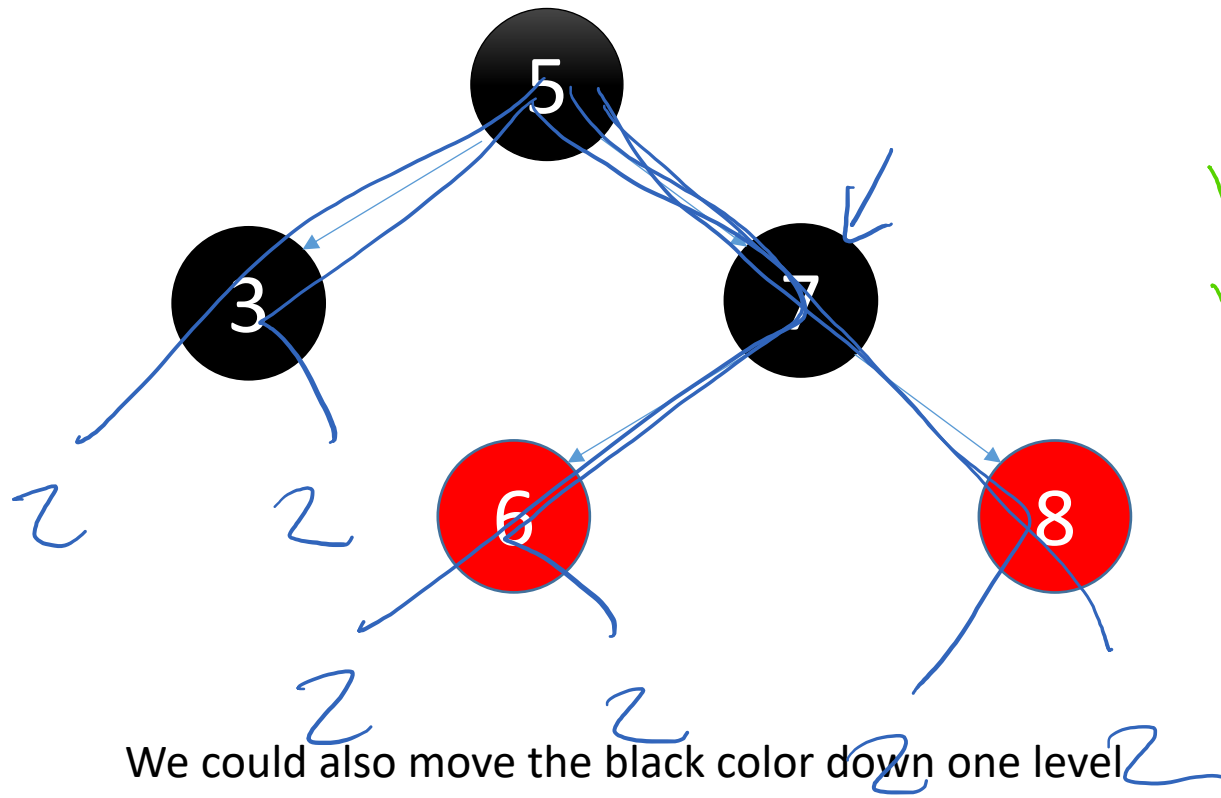
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Red-Black Trees



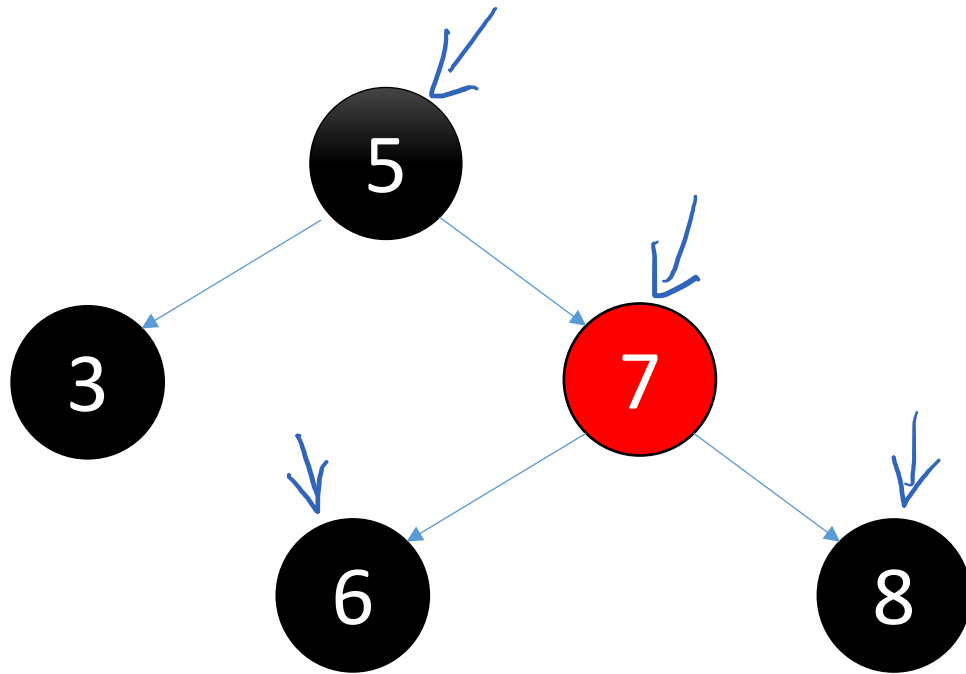
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Red-Black Trees



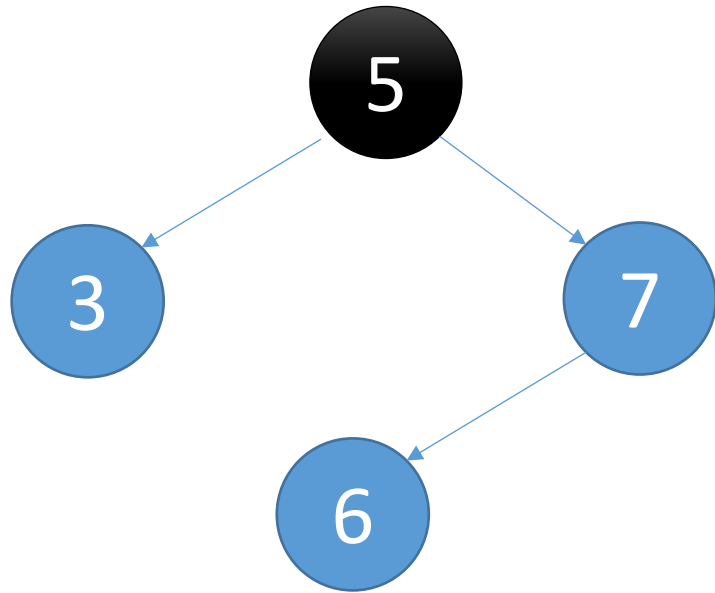
- ✓ 1. Each node must be labeled either **red** or black
- ✓ 2. The root must be labeled black
- ✓ 3. The tree cannot have two **red** nodes in a row (for any **red** node its parent, left, and right must be black)
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Red-Black Trees



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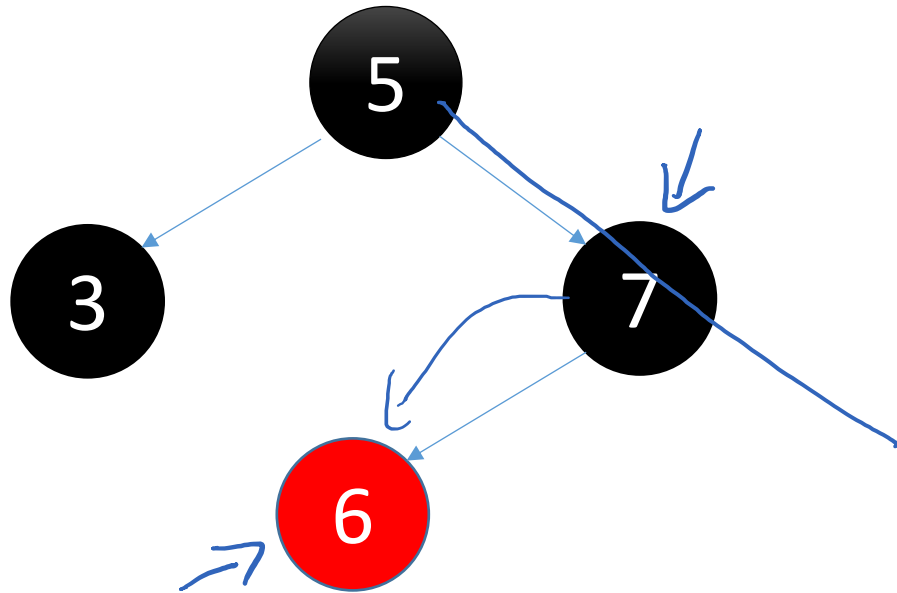
Red-Black Trees



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4. Every root-NULL path must include the same number of black nodes

Color this as a **Red**-Black Tree

Red-Black Trees



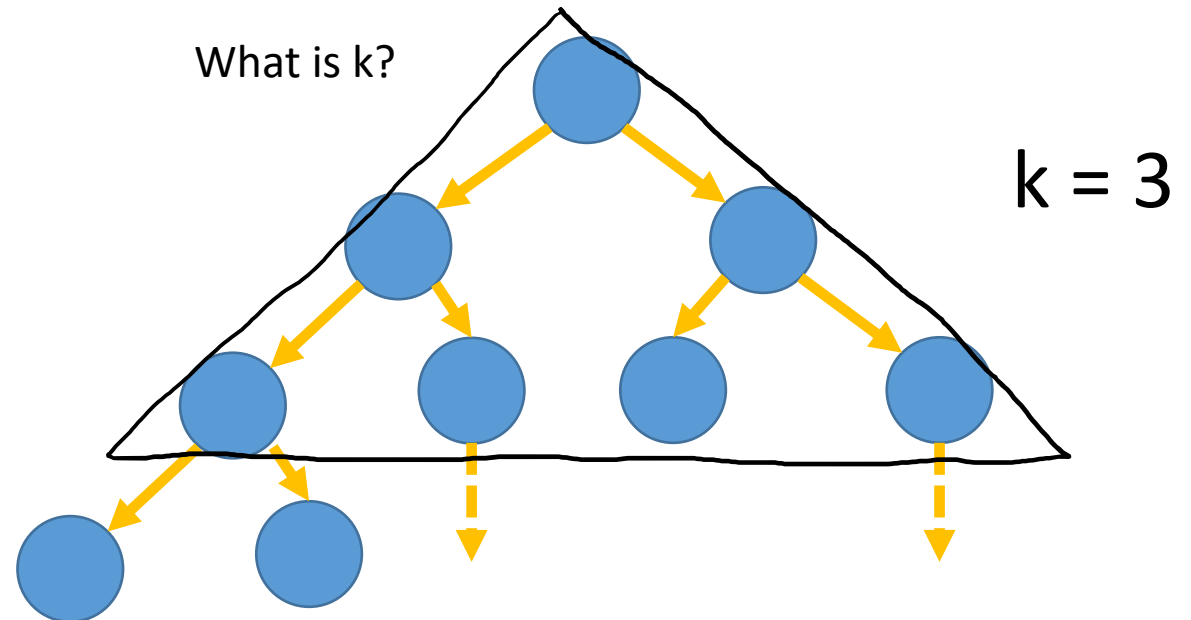
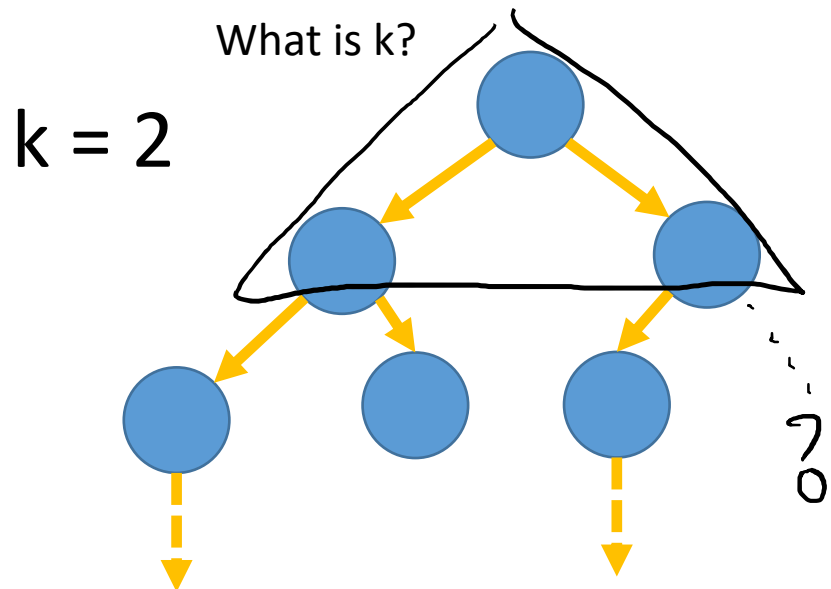
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How did Red-Black Trees get their name?

Red-Black Tree Height

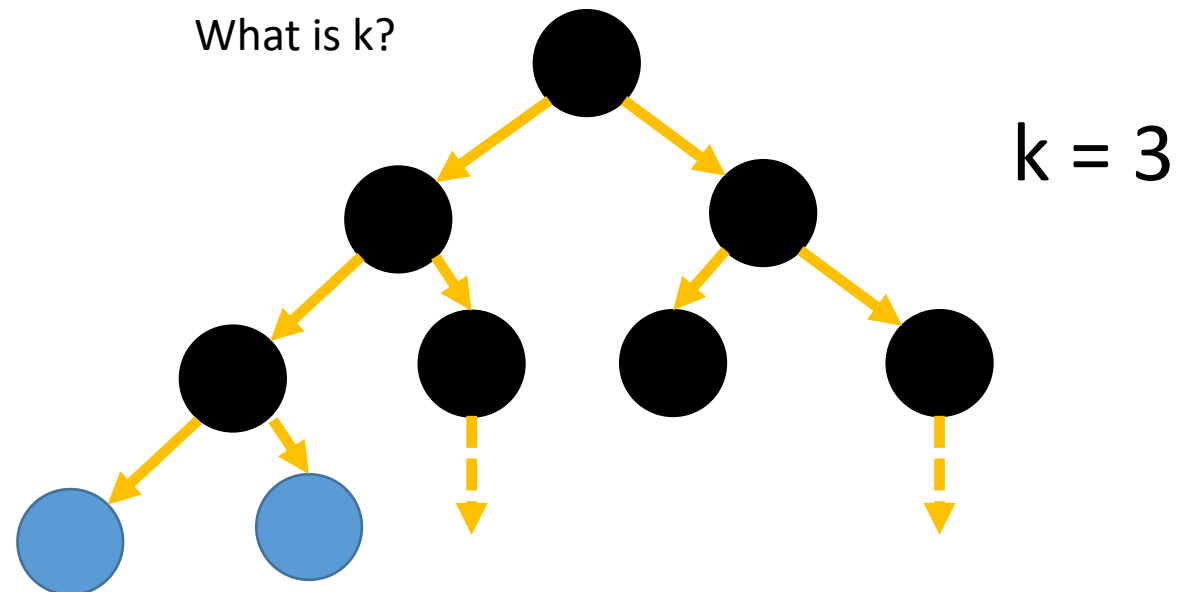
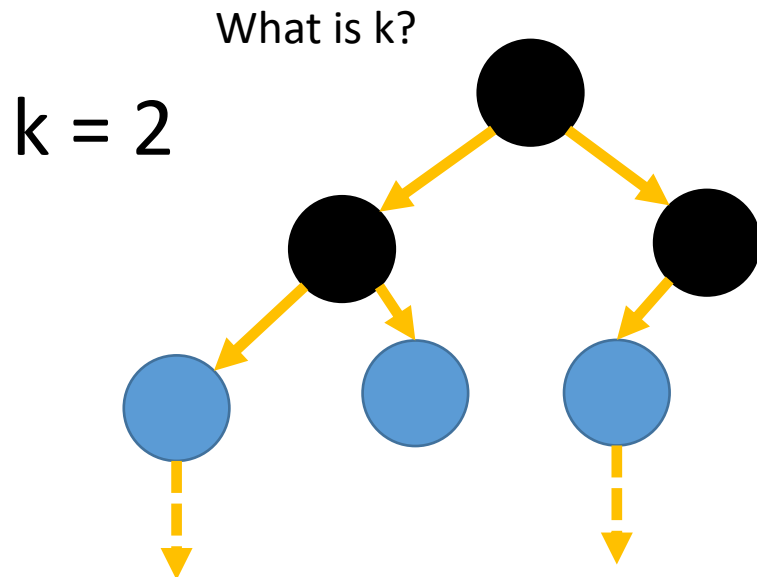
- Claim: every Red-Black tree has a $t_{height} \leq 2 \lg(n + 1) = O(\lg n)$

- ✧ Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels



Red-Black Tree Height

- Claim: every Red-Black tree has a $t_{height} \leq 2 \lg(n + 1)$
- Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels



| k | n |
|---|---|
| 1 | 1 |

Red-Black Tree Height

- Claim: every Red-Black tree has a $t_{height} \leq 2 \lg(n + 1)$
- Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels

What is the
minimum number of
nodes (n) in the tree
based on k ?

Exercise question 1

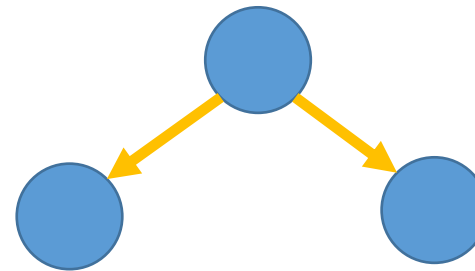


| k | n |
|---|---|
| 1 | 1 |
| 2 | 3 |

Red-Black Tree Height

- Claim: every Red-Black tree has a $t_{height} \leq 2 \lg(n + 1)$
- Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels

What is the minimum number of nodes (n) in the tree based on k ?



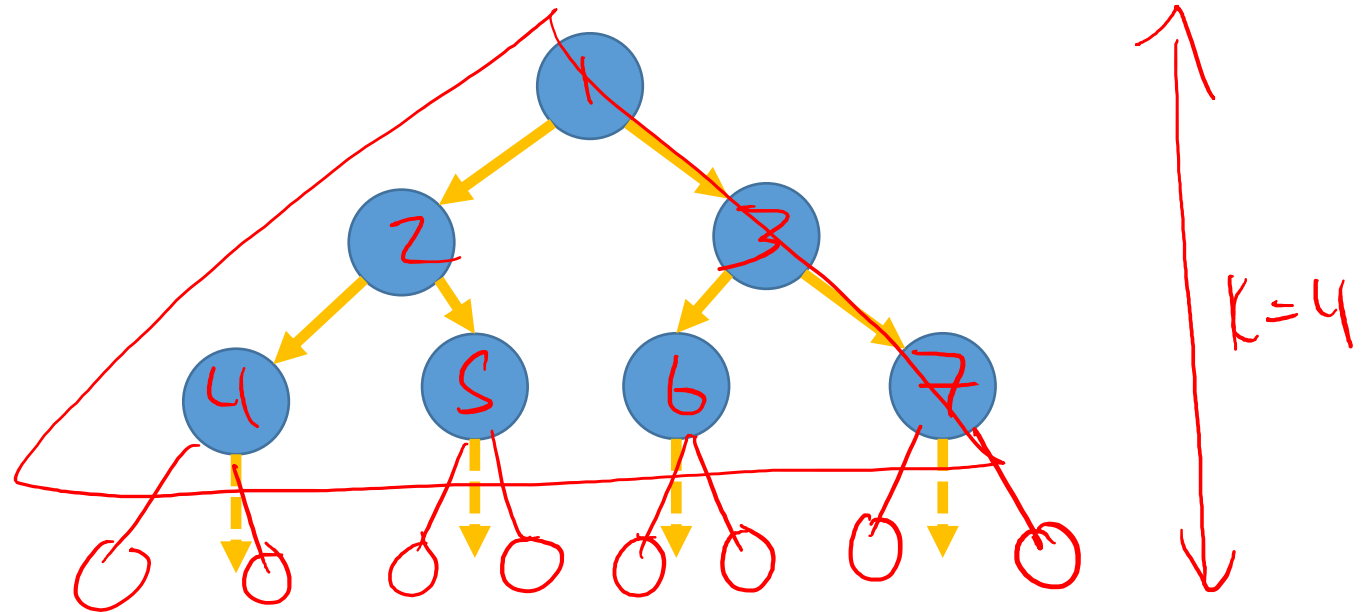
Red-Black Tree Height

$$2^k - 1$$

| k | n |
|---|----|
| 1 | 1 |
| 2 | 3 |
| 3 | 7 |
| 4 | 15 |
| 5 | 31 |
| 6 | 63 |

- Claim: every Red-Black tree has a $t_{height} \leq 2 \lg(n + 1)$
- Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels

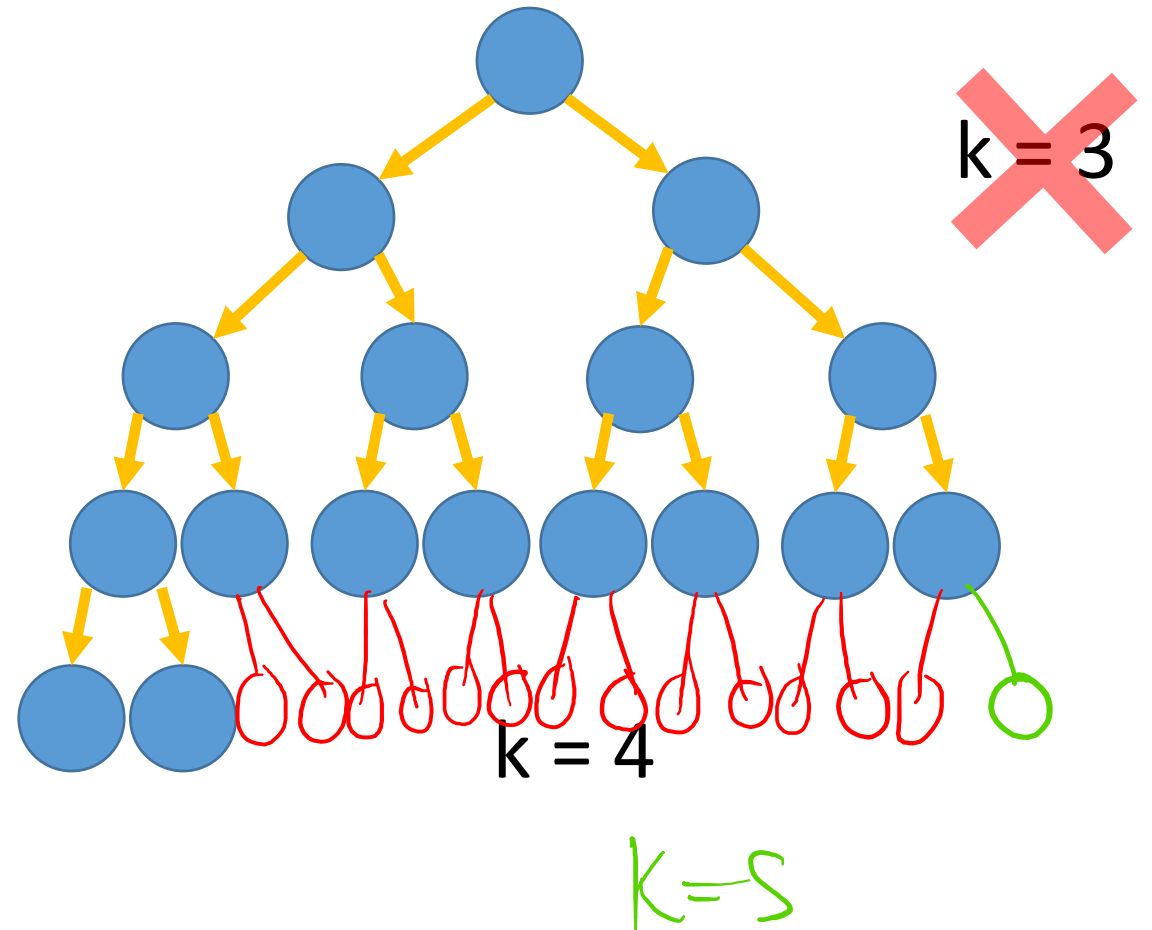
What is the minimum number of nodes (n) in the tree based on k ?



Red-Black Tree Height

- Claim: every Red-Black tree has a $t_{height} \leq 2 \lg(n + 1)$
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What is the
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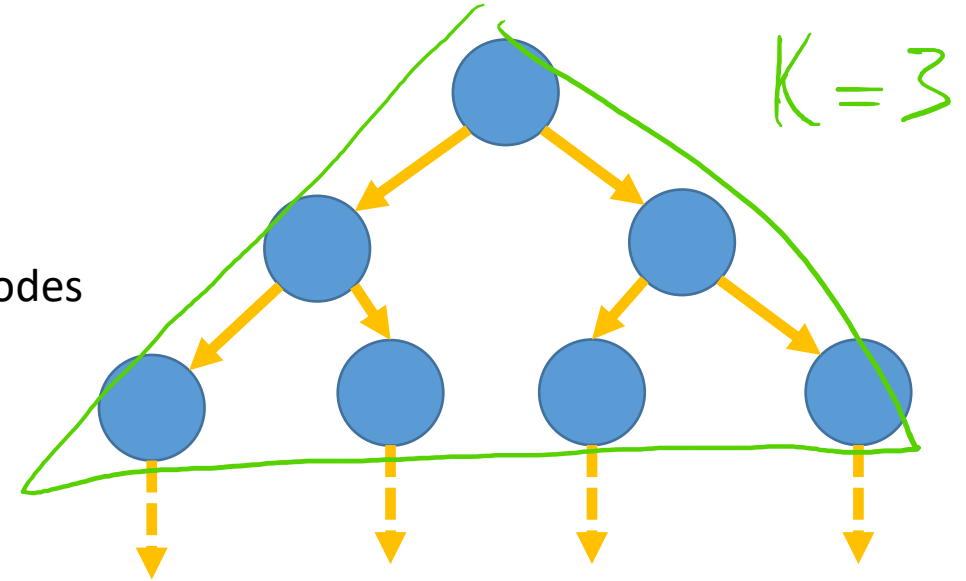


Red-Black Tree Height

- So, we have:

$2^k - 1$ was the minimum number of nodes

$$n \geq 2^k - 1$$
$$\lg(n + 1) \geq \underline{k}$$



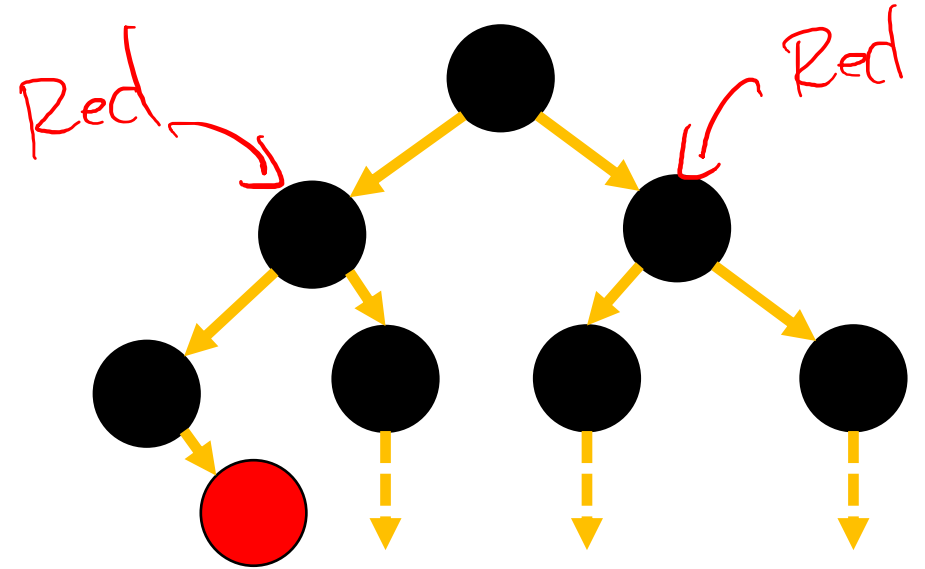
- So, we now have an upper bound on k.
- But how does k help us bound the actual height of the tree?
- What does k tell us about the number of black nodes you can have?
- ✱ • What is the maximum number of black nodes on any root-Null path?

Observation: if every **root-NULL path** has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with **k** levels

Red-Black Tree Height

- So, we have:

$$\lg(n+1) \geq k$$



- So, we now have an upper bound on k .
- But how does k help us bound the actual height of the tree?
- What does k tell us about the number of black nodes you can have?
- What is the maximum number of black nodes on any root-Null path?

Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels

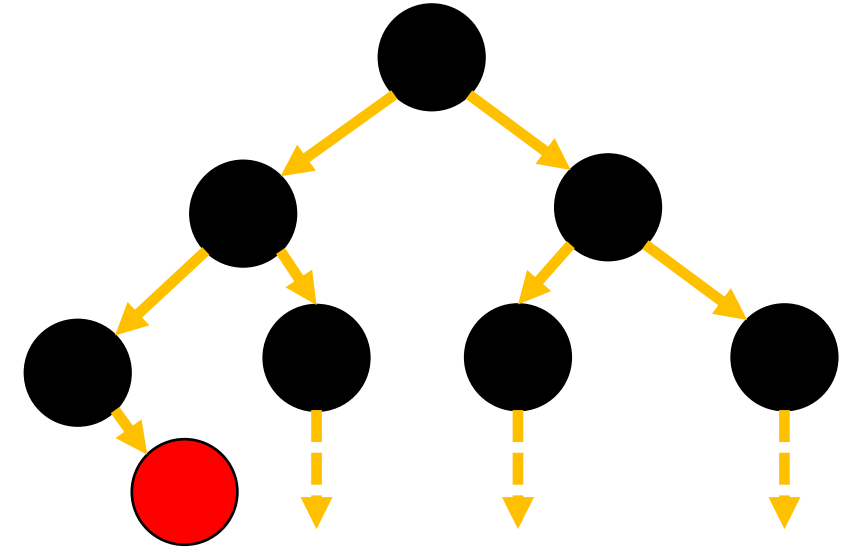
At most k black nodes

At most $\lg(n + 1)$ black nodes

Red-Black Tree Height

- So, we have:

$$n \geq 2^k - 1$$
$$\lg(n + 1) \geq k$$



- So, **How many red nodes**
- But **on any root-Null path?**
- What does k tell us about the number of black nodes you can have?
- What is the maximum number of black nodes on any root-Null path?

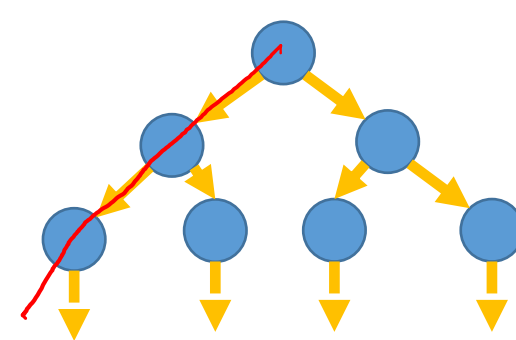
Observation: if every root-NULL path has $\geq k$ nodes, then the tree includes a perfectly balanced top portion with k levels

At most k black nodes

At most $\lg(n + 1)$ black nodes

Red-Black Tree Height

$\lg(n+1)$



- Thus: in a **Red**-Black tree with n nodes, there is a root-NULL path with **at most** $\lg(n+1)$ **black** nodes
- By invariant (4): every root-NULL path has $\leq \lg(n+1)$ **black** nodes
- By invariant (3): every root-NULL path has $\leq \lg(n+1)$ **red** nodes
- Thus, a **total** of $\leq 2\lg(n+1)$ nodes on every root-NULL path

1. Each node must be labeled either **red** or black
2. The root must be labeled black
3. The tree cannot have two **red** nodes in a row (for any **red** node its parent, left, and right must be black)
4. Every root-NULL path must include the same number of black nodes

$$T_n = \# \text{ of Red} + \# \text{ of Black nodes}$$

Red-Black Trees

- If our tree can be colored as a Red-Black tree, then every root-NULL path has $\leq 2\lg(n + 1)$ nodes total

- The longest path will dictate the height of the tree

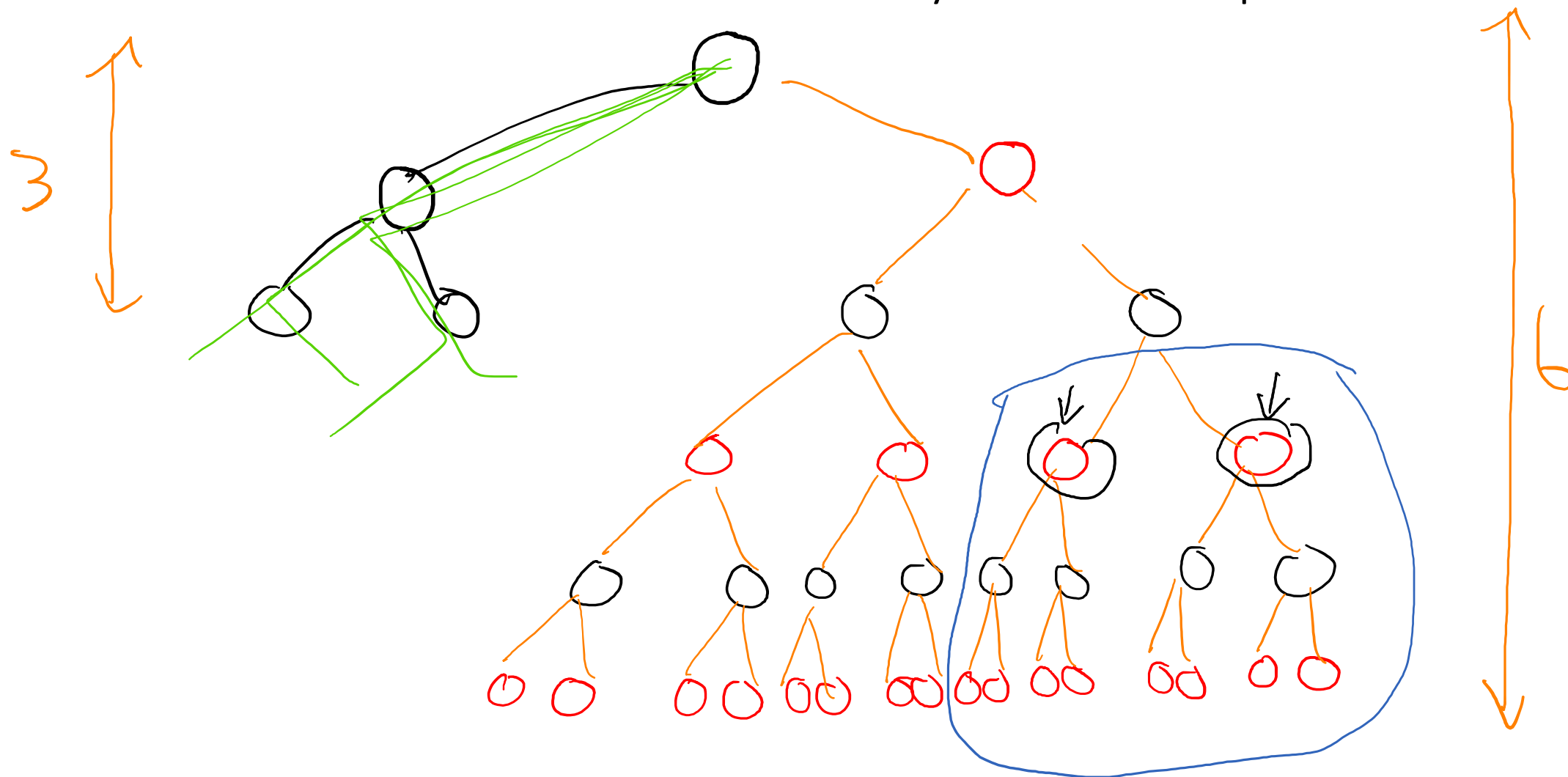
- So, height of the tree is at most $2\lg(n + 1)$ \downarrow $\lg(n+1) = \lg n + \lg(1 + 1/n) = \lg n + C$

- A tree cannot contain a *chain* of three nodes

- Thus, the height of the tree is $O(\lg n)$ \rightarrow all ops take $O(\lg n)$
- Why is this important?

Exercise question 2

Draw a Worst-Case (most lopsided) Red-Black Tree with a minimum of 3 black nodes on every root-NULL path



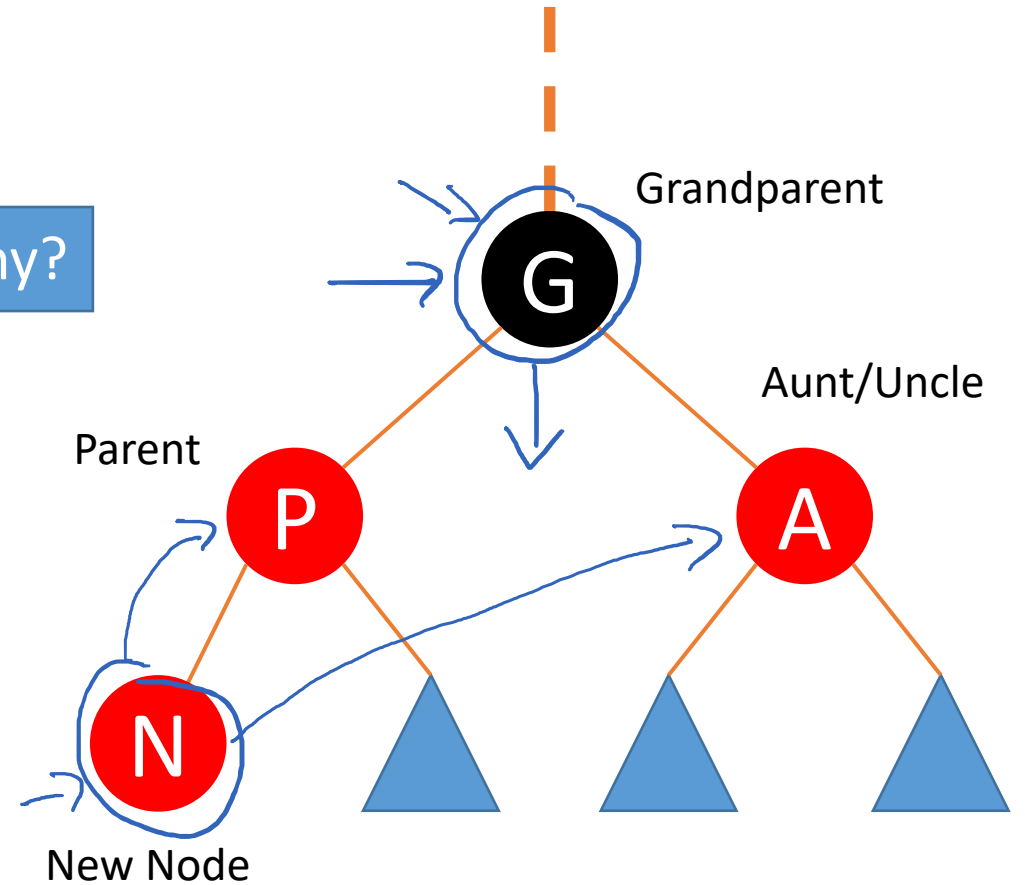
Red-Black Trees, Inserting a Node

1. Insert the new node
2. Color it red
3. Fix colors to enforce Red-Black Tree invariants
 1. This is a recursive process

Red-Black Trees, Inserting a Node

Move the black color down

1. Insert the new node (always insert as a leaf)
2. If the inserted node is the root, then color it black, otherwise color it red
3. If the new node is not root and its parent is black, then we are done
4. Otherwise, look at the node's aunt
 - a) If aunt is red
 - I. Change color of parent and aunt to black
 - II. Change color of the new node and the grandparent to red
 - III. Go to step (2) and treat grandparent as new node

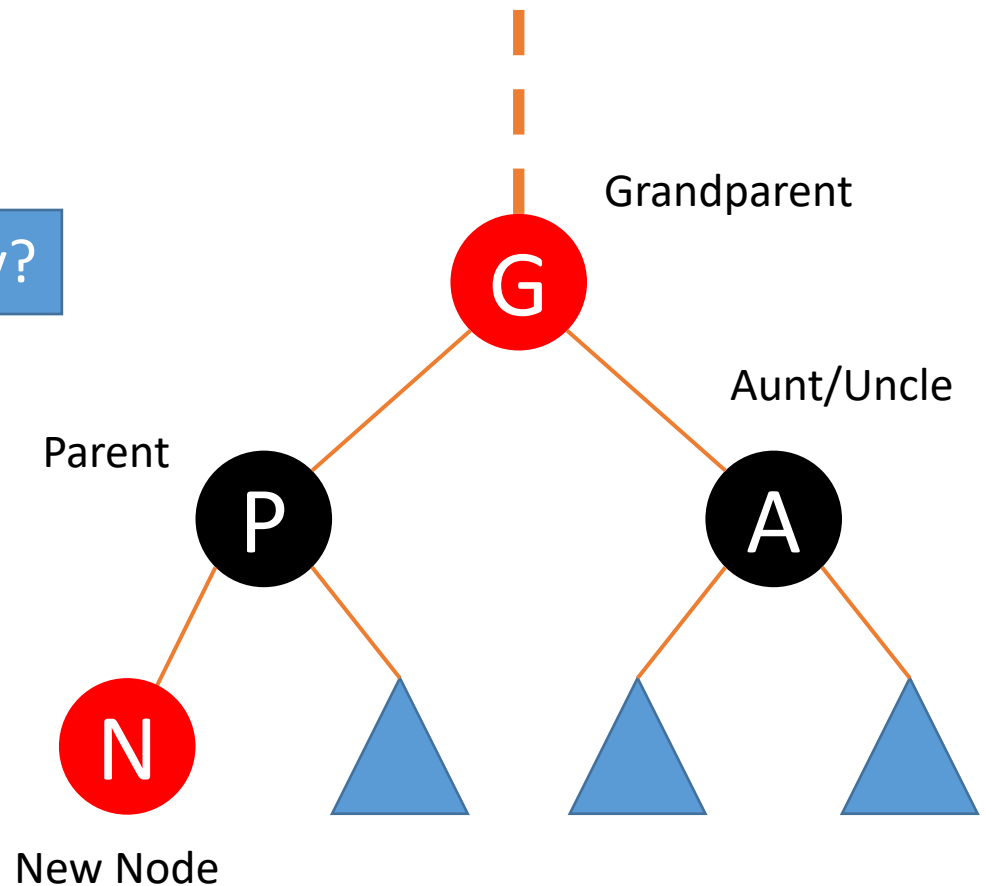


“Aunt” is usually called “Uncle”

Red-Black Trees, Inserting a Node

Move the black color down

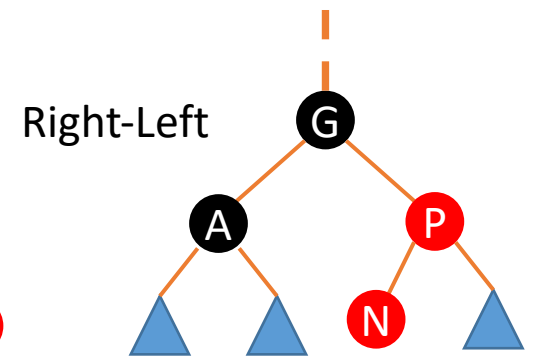
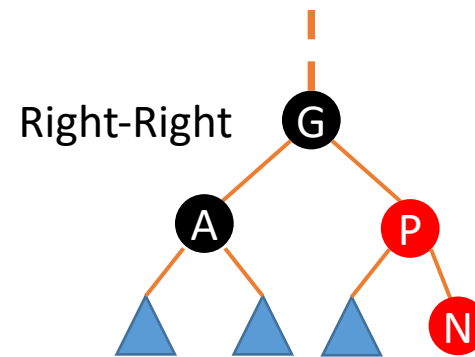
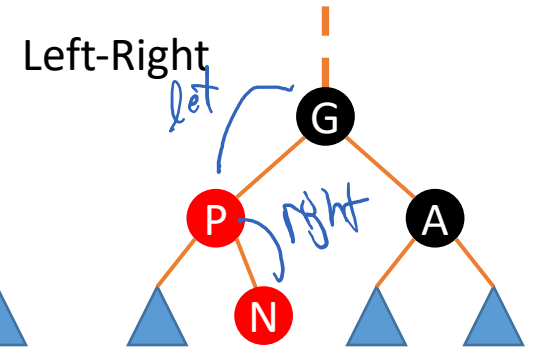
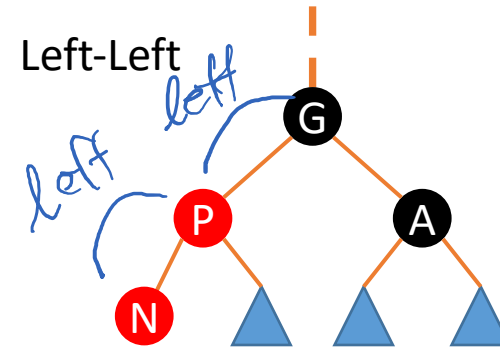
1. Insert the new node (always insert as a leaf) Why?
2. If the inserted node is the root, then color it black, otherwise color it red Why?
3. If the new node is not root and its parent is black, then we are done
4. Otherwise, look at the node's aunt
 - a) If aunt is red
 - I. Change color of parent and aunt to black
 - II. Change color of the new node and the grandparent to red
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“Aunt” is usually called “Uncle”

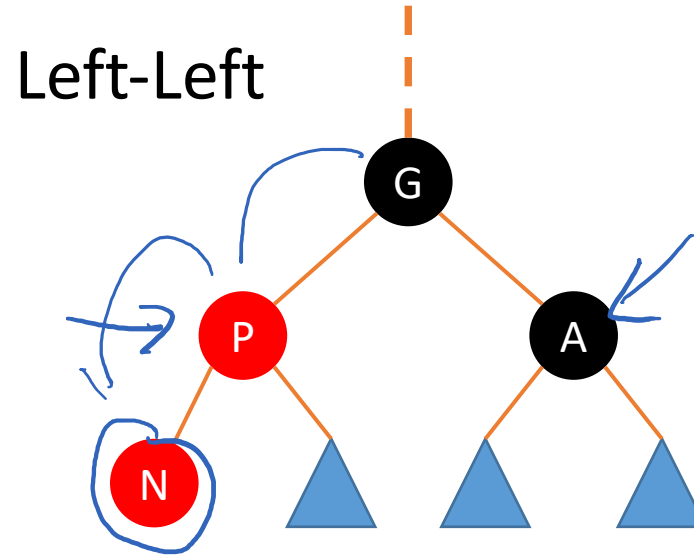
Red-Black Trees, Inserting a Node

1. Insert the new node
(always insert as a leaf)
2. If the inserted node is the root, then
color it black, otherwise color it red
3. If the new node is not root and its
parent is black, then we are done
4. Otherwise, look at the node's aunt
 - a) If aunt is red
 - I. Put the new node, its parent, and the
grandparent "in order" with the middle
node as the root
 - II. We have four possibilities for the current
positions of N, P, and G
 - b) If aunt is black

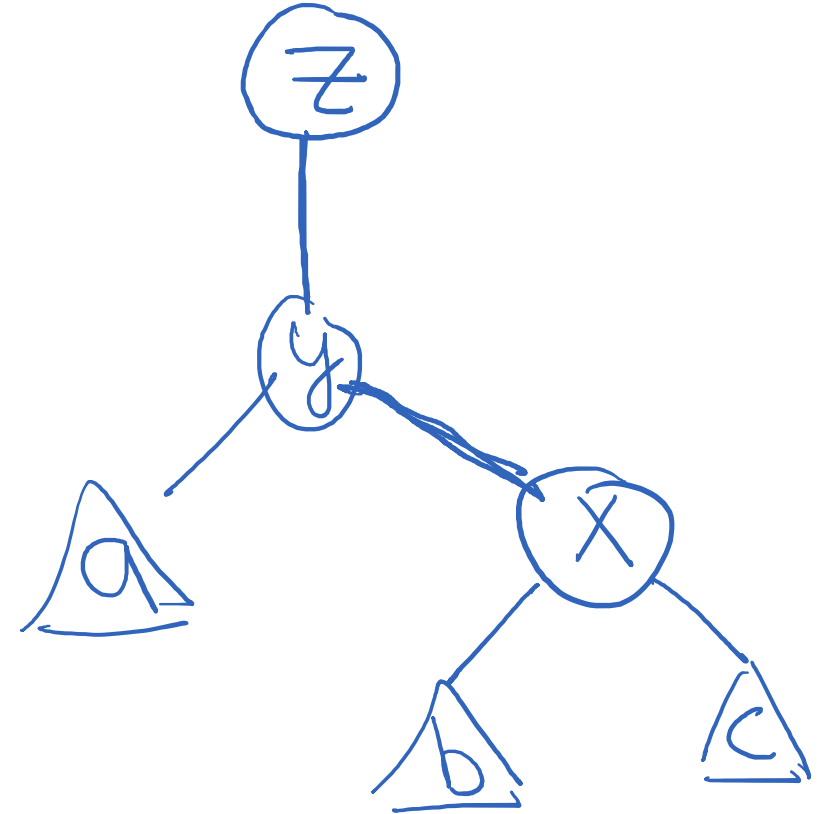
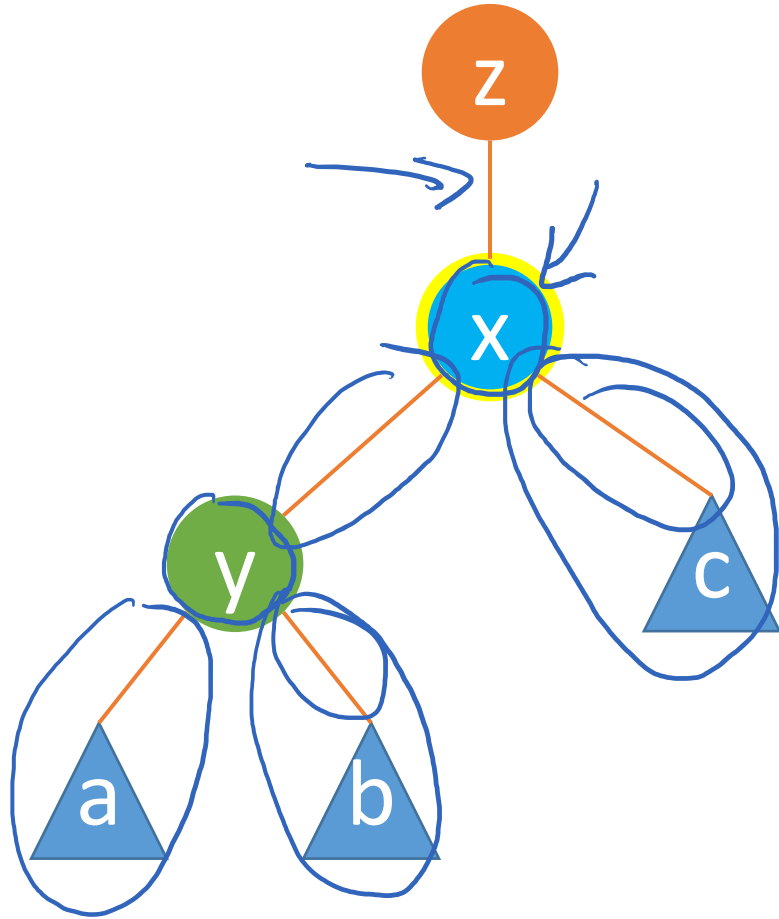


Red-Black Trees, Inserting a Node: Left-Left

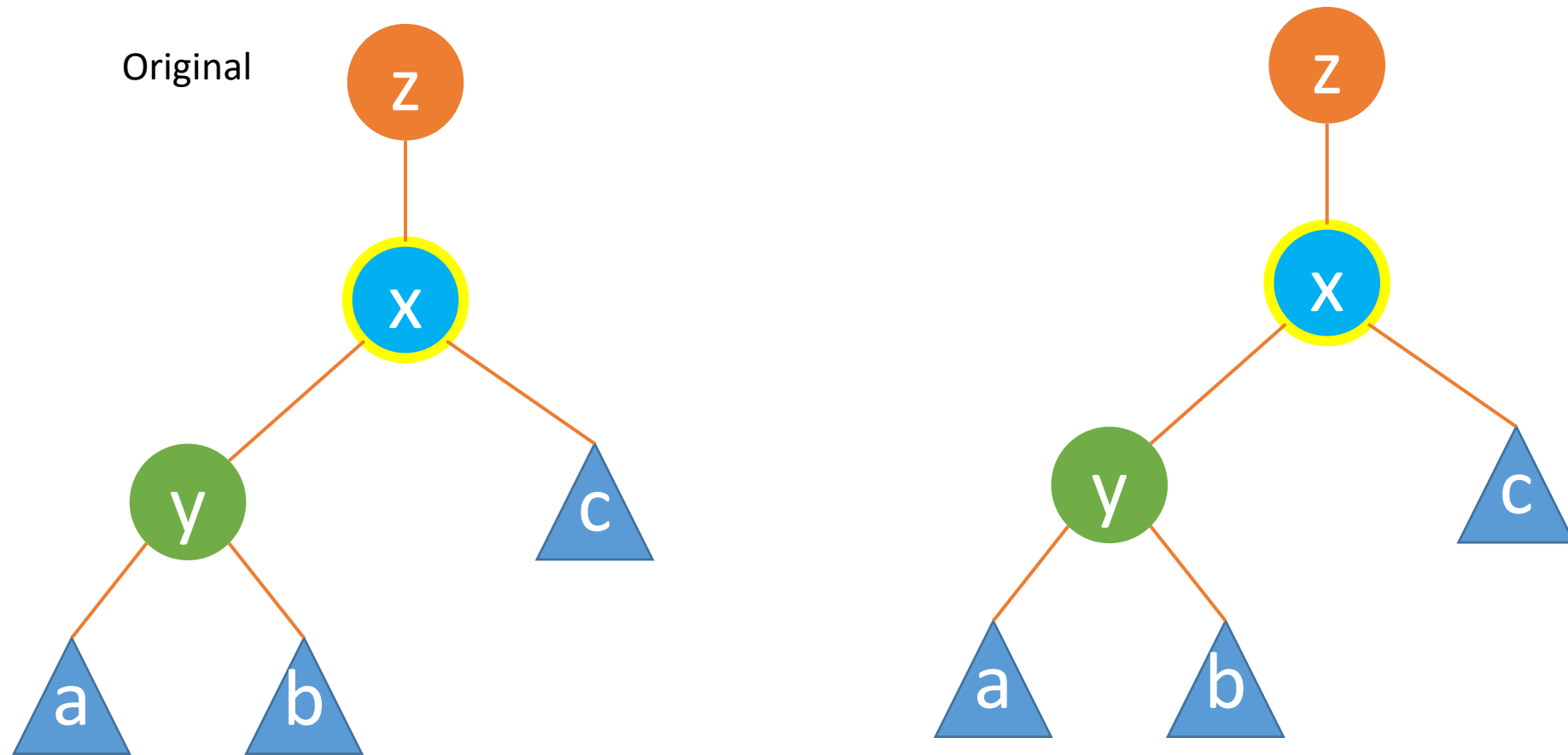
1. Right **rotate** around the grandparent



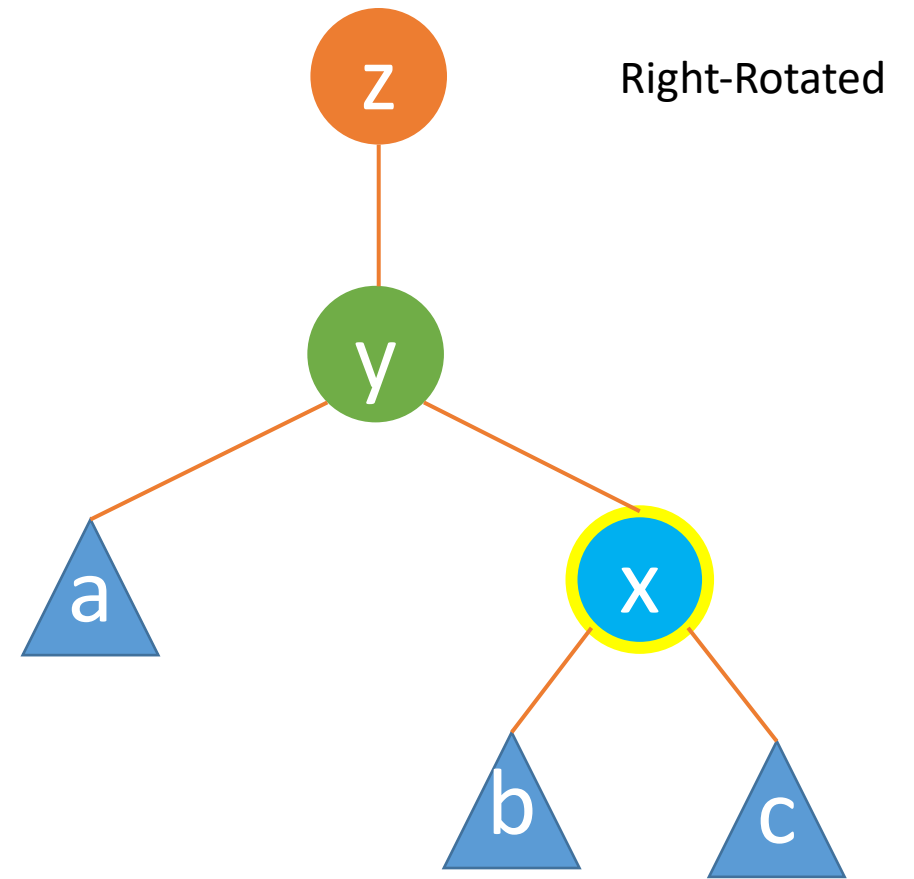
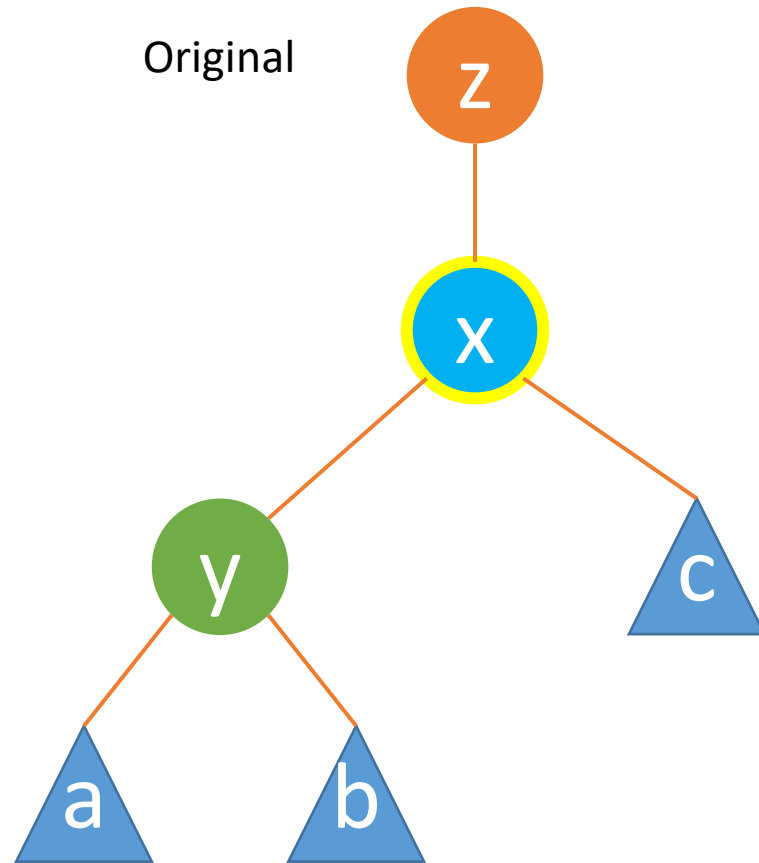
Tree Rotations: Right



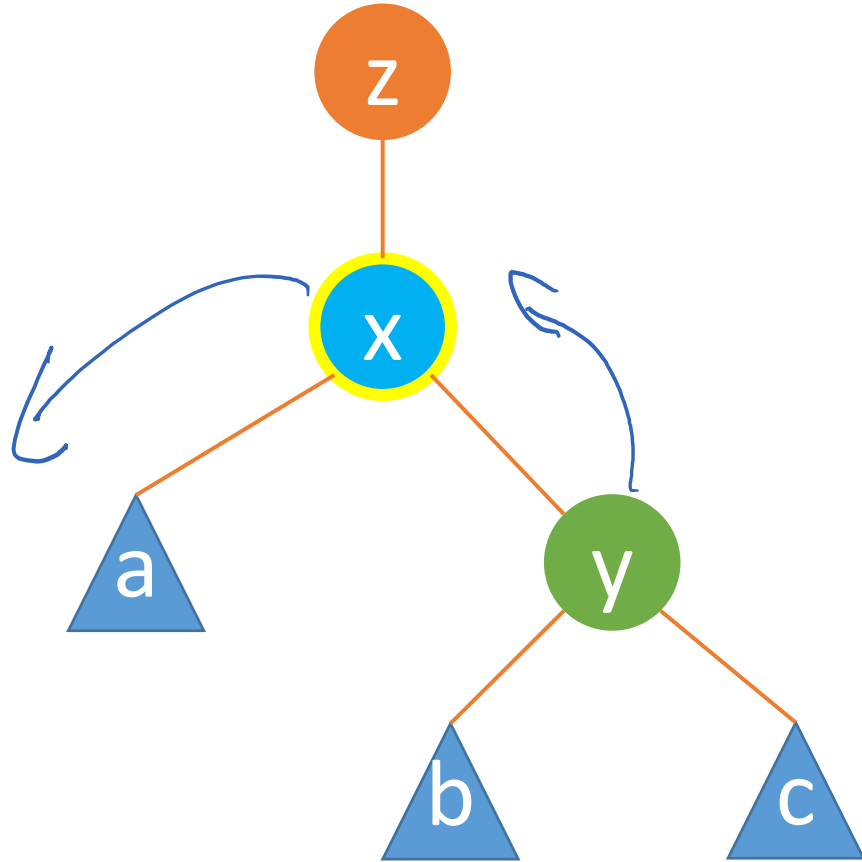
Tree Rotations: Right



Tree Rotations: Right

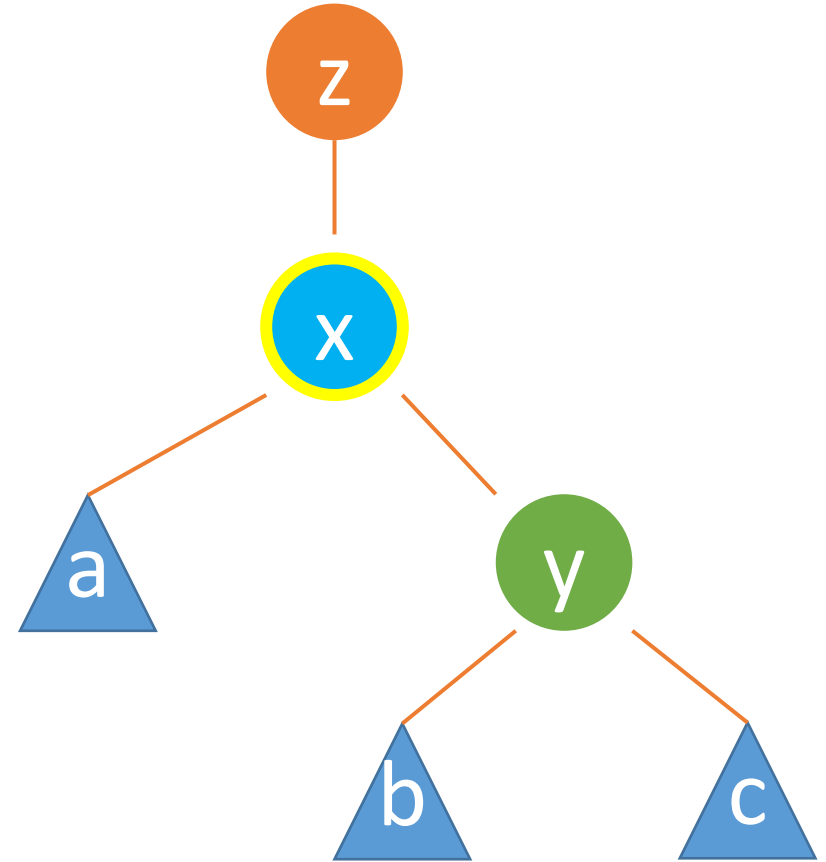
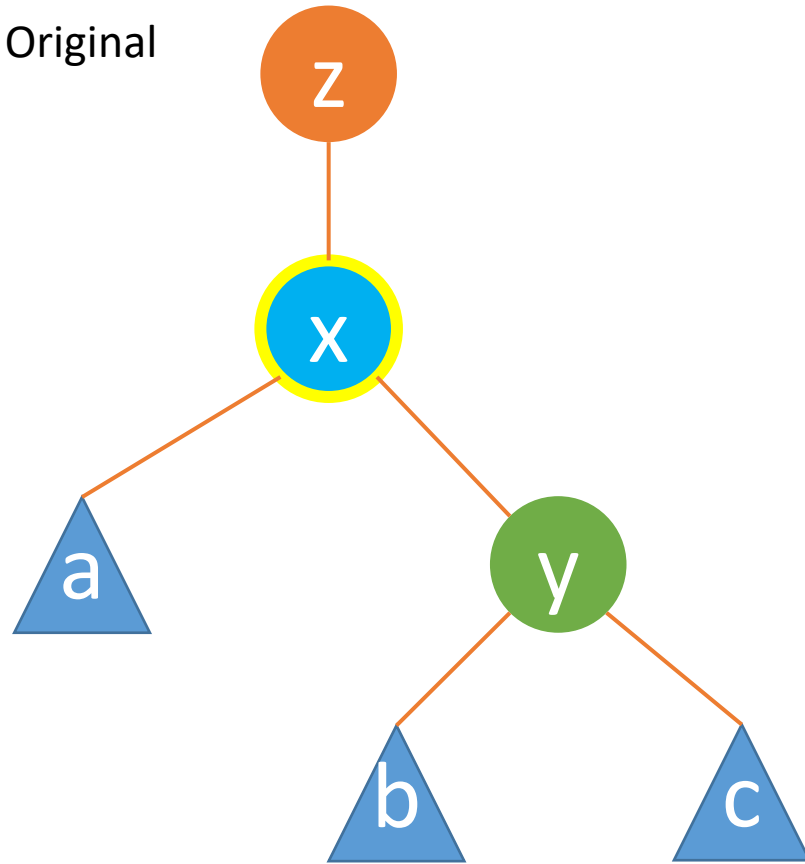


Tree Rotations: Left



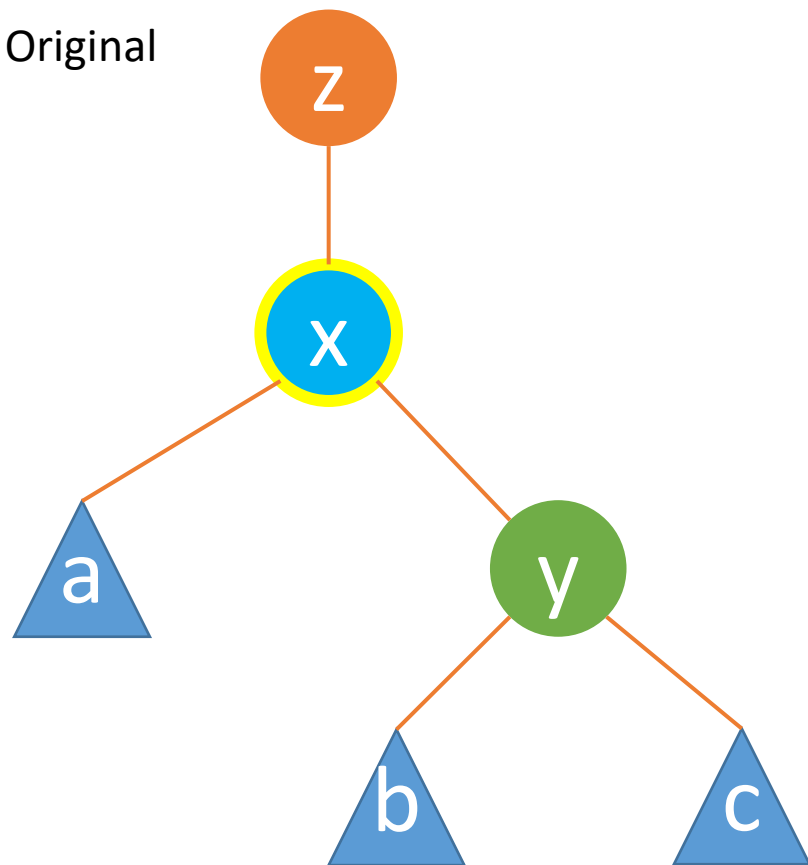
Tree Rotations: Left

Original

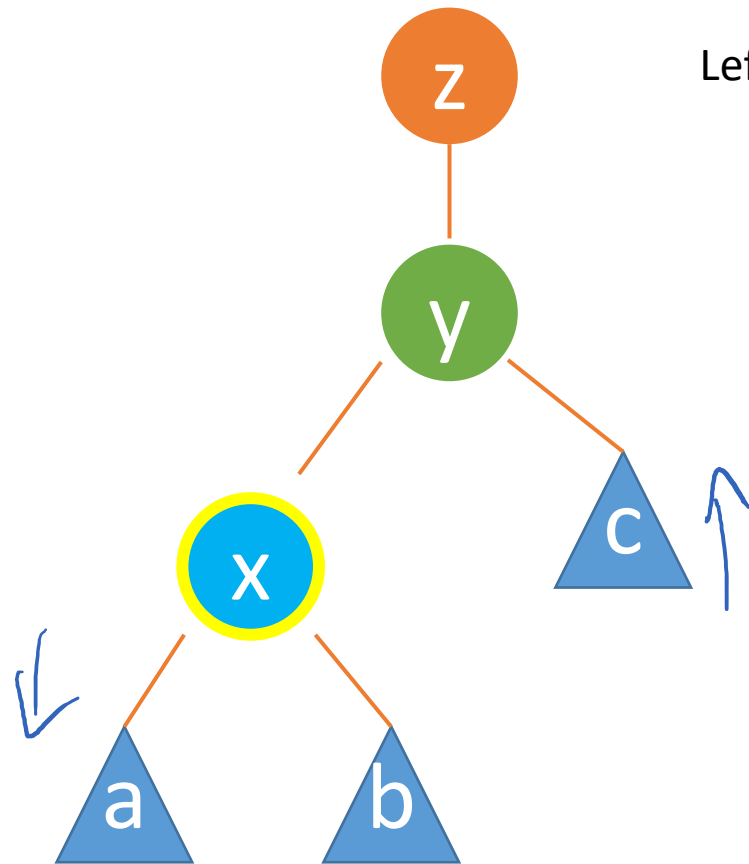


Tree Rotations: Left

Original

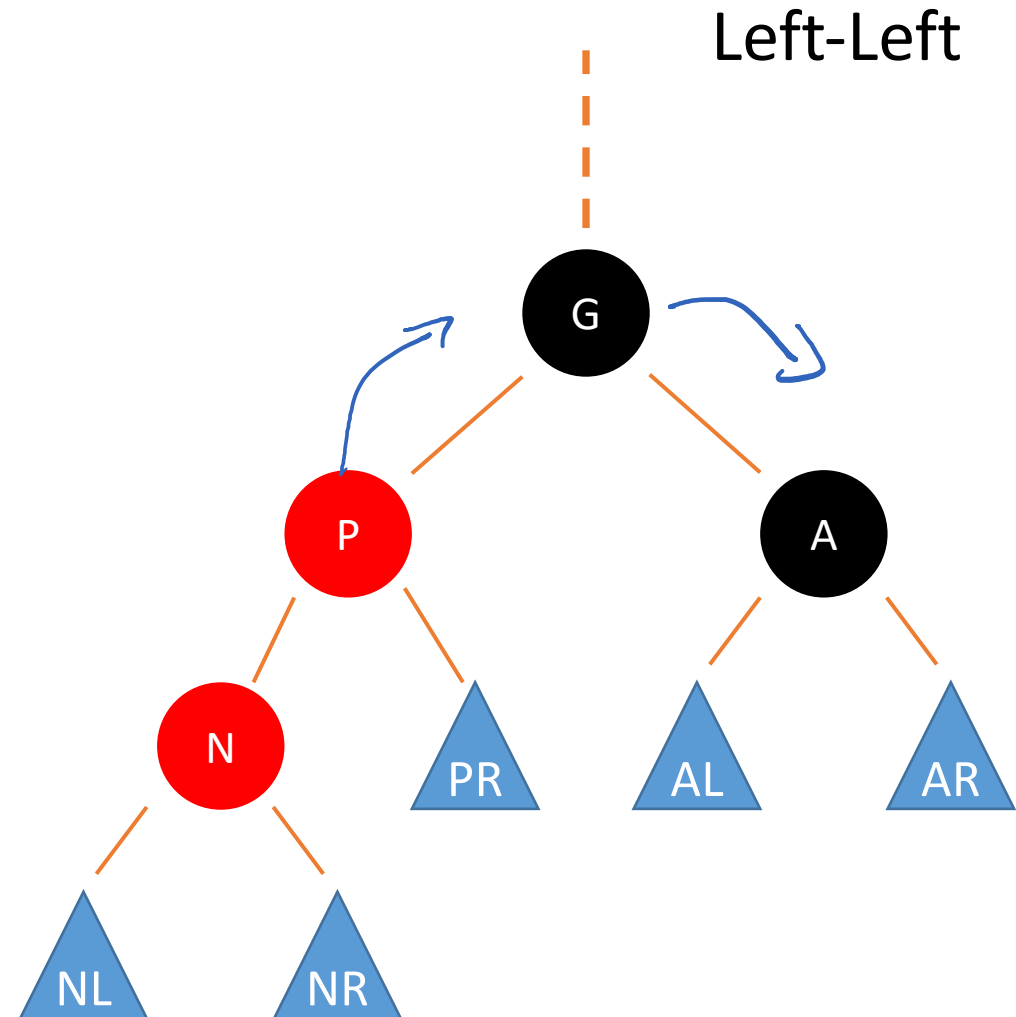


Left-Rotated



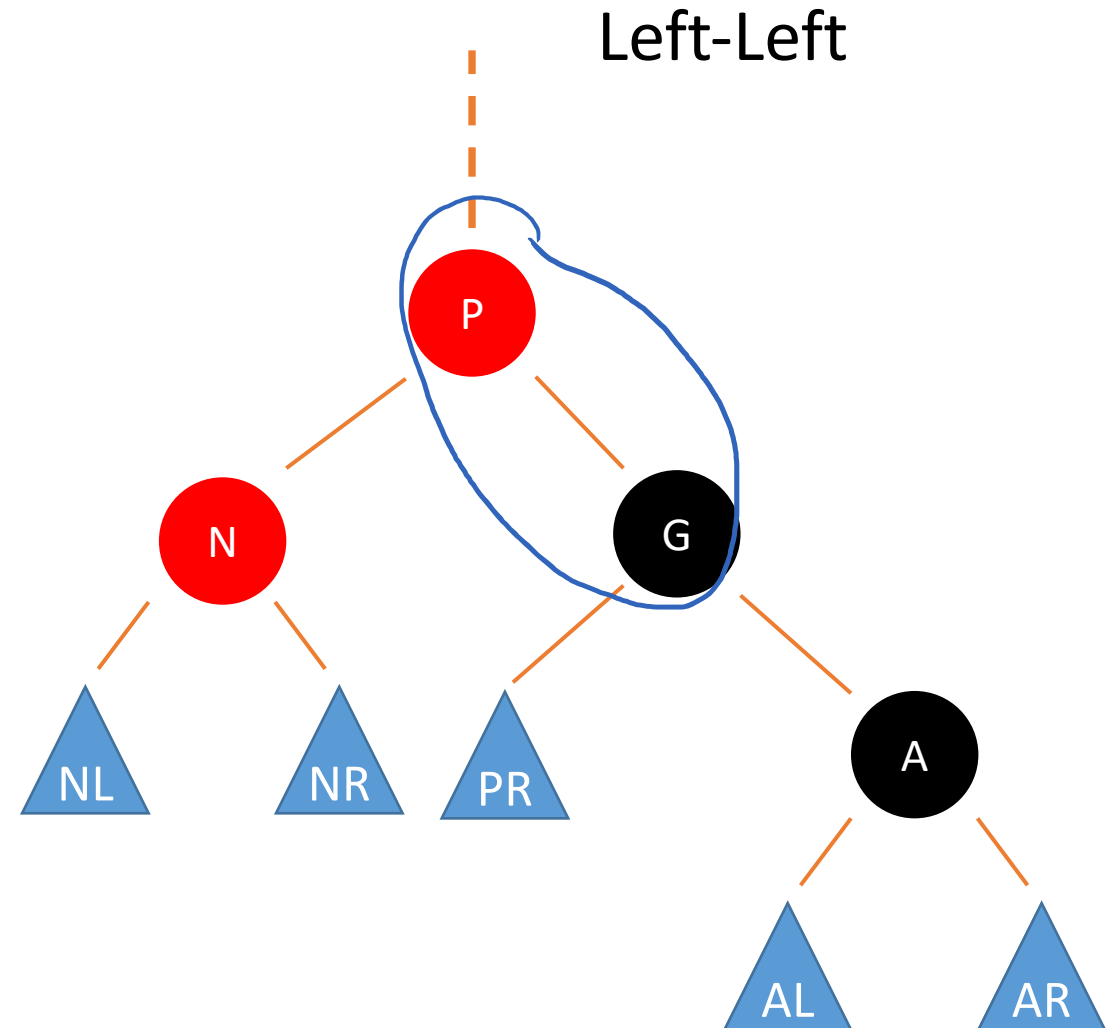
Red-Black Trees, Inserting a Node: Left, Left

1. Right **rotate** around the grandparent



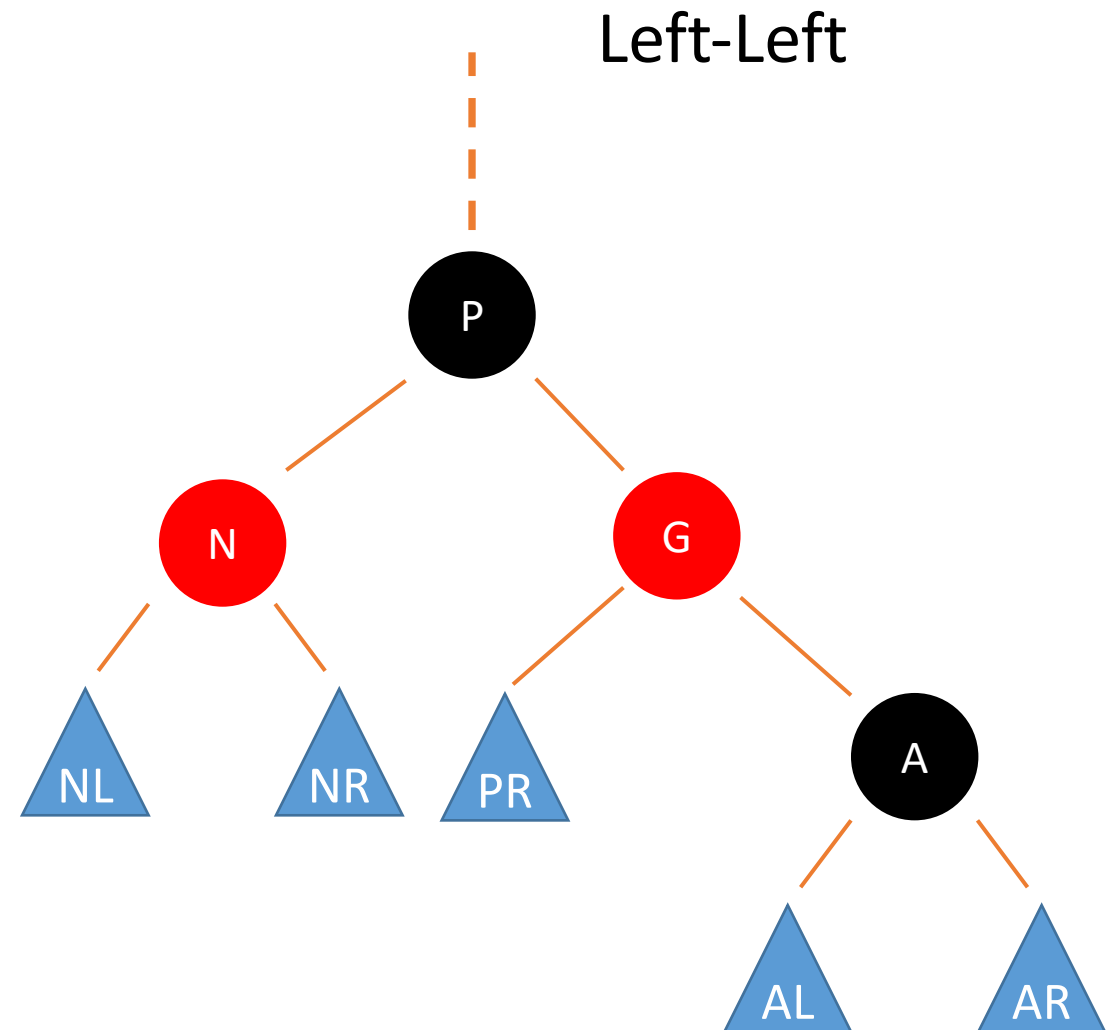
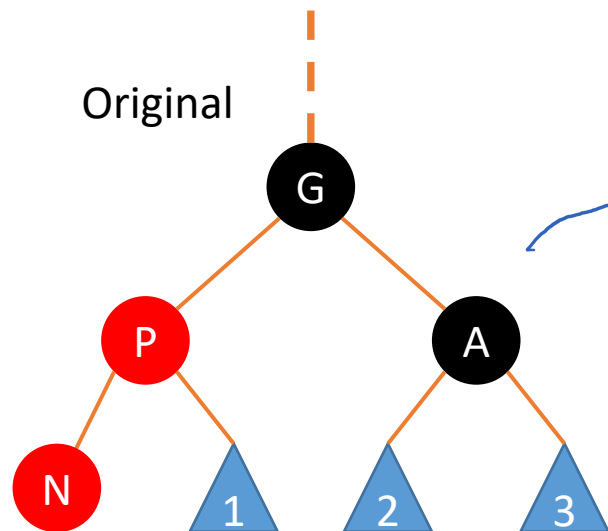
Red-Black Trees, Inserting a Node: Left, Left

1. Right **rotate** around the grandparent
2. Swap the colors of the grandparent and the parent



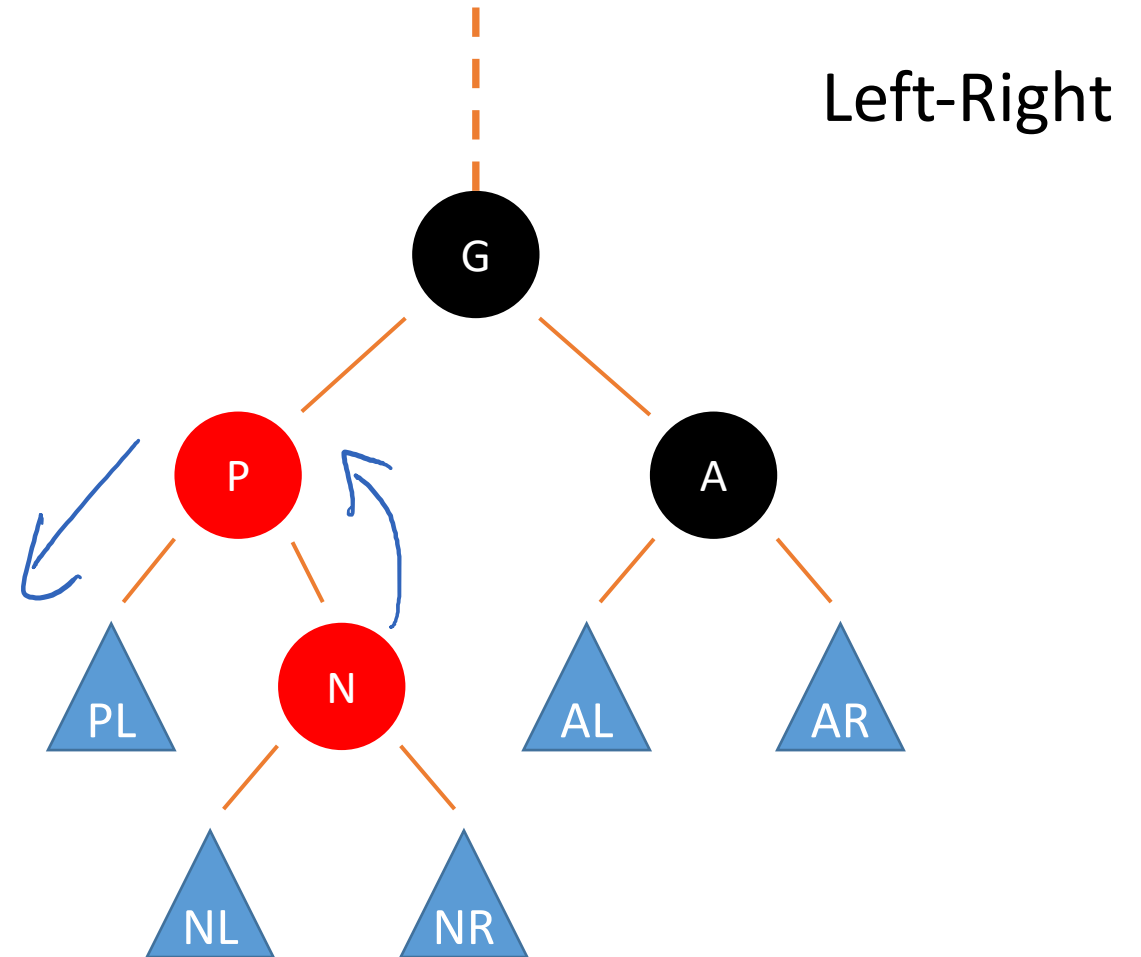
Red-Black Trees, Inserting a Node: Left, Left

1. Right **rotate** around the grandparent
2. Swap the colors of the grandparent and the parent



Red-Black Trees, Inserting a Node: Left, Right

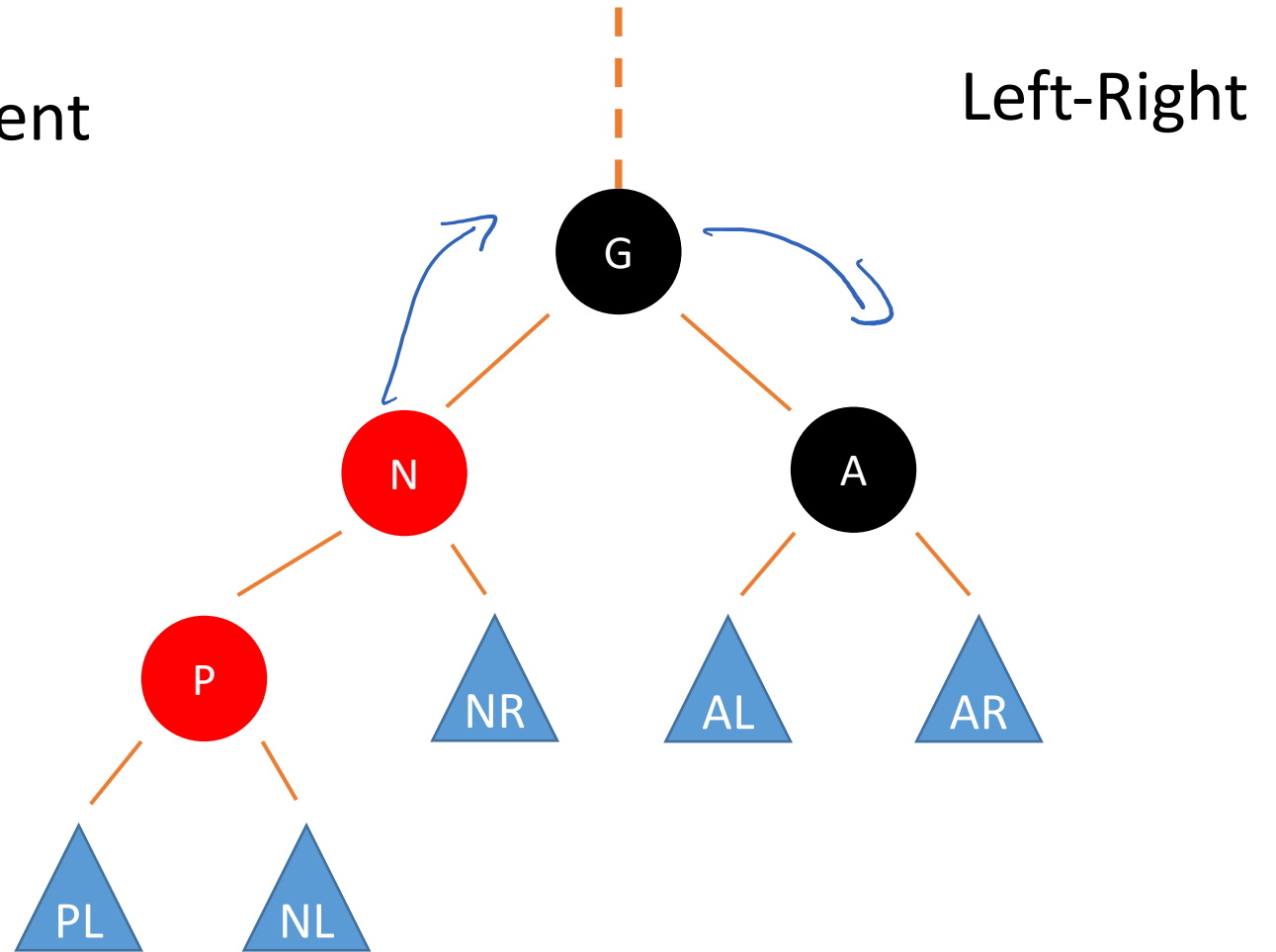
1. Left rotate around the parent



Red-Black Trees, Inserting a Node: Left, Right

1. Left rotate around the parent

2. Right rotate around the grandparent

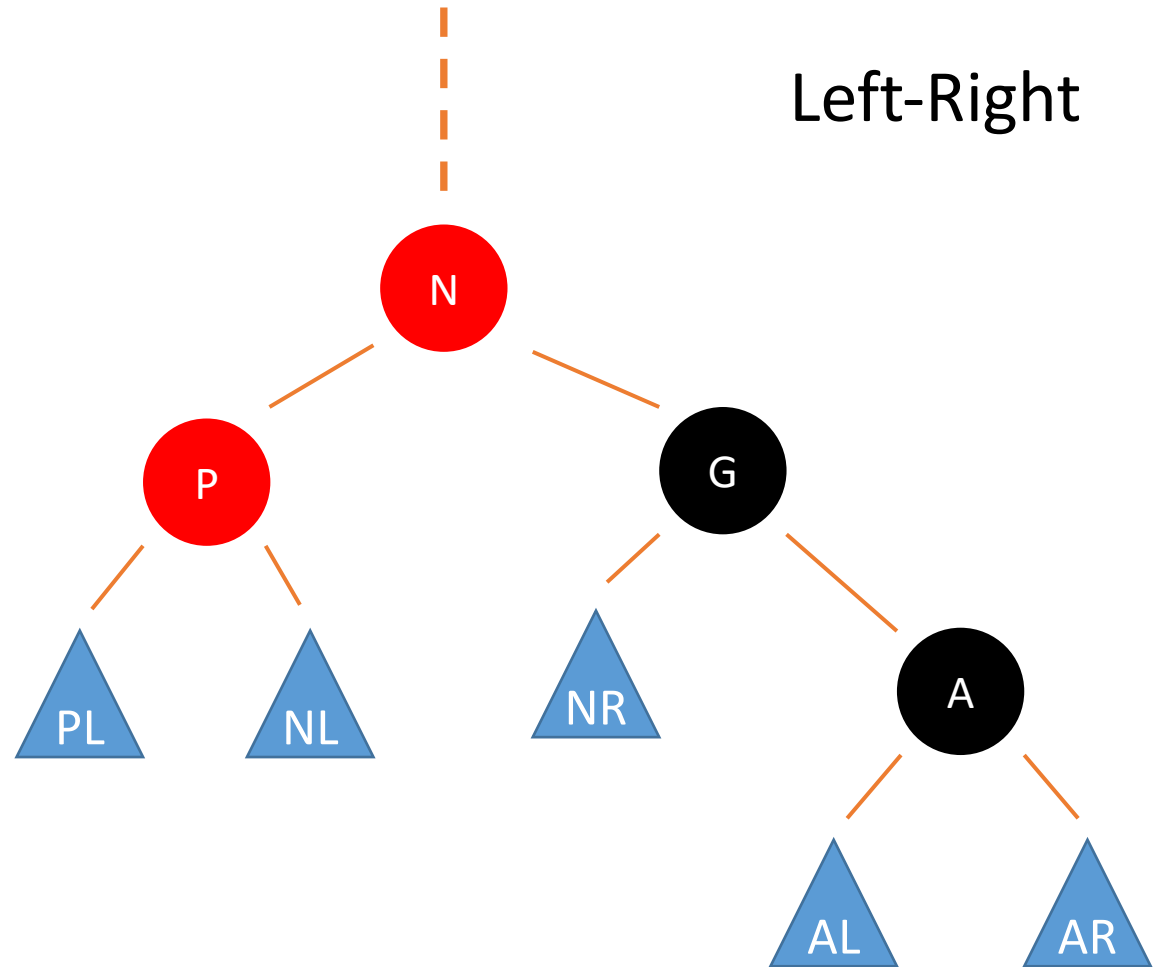


Red-Black Trees, Inserting a Node: Left, Right

1. Left rotate around the parent

2. Right rotate around the grandparent

3. Swap the colors of the grandparent and the new node

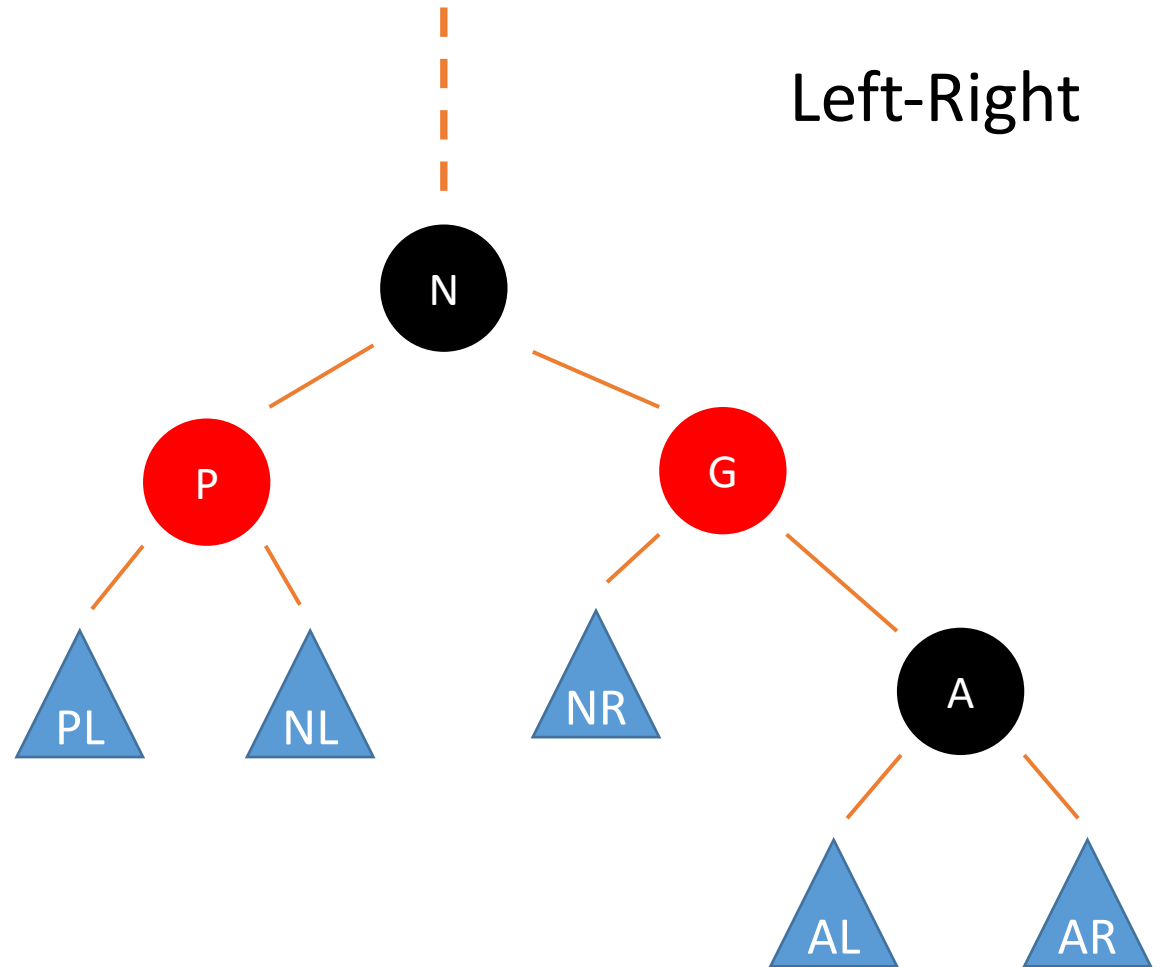


Red-Black Trees, Inserting a Node: Left, Right


1. Left rotate around the parent

2. Right rotate around the grandparent

3. Swap the colors of the grandparent and the new node



Red-Black Trees, Inserting a Node

- What about the Right-Right and Right-Left options?
- They are the **inverse** of the cases we've just covered.
- What are the running times of these procedures?
 - Inserting the new node?
 - Recoloring?
 - Restructuring?
- We're not going to cover deletion, but what are your thoughts? 
 - Operation? (<http://www.geeksforgeeks.org/red-black-tree-set-3-delete-2/>)
 - Running time?

FUNCTION RBTreeInsert(tree, new_node)

Search for position of new_node

parent = **NONE**

current_node = tree.root

WHILE current_node **!=** **NONE**

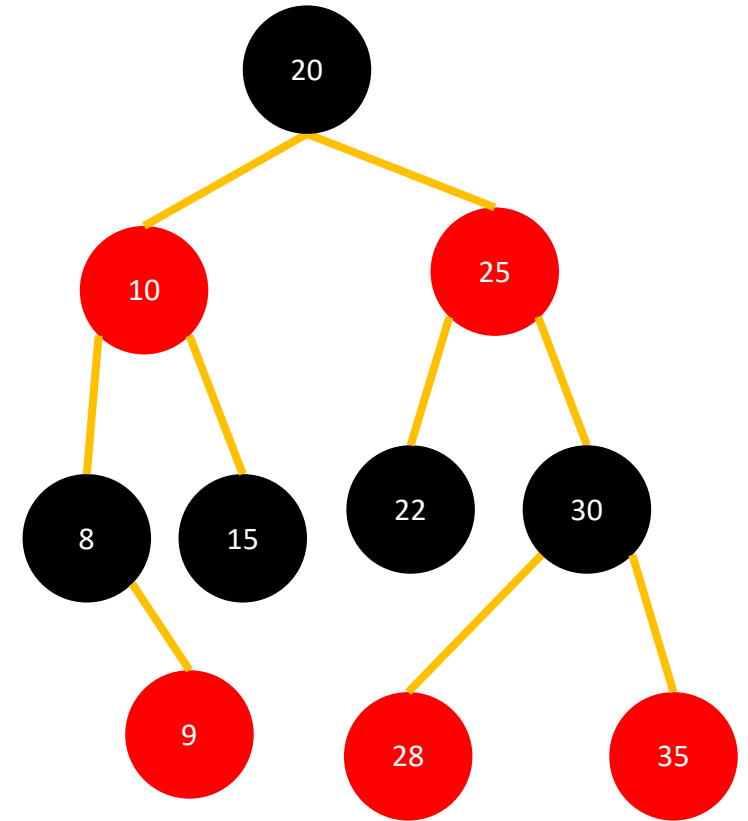
 parent = current_node

IF new_node.key < current_node.key
 current_node = current_node.left

ELSE

 current_node = current_node.right

new_node.parent = parent



FUNCTION RBTreeInsert(tree, new_node)

Search for position of new_node

...

Insert new_node as root or left/right child

IF parent == NONE

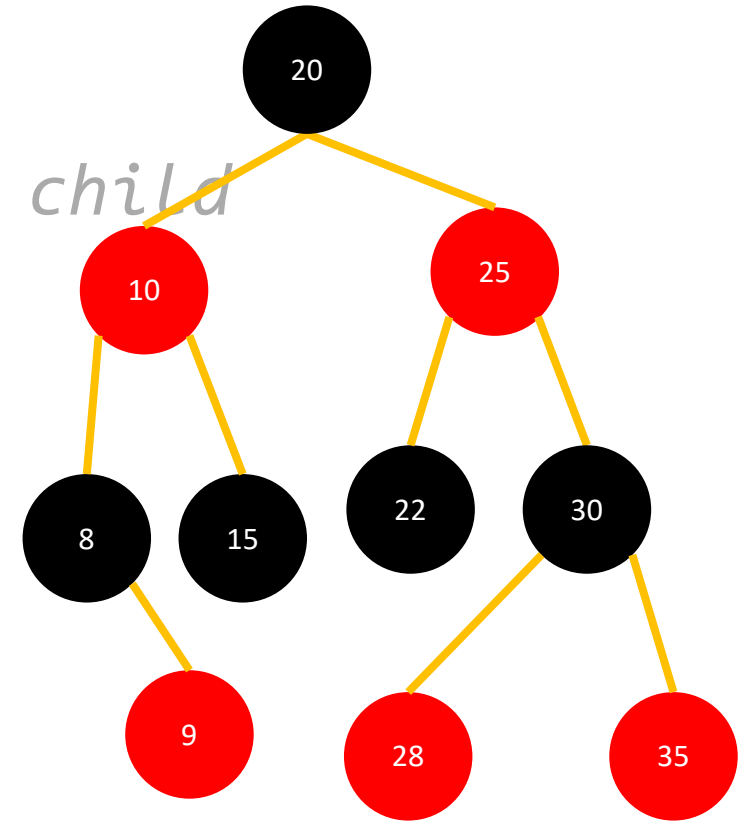
tree.root = new_node

ELSE IF new_node.key < parent.key

parent.left = new_node

ELSE

parent.right = new_node



FUNCTION **RBTreeInsert**(tree, new_node)

Search for position of new_node

...

Insert new_node as root or left/right child

...

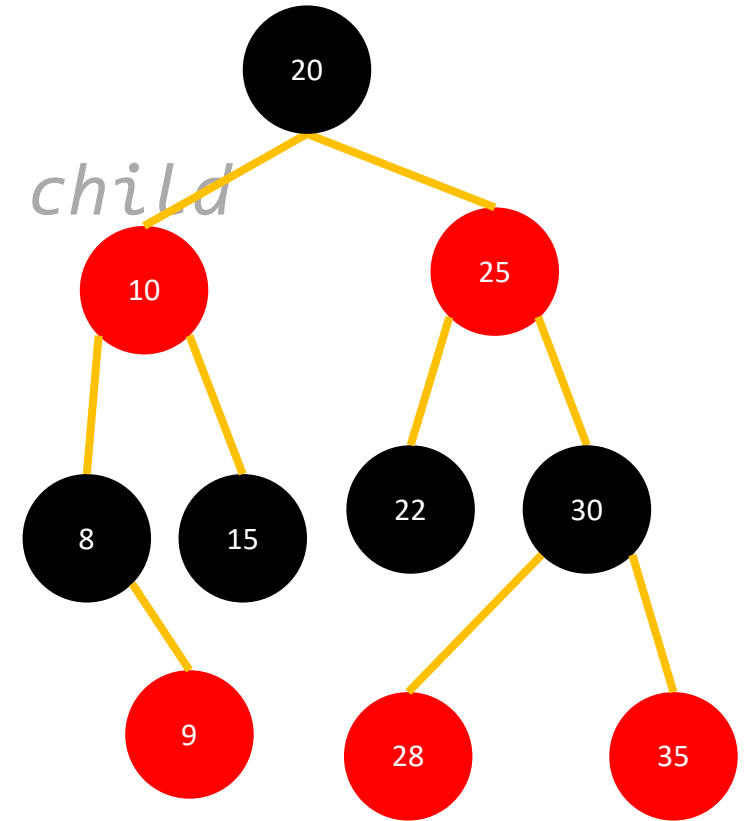
Initialize the new_node

new_node.left = **NONE**

new_node.right = **NONE**

new_node.color = **RED**

RBTreeFixColors(tree, new_node)




```
FUNCTION RBTreeFixColors(tree, node)
```

```
  WHILE node.parent.color == RED
```

```
    # Look for aunt/uncle node
```

```
    IF node.parent == node.parent.parent.left
```

```
      aunt = node.parent.parent.right
```

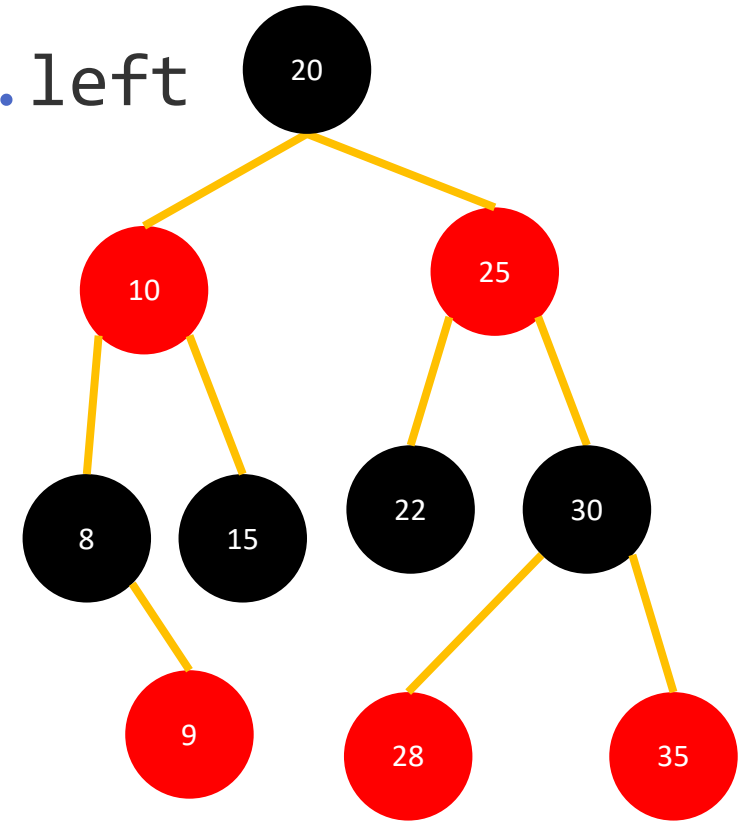
```
      IF aunt.color == RED
```

```
        node.parent.color = BLACK
```

```
        aunt.color = BLACK
```

```
        node.parent.parent.color = RED
```

```
        node = node.parent.parent
```



```
FUNCTION RBTreeFixColors(tree, node)
```

```
    WHILE node.parent.color == RED
```

```
        # Look for aunt/uncle node
```

```
        IF node.parent == node.parent.parent.left
```

```
            aunt = node.parent.parent.right
```

```
            IF aunt.color == RED
```

```
                ...
```

```
            ELSE
```

```
                IF node == node.parent.right
```

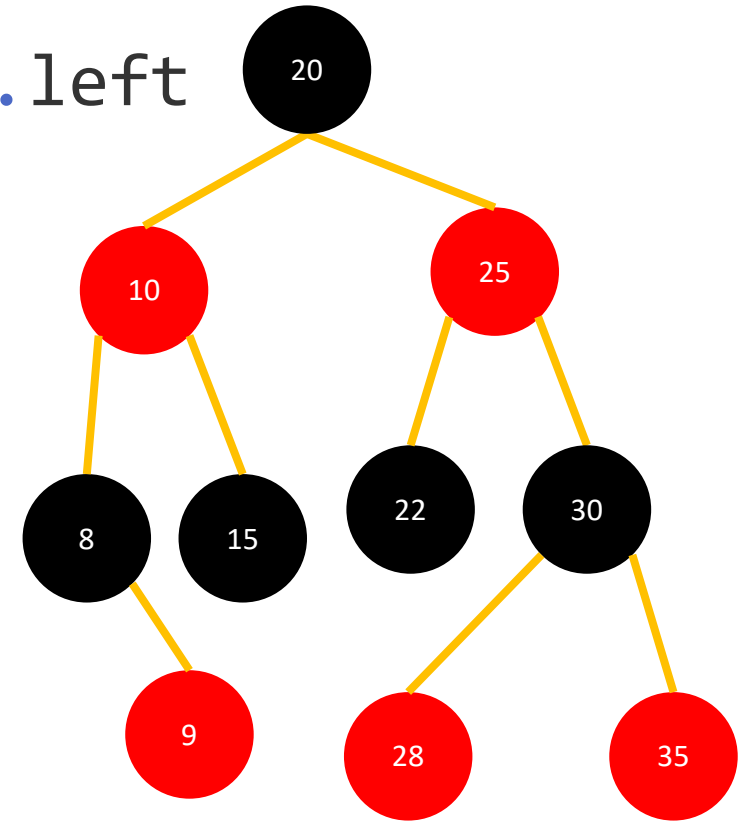
```
                    node = node.parent
```

```
                    LeftRotate(tree, node)
```

```
                    node.parent.color = BLACK
```

```
                    node.parent.parent.color = RED
```

```
                    RightRotate(tree, node.parent.parent)
```



```
FUNCTION RBTreeFixColors(tree, node)
```

```
  WHILE node.parent.color == RED
```

```
    # Look for aunt/uncle node
```

```
    IF node.parent == node.parent.parent.left  
      aunt = node.parent.parent.right
```

```
    ...
```

```
  ELSE
```

```
    aunt = node.parent.parent.left
```

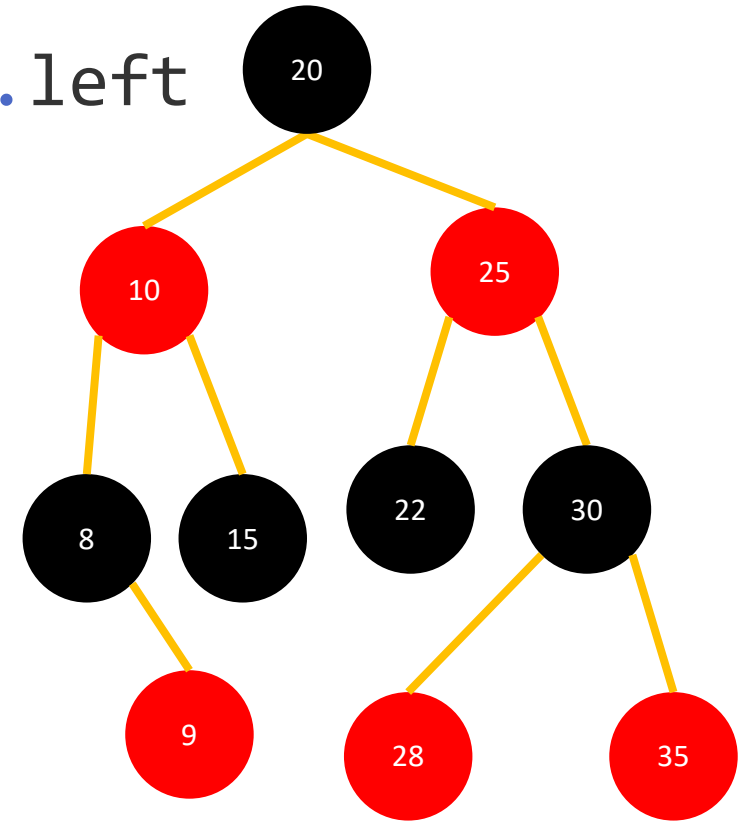
```
    IF aunt.color == RED
```

```
      node.parent.color = BLACK
```

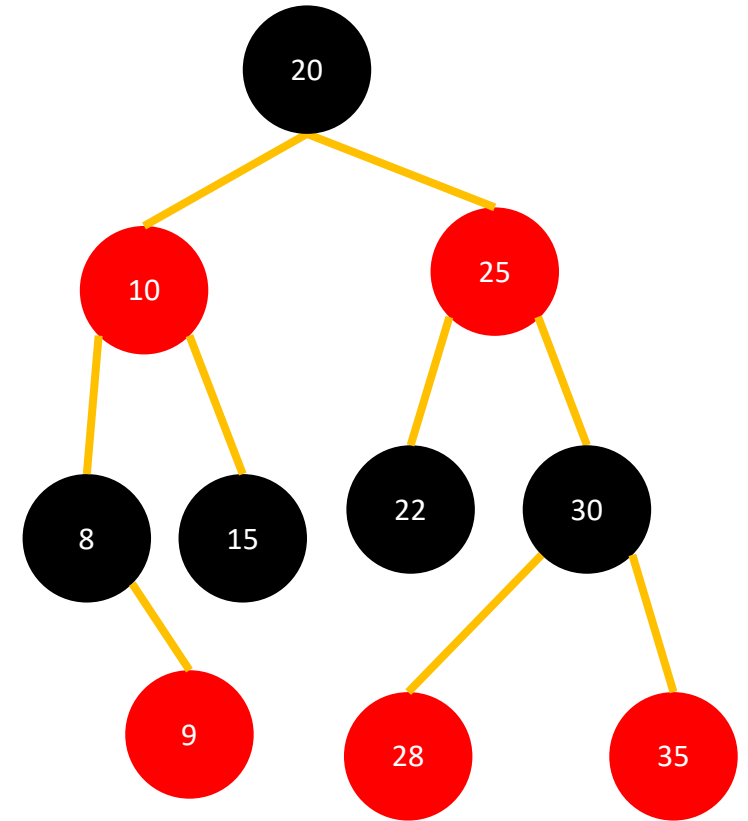
```
      aunt.color = BLACK
```

```
      node.parent.parent.color = RED
```

```
      node = node.parent.parent
```



```
FUNCTION RBTreeFixColors(tree, node)
  WHILE node.parent.color == RED
    # Look for aunt/uncle node
    ...
  ELSE
    aunt = node.parent.parent.left
    ...
  ELSE
    IF node == node.parent.left
      node = node.parent
      RightRotate(tree, node)
    node.parent.color = BLACK
    node.parent.parent.color = RED
    LeftRotate(tree, node.parent.parent)
```



```
FUNCTION RBTreeFixColors(tree, node)
```

```
  WHILE node.parent.color == RED
```

```
    # Look for aunt/uncle node
```

```
    IF node.parent == node.parent.parent.left
```

```
      aunt = node.parent.parent.right
```

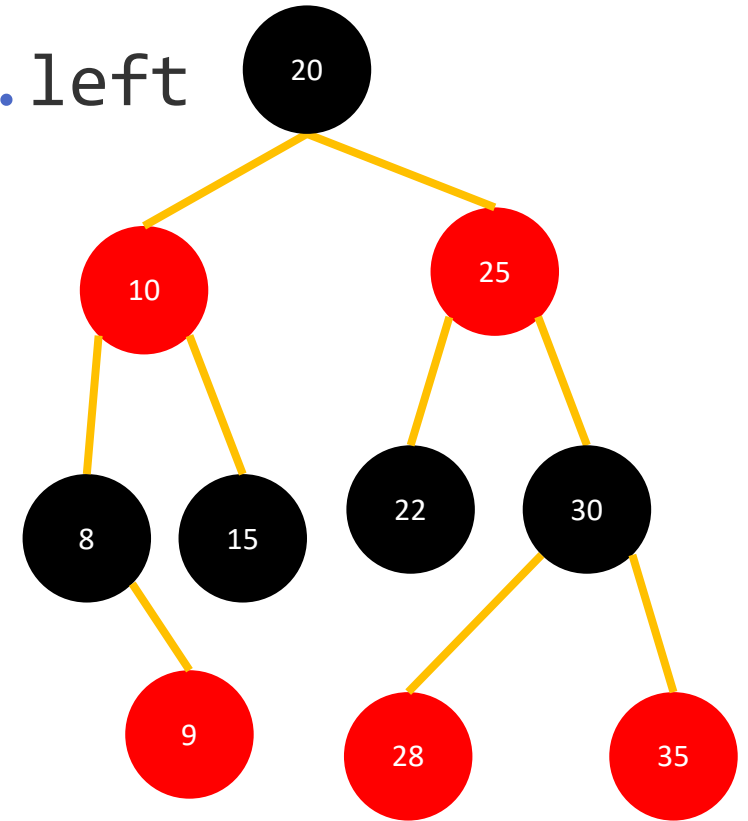
```
      ...
```

```
    ELSE
```

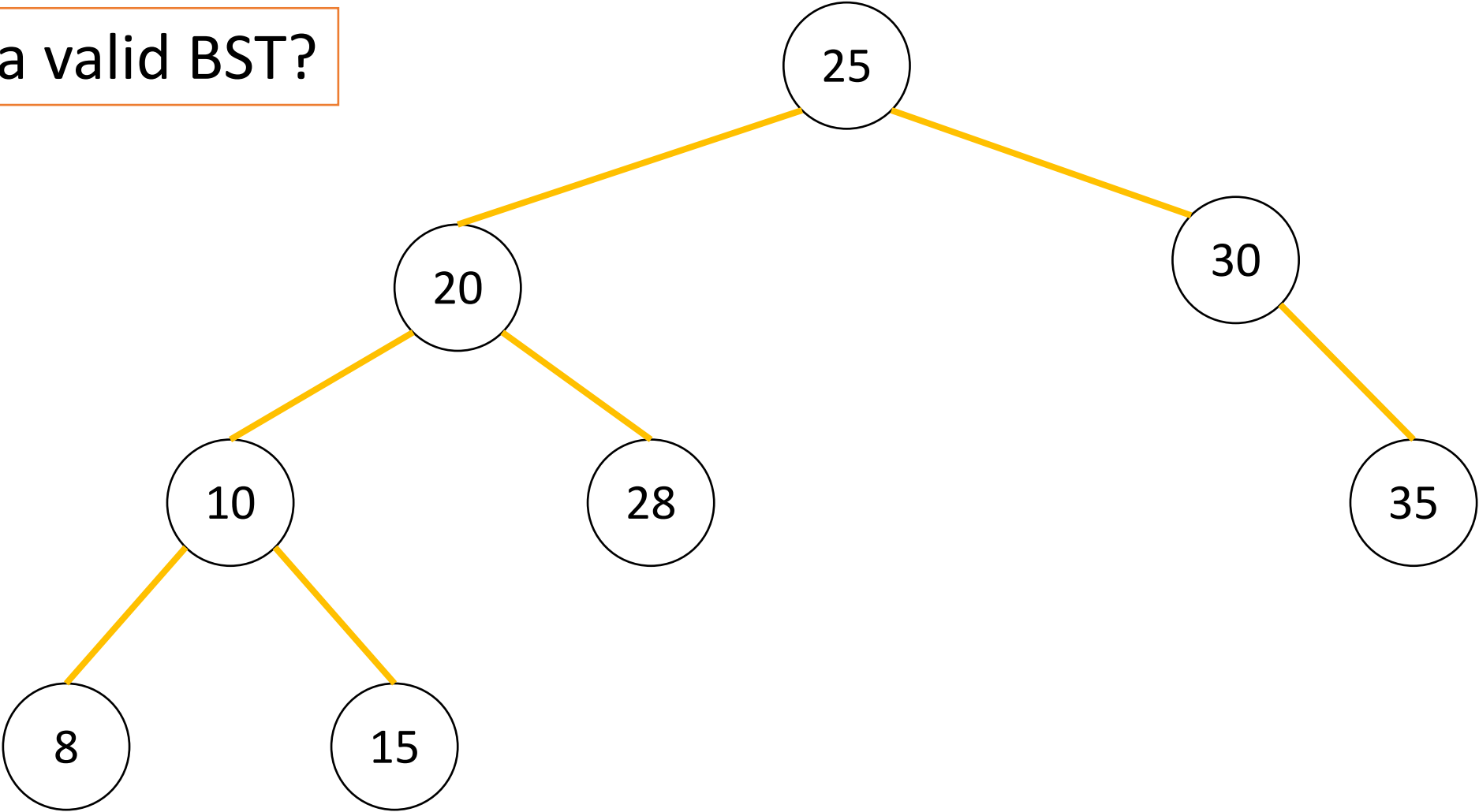
```
      aunt = node.parent.parent.left
```

```
      ...
```

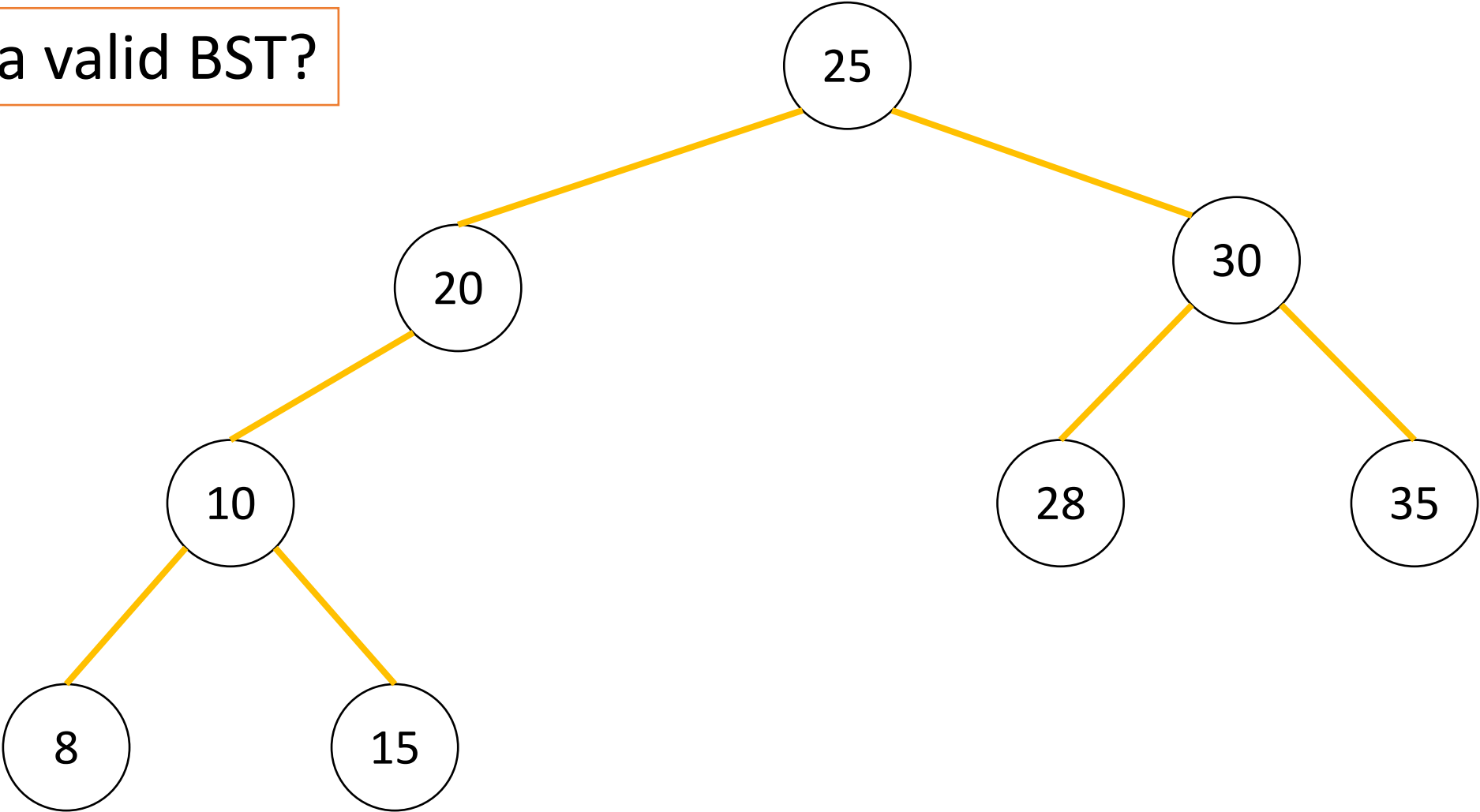
```
  tree.root.color = BLACK
```



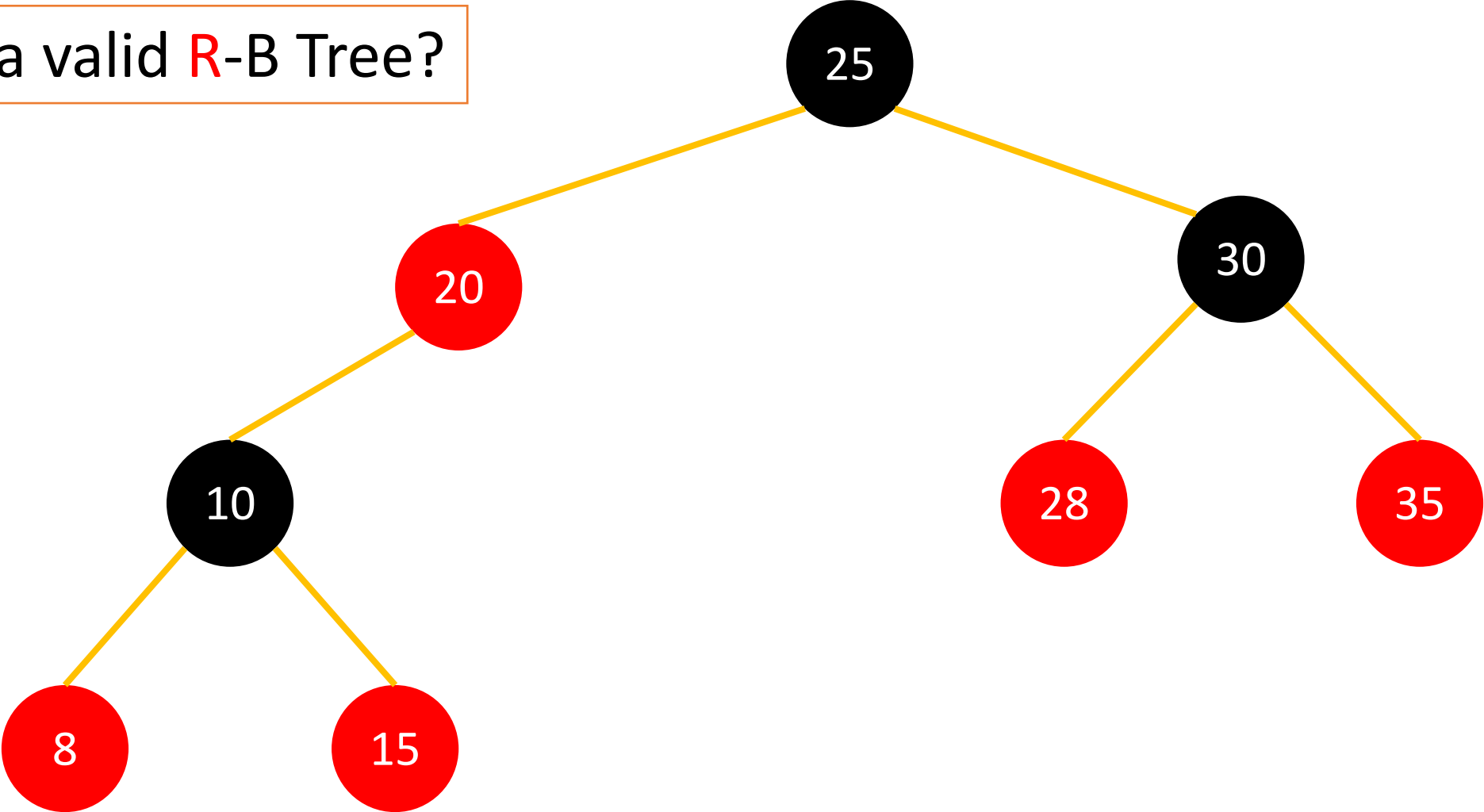
Is this a valid BST?



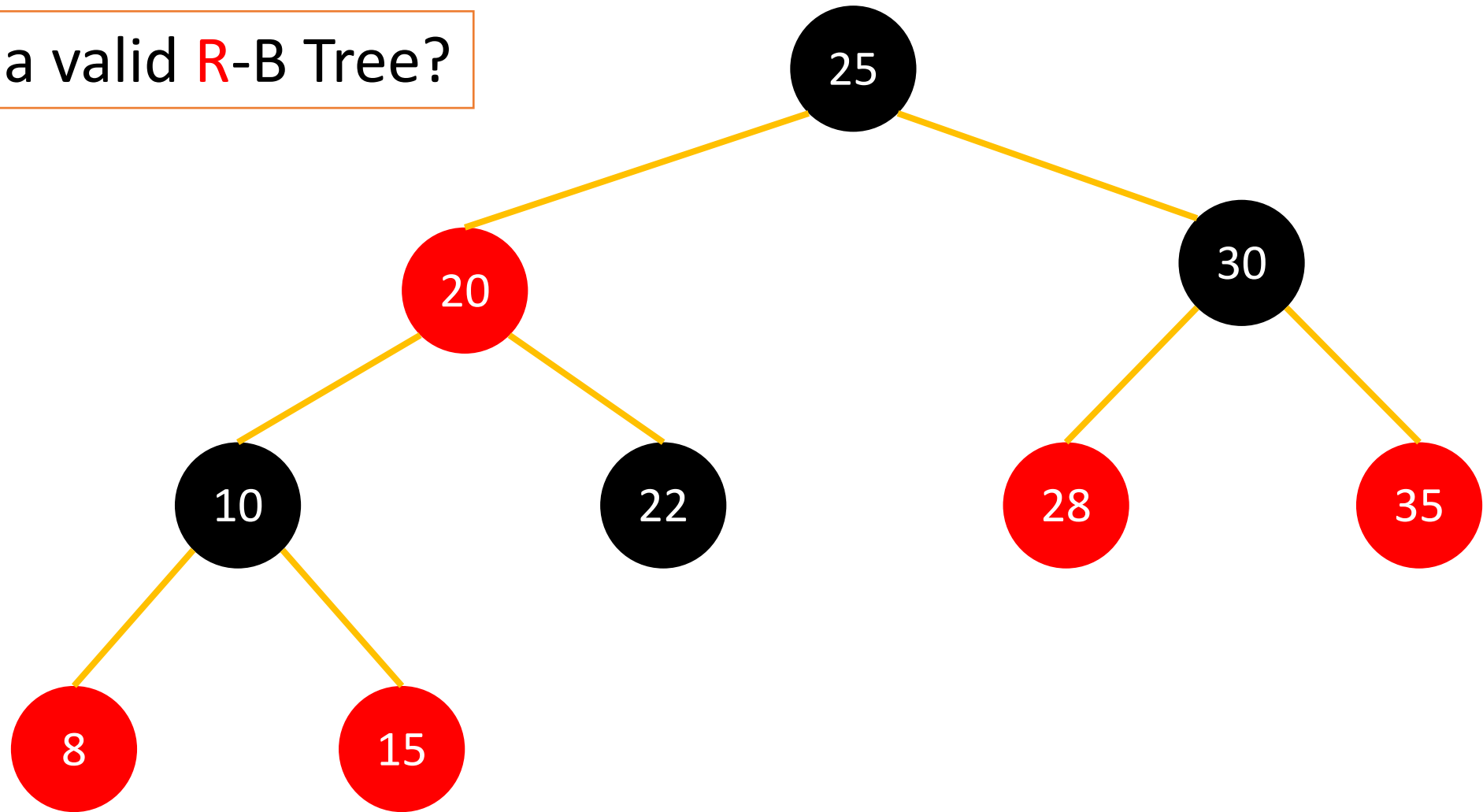
Is this a valid BST?



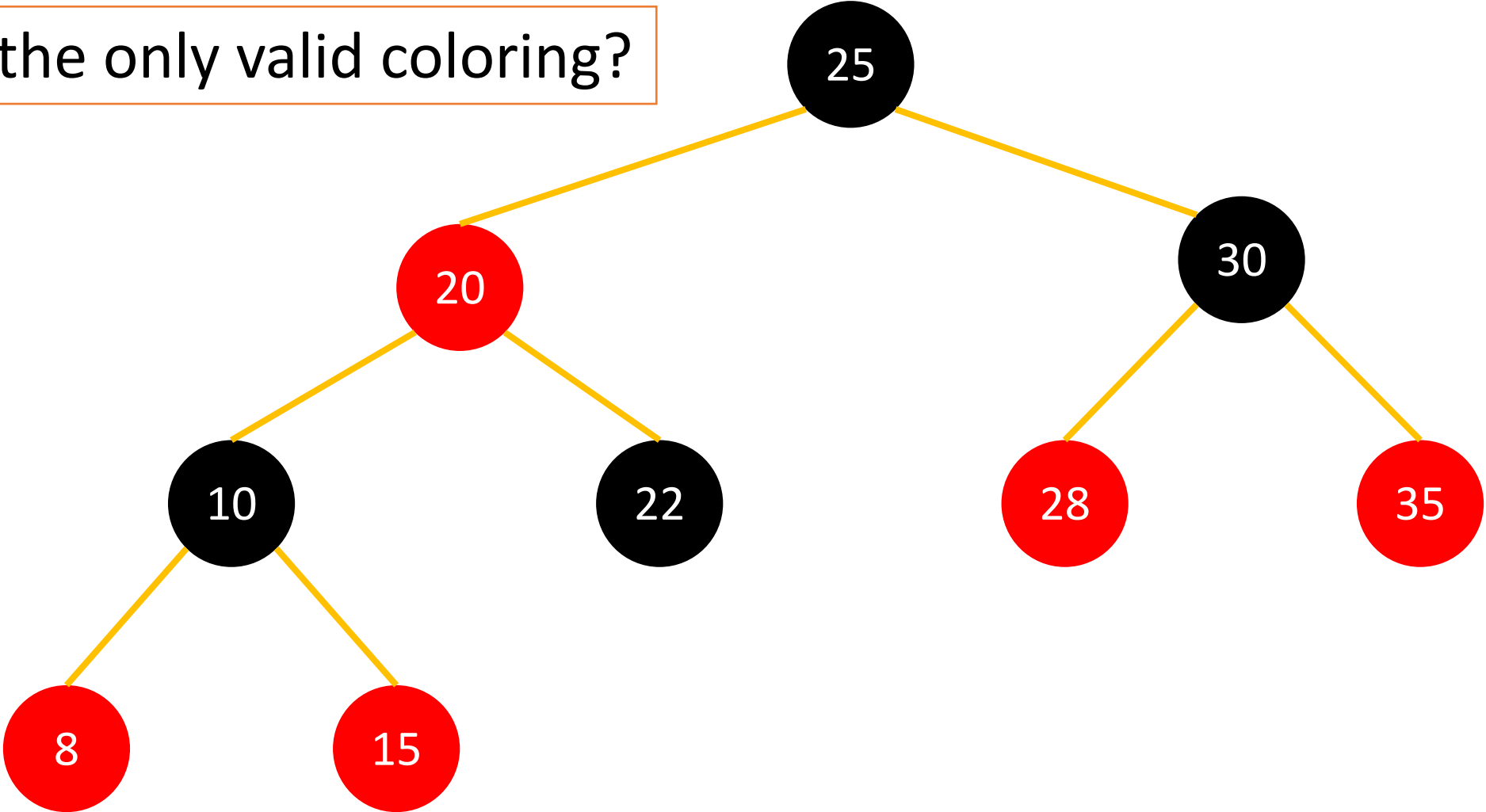
Is this a valid **R**-B Tree?



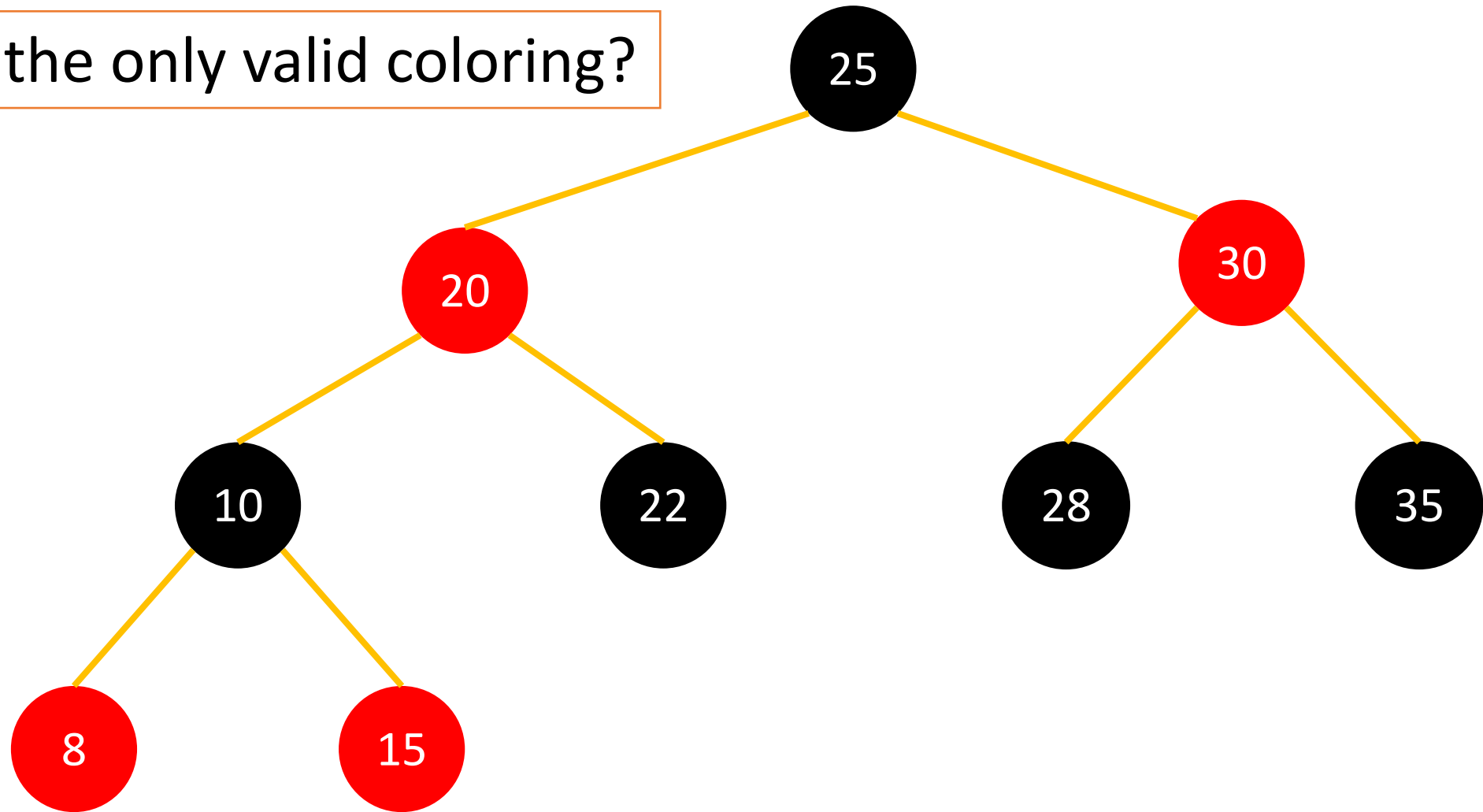
Is this a valid **R**-B Tree?



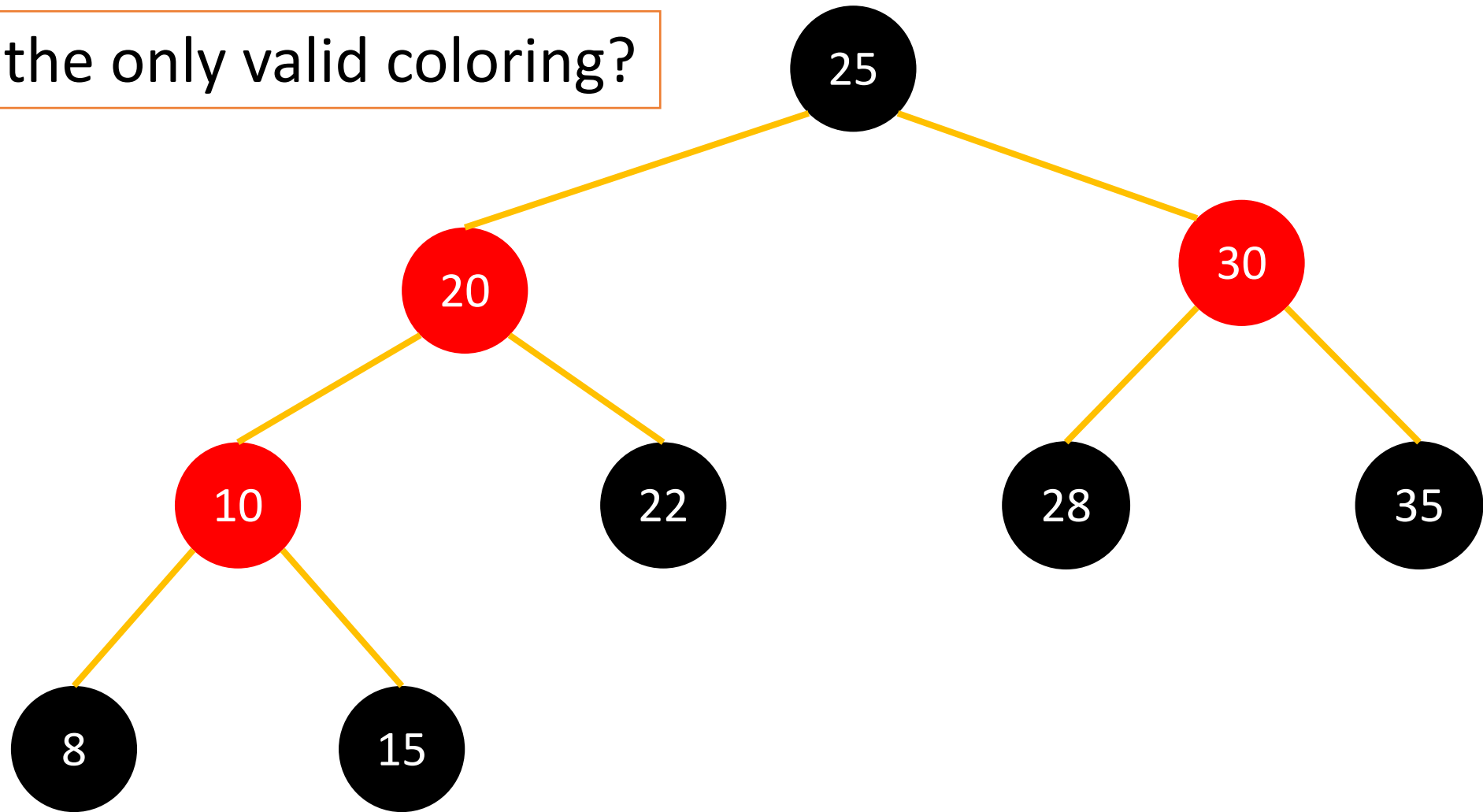
Is this the only valid coloring?



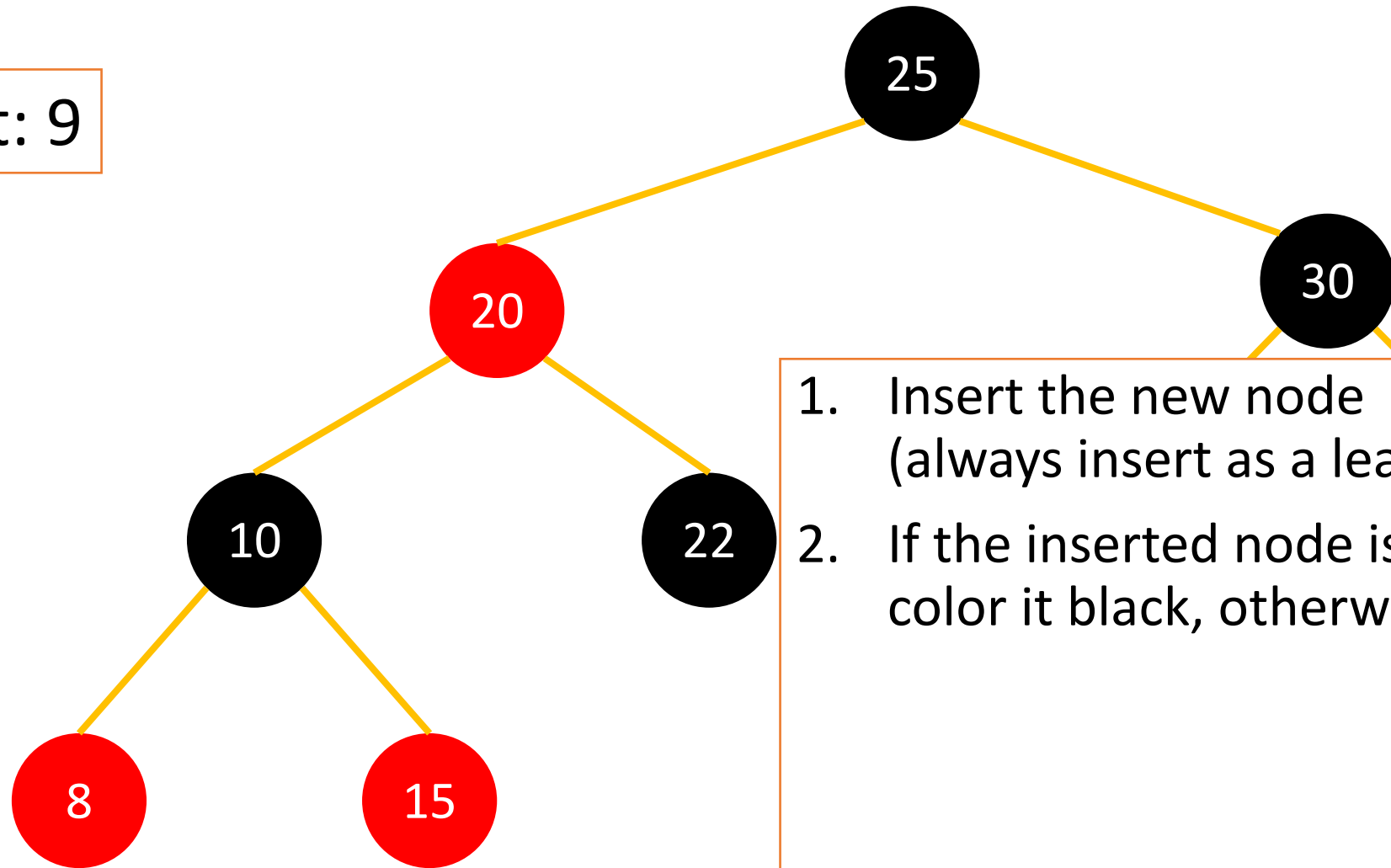
Is this the only valid coloring?



Is this the only valid coloring?

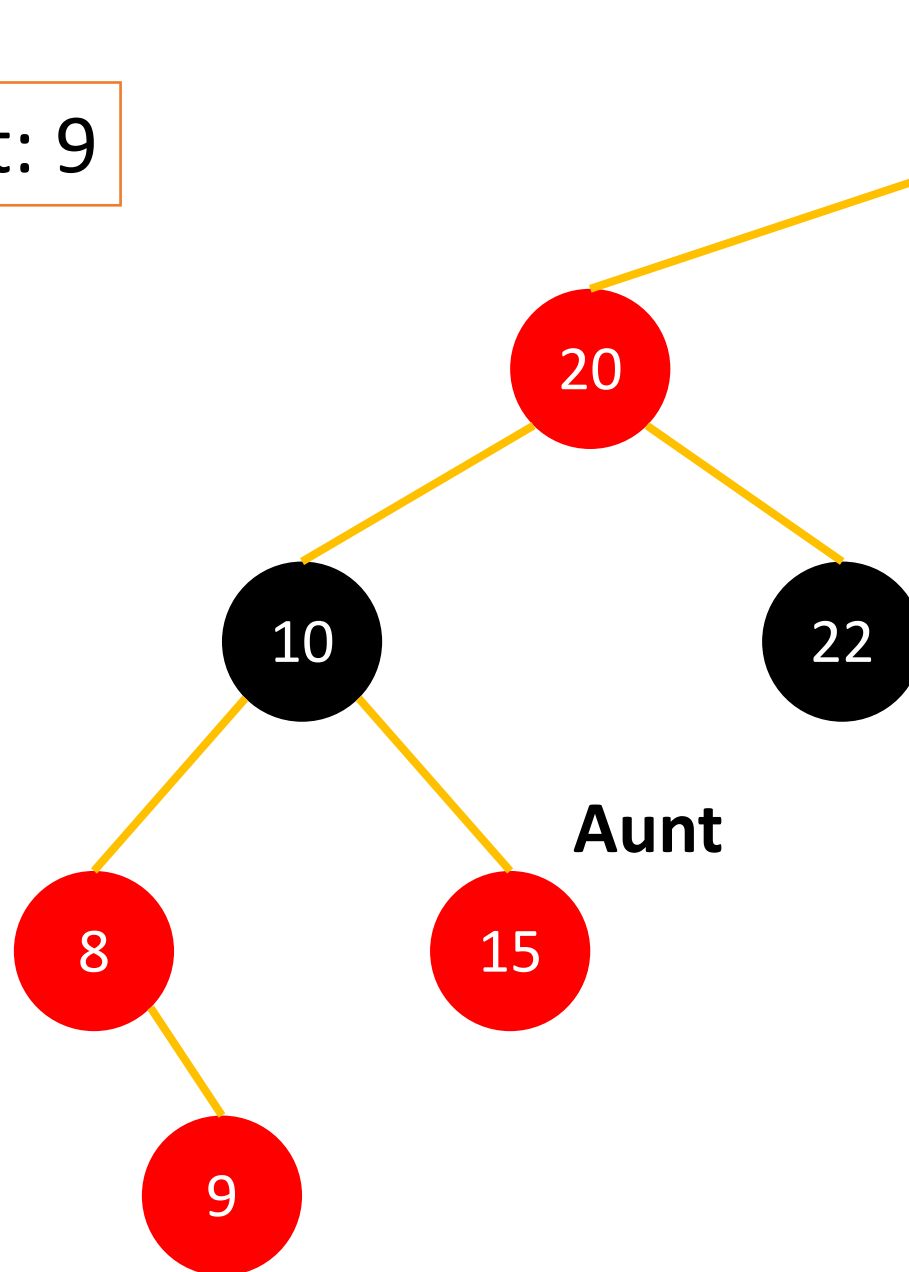


Insert: 9



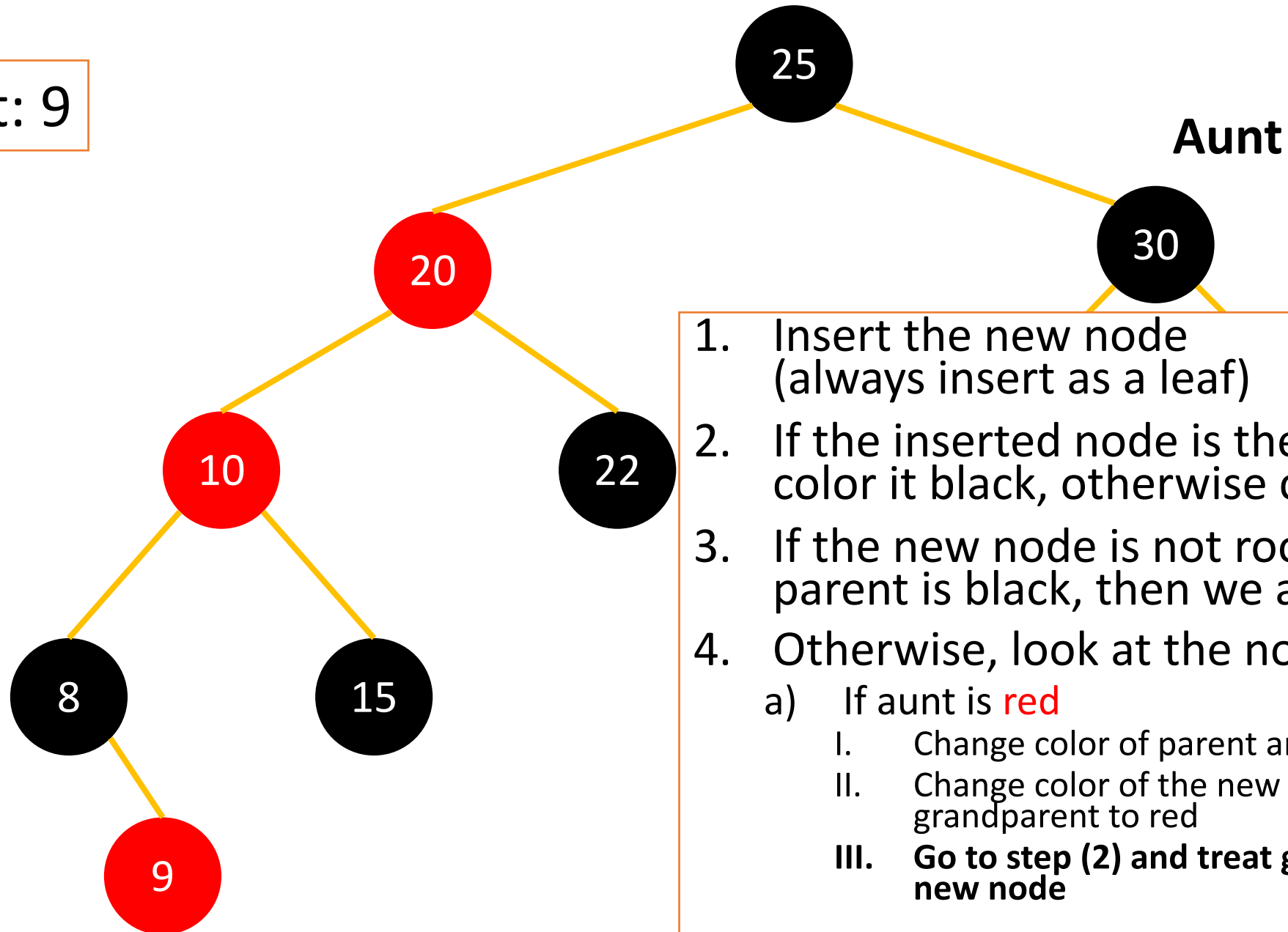
1. Insert the new node (always insert as a leaf)
2. If the inserted node is the root, then color it black, otherwise color it red

Insert: 9



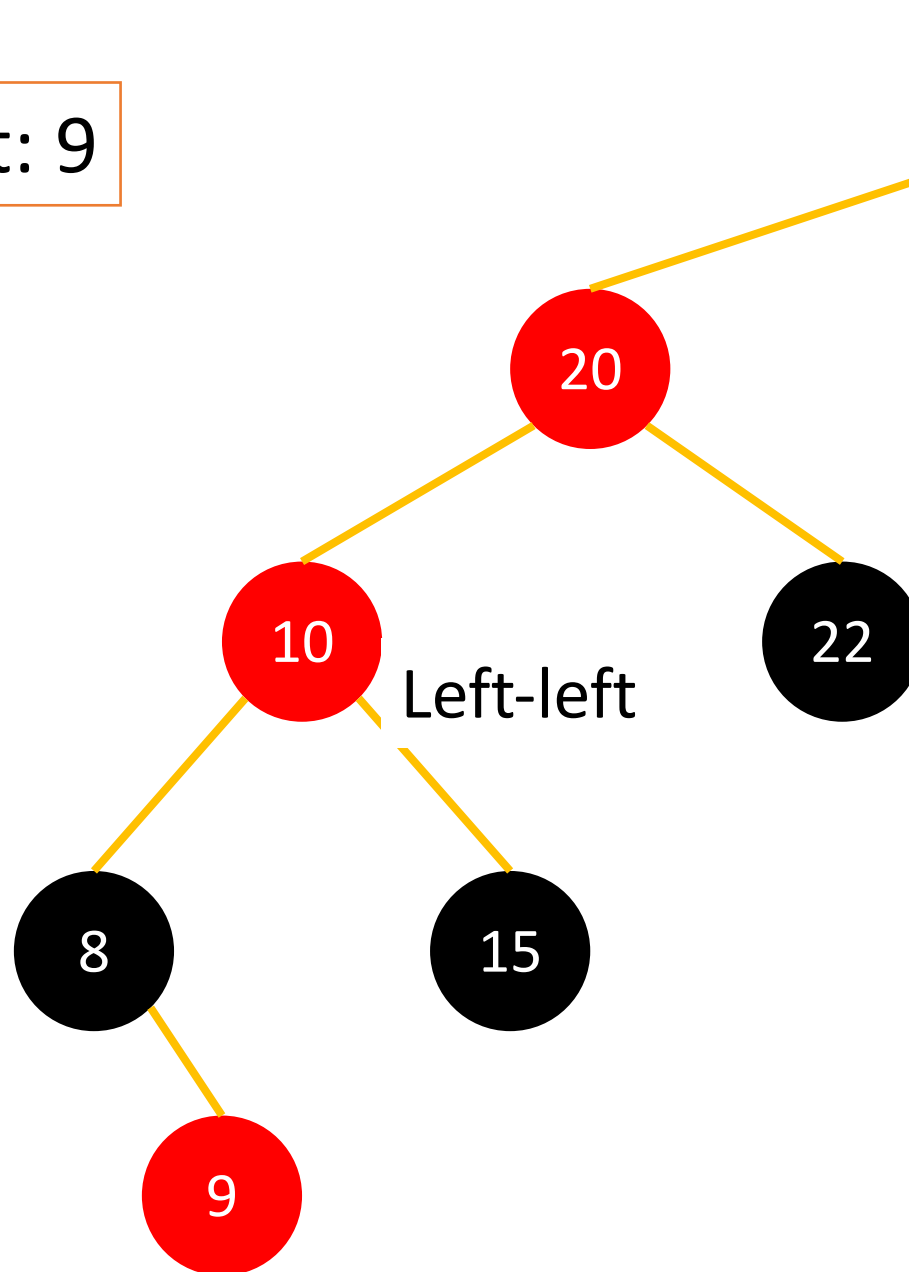
1. Insert the new node (always insert as a leaf)
2. If the inserted node is the root, then color it black, otherwise color it **red**
3. If the new node is not root and its parent is black, then we are done
4. Otherwise, look at the node's aunt
 - a) If aunt is **red**
 - I. Change color of parent and aunt to black
 - II. Change color of the new node and the grandparent to red
 - III. Go to step (2) and treat grandparent as new node

Insert: 9



1. Insert the new node (always insert as a leaf)
2. If the inserted node is the root, then color it black, otherwise color it **red**
3. If the new node is not root and its parent is black, then we are done
4. Otherwise, look at the node's aunt
 - a) If aunt is **red**
 - I. Change color of parent and aunt to black
 - II. Change color of the new node and the grandparent to red
 - III. **Go to step (2) and treat grandparent as new node**

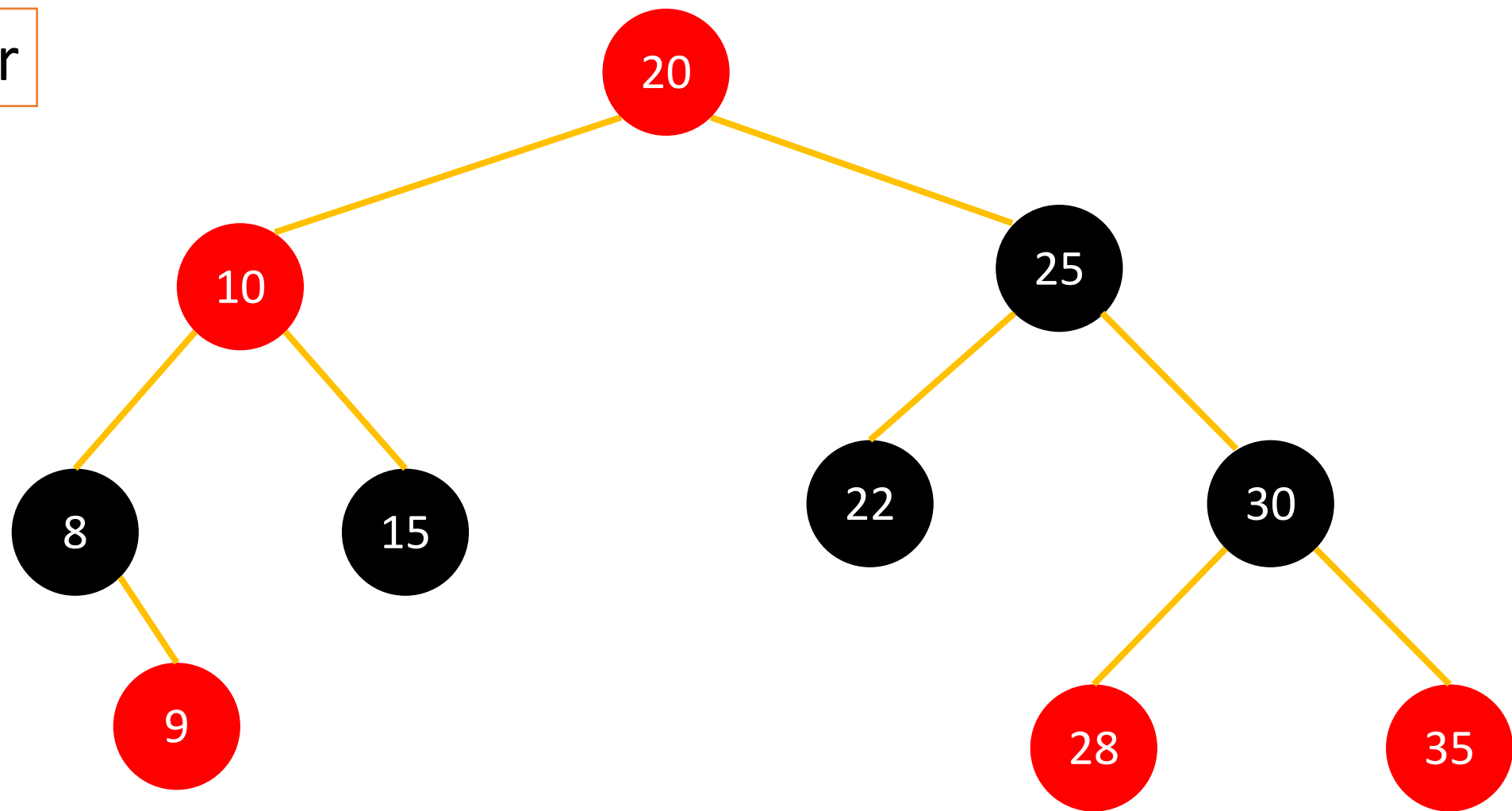
Insert: 9



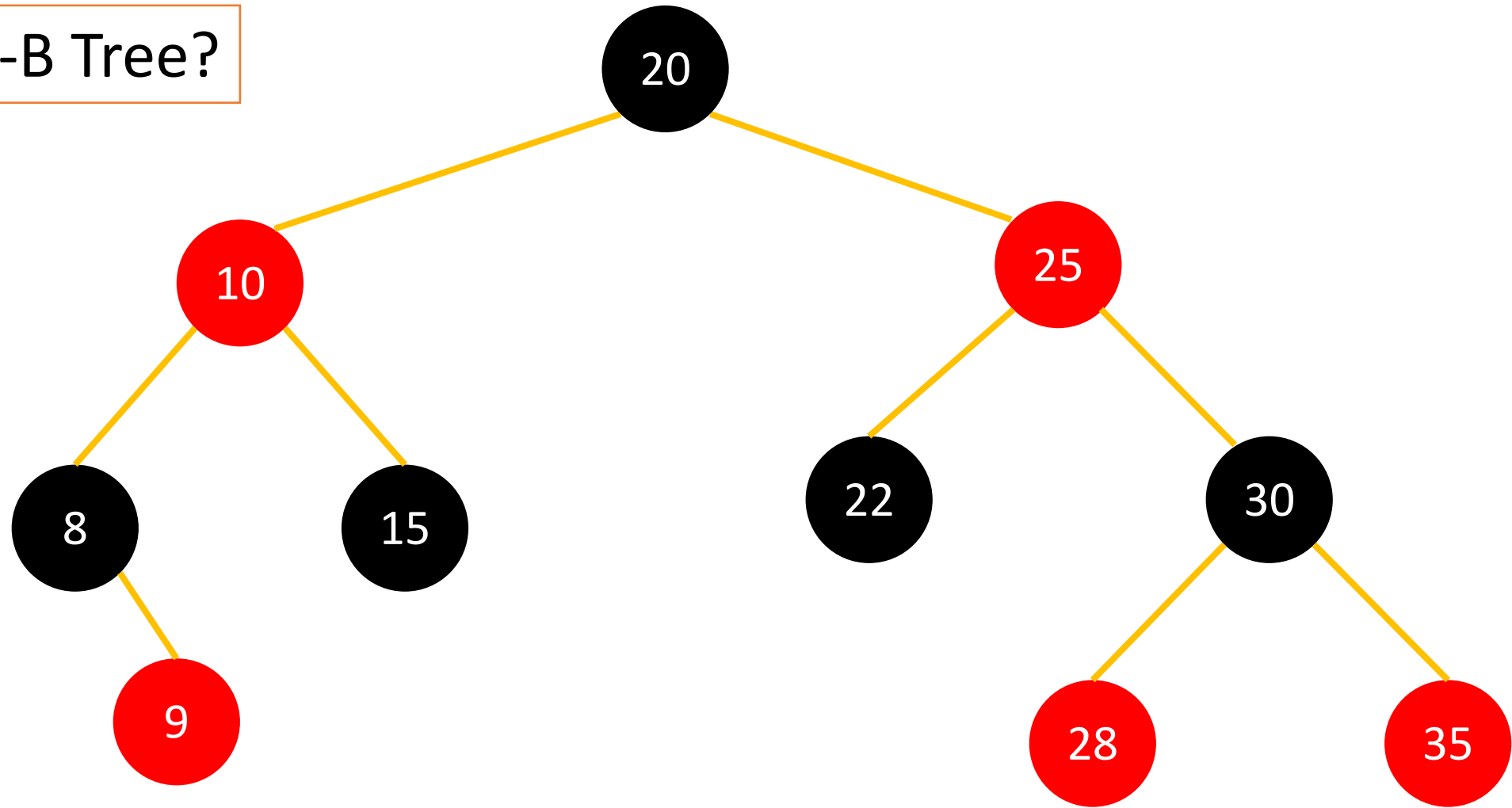
Check the **Aunt**

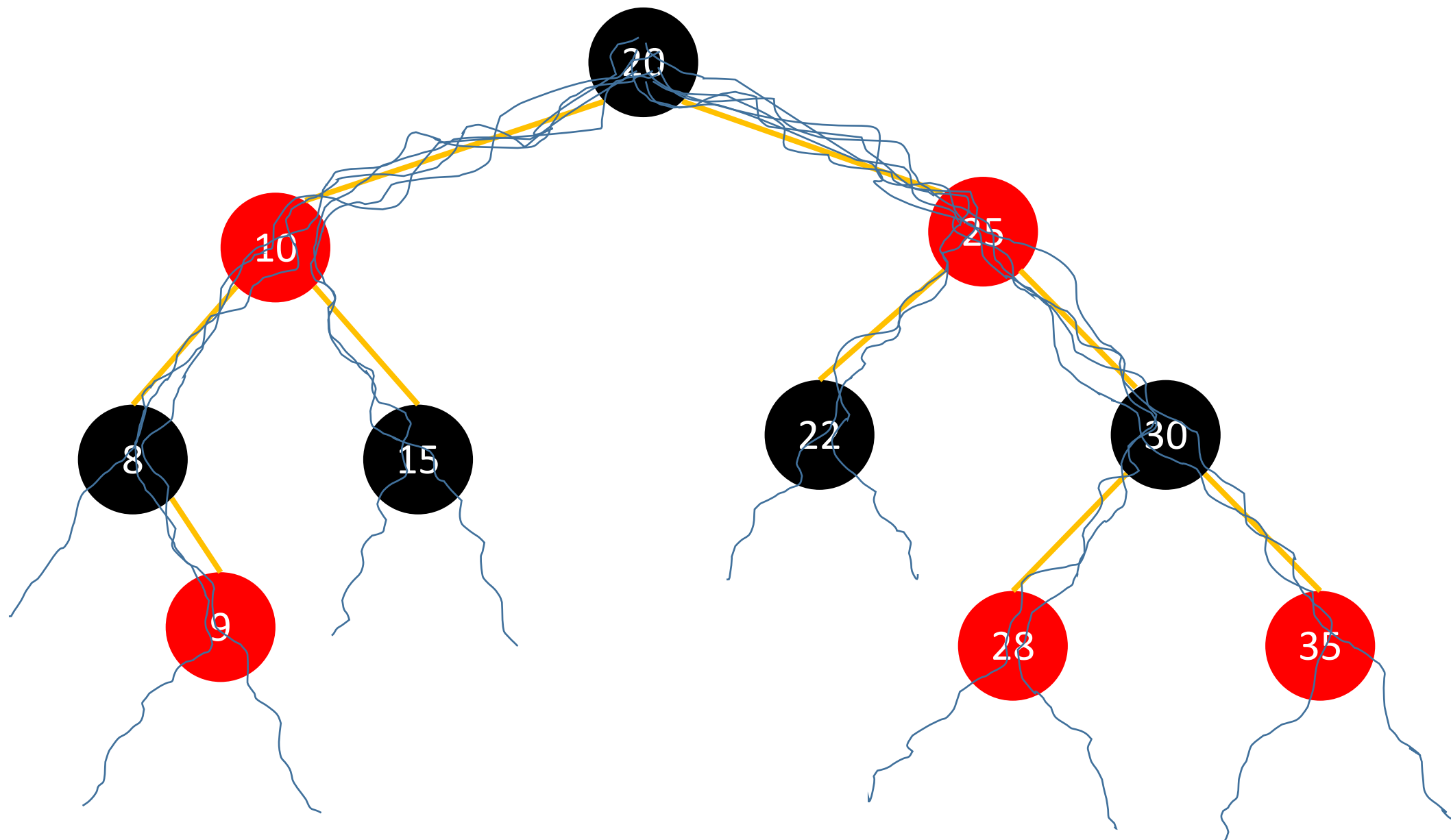
1. Insert the new node (always insert as a leaf)
2. If the inserted node is the root, then color it black, otherwise color it **red**
3. If the new node is not root and its parent is black, then we are done
4. Otherwise, look at the node's aunt
 - a) If aunt is black and left-left
 - a) Right **rotate** around the grandparent
 - b) Swap the colors of the grandparent and the parent
 - c) Go to step (2) and treat grandparent as new node

Recolor



Valid **R**-B Tree?





BST Summary

- Most BST operations take $O(\text{height})$ time.
- With an unbalanced tree this could be as bad as $O(n)$
- We want to ensure that the height of the tree is $O(\lg n)$
- **Red**-Black trees provide one mechanism for creating balanced trees, meaning that they guarantee $O(\lg n)$ for applicable BST operation
- This requires extra work while inserting and deleting in the form of tree rotations
- Bottom line: as long as our tree satisfies the Red-Black tree invariants (which it does with appropriate insert/delete procedures), then we can assume optimal running time for BSTs