

# Red-Black Trees

# Outline

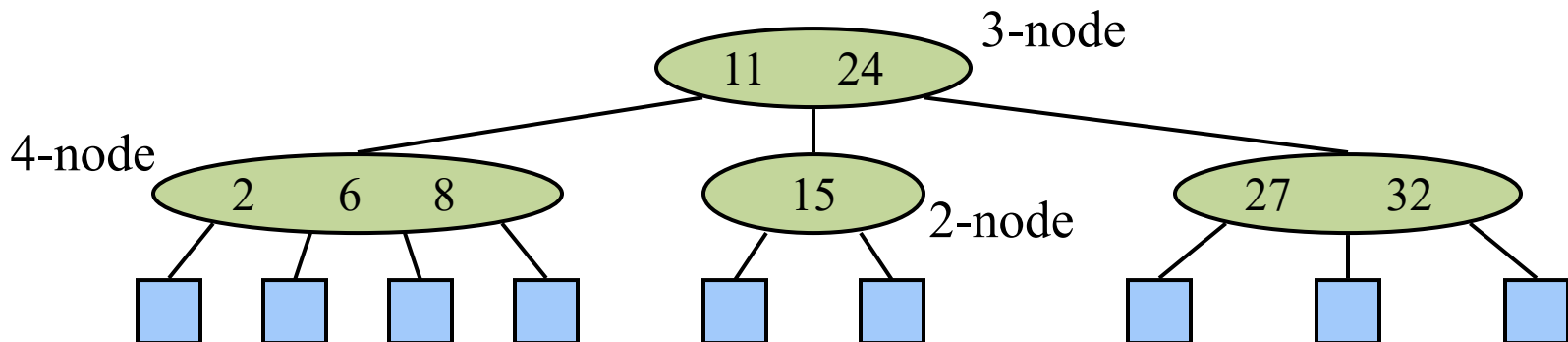
- From (2,4) trees to Red-Black trees
- Definition and height
- Search
- Insertion
  - Restructuring
  - Recoloring
- Deletion
  - Restructuring
  - Recoloring
  - Adjustment

# (2,4) Trees

A multi-way search tree, where an internal node has  $k$  children and stores  $k-1$  elements, and it has the following additional properties:

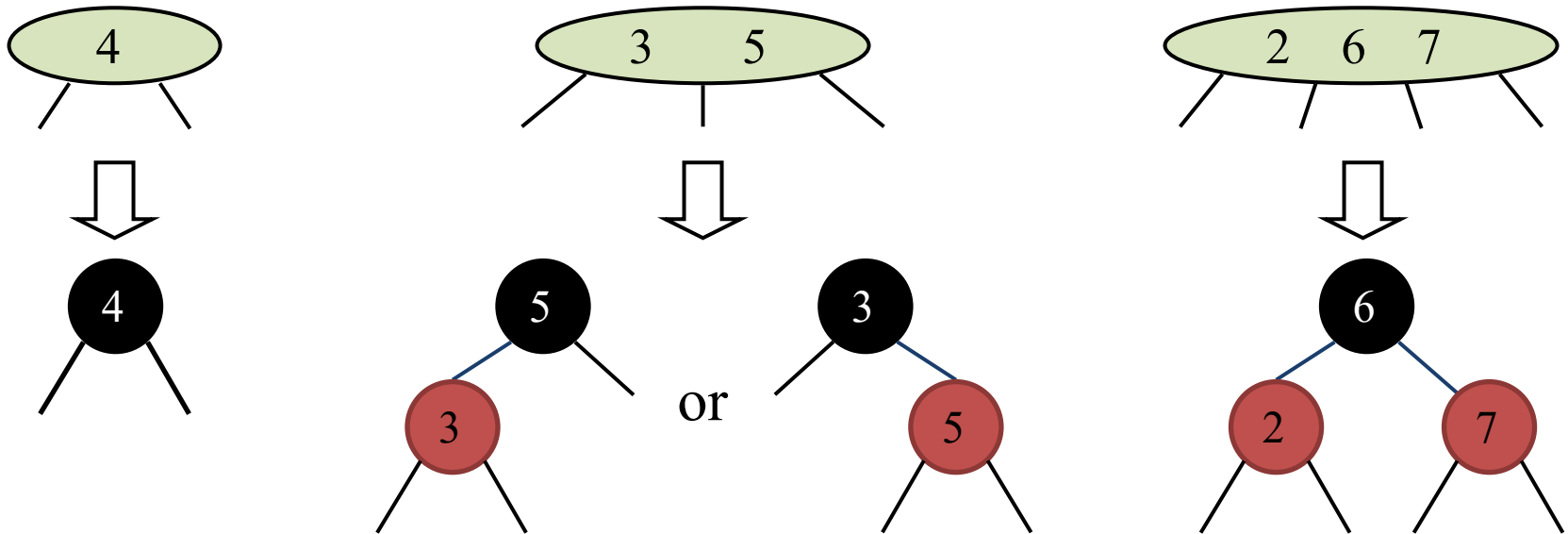
- **Node-Size property:** all internal nodes have at most four children (i.e.,  $k = 2,3,4$ )
- **Depth property:** all external nodes have the same depth

Depending on the number of children, an internal node is called either a 2-node, 3-node, or 4-node



# From (2,4) to Red-Black Trees

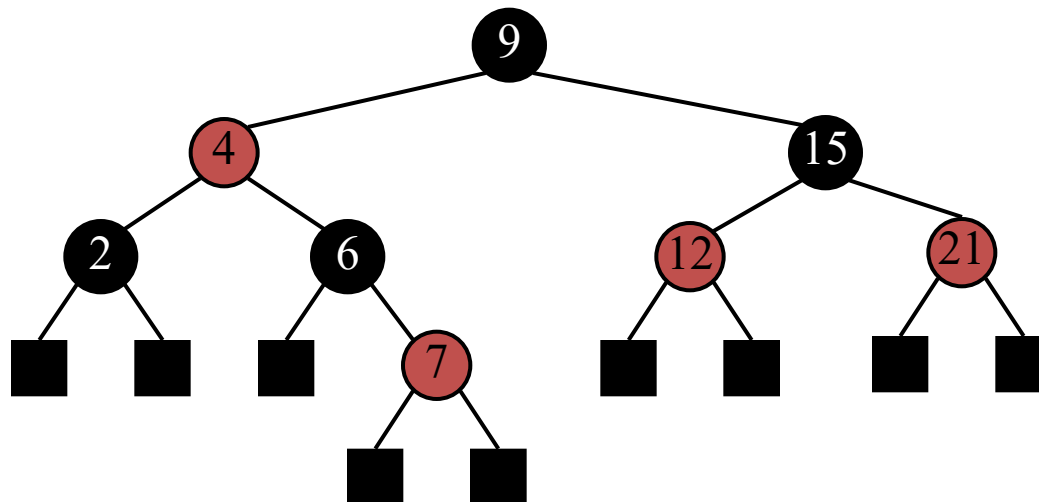
- A red-black tree is a representation of a (2,4) tree by means of a binary tree whose nodes are colored red or black.
- In comparison with a (2,4) tree, a red-black tree has
  - same logarithmic time performance
  - simpler implementation with a single node type



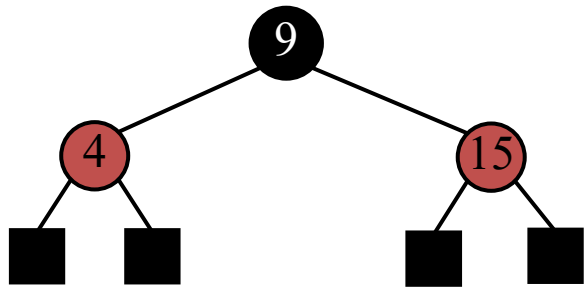
# Red-Black Trees

A **binary search tree** with nodes colored red and black in a way that satisfies the following color properties:

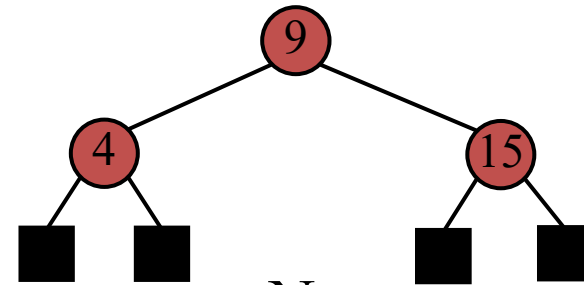
1. **Root property:** the root is black.
2. **External property:** every leaf is black.
3. **Internal property:** the children of a red node are black.
4. **Depth property:** all leaves have the same black depth.



# Ex: Is it a Red-Black Tree?

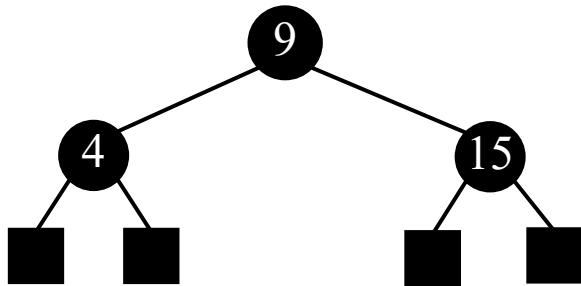


Yes

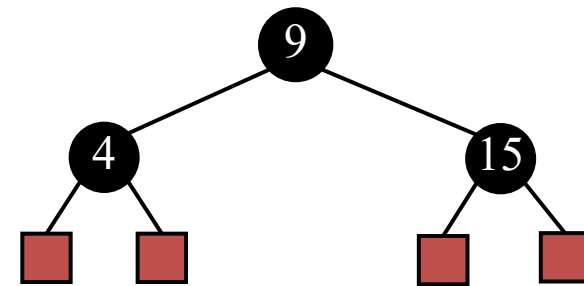


No

Violates root & internal property



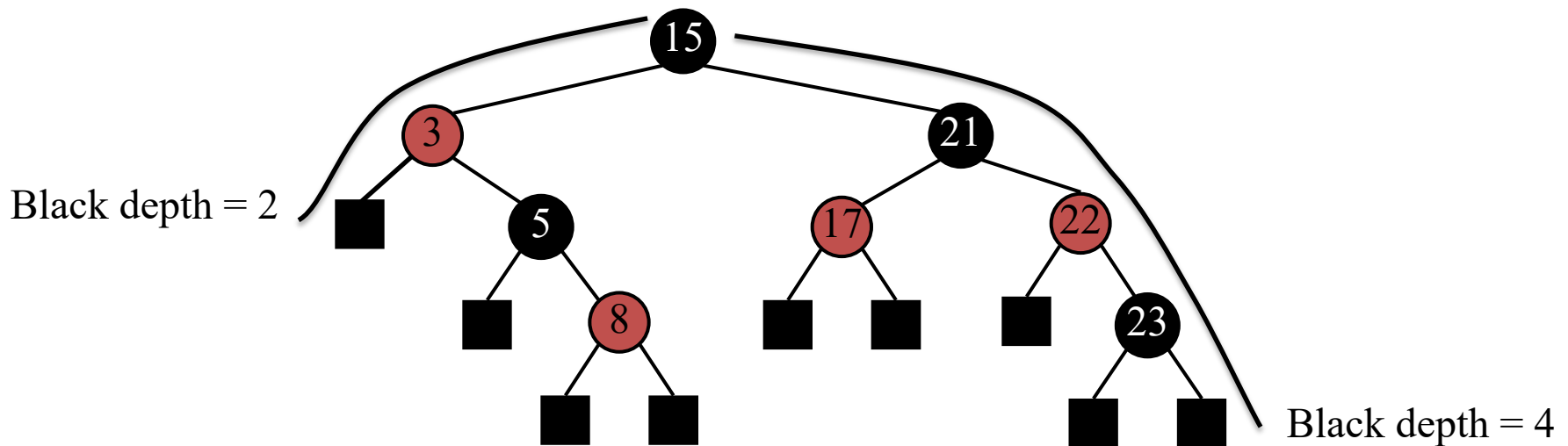
Yes



No

Violates external property

# Ex: Is it a Red-Black Tree?



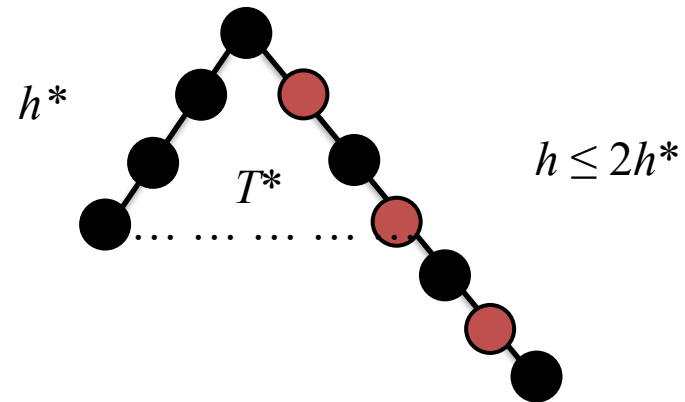
No  
Violates depth property

# Height of a Red-Black Tree

**Theorem:** A red-black tree storing  $n$  items has height  $O(\log n)$

Proof:

Consider the shortest path (left) and longest path (right) from the root to an external node.



Let  $T^*$  be the portion of the tree  $T$  consisting of all nodes with depth  $\leq h^*$

$T^*$  is complete. Thus,  $h^* \leq \log n$ .

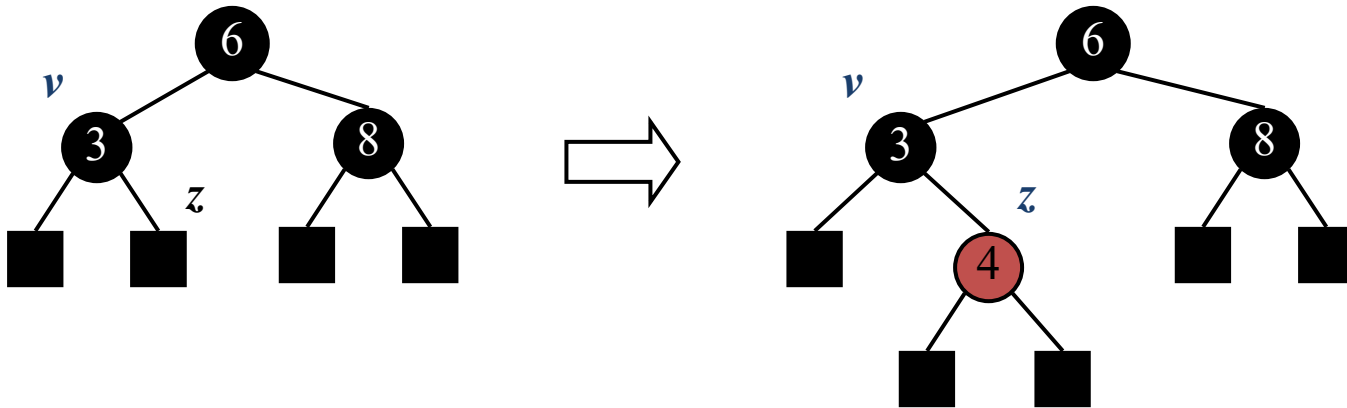
Because  $h \leq 2h^*$ ,  $h \leq 2\log n \in O(\log n)$ .

- The search algorithm for a red-black tree is the same as that for a binary search tree.
- By the above theorem, searching takes  $O(\log n)$  time



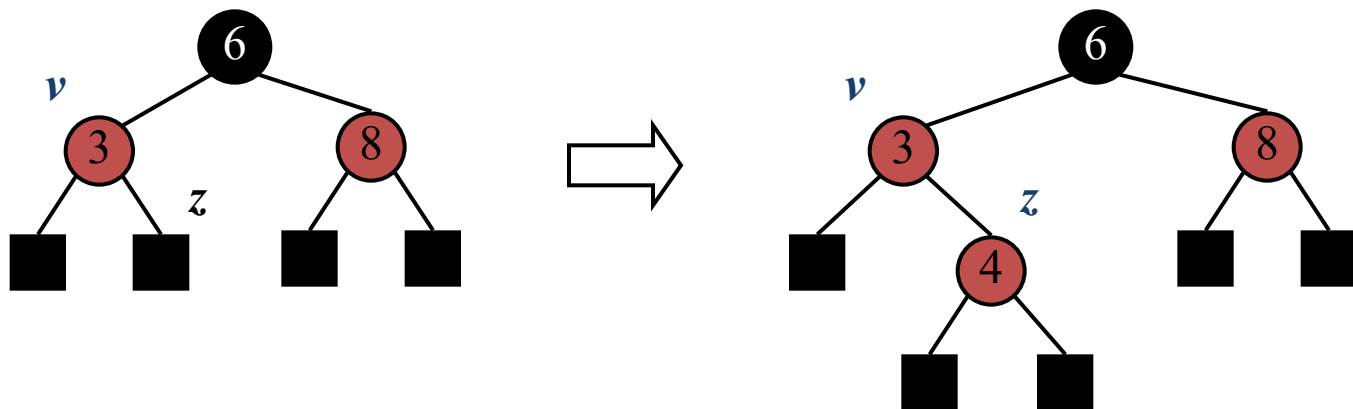
# Insertion

- Use insertion algorithm for binary search trees and color **red** the newly inserted node  $z$ , unless it's the root.
  - we preserve the root, external, and depth properties
  - **if the parent  $v$  of  $z$  is black**, we also preserve the internal property and we are done



# Insertion

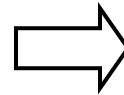
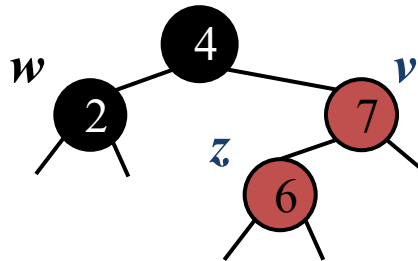
- Use insertion algorithm for binary search trees and color **red** the newly inserted node  $z$ , unless it's the root.
  - we preserve the root, external, and depth properties
  - if the parent  $v$  of  $z$  is black, we also preserve the internal property and we are done
  - **if the parent  $v$  of  $z$  is red**, we have a **double red** (a violation of the internal property), which requires a reorganization of the tree
- Ex: Insert 4 causes a double red



# Fixing a Double Red

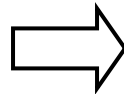
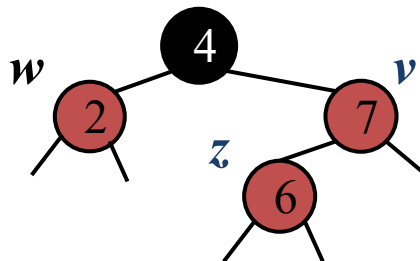
Consider a double red with child  $z$  and parent  $v$ , and let  $w$  be the sibling of  $v$

- Case 1:  $w$  is **black**



**Restructuring**

- Case 2:  $w$  is **red**

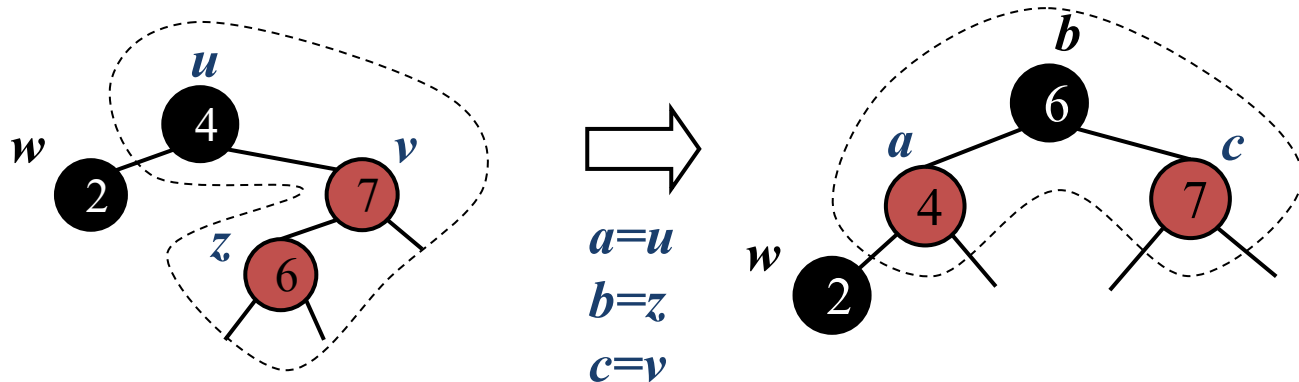


**Recoloring**

Note: pictures with dangling edges are a visualization of a small portion of larger tree

# Restructuring

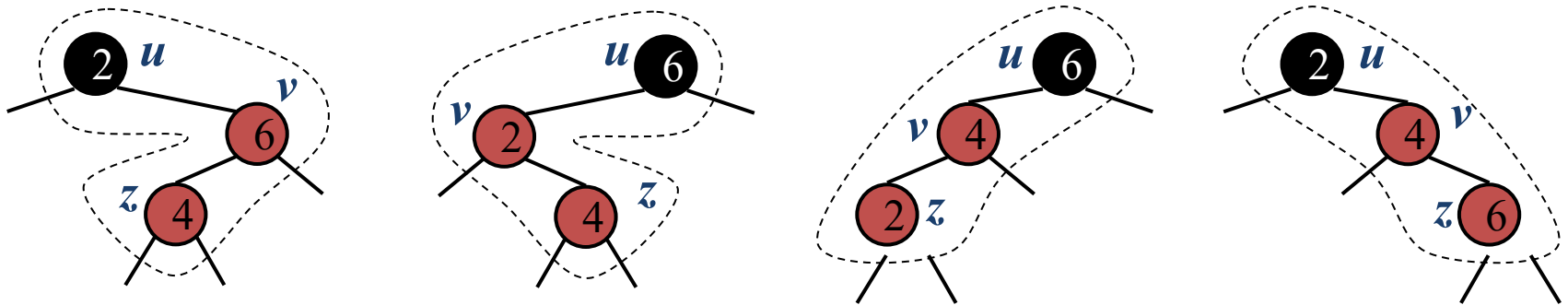
Consider a double red with child  $z$  and parent  $v$  and let  $w$  be the sibling of  $v$ . Let  $u$  be the parent of  $v$ .



1. Relabel nodes  $z$ ,  $v$ ,  $u$  temporarily as  $a$ ,  $b$ ,  $c$  so that  $a$ ,  $b$ ,  $c$  will be visited in this order by an inorder tree traversal.
2. Replace  $u$  with the node labeled  $b$  (colored **black**). Make nodes  $a$  and  $c$  the left and right child of  $b$  (each colored **red**).

# Restructuring

There are four restructuring configurations depending on the in-order traversal of nodes  $z$ ,  $v$ ,  $u$



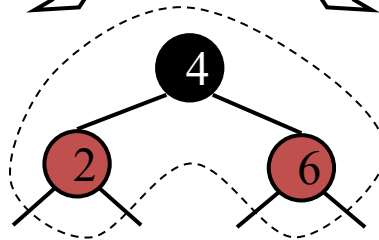
Inorder traversal:

$u, z, v$

$v, z, u$

$z, v, u$

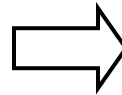
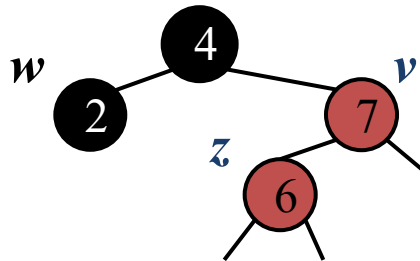
$u, v, z$



# Fixing a Double Red

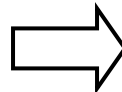
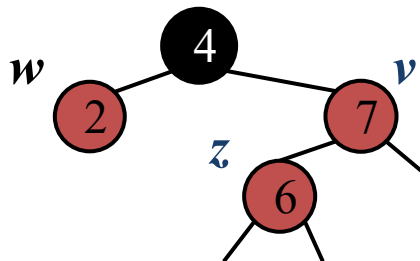
Consider a double red with child  $z$  and parent  $v$ , and let  $w$  be the sibling of  $v$

- Case 1:  $w$  is **black**



**Restructuring**

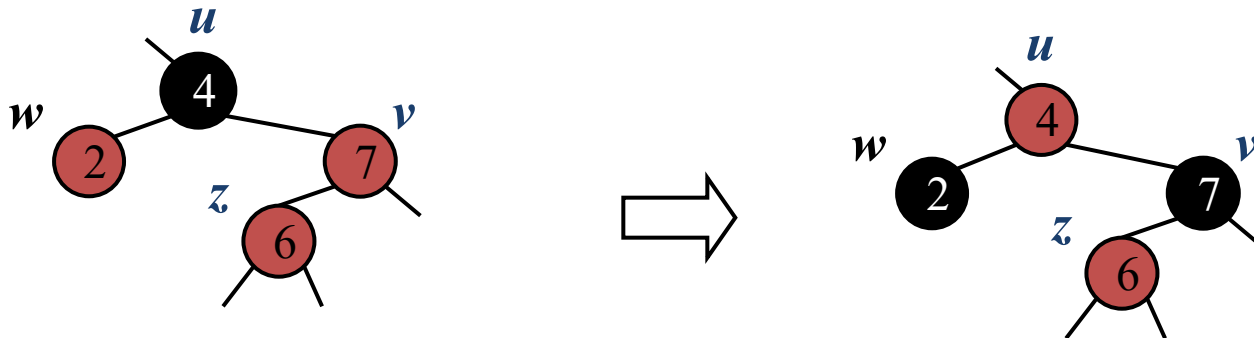
- Case 2:  $w$  is **red**



**Recoloring**

# Recoloring

Consider a double red with child  $z$  and parent  $v$ , and let  $w$  be the sibling of  $v$ . Let  $u$  be the parent of  $v$ .



1. Color  $v$  and  $w$  **black**.
2. Color  $u$  **red**, unless it's the root.
3. If the double-red problem reappears at  $u$ , then repeat the process for fixing two reds at  $u$  (either with restructuring or recoloring).

Fixes problem locally, but can propagate double-red problem up the tree.

# Analysis of Insertion

## Algorithm *insertItem(k, o)*

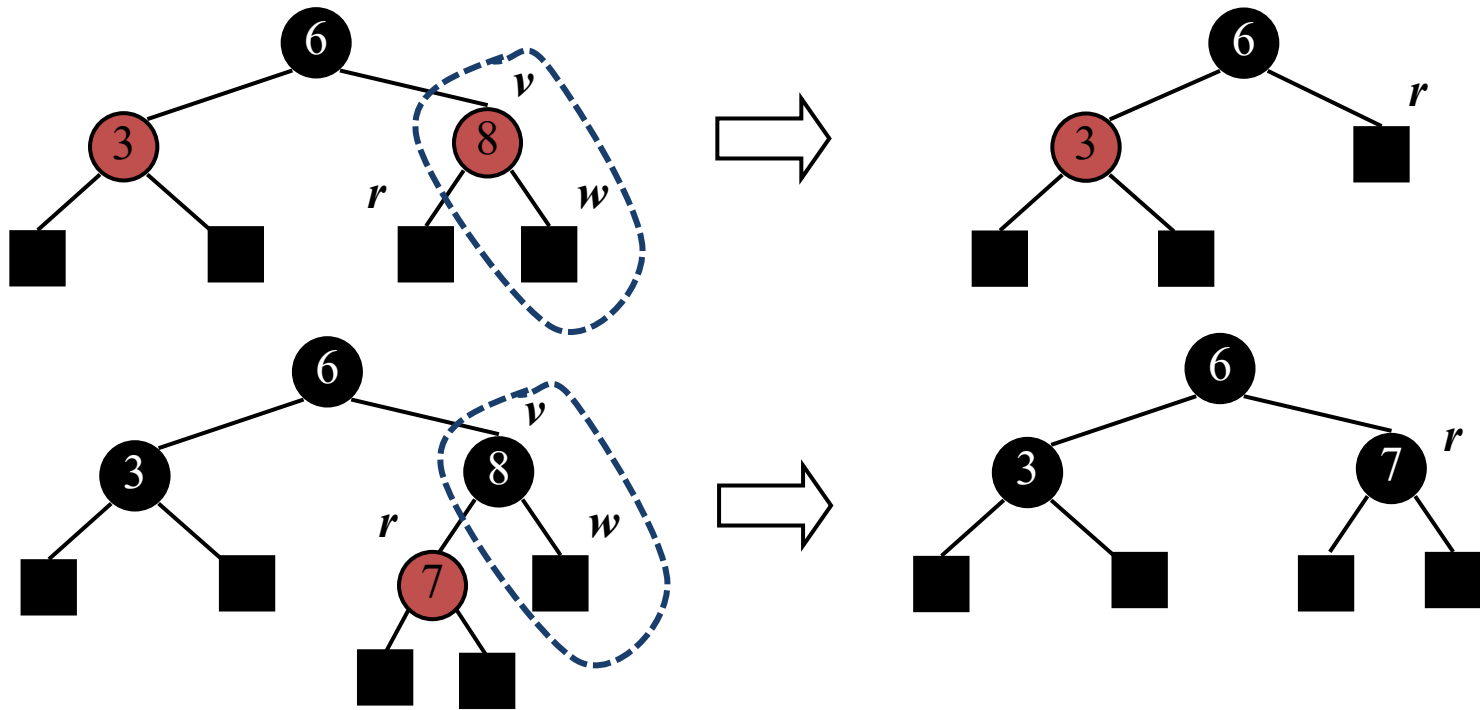
1. We search for key  $k$  to locate the insertion node  $z$
2. We add the new item  $(k, o)$  at node  $z$  and color  $z$  red
3. **while** *doubleRed*( $z$ )  
    **if** *isBlack*(*sibling*(*parent*( $z$ )))  
        *restructure*( $z$ )  
    **return**  
    **else** { *sibling*(*parent*( $z$ )) is red }  
         $z \leftarrow$  *recolor*( $z$ )

- Recall that a red-black tree has  $O(\log n)$  height
- Step 1 takes  $O(\log n)$  time because we visit  $O(\log n)$  nodes
- Step 2 takes  $O(1)$  time
- Step 3 takes  $O(\log n)$  time because we perform
  - $O(\log n)$  recolorings, each taking  $O(1)$  time, and
  - at most one restructuring taking  $O(1)$  time
- Thus, an insertion in a red-black tree takes  $O(\log n)$  time



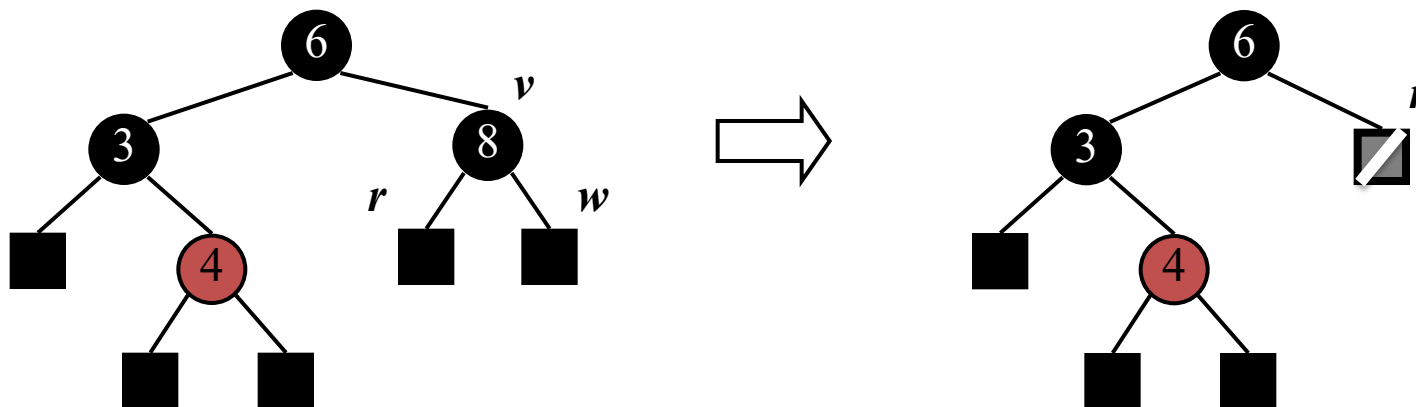
# Deletion

- Use deletion algorithm for binary search trees so as to delete internal node  $v$  and its external child  $w$ . Let  $r$  be the sibling of  $w$ .
  - if  $v$  is red or  $r$  is red, then color  $r$  black and we are done.



# Deletion

- Use deletion algorithm for binary search trees so as to delete internal node  $v$  and its external child  $w$ . Let  $r$  be the sibling of  $w$ .
  - if  $v$  is **red** or  $r$  is **red**, then color  $r$  **black** and we are done.
  - otherwise ( $v$  and  $r$  are black) we color  $r$  **double black**, which requires a reorganization of the tree
- Ex: Delete 8 causes a double black

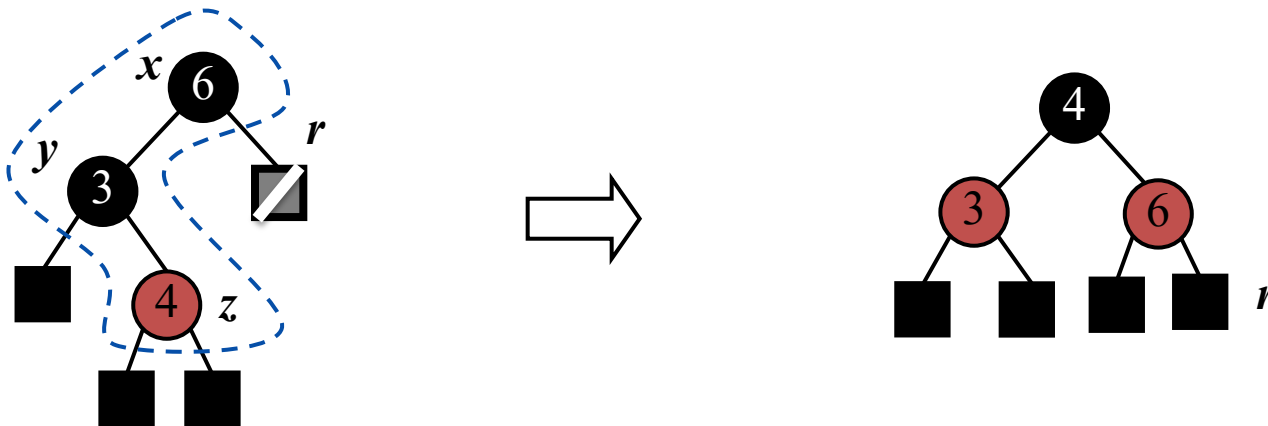


# Fixing a Double Black

Let  $y$  be the sibling and  $x$  be the parent of the double black node. The algorithm to fix a double black node considers three cases:

**Case 1:**  $y$  is black and has a red child  $z$

- We perform a **restructuring** on  $y$ ,  $x$ ,  $z$ , and we are done



# Fixing a Double Black

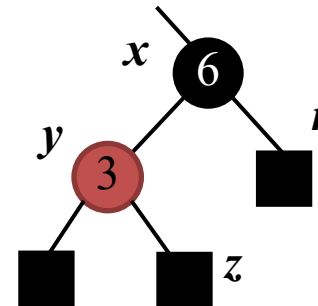
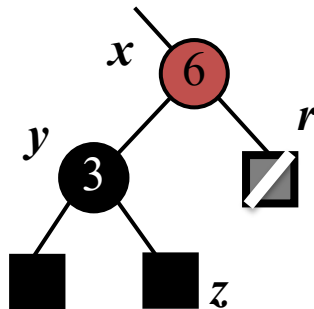
Let  $y$  be the sibling and  $x$  be the parent of the double black node. The algorithm to fix a double black node considers three cases:

**Case 1:**  $y$  is black and has a red child  $z$

- We perform a restructuring on  $y$ ,  $x$ ,  $z$ , and we are done

**Case 2:**  $y$  is black and its children are both black

- We perform a **recoloring**. Color  $r$  **black**, and  $y$  **red**.
  - If  $x$  is red, color it **black**. Otherwise, color  $x$  **double-black**.
  - This may propagate up the double black violation



# Fixing a Double Black

Let  $y$  be the sibling and  $x$  be the parent of the double black node. The algorithm to fix a double black node considers three cases:

**Case 1:**  $y$  is black and has a red child  $z$

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  - If  $x$  is red, color it **black**. Otherwise, color  $x$  **double-black**.
  - This may propagate up the double black violation

**Case 3:**  $y$  is red

- We perform an **adjustment**, after which either Case 1 or Case 2 applies

Deletion in a red-black tree takes  $O(\log n)$  time.

# Red-Black Tree Reorganization

| <b>Insertion</b><br>(fix double red) |  | result                              |
|--------------------------------------|--|-------------------------------------|
| restructuring                        |  | double red removed                  |
| recoloring                           |  | double red removed or propagated up |

| <b>Deletion</b><br>(fix double black) |  | result                                |
|---------------------------------------|--|---------------------------------------|
| restructuring                         |  | double black removed                  |
| recoloring                            |  | double black removed or propagated up |
| adjustment                            |  | restructuring or recoloring follows   |