

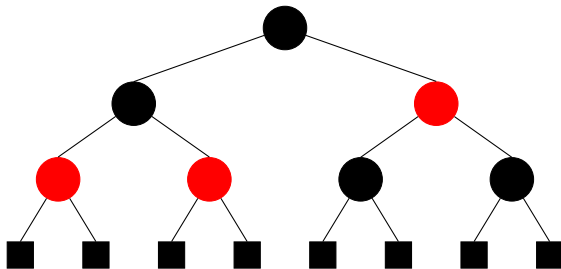
Balanced Trees (*Red-Black* Trees)

Warren Kim

Quick Definition

Definition

A **red-black** tree is a type of **self-balancing** binary search tree that guarantees $\mathcal{O}(\log n)$ performance.



Applications

Red-Black Trees have a variety of applications. Some include:

- Linux CPU scheduler (Completely Fair Scheduler)
- Linux Virtual Memory Areas (VMA)
- STL Data Structures (e.g. C++'s `std::map`, Java's `HashMap`)
- Graph algorithm optimizations (for AI/ML)[e.g. K-mean clustering]
- Priority Queues (e.g. Range Queries)

Motivation

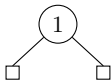
Why do we want balanced binary trees?

- Raw binary search tree performance is highly dependant on input order.
- We want to ensure $\mathcal{O}(\log n)$ performance.

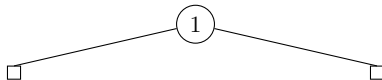
Example

Suppose we have the input set $\{1, 2, 3, 4, 5, 6, 7\}$ and consider two input orders:

$\{1, 2, 3, 4, 5, 6, 7\}$



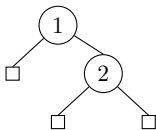
$\{1, 7, 2, 6, 3, 5, 4\}$



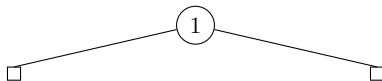
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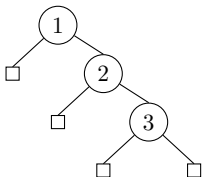
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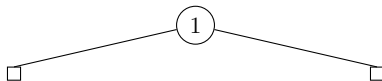
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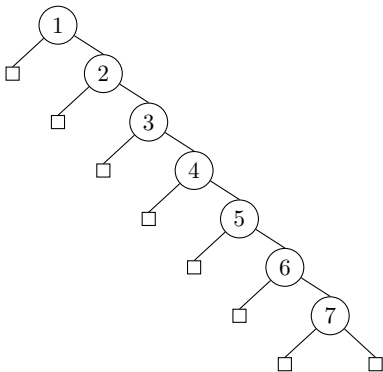
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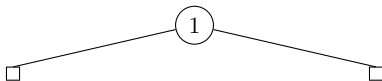
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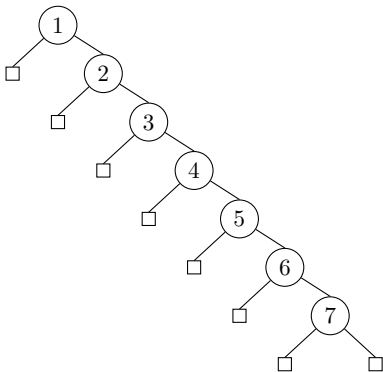
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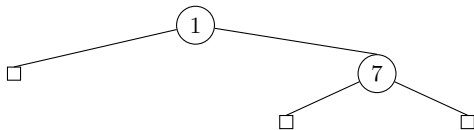
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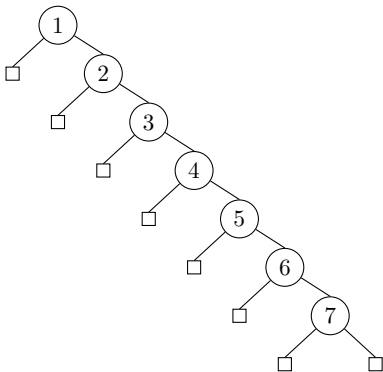
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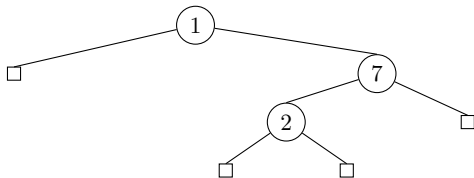
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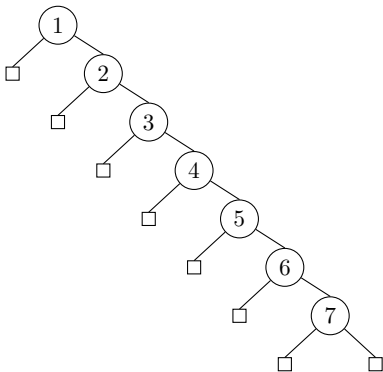
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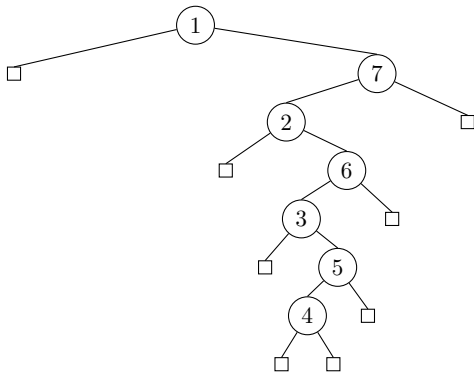
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Intuition

How do we balance binary trees?

We can *dynamically* balance the tree!

→ We can add metadata¹ to our `Node` struct.

→ We can define a set of conditions that enforce balance.

¹Metadata: Additional member variables

Definition and Properties

Definition

A **red-black** tree is a type of **self-balancing** binary search tree that guarantees $O(\log n)$ search, insertion, and deletion operations with the following properties:

- (i) *Color:* Every node is either **red** or **black**

```
enum Color { RED, BLACK };

struct Node {
    Color color;
    Node *left;
    Node *right;
    Node *parent;

    int data;
};
```

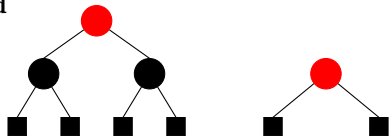
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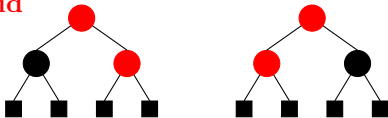
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- (ii) *Internal:* A **red** node does not have a **red** child

Valid



Invalid

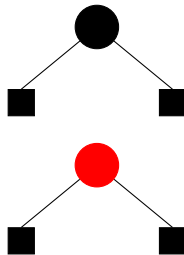


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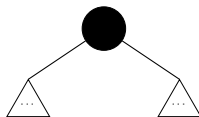


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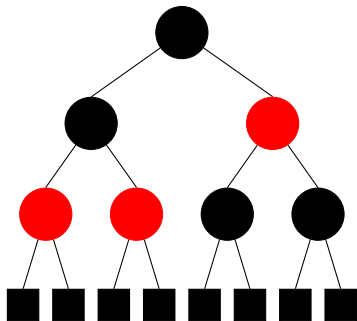


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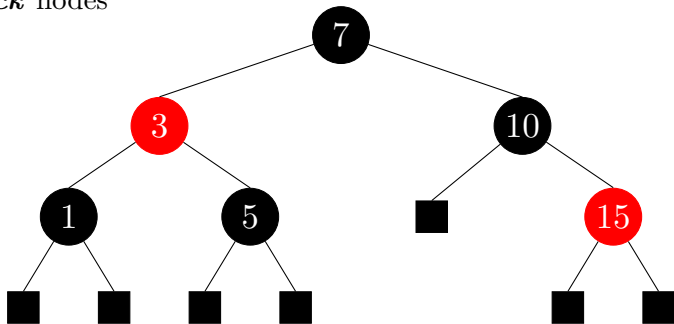
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- (v) *Depth:* Every path from the root to *any* nil node passes through the same number of **black** nodes



Depth Property

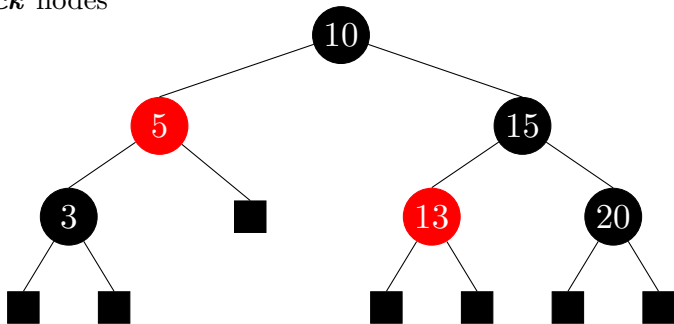
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Valid

Depth Property

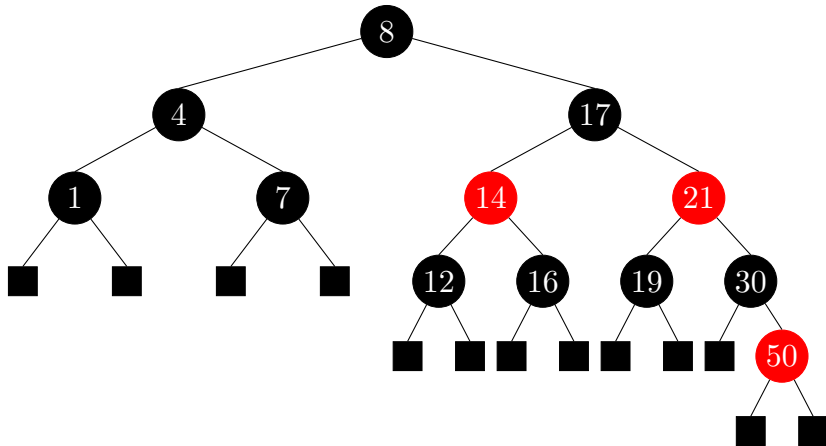
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- (iii) Fix double *red* violations, if any.

Insertion

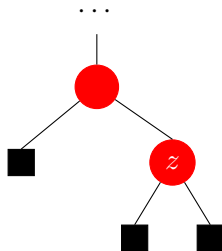
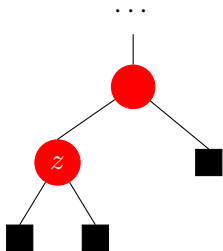
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- (i) Like a BST, insert z .
- (ii) Color z *red*.
- (iii) Fix double *red* violations, if any.
- (iv) Recursively fix violations upward.

Double Red Violations

Recall *Property (ii)*: A **red** node does not have a **red** child.

When we insert our node z (**red** by definition), its parent may be **red**. Below are examples of such cases.



Fixing Double Red Violations

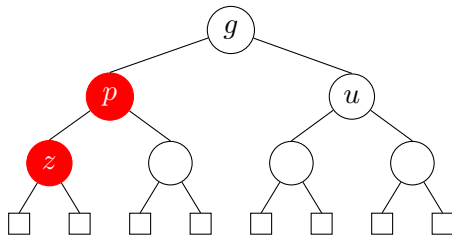
Terminology

With respect to inserted node z ,

→ *Parent* (p): z 's direct parent

→ *Uncle* (u): p 's sibling

→ *Grandparent* (g): p 's parent



Fixing Double Red Violations

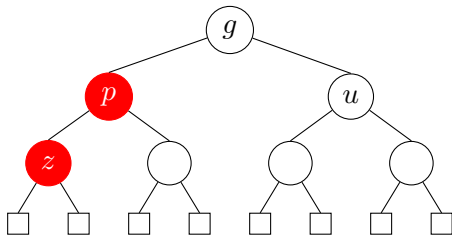
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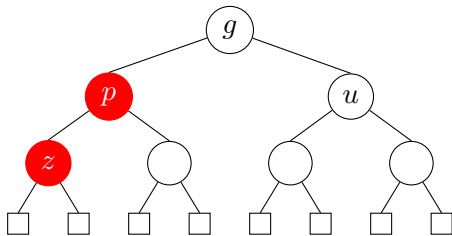
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There are two cases:

(i) **Recolor**: If both the *parent* and *uncle* are **red**, perform a *recolor*.

Fixing Double Red Violations

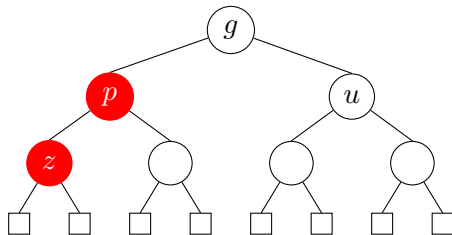
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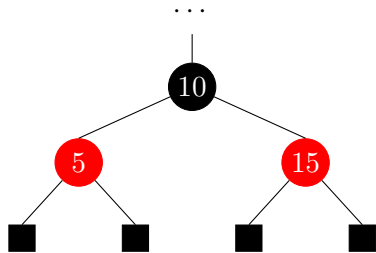
→ *Grandparent* (g): p 's parent



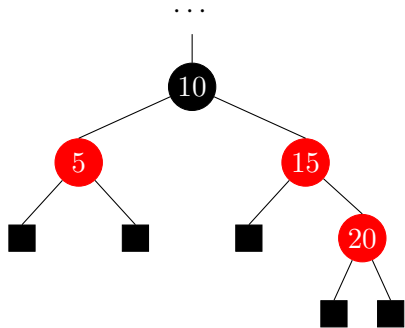
There are two cases:

- (i) **Recolor:** If both the *parent* and *uncle* are **red**, perform a *recolor*.
- (ii) **Restructure:** If the *parent* is **red** but the *uncle* is **black**, perform a *tri-node restructure*.

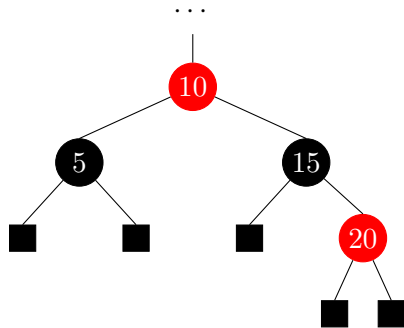
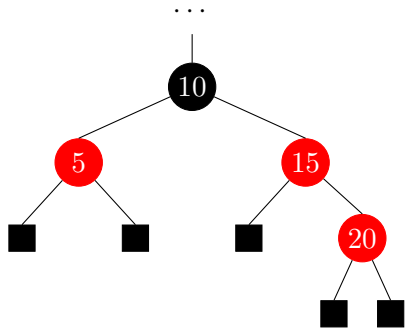
Recolor



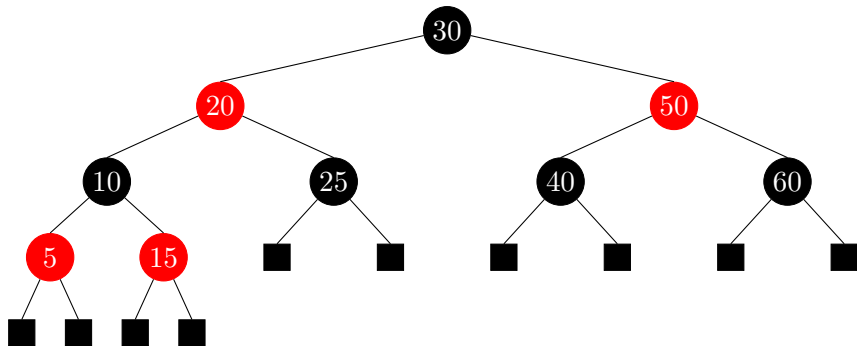
Recolor



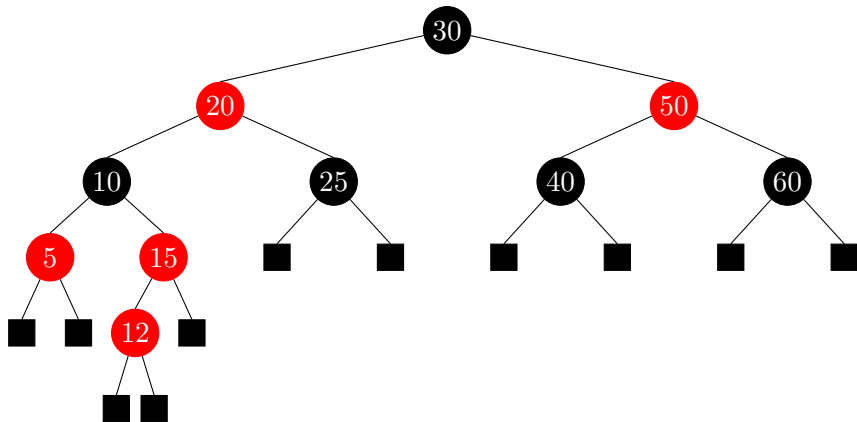
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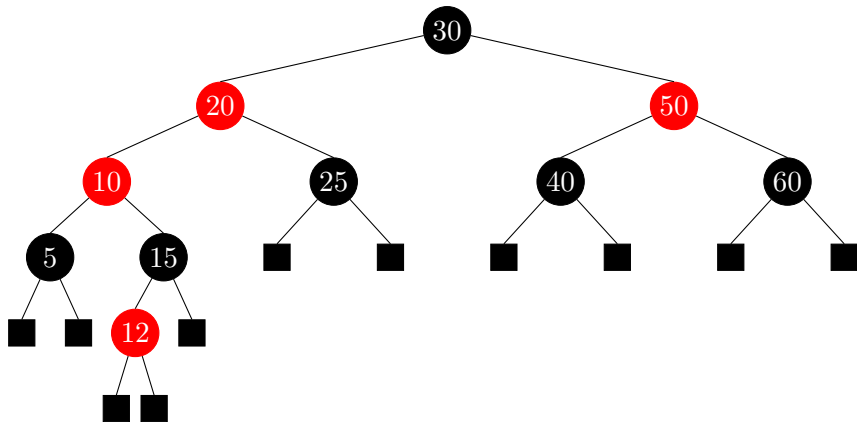
Recolor (Recursive)



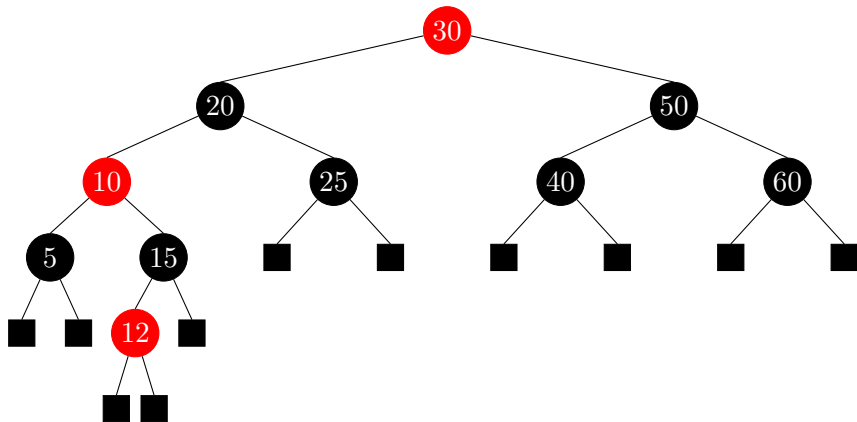
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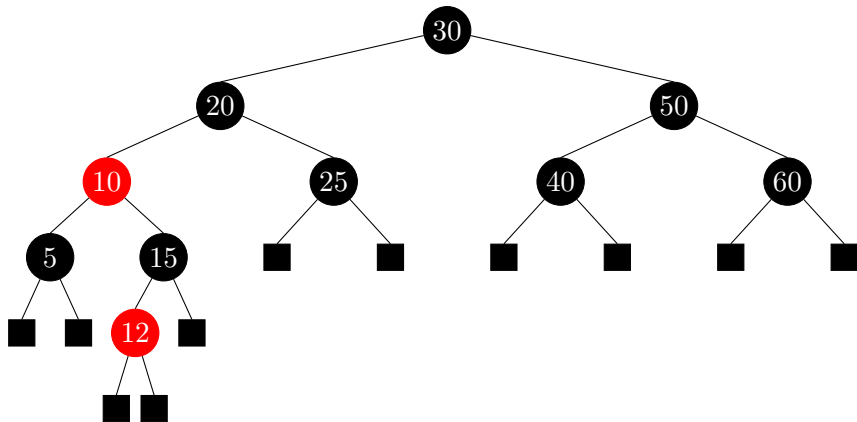
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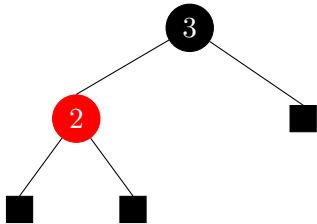


Tri-Node Restructure

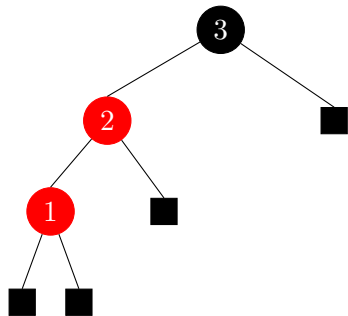
There are four cases:

- (i)* Left-Left
- (ii)* Right-Right
- (iii)* Left-Right
- (iv)* Right-Left

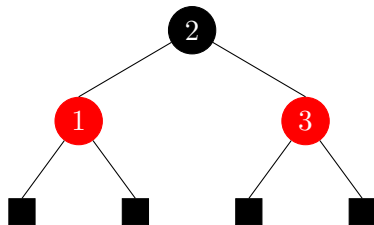
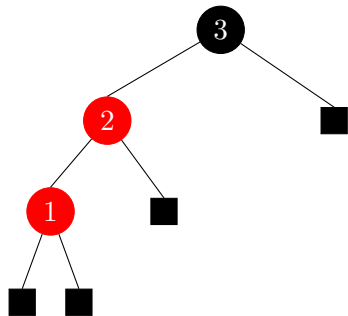
Case: Left-Left (Simple)



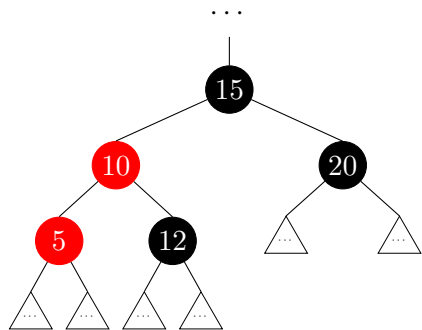
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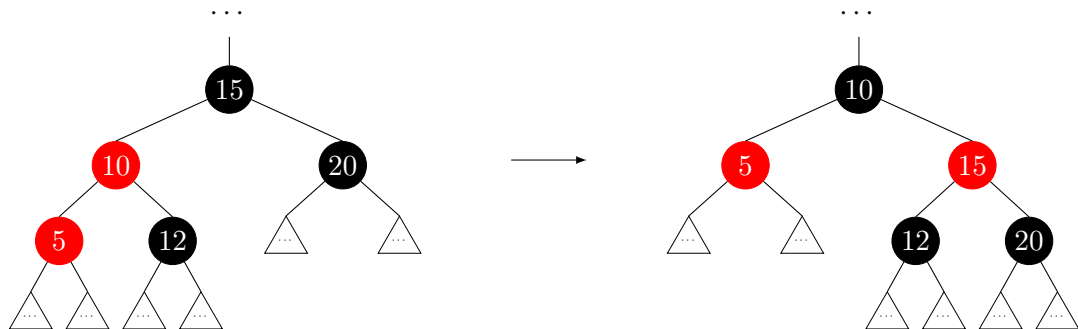



Case: Left-Left (General)



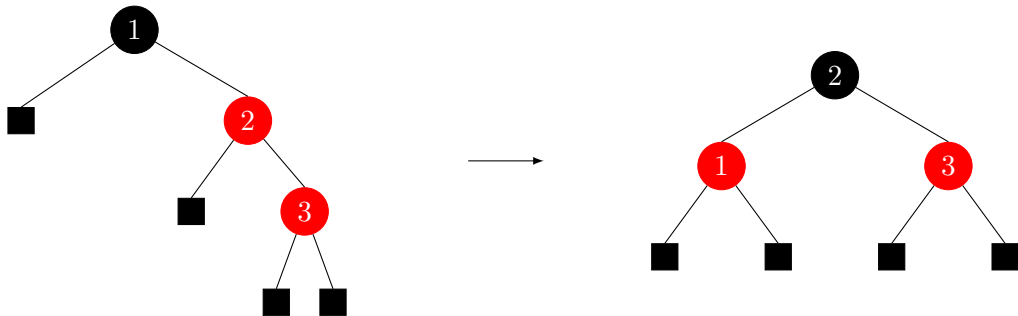
Here, \triangle represents a subtree and \dots represents the rest of the tree.

Case: Left-Left (General)

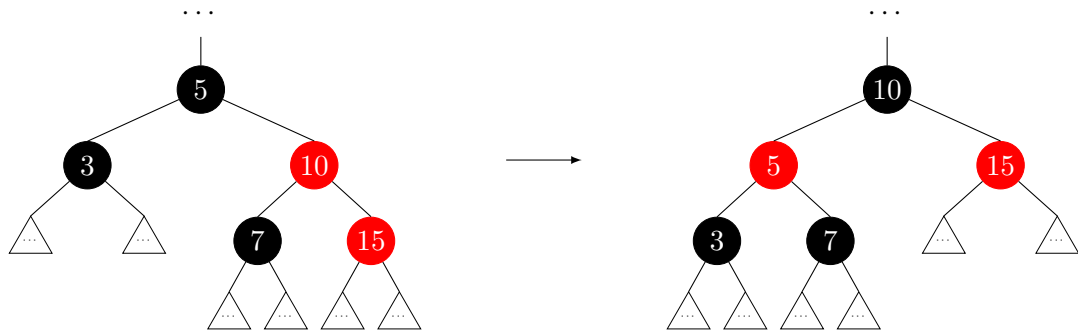



Here,  represents a subtree and ... represents the rest of the tree.

Case: Right-Right (Simple)

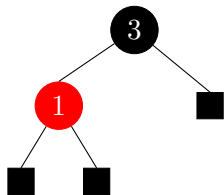


Case: Right-Right (General)

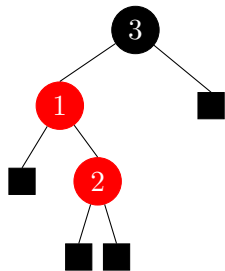


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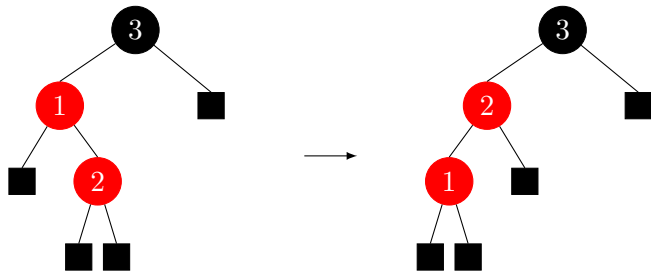
Case: Left-Right (Simple)



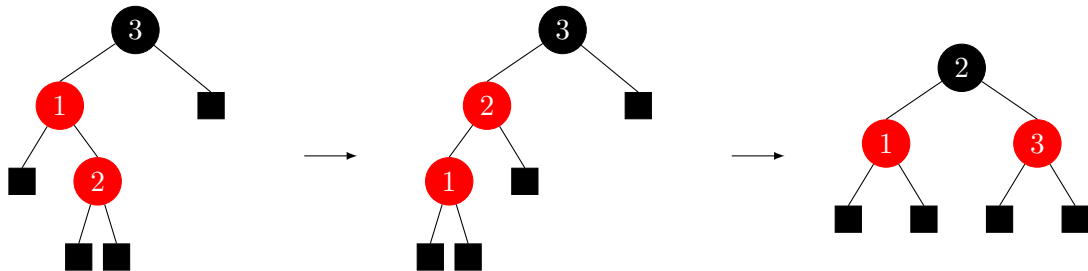
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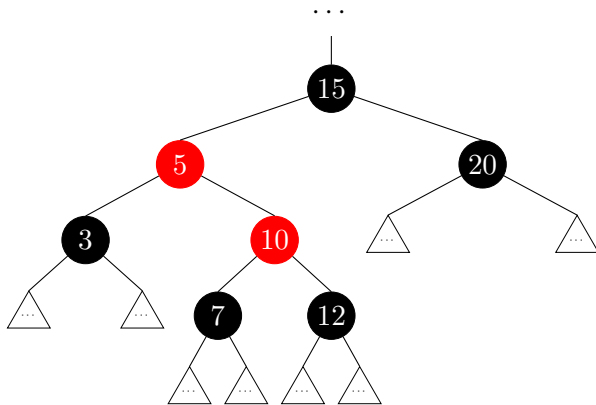


Case: Left-Right (Simple)



Case: Left-Right (General)

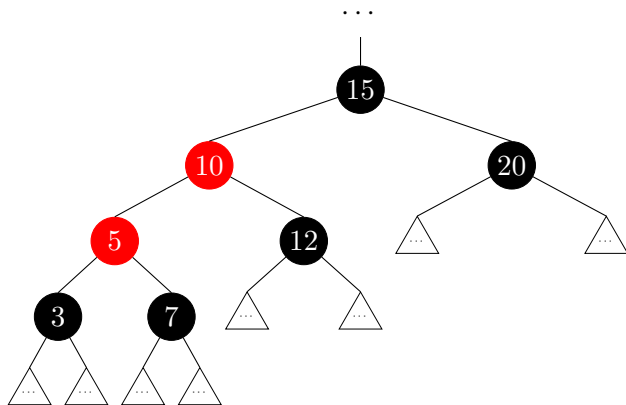
Step 1



Here, \triangle represents a subtree and \dots represents the rest of the tree.

Case: Left-Right (General)

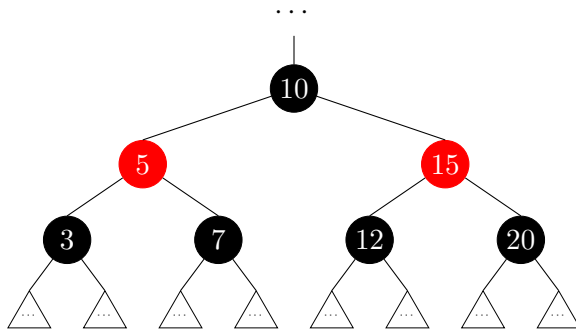
Step 2



Here, \triangle represents a subtree and \dots represents the rest of the tree.

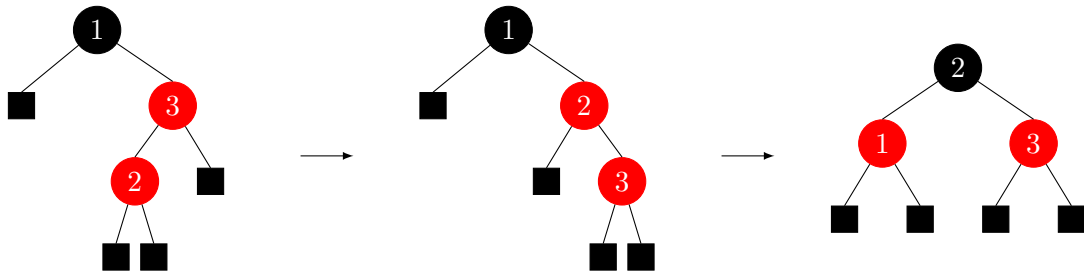
Case: Left-Right (General)

Step 3

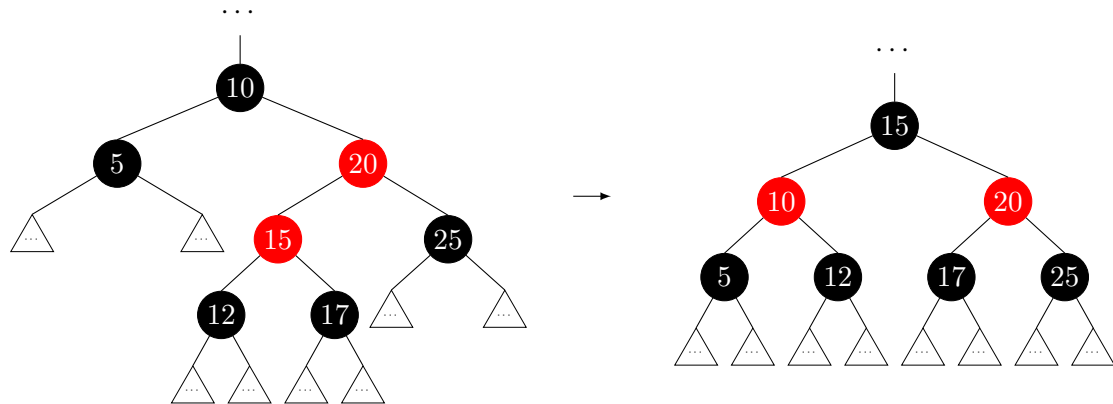


Here, \triangle represents a subtree and \dots represents the rest of the tree.

Case: Right-Left (Simple)



Case: Right-Left (General)



Here, \triangle represents a subtree and \dots represents the rest of the tree.

Time and Space Complexities

→ ***Insertion:*** $\mathcal{O}(\log n)$

→ ***Deletion:*** $\mathcal{O}(\log n)$

→ ***Search:*** $\mathcal{O}(\log n)$

→ ***Space:*** $\mathcal{O}(n)$

End

Thank you!

Appendix

Below are slides that didn't make the cut.

Corollaries

Proposition

*If a node z has exactly one child, c , then (a) c is **red**, (b) z is **black**, and (c) c has no children.*

Proof. Suppose we have a valid **red-black** tree. Consider a node z with exactly one child. Without loss of generality, choose z 's left node to be the child and call it c .

- (a) z passes through no **black** nodes on the right side by assumption. If c were **black**, then z would pass through 1 **black** node, a contradiction since this violates the *depth property*.
- (b) By (a), z 's child is **red** and by the *internal property*, z is **black**.
- (c) Since z passes through no **black** nodes on the right side by assumption, z cannot pass through any **black** nodes on the left side by the *the depth property*. Then, since c is **red** by (a), c has only nil nodes

□

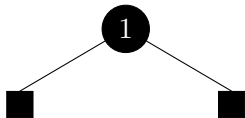
Height of a Red-Black Tree

Theorem

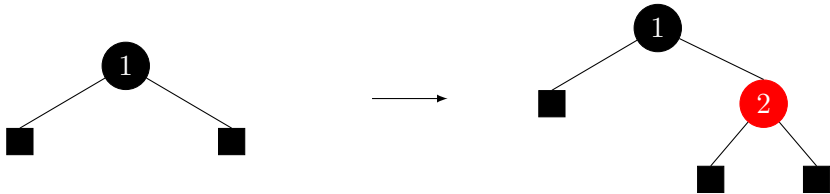
*A **red-black** tree with n nodes has a height h that is $\mathcal{O}(\log n)$.*

Proof. Suppose we have a **red-black** tree with n nodes and height h . Let b be the number of **black** nodes on the shortest path from root to any leaf. In the worst case, the longest path alternates between **red** and **black** nodes and thus has a height of $2b$. Then, h is bounded above by $2b$; that is, $h \leq 2b$. There are $2^b - 1 \leq n$ nodes in this tree. Solving for b , we get $b \leq \log(n + 1)$. Substituting b , we get $b \leq \log(n + 1) \leq h \leq 2b \leq 2 \log(n + 1)$ so h is bounded below by $\log(n + 1)$ and above by $2 \log(n + 1)$; that is, $\log(n + 1) \leq h \leq 2 \log(n + 1)$. So, h is $\mathcal{O}(\log n)$. \square

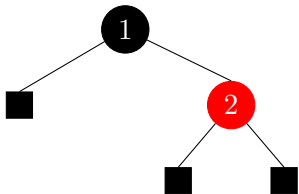
Red-Black Tree: Example



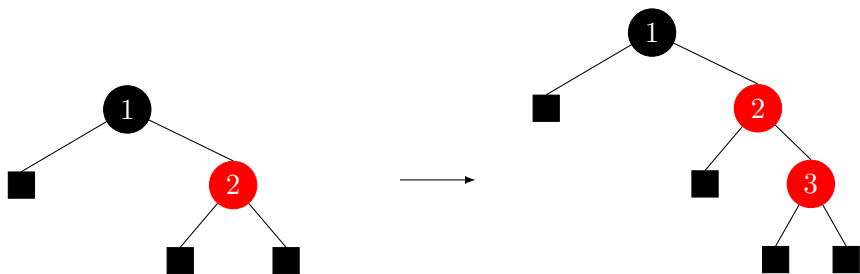
Red-Black Tree: Example



Red-Black Tree: Example

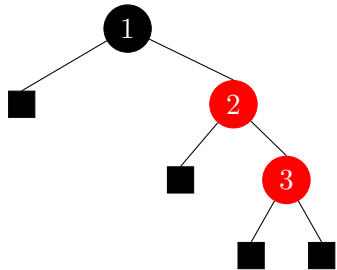


Red-Black Tree: Example



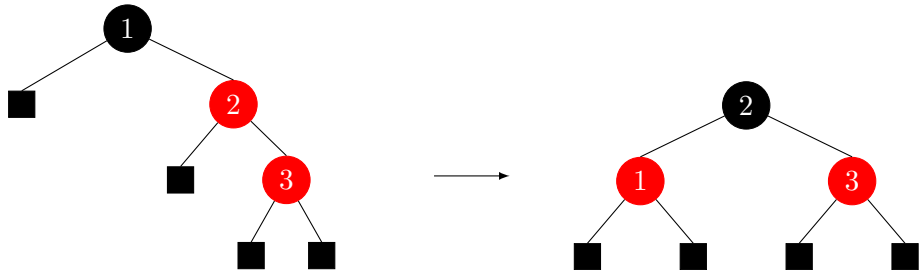
Case: Right-Right

Red-Black Tree: Example



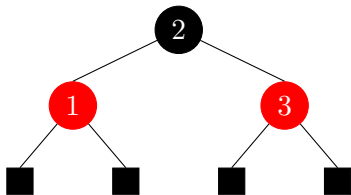
Case: Right-Right

Red-Black Tree: Example

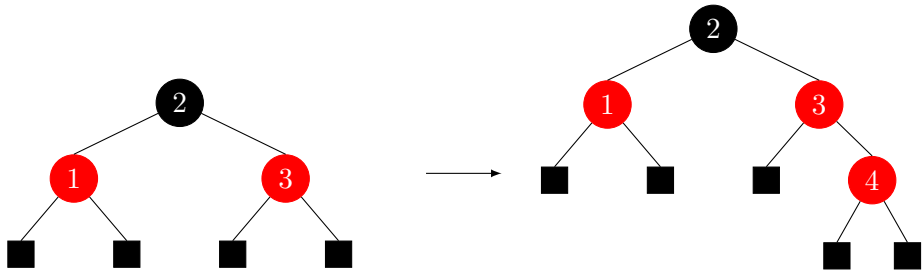


Case: Right-Right

Red-Black Tree: Example

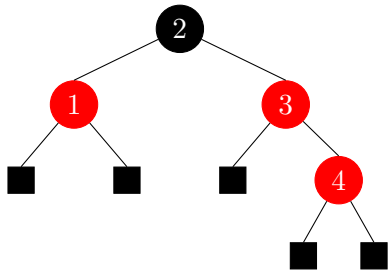


Red-Black Tree: Example



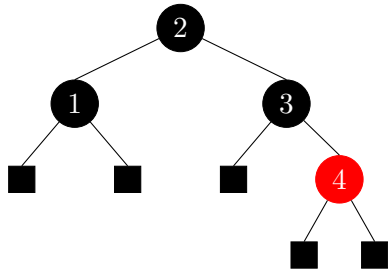
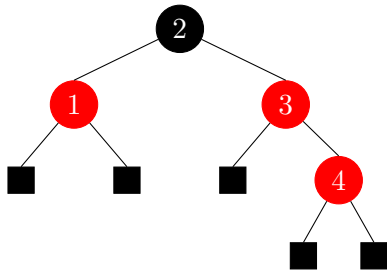
Case: Recolor

Red-Black Tree: Example



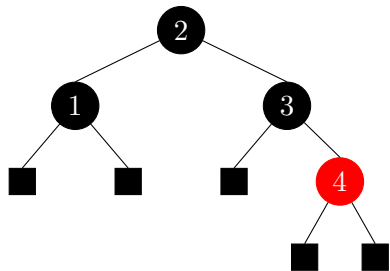
Case: Recolor

Red-Black Tree: Example

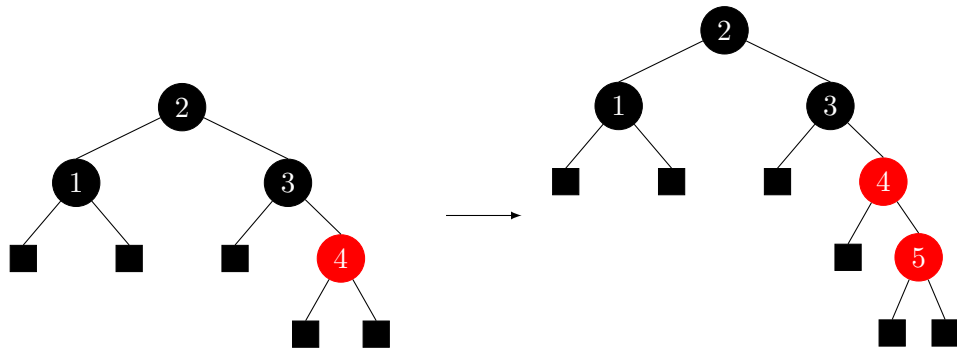


Case: Recolor

Red-Black Tree: Example

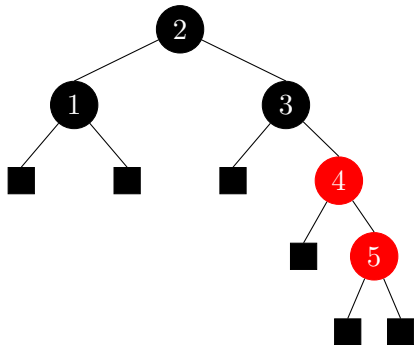


Red-Black Tree: Example



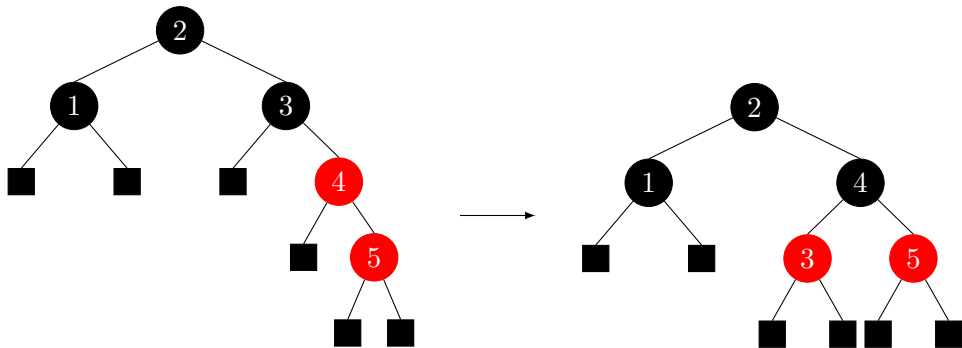
Case: Right-Right

Red-Black Tree: Example



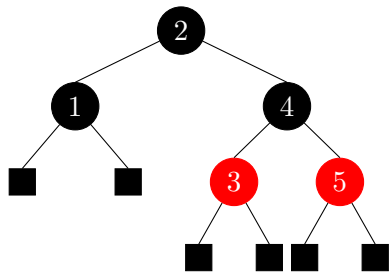
Case: Right-Right

Red-Black Tree: Example

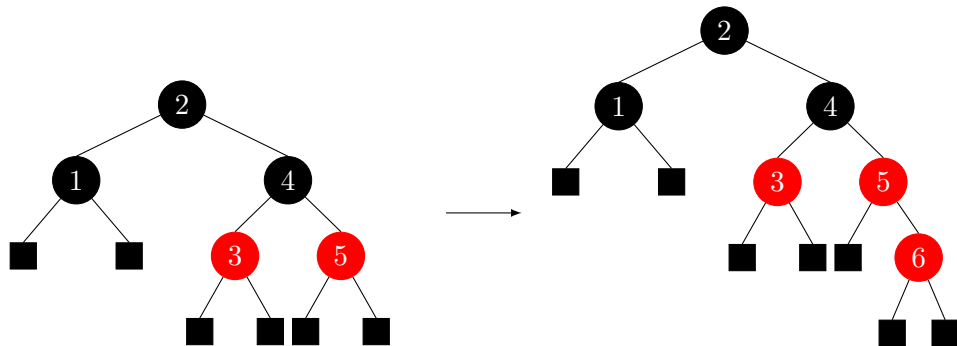


Case: Right-Right

Red-Black Tree: Example

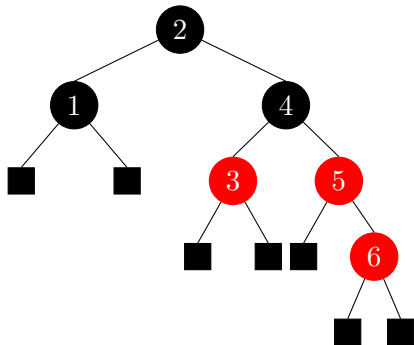


Red-Black Tree: Example



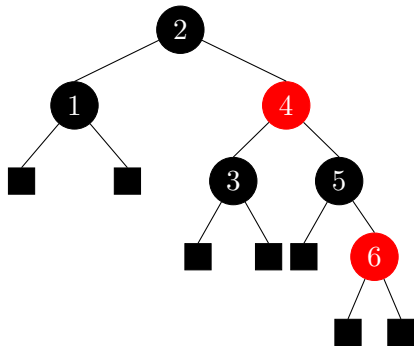
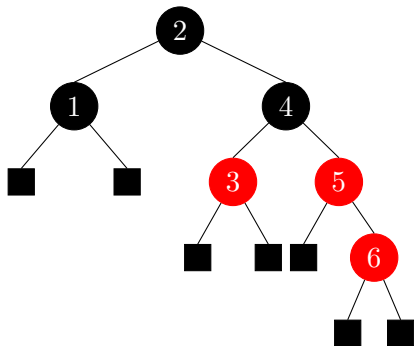
Case: Recolor

Red-Black Tree: Example



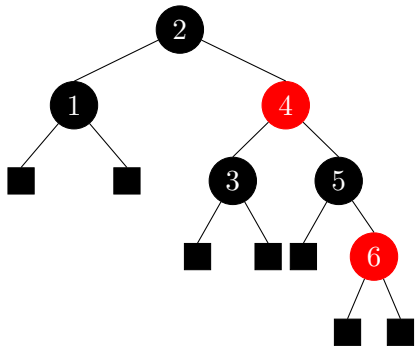
Case: Recolor

Red-Black Tree: Example

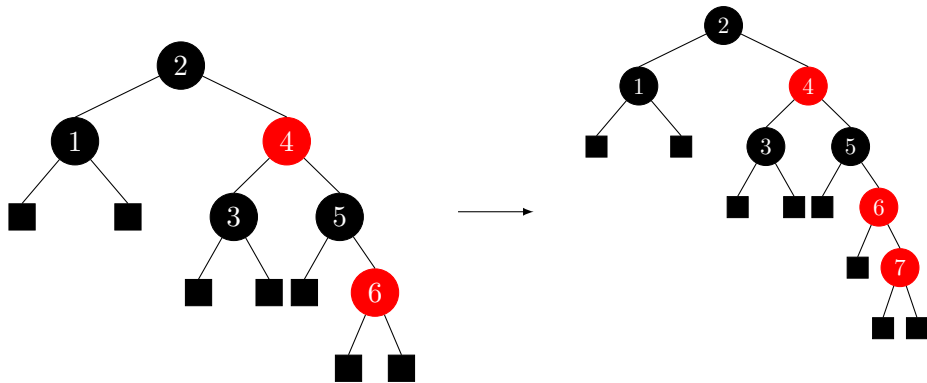


Case: Recolor

Red-Black Tree: Example

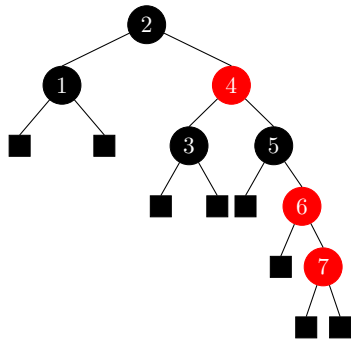


Red-Black Tree: Example



Case: Right-Right

Red-Black Tree: Example



Red-Black Tree: Example

