CSE-200 Final Presentation

Red Black Tree

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Department of CSE
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

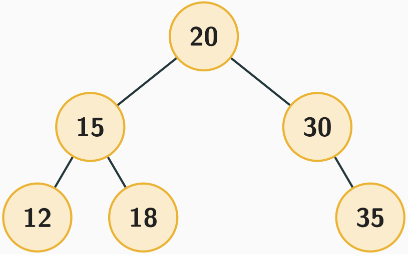
- Everything is **tree-structured**
- **Insert** data into the structure
- **Delete** data efficiently
- **Search** for data quickly

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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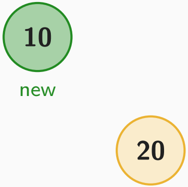
How does BST decide where to put a node?

- **Smaller than me?** Go **Left**



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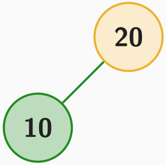

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- **Smaller than me?** Go **Left**
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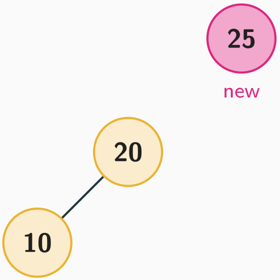

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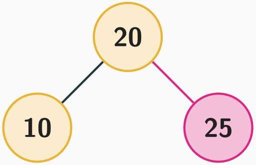

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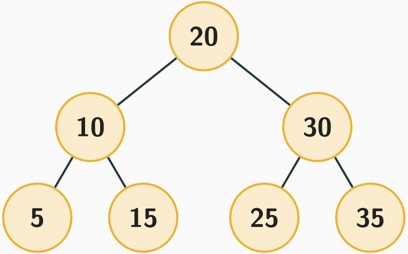

Good technique!

Insert the roll numbers in a class sequentially

1, 2, 3, 4 ...10

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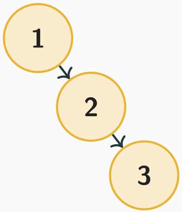

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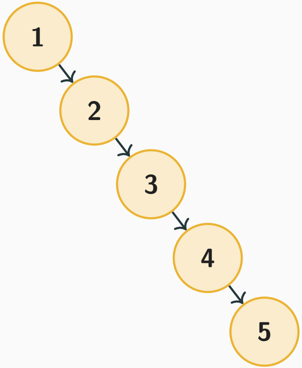

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- The tree just keeps **growing** right...

...and on

Insert the roll numbers in a class sequentially

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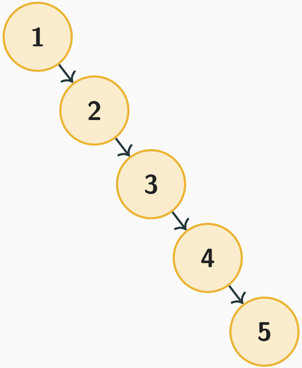

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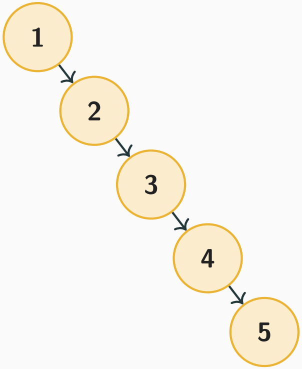
Still works!

...and on

But, What's the Problem?

- **Height becomes *n***



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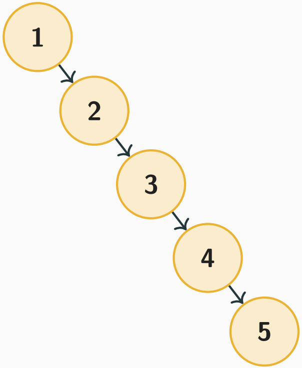
- **Height becomes n**
- Insertion takes $O(n)$



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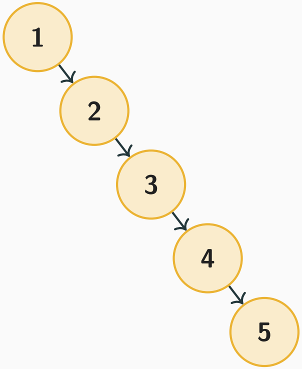

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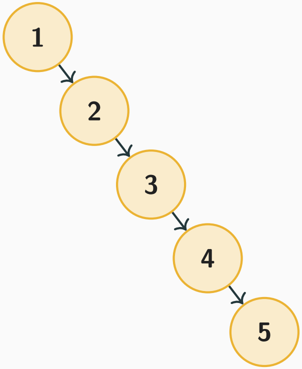

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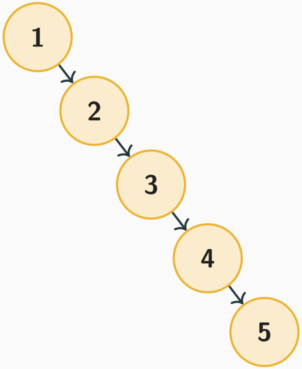

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- Insertion takes $O(n)$
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Time complexity becomes $O(n)$

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

The Solution?

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- AVL Tree
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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!

How does RBT do it:Properties

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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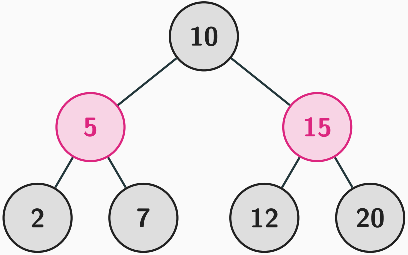

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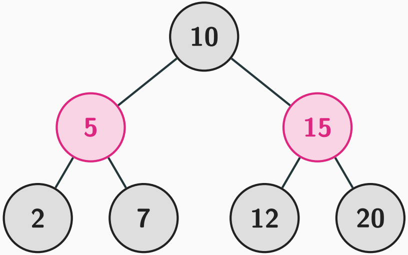

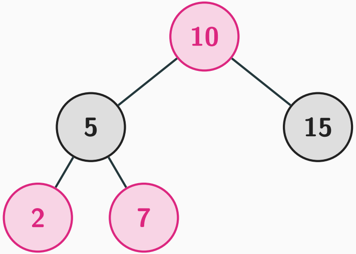

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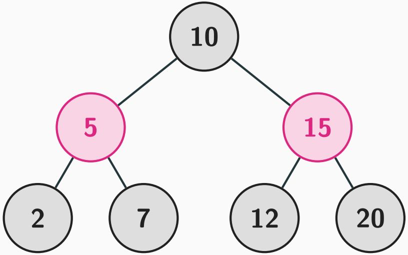

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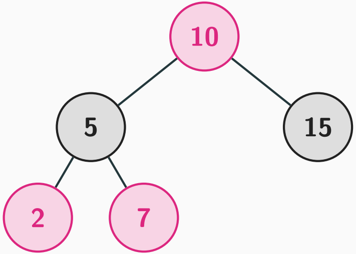

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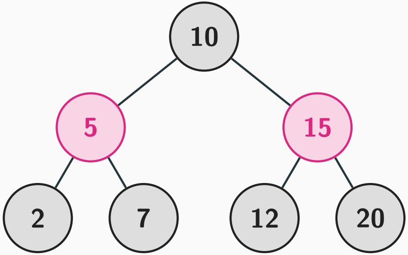

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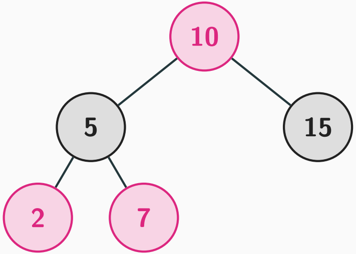

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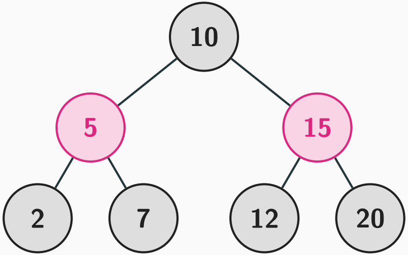

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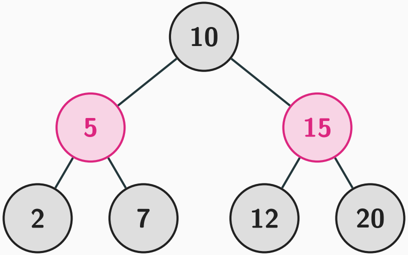

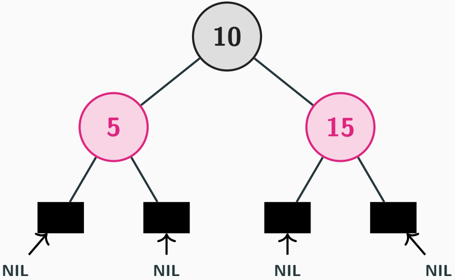

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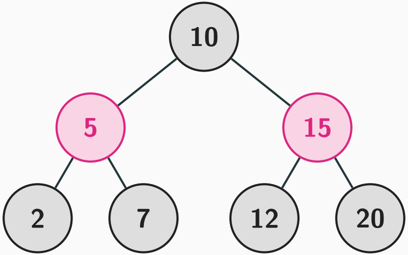
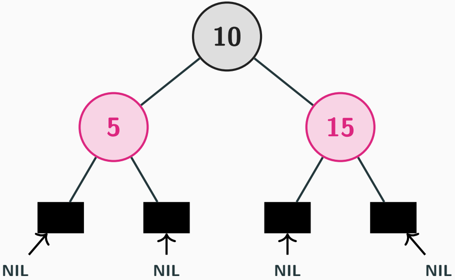


Black Leaves



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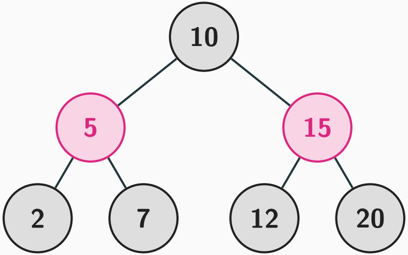

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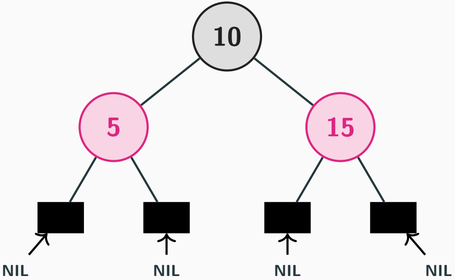

NIL nodes (counted as Black)

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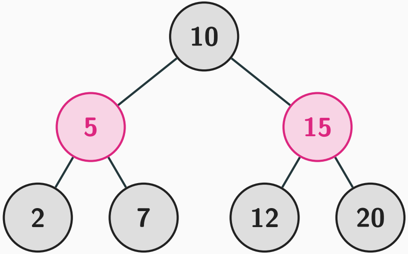

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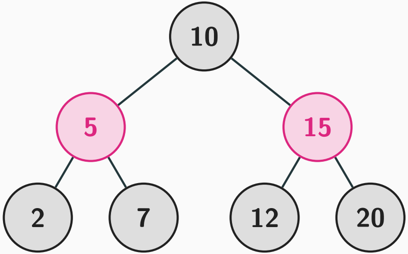

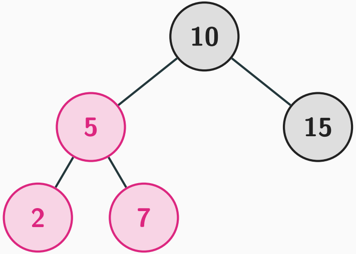

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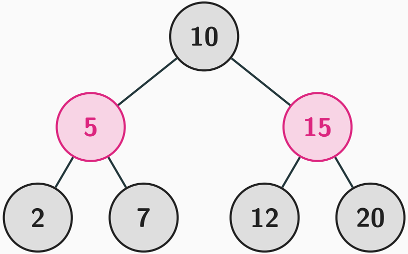

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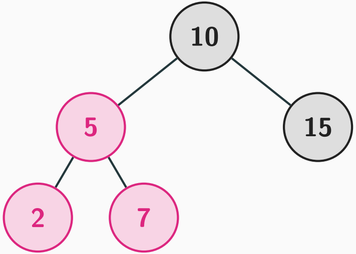

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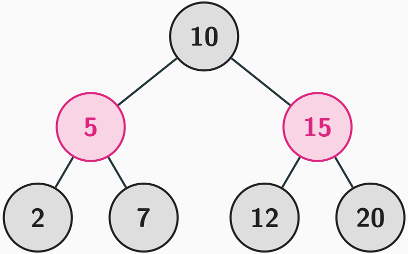

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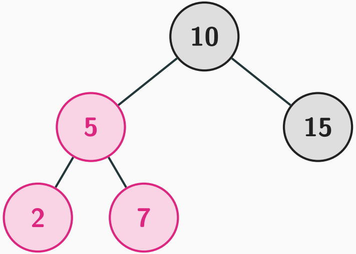

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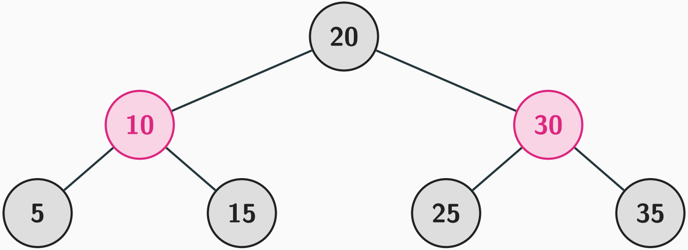

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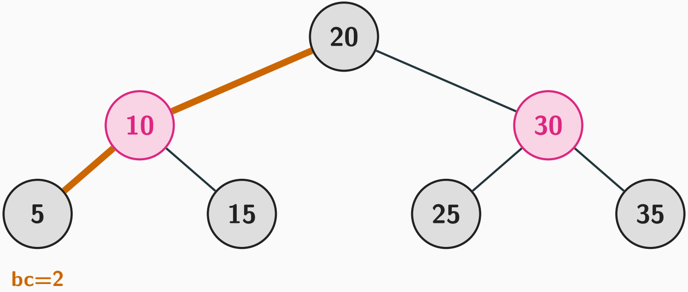

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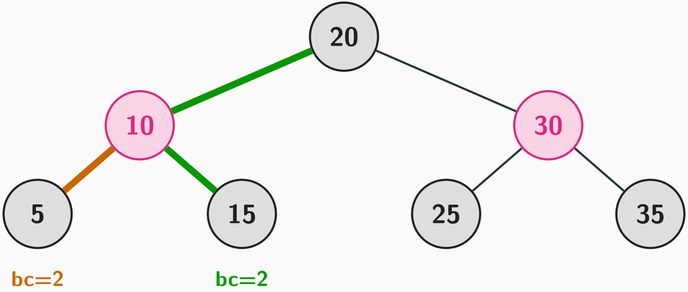

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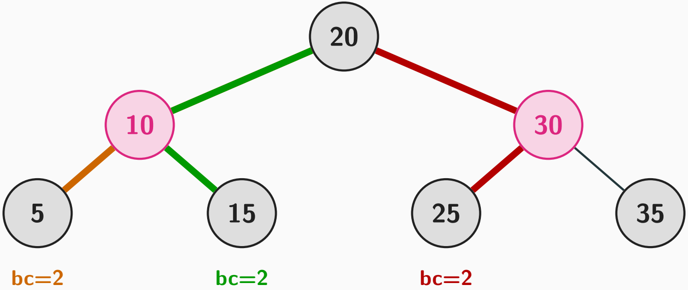

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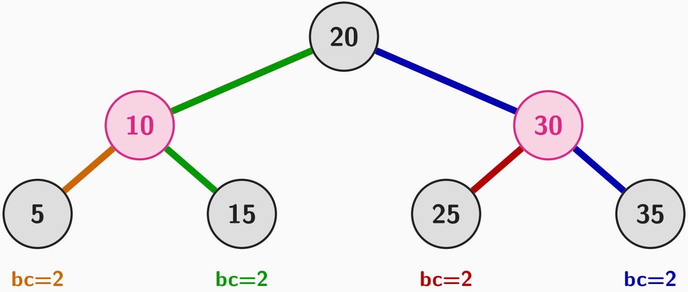

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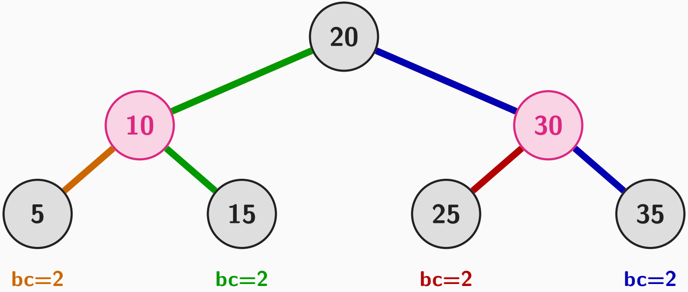

All paths from root have same black count = 2

RBT Operations

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

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Let’s see some operations....

Insertion

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Pseudocode

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color[x] = RED

y = root[T]

while y ≠ NIL do
  if key[x] > key[y]
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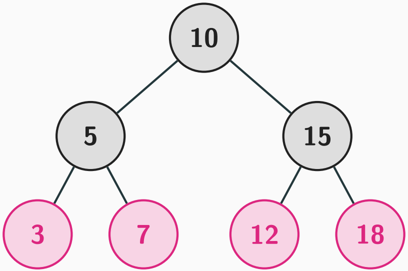
Existing RBT



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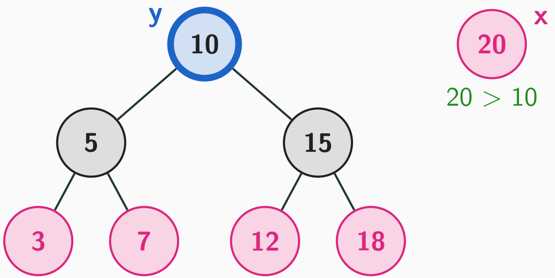

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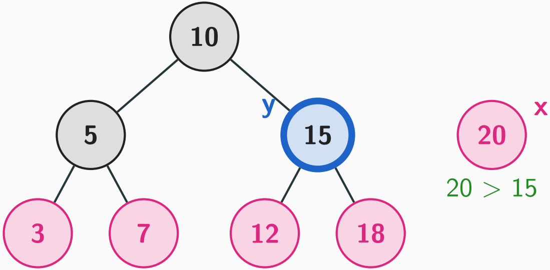

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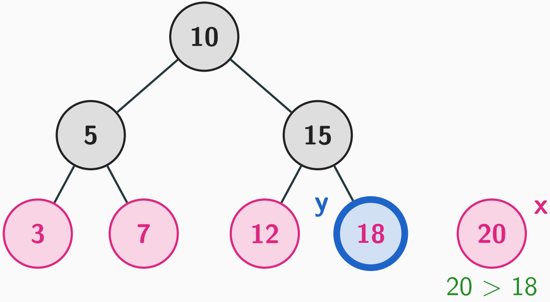

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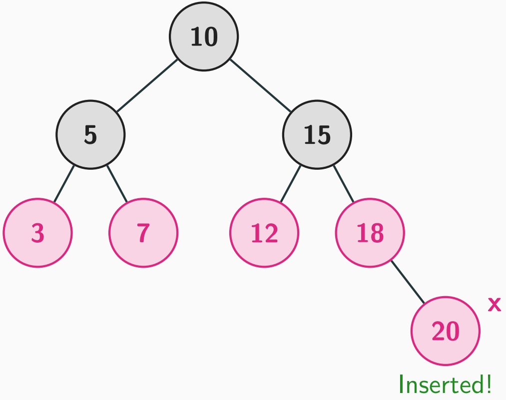
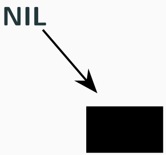


What can go wrong

Insert 10



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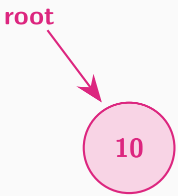

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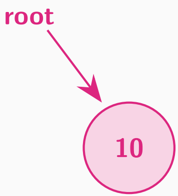

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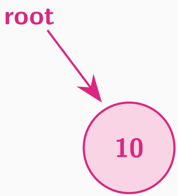
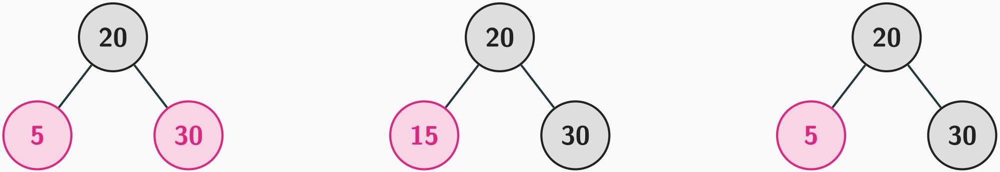


Root can't be RED

Case 1

What can go wrong

Insert 10



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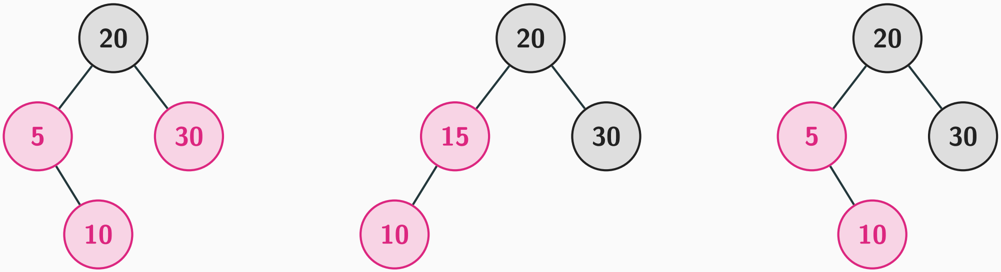
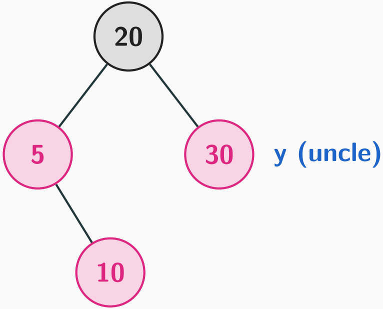


How insertion violates RBT properties

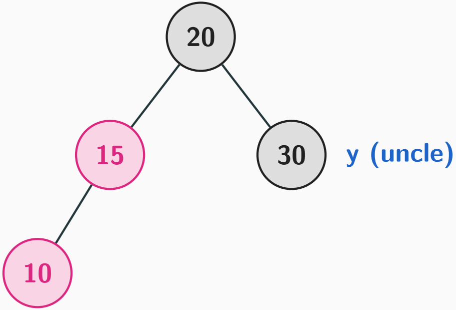


Uncle **y** is **RED**

Case 2

Insertion Violation

How insertion violates RBT properties

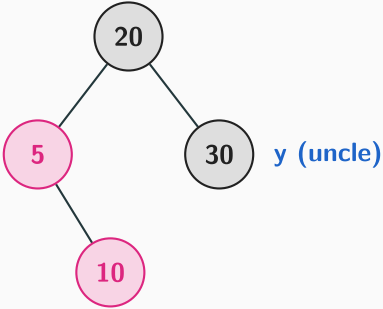


Uncle **y** is **BLACK**

(Left-Left Case)

Case 3

How insertion violates RBT properties



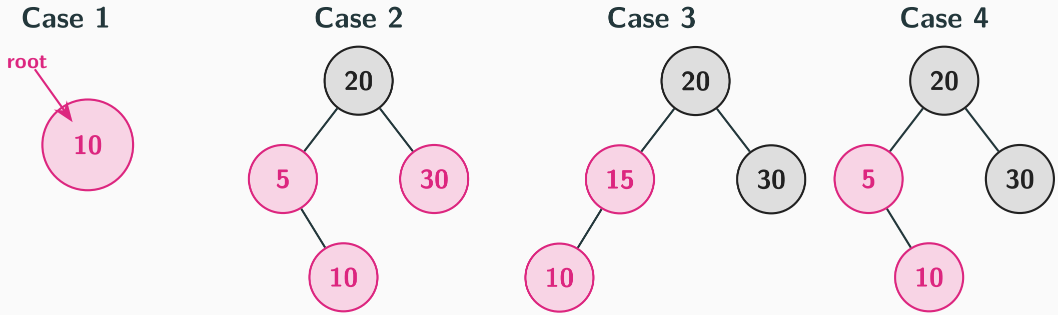
Uncle **y** is **BLACK**

(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

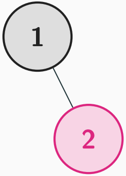
Insert 2

- 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** ✔

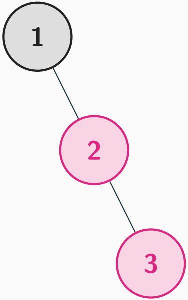
After Insert



Insert 3

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

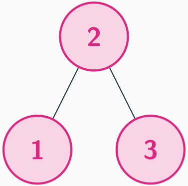
Violation — Two RED in a row!



Insert 3

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

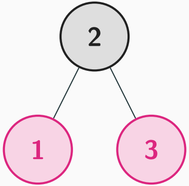
After Left Rotation



Insert 3

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

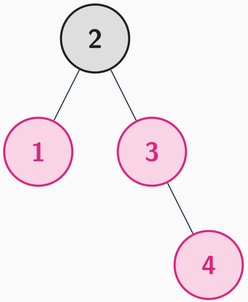
After Recolor



Insert 4

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

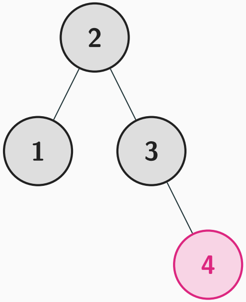
Violation — Uncle is RED



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!**

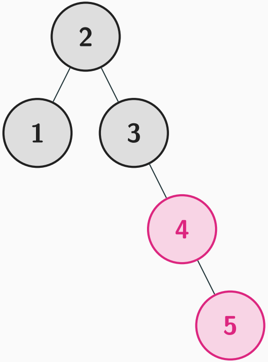
After Recolor



Insert 5

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

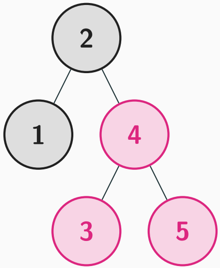
Violation — Two RED in a row!



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

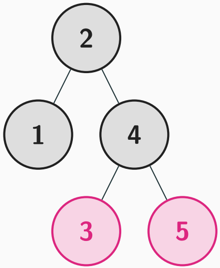
After Left Rotation



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!**

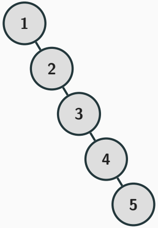
After Recolor



BST vs. Red-Black Tree

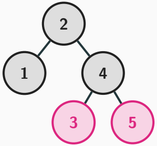
Inserting $\{1, 2, 3, 4, 5\}$ in order

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!

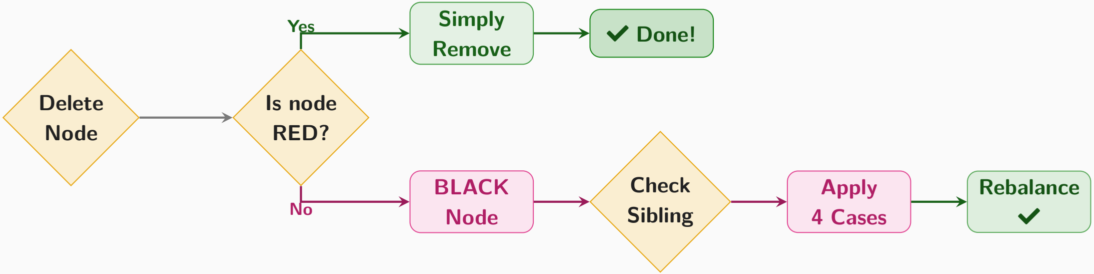
Deleting a RED node

- 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



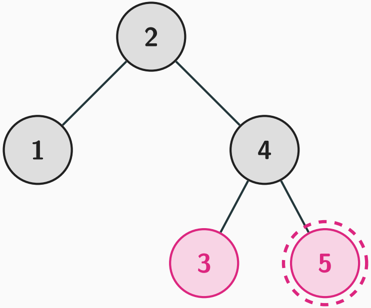
Top path (RED node) = straightforward

Bottom path (BLACK node) = complex

Case 1: Deleting a RED Node

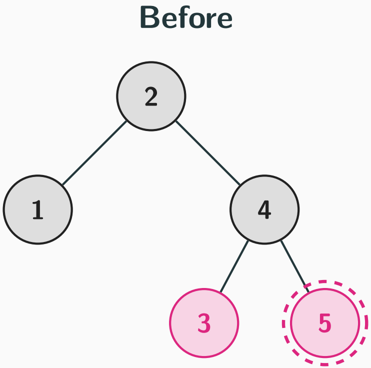
Delete node **5** from the tree

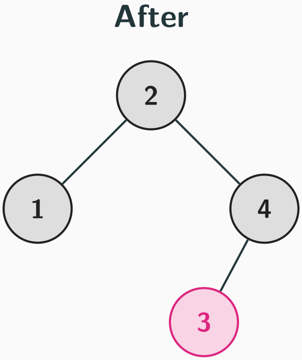
Before



Case 1: Deleting a RED Node

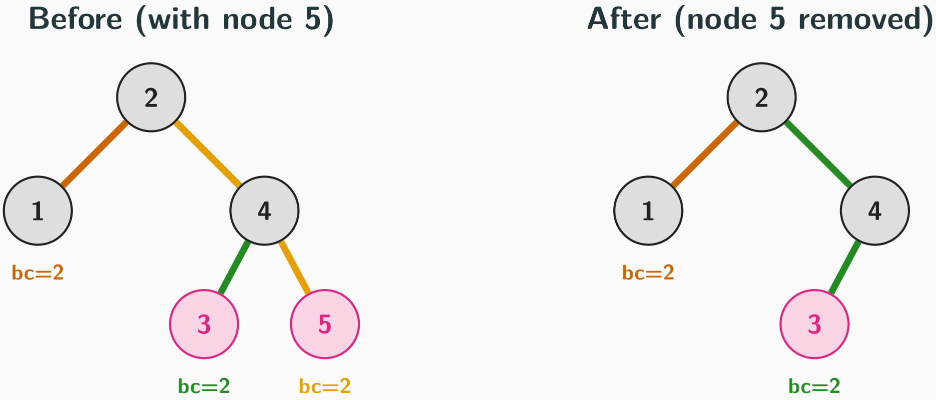
Delete node **5** from the tree





Case 1: Black-Height Stays the Same

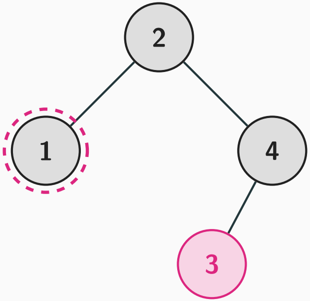
Every path still has **bc = 2** black nodes after removing 5



Case 2: Deleting a BLACK Node

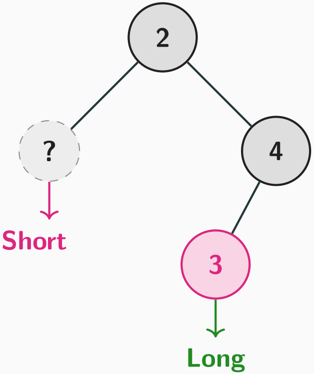
Delete node **1** from the tree

Before deletion:



Case 2: After Deleting the BLACK Node

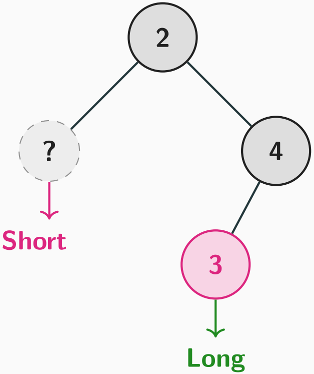
The node is gone - but now we have a **problem**



- 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!**
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IMBALANCED - must fix!

Case 2: The Fix-up

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

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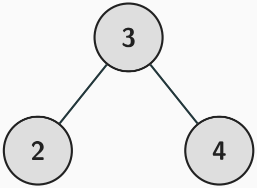

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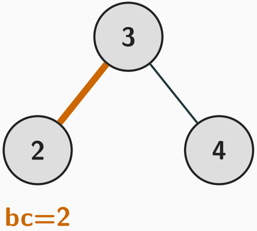

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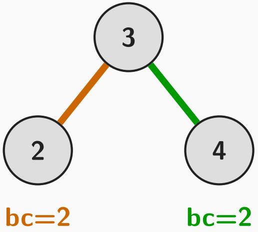
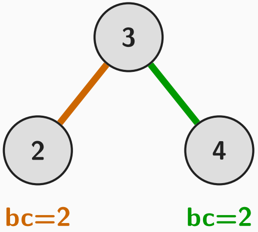


Case 2: The Fix-up

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



Fixing Double-Black: 4 Cases

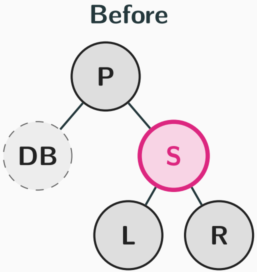
When we have a **Double-Black** node,

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

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

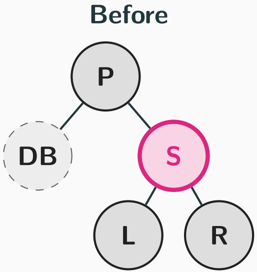
DB = Double-Black node

The Sibling S is RED



Fix Case 1 of 4: Sibling is RED

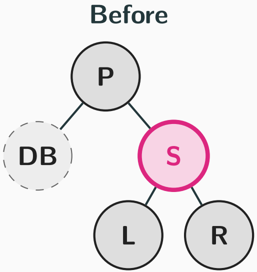
The Sibling S is RED

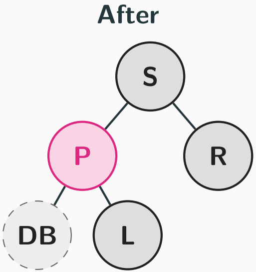


- **Rotate** P to the left
- **Recolor:** S $\rightarrow$ Black, P $\rightarrow$ Red

Fix Case 1 of 4: Sibling is RED

The Sibling S is RED





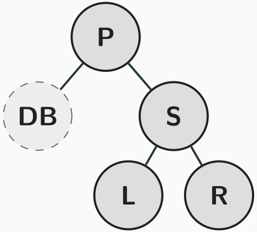
Now apply Case 2, 3, or 4 to DB

- **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

Before



Fix Case 2 of 4: Sibling & Children All BLACK

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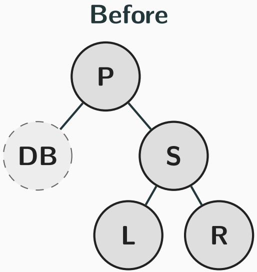
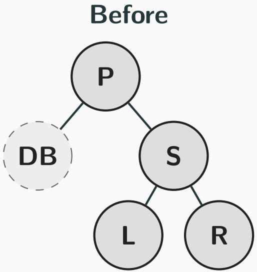
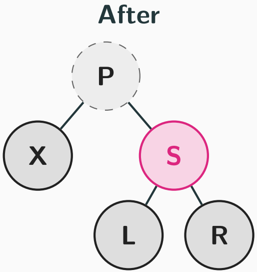


- **Recolor** S $\rightarrow$ Red
- Push the Double-Black **up to P**

Fix Case 2 of 4: Sibling & Children All BLACK

S and both children are BLACK

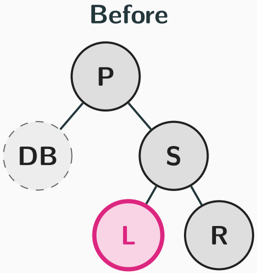




DB pushed to P — continue fixing

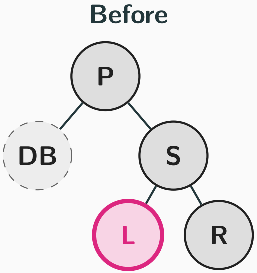
- **Recolor** S $\rightarrow$ Red
- Push the Double-Black **up to P**

S is Black, S's Left child is RED



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

S is Black, S's Left child is RED



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

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

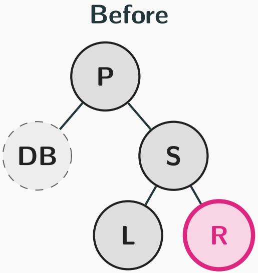
S is Black, S's Left child is RED

Now proceed with Case 4

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

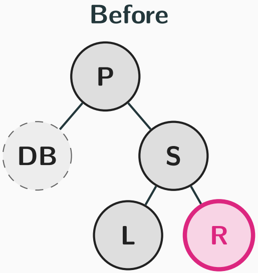
Fix Case 4 of 4: Sibling's Right Child is RED

S is Black, S's Right child is RED



Fix Case 4 of 4: Sibling's Right Child is RED

S is Black, S's Right child is RED

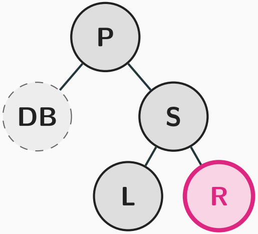


- **Left-rotate** at P
- **Recolor** R $\rightarrow$ Black

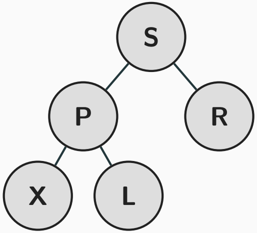
Fix Case 4 of 4: Sibling's Right Child is RED

S is Black, S's Right child is RED

Before

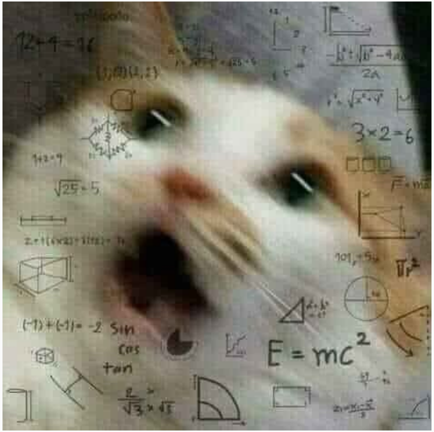


After



Double-Black fully resolved!

- **Left-rotate** at P
- **Recolor** R $\rightarrow$ Black



Confused?

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

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

Was All That Worth It?

All that work.

What did it actually buy us?

Let's finally see the payoff.

Rotation Complexity: $O(1)$ Operations

Why Rotations Work: The Magic Behind Balance

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Left Rotation:

- Restructures tree locally

Right Rotation:

- Mirror of left rotation

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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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A red-black tree with n internal nodes has height $\leq 2\log_2(n+1)$

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A red-black tree with n internal nodes has height $\leq 2\log_2(n+1)$

Proof Sketch:

1. Every path from root to leaf has same number of black nodes
2. Red nodes can't have red children
3. At least half nodes on any path are black

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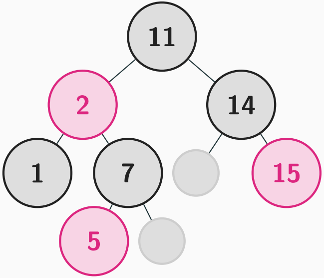

Black height $= 2$, Total height $= 4$

Why Red-Black Trees Are Space Efficient

Space Complexity: $O(n)$ Memory Usage

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Memory Requirements:

- Each node stores: key, color and 2 pointers

Comparison:

- AVL trees: height field per node

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- No extra storage for balance info

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- RBTs: minimal overhead **[squirrel-level efficient]**

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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!

50+ Years of Tree Balancing Innovation

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The Evolution: From Red-Black to Modern Trees

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What to do with these trees?

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

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

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

Red-Black Trees in Modern Tech

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Traditional Uses:

- CPU scheduling algorithms

Red-Black Trees in Modern Tech

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- ML indexing, cloud storage, blockchain, AI pathfinding!

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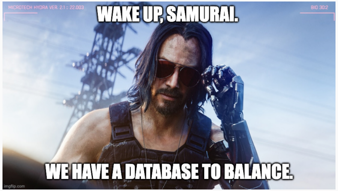
- RBTs: Keanu Reeves of data structures - always reliable!



Why Choose Red-Black Trees?

The Ultimate Showdown: RBT vs Other Trees

Why Choose Red-Black Trees?

Tree Type	Search	Insert	Delete	Space
Red-Black	$O(\log n)$	$O(\log n)$	$O(\log n)$	$O(n)$
AVL	$O(\log n)$	$O(\log n)$	$O(\log n)$	$O(n)$
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Red-Black Advantages: The Meme Edition

Why Red-Black Trees Are the Perfect Choice

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Not too fast, not too slow, just right!

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Perfect Balance
Like coffee - balanced and reliable!

The Real Story Behind the Scenes

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Tech Giants & RBTs:

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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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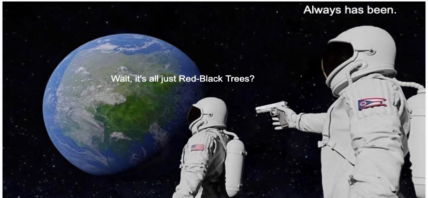

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The Future: Where Are Trees Heading?

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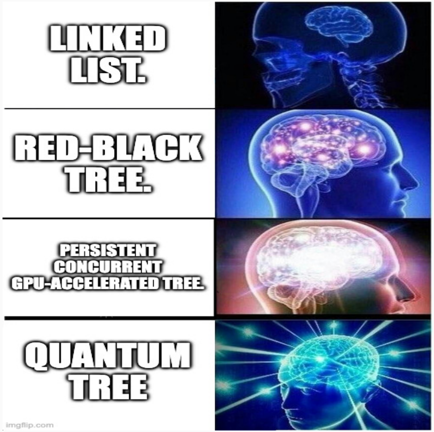

So There You Have It!

Red-Black Trees: The Unsung Heroes

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Red-Black Trees: Not all heroes wear capes!

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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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