CSE-200 Final Presentation

Red Black Tree

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Bangladesh University of Engineering and Technology

We Need to Store and Search Data

- Everything is **tree-structured**

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- **Insert** data into the structure

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We Need to Store and Search Data

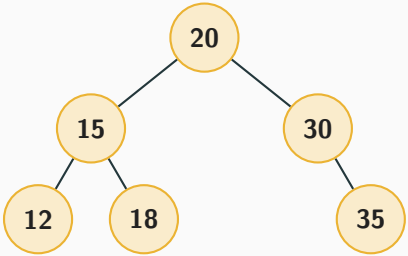
- Everything is **tree-structured**
- **Insert** data into the structure
- **Delete** data efficiently
- **Search** for data quickly

Good way to do all of this?

Use a BST!

The BST Rule

How does BST decide where to put a node?



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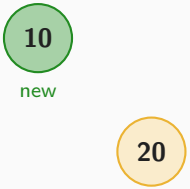

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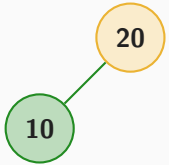

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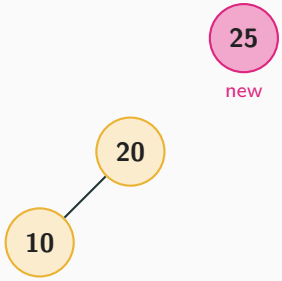

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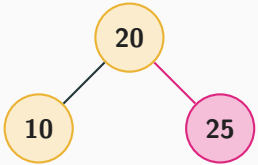

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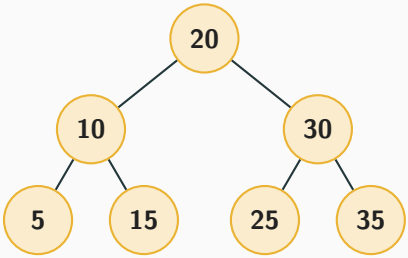

Good technique!

Insert the roll numbers in a class sequentially

1, 2, 3, 4 ...10

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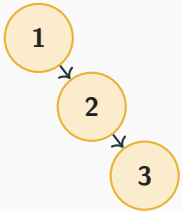

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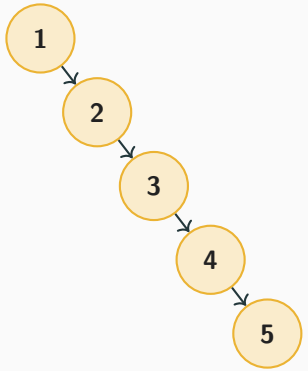
- The tree just keeps **growing** right...



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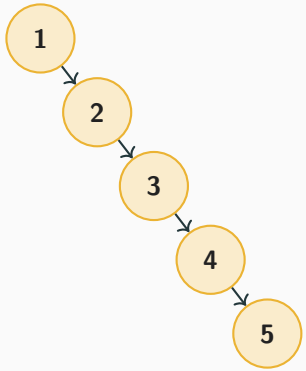

Still works!

...and on

But, What's the Problem?

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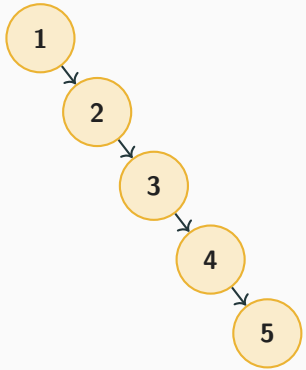

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But, What's the Problem?

- **Height becomes n**
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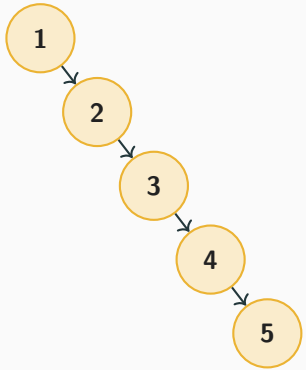

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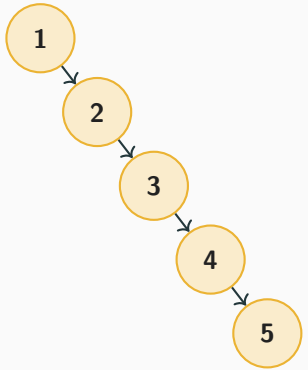

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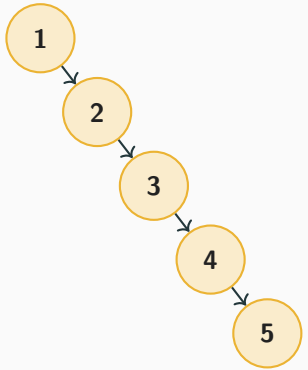

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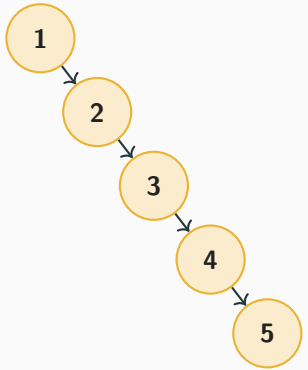

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- Insertion takes $O(n)$
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- A linked list in disguise

Time complexity becomes $O(n)$

The Solution?

Use a BST that **promises** to keep its height **logarithmic**

no matter how and what element you insert.

The Solution?

Examples of Self-Balancing Trees:

- AVL Tree
- **Red-Black Tree**
- Splay Tree
- B-Tree

Let's look at Red-**Black** Trees

What is Red-Black Tree

A Red-Black Tree rebalances itself by coloring nodes **red** and **black**, ensuring no two **red** nodes are **adjacent** and all **paths** have the same **black-height**, which keeps its height **logarithmic**.

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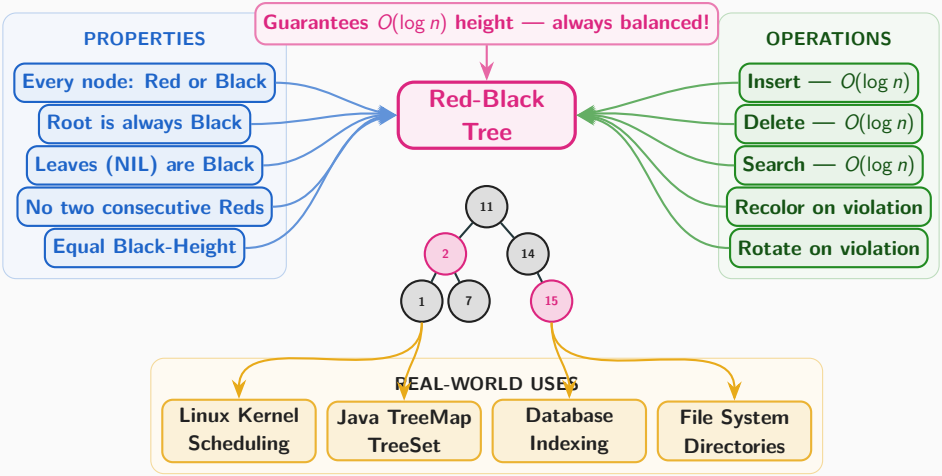
Height becomes log(n) here!

Red-Black Tree — Complete Overview



Five points to remember

How does RBT do it:Properties

- **Property 1:** Every node is either red or black

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Hence, the name Red Black Tree

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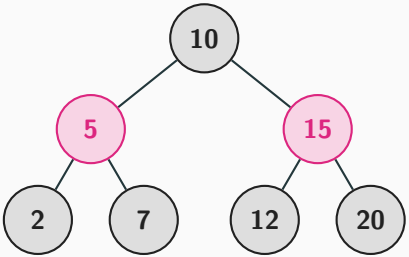

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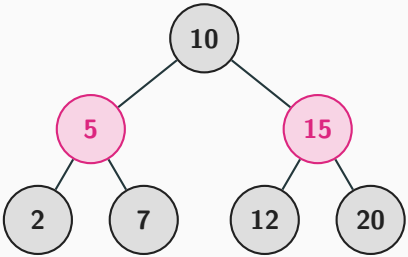

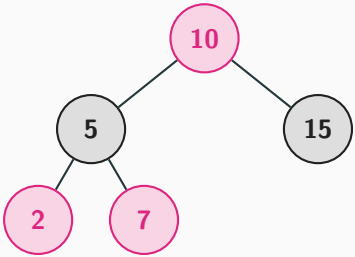

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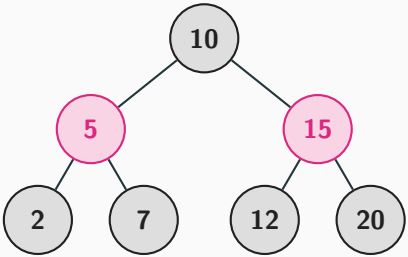

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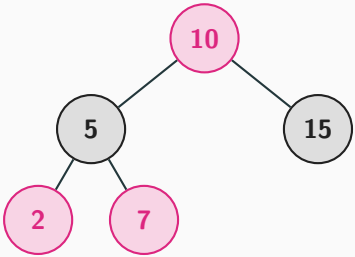

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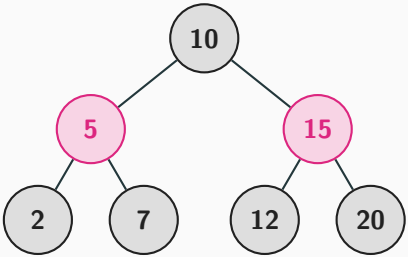

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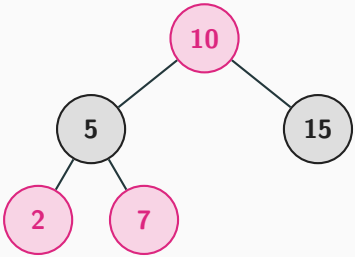

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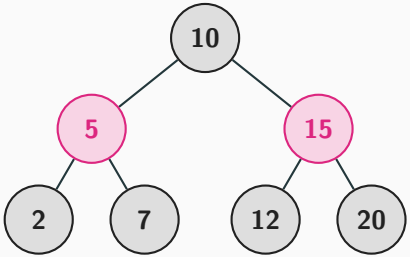

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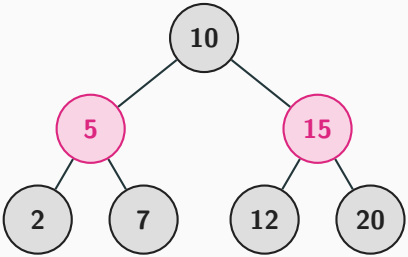

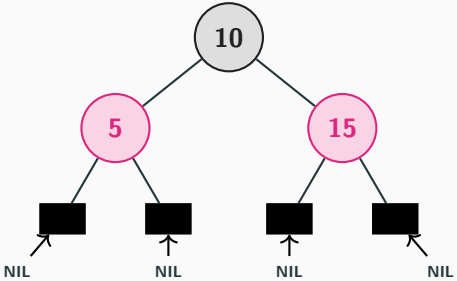

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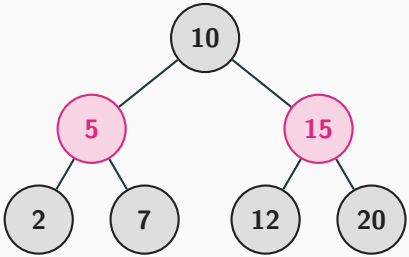
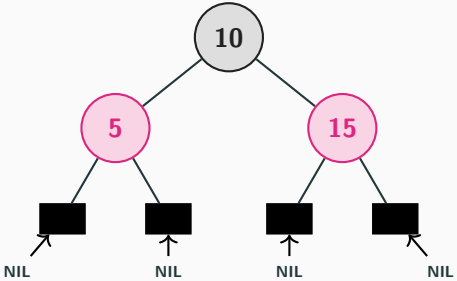


Black Leaves



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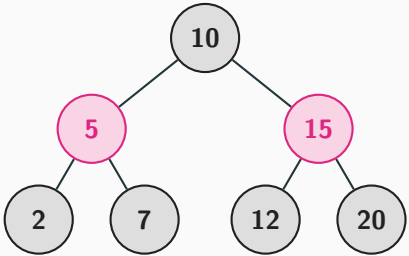

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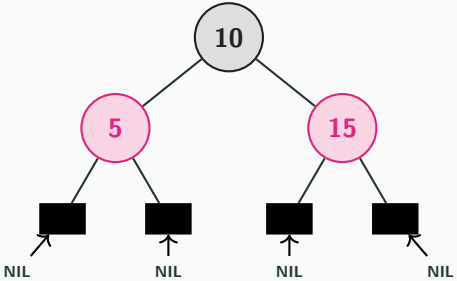

NIL nodes (counted as Black)

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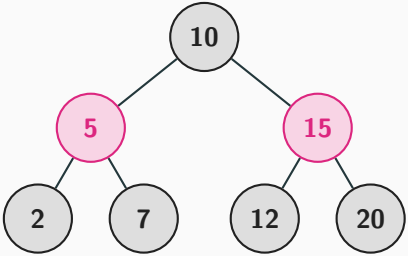

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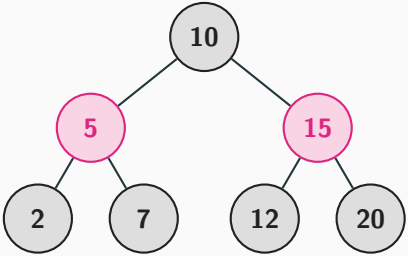

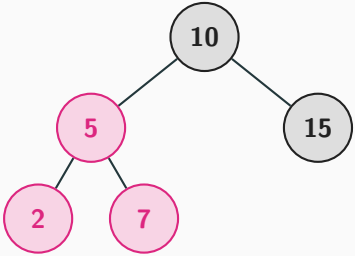

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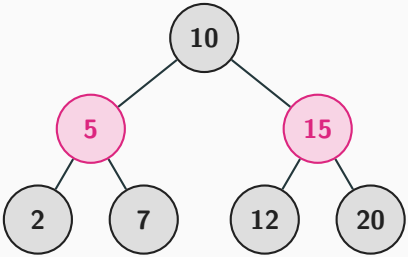

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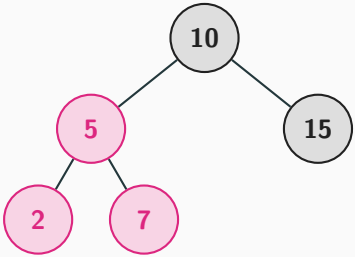

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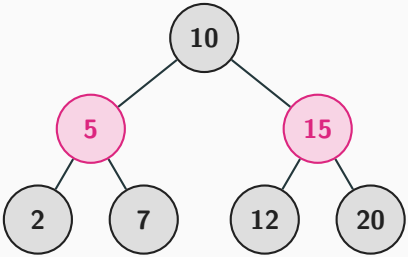

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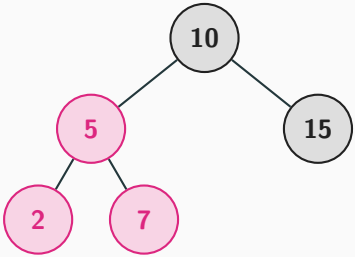

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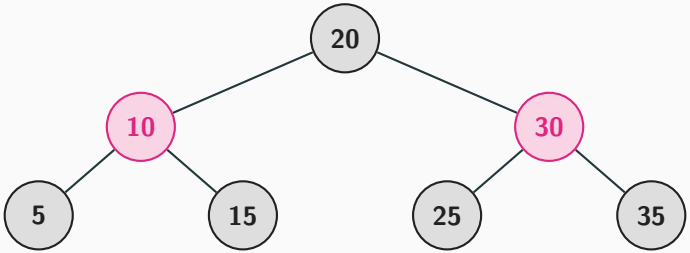

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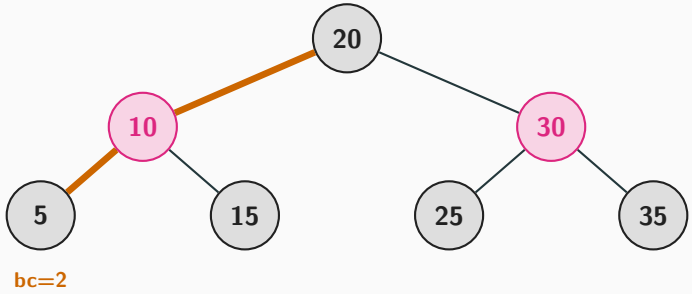

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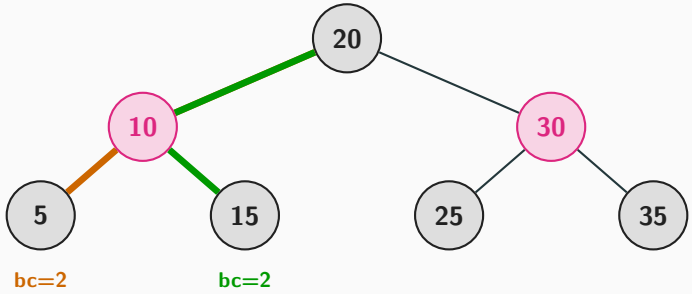

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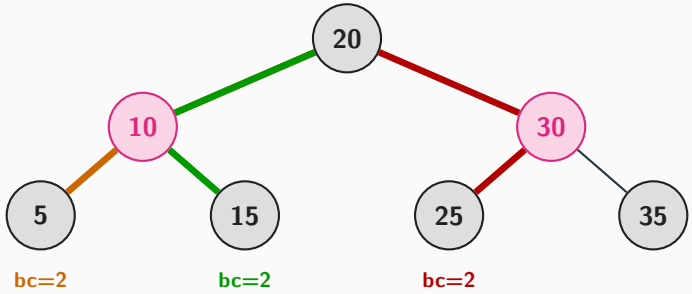

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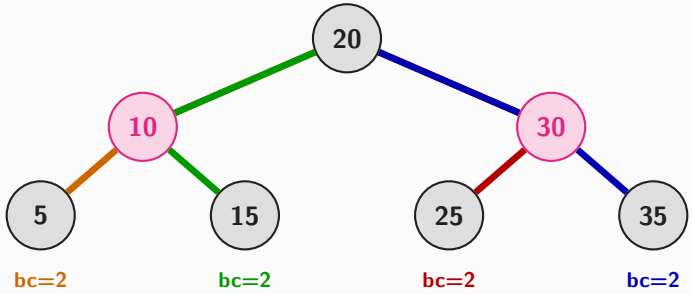

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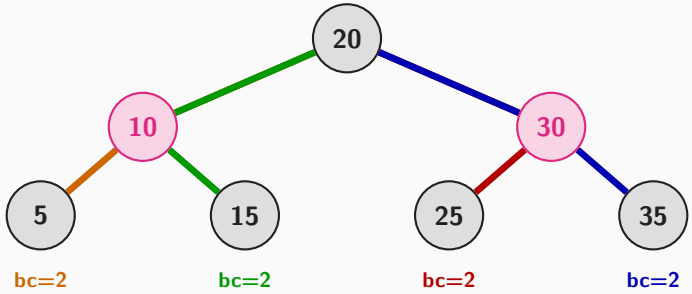

All paths from root have same black count = 2

RBT Operations

Now, How do these points ensure the "rebalancing" feature of Red Black Tree?

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Let's see some operations....

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Pseudocode

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y = root[T]

while y ≠ NIL do
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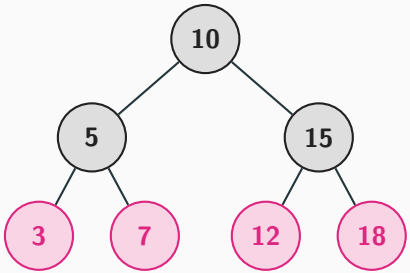
Existing RBT



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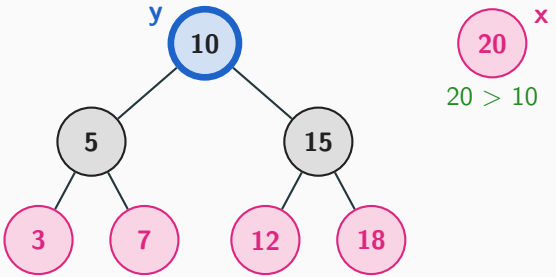

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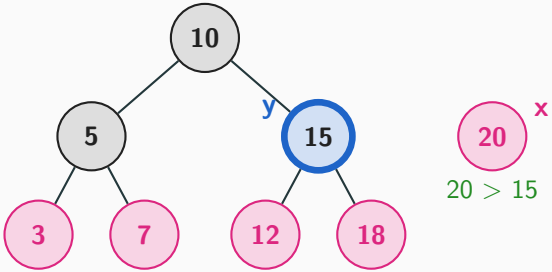

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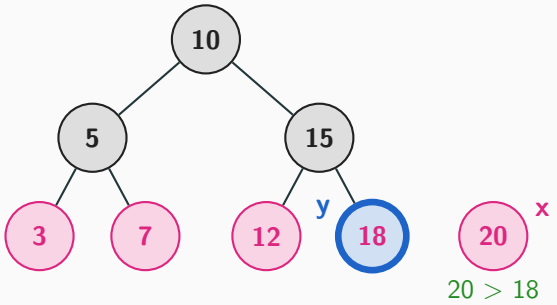
```

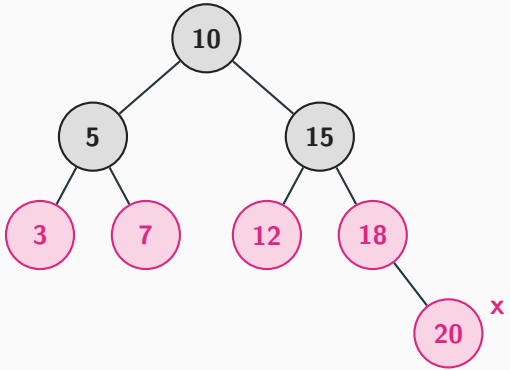


Insertion

Insert node x in a Red Black Tree

Pseudocode

```
color[x] = RED
y = root[T]
while y ≠ NIL do
  if key[x] > key[y]
    y = right[y]
  else
    y = left[y]
```

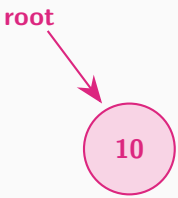


What can go wrong

Insert 10

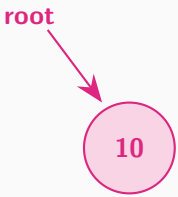
What can go wrong

Insert 10



What can go wrong

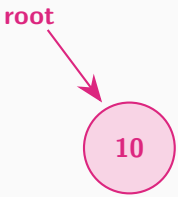
Insert 10



Root can't be RED

What can go wrong

Insert 10

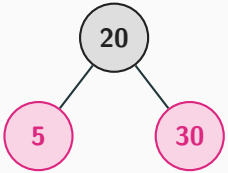


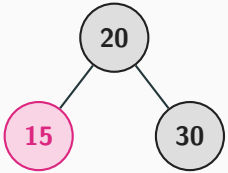
Root can't be RED

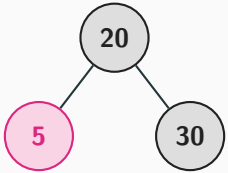
Case 1

What can go wrong

Insert 10

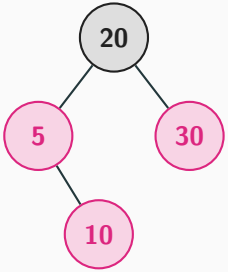


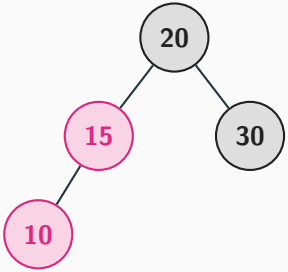


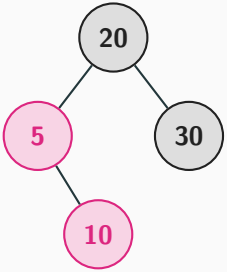


What can go wrong

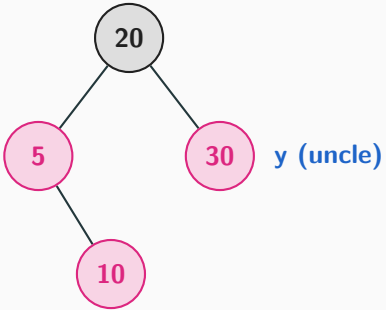
Insert 10







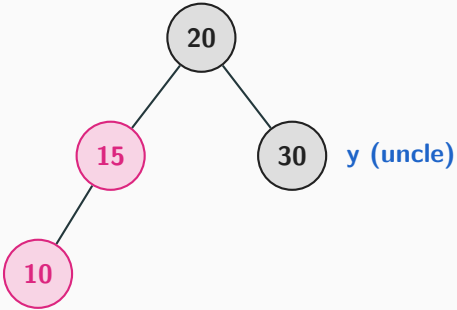
How insertion violates RBT properties



Uncle **y** is **RED**

Case 2

How insertion violates RBT properties

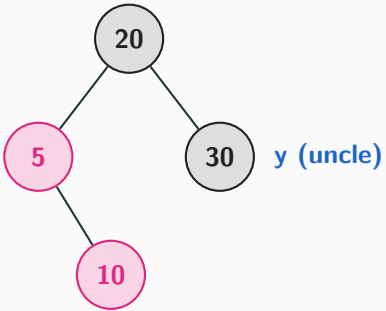


Uncle **y** is **BLACK**

(Left-Left Case)

Case 3

How insertion violates RBT properties



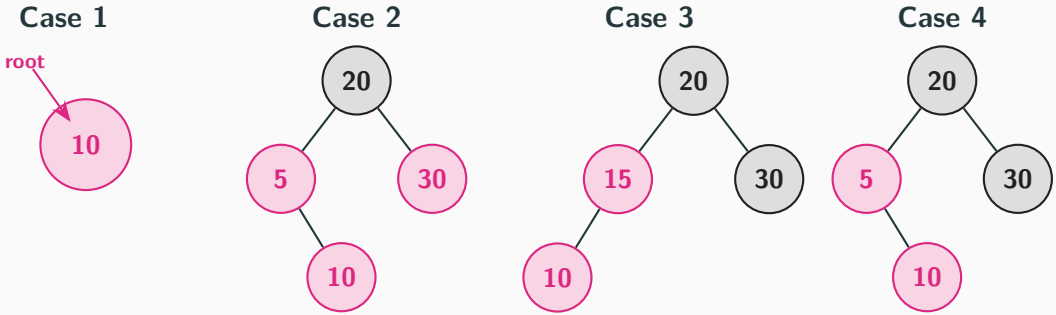
Uncle **y** is **BLACK**

(Left-Right Case)

Case 4

Insertion Violation Cases

Four main violation cases in Red-Black Tree insertion:



How to solve this?

Remember This Problem?

Let's insert 1, 2, 3, 4, 5 again

But this time in a Red-Black Tree

Insert 1

- First node is always **root**
- Insert as **RED** (default color)
- But Root cannot be **RED!**
  Property 2 violated - Case : 1

After Insert — Violation!

Insert 1

- First node is always **root**
- Insert as **RED** (default color)
- But Root cannot be **RED!**
  Property 2 violated - Case : 1
- Recolor root to **BLACK**
- **Fixed!**

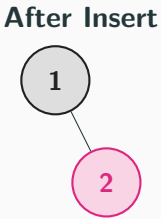
After Recolor

Insert 2

- Right child of 1
- Insert as **RED** (default color)

Insert 2

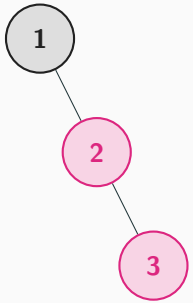
- Right child of 1
- Insert as **RED** (default color)
- Parent is BLACK — **no violation** ✔



Insert 3

- Right child of 2
- Insert as **RED** (default)
- Uncle is **NIL/BLACK** — **Case: 3**

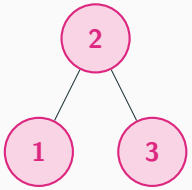
Violation — Two RED in a row!



Insert 3

- Right child of 2
- Insert as **RED** (default)
- Uncle is **NIL/BLACK** — **Case: 3**
- Left rotate at node 1

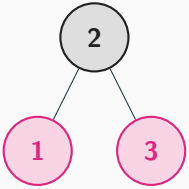
After Left Rotation



Insert 3

- Right child of 2
- Insert as **RED** (default)
- Uncle is **NIL/BLACK** — **Case: 3**
- Left rotate at node 1
- Recolor: 2 → **BLACK**, children → **RED**
- **Fixed!**

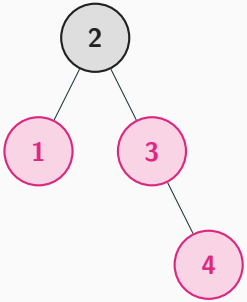
After Recolor



Insert 4

- Right child of 3
- Insert as **RED** (default)
- Uncle (node 1) is **RED** — **CASE 2**

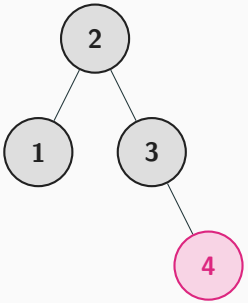
Violation — Uncle is RED



Insert 4

- Right child of 3
- Insert as **RED** (default)
- Uncle (node 1) is **RED** — **CASE 2**
- Recolor: parent & uncle → **BLACK**
- Grandparent stays **BLACK**
- **Fixed!**

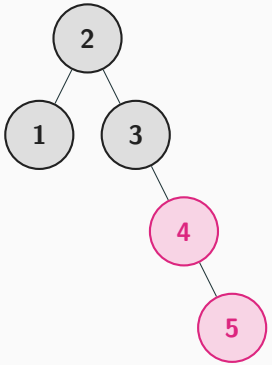
After Recolor



Insert 5

- Right child of 4
- Insert as **RED** (default)
- Uncle (node 1) is **BLACK** — **CASE 3**

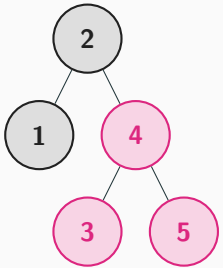
Violation — Two RED in a row!



Insert 5

- Right child of 4
- Insert as **RED** (default)
- Uncle (node 1) is **BLACK** — **CASE 3**
- Left rotate at node 3 $\rightarrow$ 4 moves up

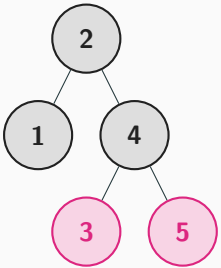
After Left Rotation



Insert 5

- Right child of 4
- Insert as **RED** (default)
- Uncle (node 1) is **BLACK** — **CASE 3**
- Left rotate at node 3 $\rightarrow$ 4 moves up
- Recolor: 4 $\rightarrow$ **BLACK**, children $\rightarrow$ **RED**
- **We're done!**

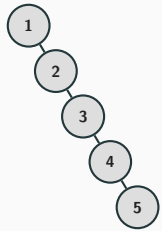
After Recolor



BST vs. Red-Black Tree

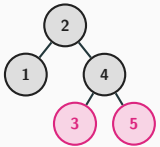
Inserting $\{1, 2, 3, 4, 5\}$ in order

Regular BST



Height = 5 ▪ $O(n)$

Red-Black Tree



Height = 3 ▪ $O(\log n)$

Insertion is the easy half

Now, What happens when we delete a node?

Deletion is even more... interesting!

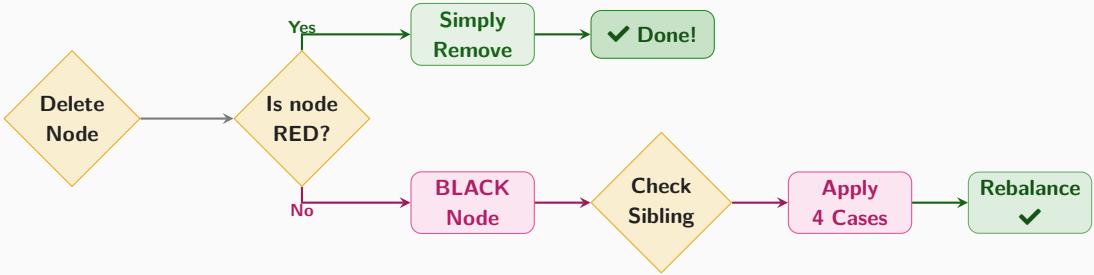
Deleting a RED node

- No problem!
- Just remove it
- **Properties still hold**

Deleting a BLACK node

- Oh boy...
- Black height changes!
- **Need "double black" fix**
- Complex cases

Deletion Decision Flowchart



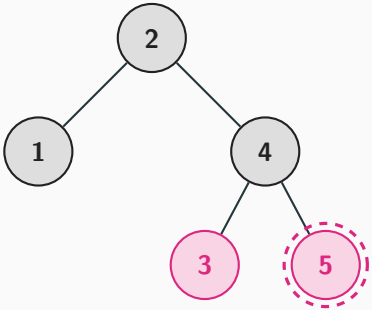
Top path (RED node) = straightforward

Bottom path (BLACK node) = complex

Case 1: Deleting a RED Node

Delete node **5** from the tree

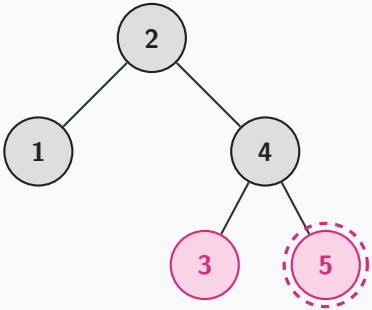
Before



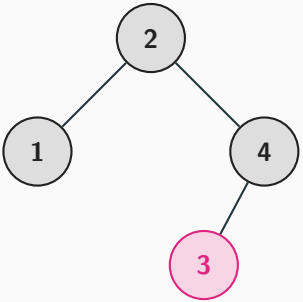
Case 1: Deleting a RED Node

Delete node **5** from the tree

Before



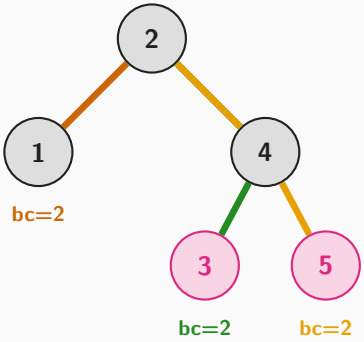
After



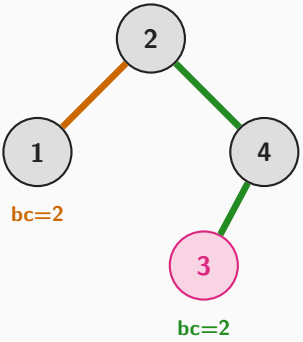
Case 1: Black-Height Stays the Same

Every path still has **bc = 2** black nodes after removing 5

Before (with node 5)



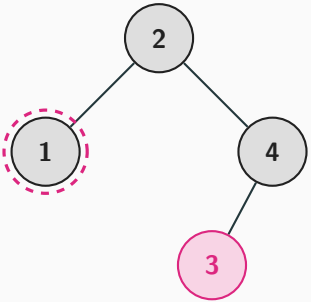
After (node 5 removed)



Case 2: Deleting a BLACK Node

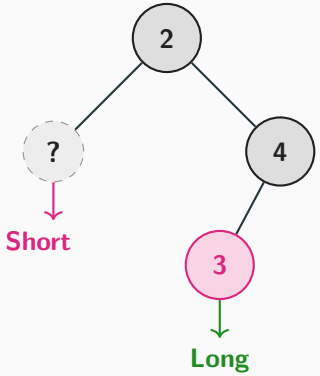
Delete node **1** from the tree

Before deletion:



Case 2: After Deleting the BLACK Node

The node is gone - but now we have a **problem**

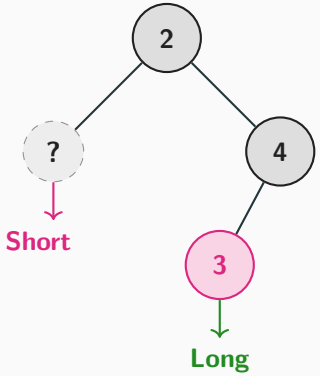


- Left path is now **shorter**
- Black-height **violated!**
- We call this a

  "Double-Black" node

Case 2: After Deleting the BLACK Node

The node is gone - but now we have a **problem**



- Left path is now **shorter**
- Black-height **violated!**
- We call this a

  "Double-Black" node

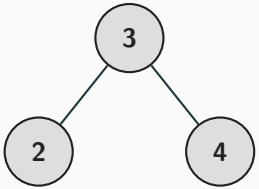
IMBALANCED - must fix!

Case 2: The Fix-up

- **Rotate:** Right at 4, then left at 2
- **Recolor:** Node 3 $\rightarrow$ Black

Case 2: The Fix-up

- **Rotate:** Right at 4, then left at 2
- **Recolor:** Node 3 $\rightarrow$ Black



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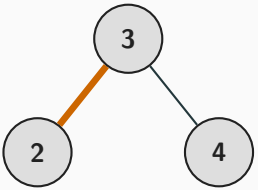

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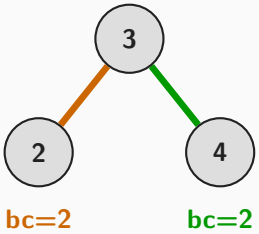
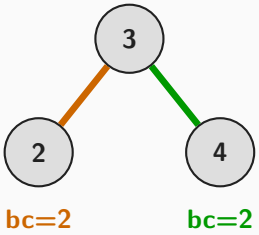


Case 2: The Fix-up

- **Rotate:** Right at 4, then left at 2
- **Recolor:** Node 3 $\rightarrow$ Black
- **Tree is balanced!**



Fixing Double-Black: 4 Cases

When we have a **Double-Black** node,

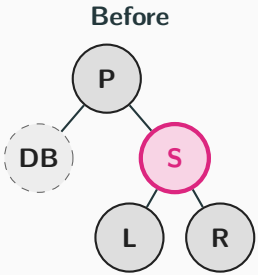
the fix depends on the **sibling's color and children**.

P = Parent **S** = Sibling **L** / **R** = S's children

= Double-Black node

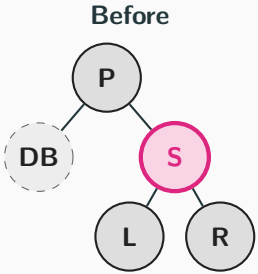
Fix Case 1 of 4: Sibling is RED

The Sibling S is RED



Fix Case 1 of 4: Sibling is RED

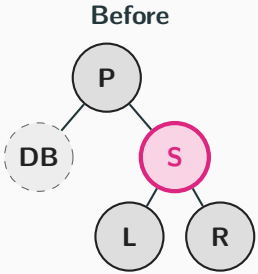
The Sibling S is RED

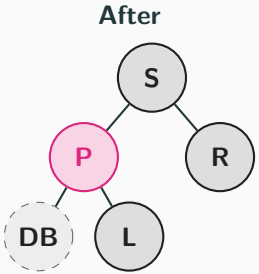


- **Rotate** P to the left
- **Recolor:** S $\rightarrow$ Black, P $\rightarrow$ Red

Fix Case 1 of 4: Sibling is RED

The Sibling S is RED



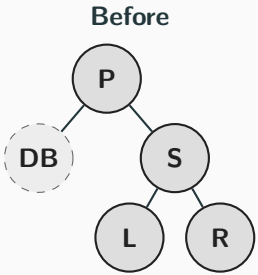


Now apply Case 2, 3, or 4 to DB

- **Rotate** P to the left
- **Recolor:** S $\rightarrow$ Black, P $\rightarrow$ Red

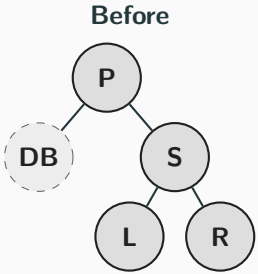
Fix Case 2 of 4: Sibling & Children All BLACK

S and both children are BLACK



Fix Case 2 of 4: Sibling & Children All BLACK

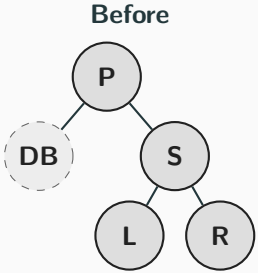
S and both children are BLACK

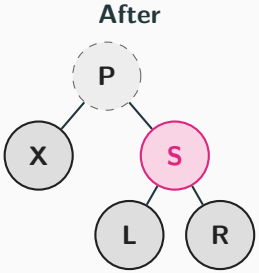


- **Recolor** S $\rightarrow$ Red
- Push the Double-Black **up to P**

Fix Case 2 of 4: Sibling & Children All BLACK

S and both children are BLACK



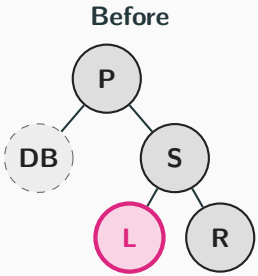


DB pushed to P — continue fixing

- **Recolor** S → Red
- Push the Double-Black **up to P**

Fix Case 3 of 4: Sibling's Left Child is RED

S is Black, S's Left child is RED



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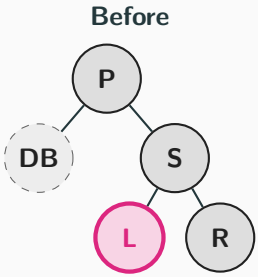

- **Right-rotate** at S, & **Swap colors** of S and L

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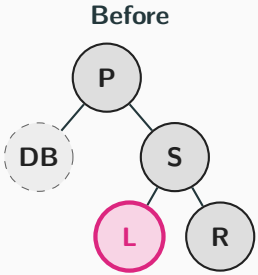

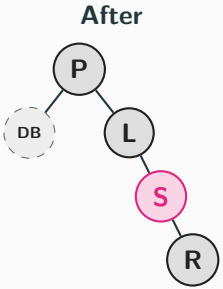

Now proceed with Case 4

- **Right-rotate** at S, & **Swap colors** of S and L

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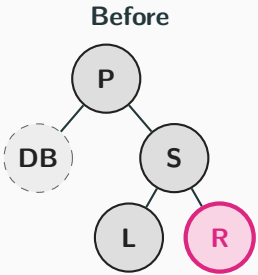

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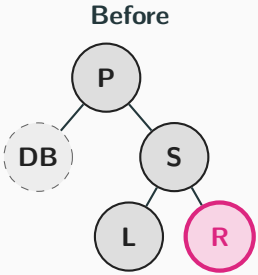

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- **Recolor** R → Black

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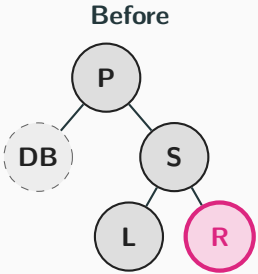

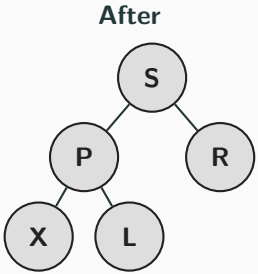

Double-Black fully resolved!

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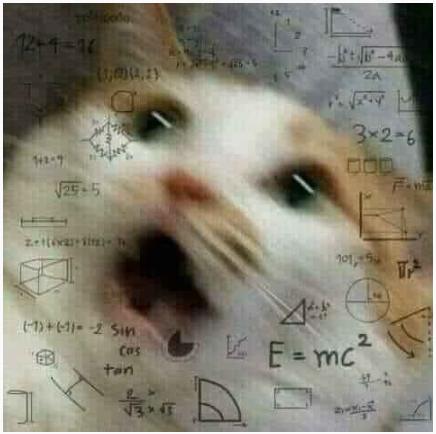
Too Many Cases?



Confused?

If this felt like **a lot** at once -
that's because **it is !**

We know deletion is complex - and that's *okay!*

All that work.

What did it actually buy us?

Let's finally see the payoff.

Rotation Complexity: $O(1)$ Operations

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Left Rotation:

- Restructures tree locally

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Rotations are $O(1)$ because they only change a constant number of pointers! No tree traversal needed - just pointer gymnastics!

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Proof Sketch:

1. Every path from root to leaf has same number of black nodes
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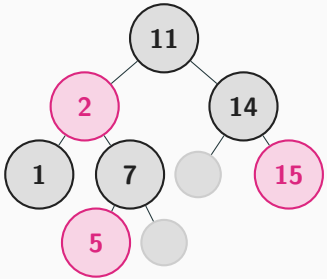

Black height = 2, Total height = 4

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Key Insight

Red-black trees achieve $O(n)$ space with just 1 extra bit per node (the color)!

That's the definition of space-efficient data structures!

The Evolution: From Red-Black to Modern Trees

50+ Years of Tree Balancing Innovation

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What to do with these trees?

"Yikes! Trees evolving faster than my code." - Some sad developer

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Fun fact: Robert Sedgewick (co-inventor of RBT) later said: *"I prefer left-leaning red-black trees now - they're simpler!"*

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- CPU scheduling algorithms

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- RBTs: Keanu Reeves of data structures - always reliable!

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Red-Black	$O(\log n)$	$O(\log n)$	$O(\log n)$	$O(n)$
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Not too fast, not too slow, just right!

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The Real Story Behind the Scenes

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Secret Sauce

Many companies use hybrid approaches - RBTs for small datasets, B-trees for large ones. It's complicated... but mostly red-black trees!

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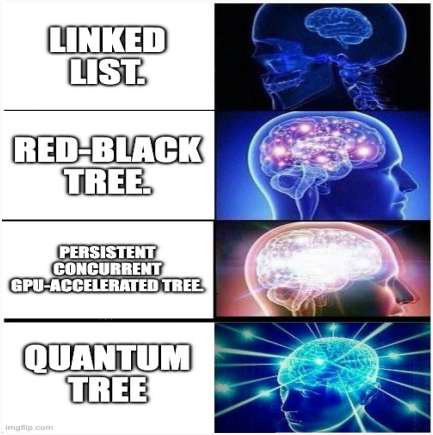

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Remember

The next time your code runs in $O(\log n)$ time...

Thank a red-black tree! ♡

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