

CSE-200 Final Presentation

Red Black Tree

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Insertion Violation Cases

Four main violation cases in Red-Black Tree insertion:

Case 1: Root is

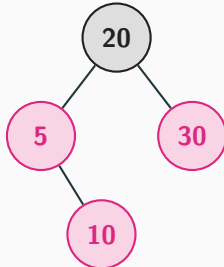
root



Red

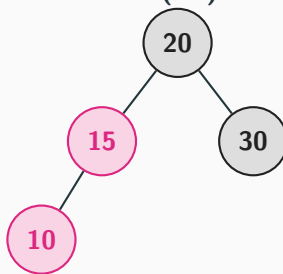
Case 2: Uncle is

RED



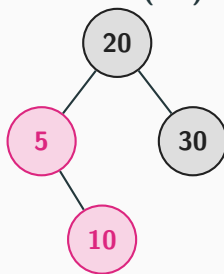
Case 3: Uncle is

BLACK (LL)



Case 4: Uncle is

BLACK (LR)



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

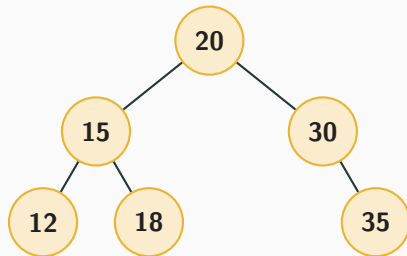
- Everything is **tree-structured**
- **Insert** data into the structure
- **Delete** data efficiently
- **Search** for data quickly

Good way to do all of this?

Use a BST!

The BST Rule

How does BST decide where to put a node?



The BST Rule

How does BST decide where to put a node?



new

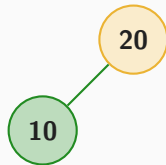


- Smaller than me? Go **Left**

The BST Rule

How does BST decide where to put a node?

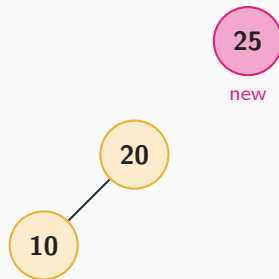
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The BST Rule

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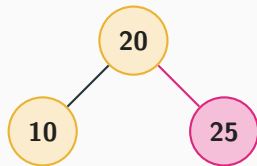
- Smaller than me? Go **Left**
- Larger than me? Go **Right**



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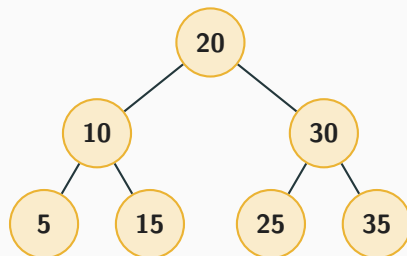
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The BST Rule

How does BST decide where to put a node?

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



Good technique!

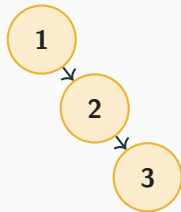
Insert the roll numbers in a class sequentially

1, 2, 3, 4 ...10

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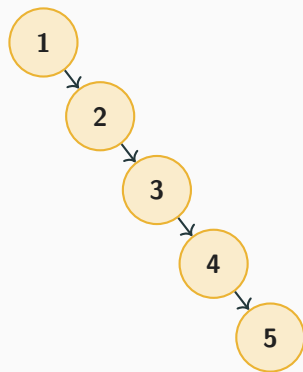
- Each goes to the **right** of the last



Insert the roll numbers in a class sequentially

1, 2, 3, 4 ...10

- Each goes to the **right** of the last
- The tree just keeps **growing** right...

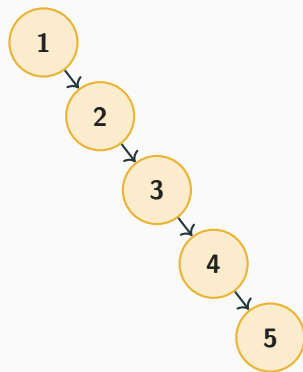


...and on

Insert the roll numbers in a class sequentially

1, 2, 3, 4 ...10

- Each goes to the **right** of the last
- The tree just keeps **growing** right...

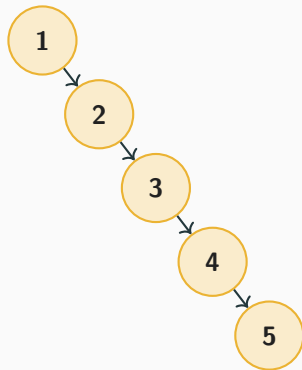


Still works!

...and on

But, What's the Problem?

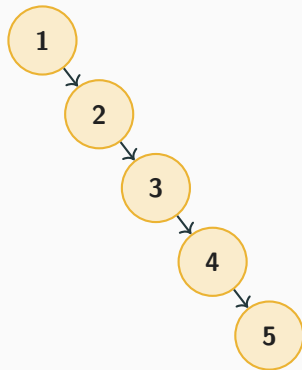
- Height becomes n



...and on

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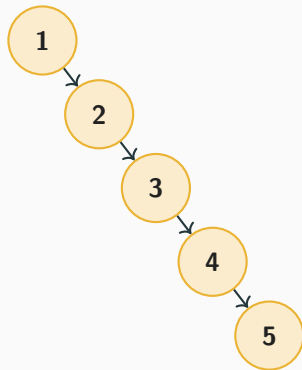
- **Height becomes n**
- Insertion takes $O(n)$



...and on

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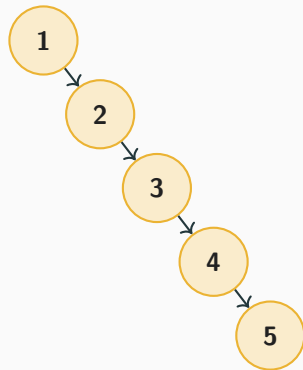
- **Height becomes n**
- Insertion takes $O(n)$
- Deletion takes $O(n)$



...and on

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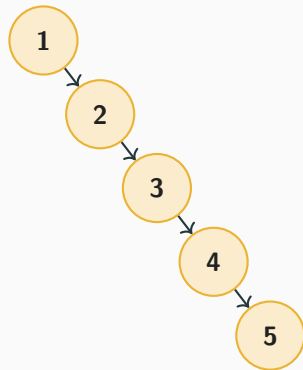
- **Height becomes n**
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But, What's the Problem?

- **Height becomes n**
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- A linked list in disguise



...and on

But, What's the Problem?

- Insertion takes $O(n)$
- Deletion takes $O(n)$
- Search takes $O(n)$
- 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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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**.

Height becomes $\log(n)$ here!

Five points to remember

How does RBT do it: Properties

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

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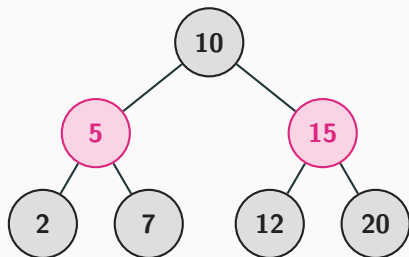
Hence, the name Red Black Tree

How does RBT do it: Properties

- **Property 2:** Root will always be a black node

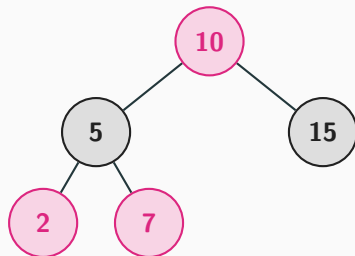
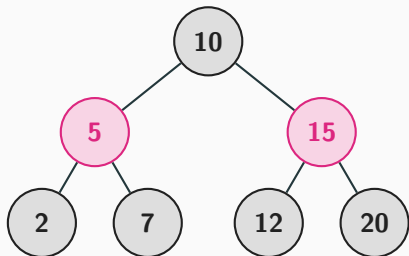
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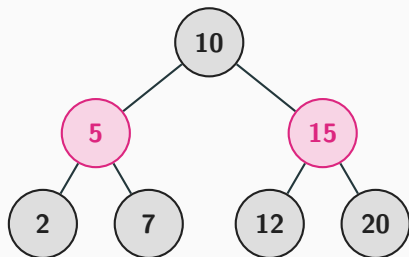
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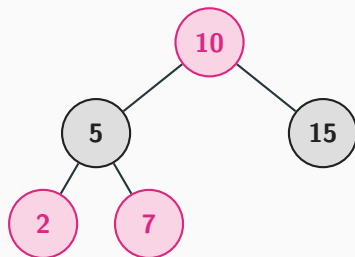


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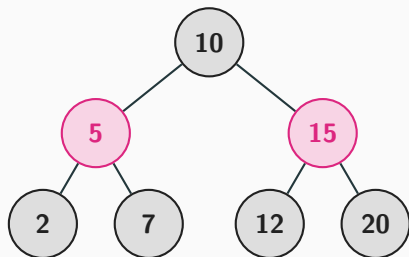


Correct

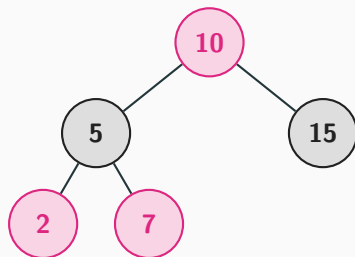


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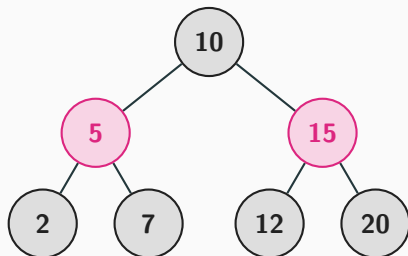
Incorrect

How does RBT do it: Properties

- **Property 3:** Leaves will either be black or NIL

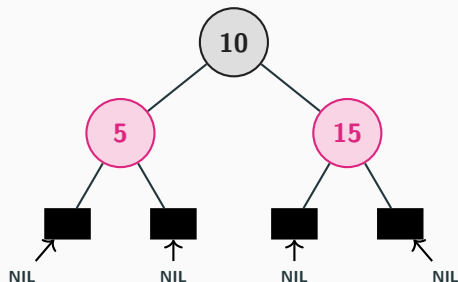
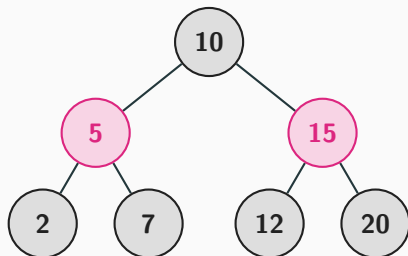
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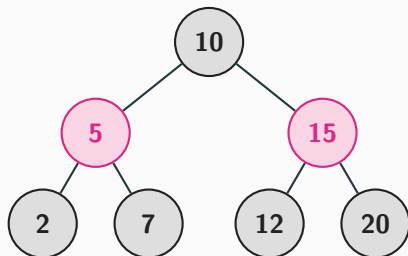
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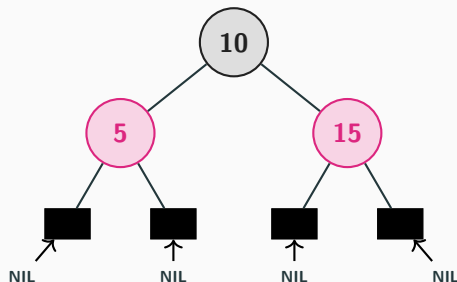


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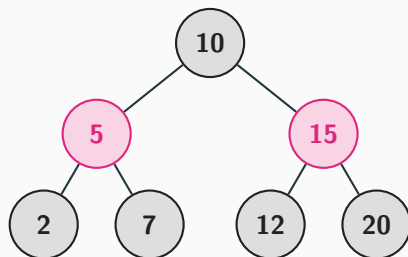


Black Leaves

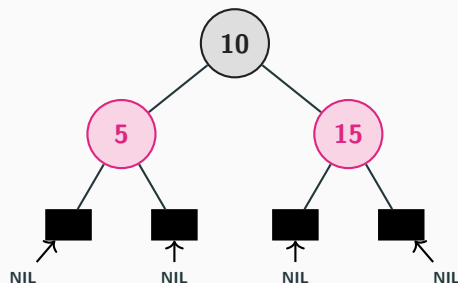


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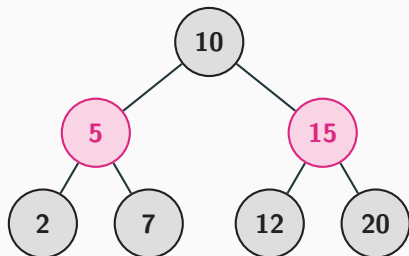
NIL nodes (counted as Black)

How does RBT do it: Properties

- **Property 4:** There will be no two consecutive red nodes

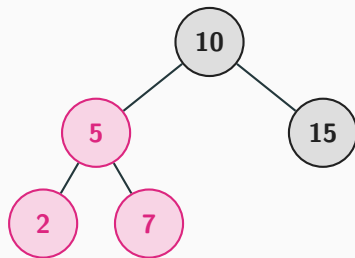
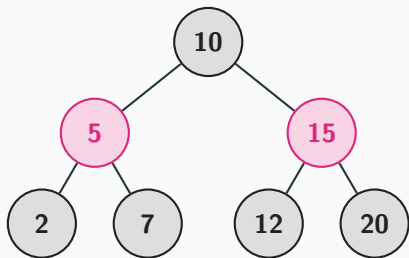
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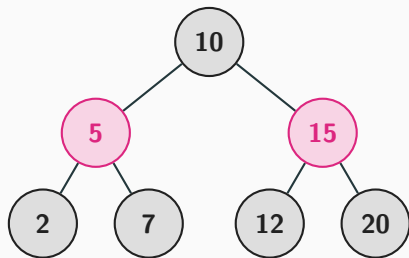
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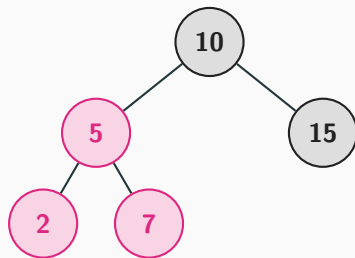


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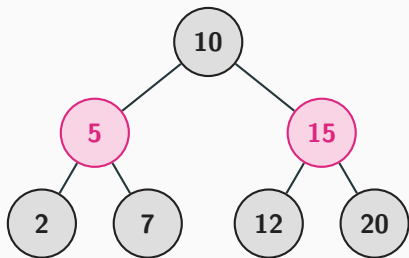


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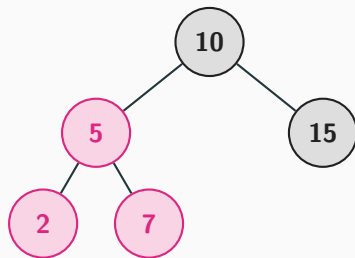


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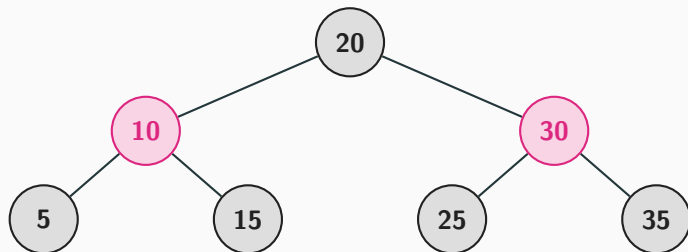
Incorrect

How does RBT do it: Properties

- **Property 5:** From a given node, the number of black nodes in any given path will always be same for that node

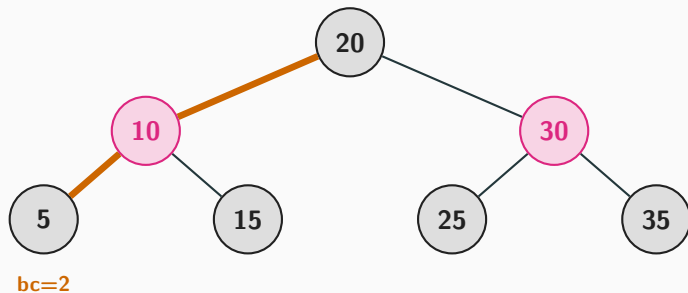
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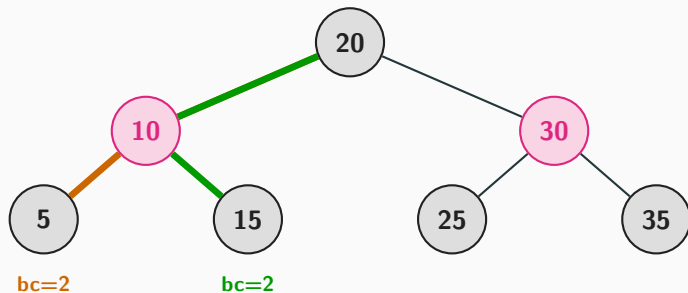
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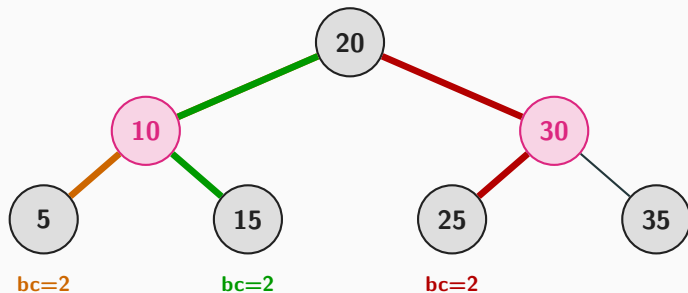
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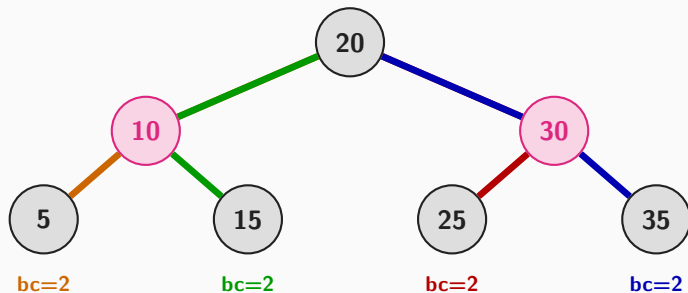
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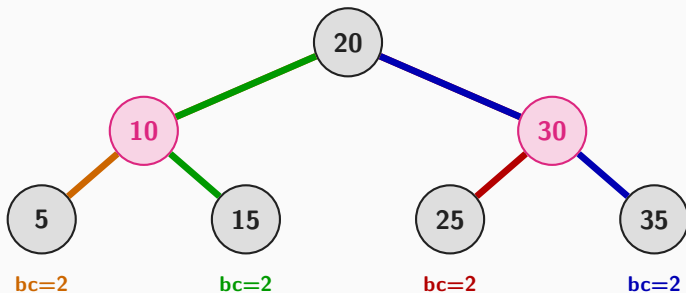
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All paths from root have same black count = 2

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

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Let's see some operations....

Insert node x in a Red Black Tree

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Pseudocode

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

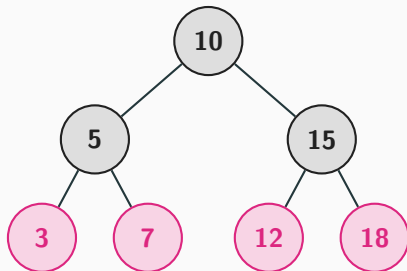
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Existing RBT

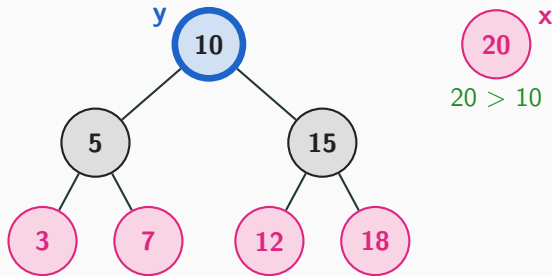


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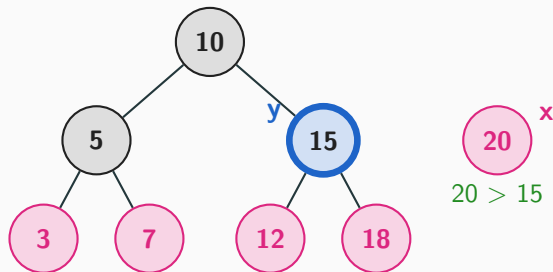


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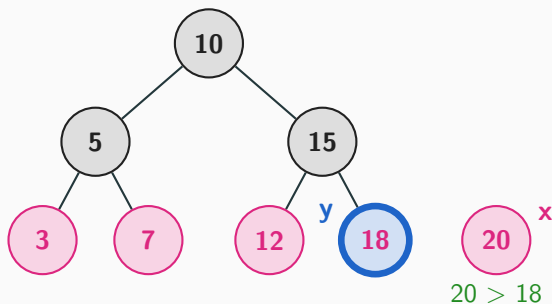


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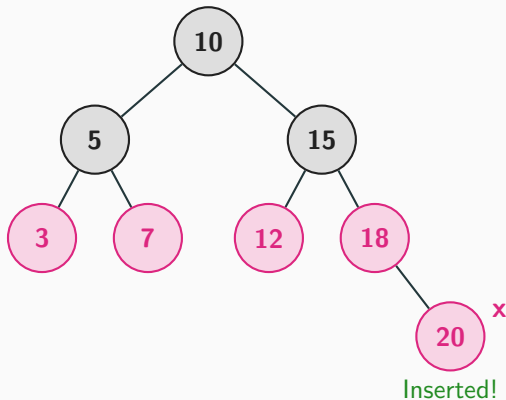


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What can go wrong

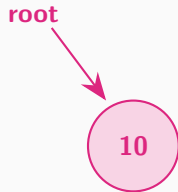
Insert 10

NIL



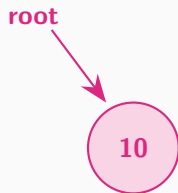
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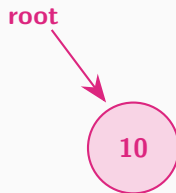
Insert 10



Root can't be RED

What can go wrong

Insert 10

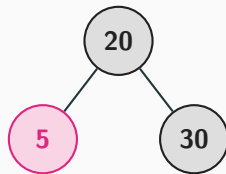
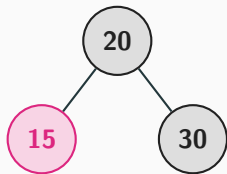
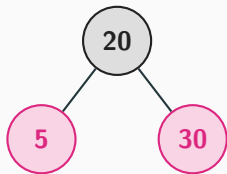


Root can't be RED

Case 1

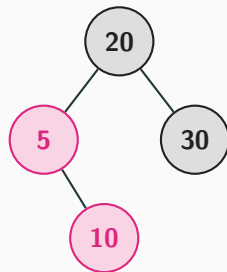
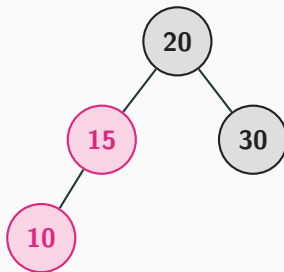
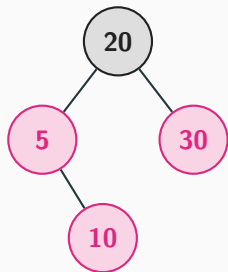
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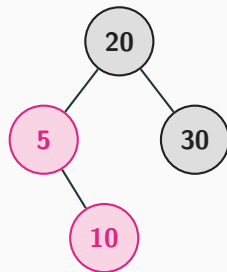
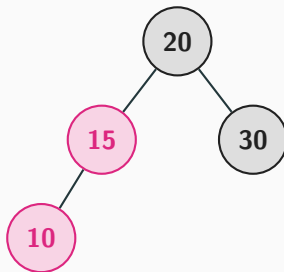
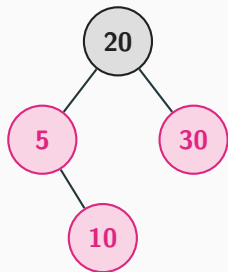
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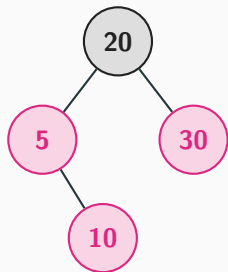
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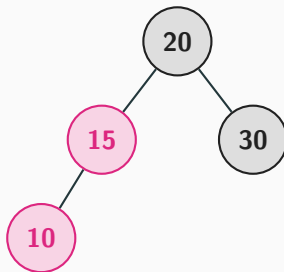
Case 2

What can go wrong

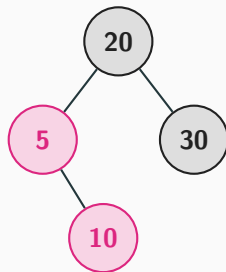
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Case 2

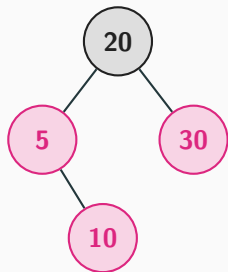


Case 3

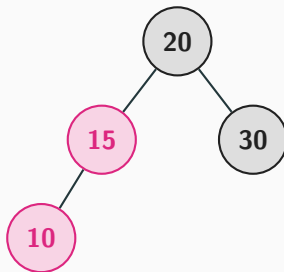


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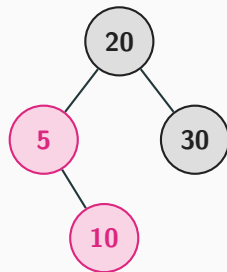
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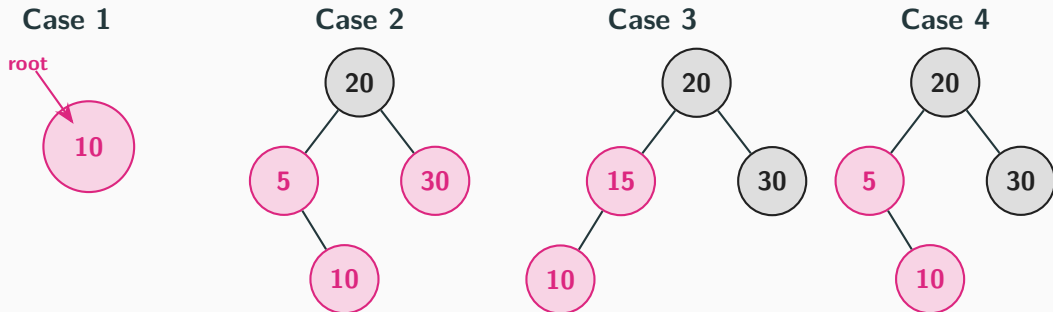
Case 3



Case 4

Insertion Violation Cases

Four main violation cases in Red-Black Tree insertion:



How to solve this?

Solutions to Violations

Case 1

Violation

Root is **RED** — Property 2 broken

Fix

Recolor root to **BLACK**

Solutions to Violations

Case 1

! Violation

Root is **RED** — Property 2 broken

🔧 Fix

Recolor root to **BLACK**

Case 2

! Violation

Uncle is **RED** — two reds adjacent

🔧 Fix

Recolor parent, uncle **BLACK**;
grandparent **RED**

Solutions to Violations

Case 1

! Violation

Root is **RED** — Property 2 broken

🔧 Fix

Recolor root to **BLACK**

Case 2

! Violation

Uncle is **RED** — two reds adjacent

🔧 Fix

Recolor parent, uncle **BLACK**;
grandparent **RED**

Case 3

! Violation

Uncle is **BLACK** — Right-Right

🔧 Fix

Left rotate at grandparent, then
recolor

Solutions to Violations

Case 1

! Violation

Root is **RED** — Property 2 broken

🔧 Fix

Recolor root to **BLACK**

Case 2

! Violation

Uncle is **RED** — two reds adjacent

🔧 Fix

Recolor parent, uncle **BLACK**;
grandparent **RED**

Case 3

! Violation

Uncle is **BLACK** — Right-Right

🔧 Fix

Left rotate at grandparent, then
recolor

Case 4

! Violation

Uncle is **BLACK** — Left-Right

🔧 Fix

Left rotate at parent, then apply Case
3

Remember This Problem?

Let's try inserting **1, 2, 3, 4, 5** again...

But this time in a **Red-Black Tree**!

Remember This Problem?

Let's try inserting **1, 2, 3, 4, 5** again...

But this time in a **Red-Black Tree**!

Watch the magic happen!

Insert 1

- First node is always **root**
- Insert as **RED** (default color)

Insert 1

- First node is always **root**
- Insert as **RED** (default color)

After Insert



Insert 1

- First node is always **root**
- Insert as **RED** (default color)
- But Root cannot be **RED**!

Property 2 violated - Case : 1

Violation — Root is RED!



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



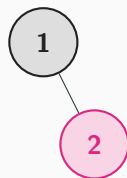
Insert 2

- 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** ✓

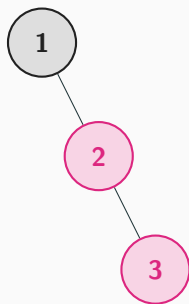
After Insert



Insert 3

- Right child of 2
- Insert as **RED** (default)

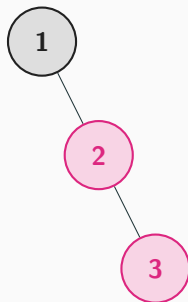
After Insert



Insert 3

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

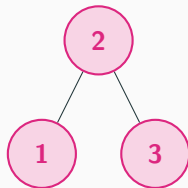
Violation Found — Two RED in a row!



Insert 3

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

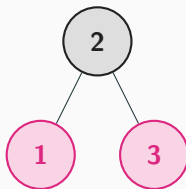
After Left Rotation



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!**

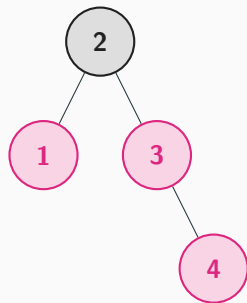
After Recolor



Insert 4

- Right child of 3
- Insert as **RED** (default)

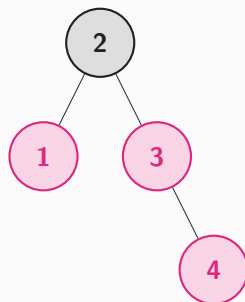
After Insert



Insert 4

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

Violation Found — Uncle is RED



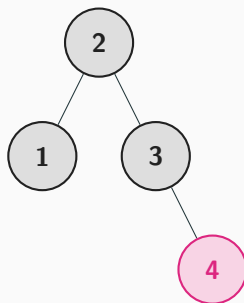
Insert 4

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

Insert 4

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

After Recolor



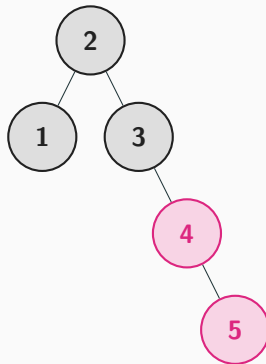
Insert 5

- Right child of 4
- Insert as **RED** (default)

Insert 5

- Right child of 4
- Insert as **RED** (default)

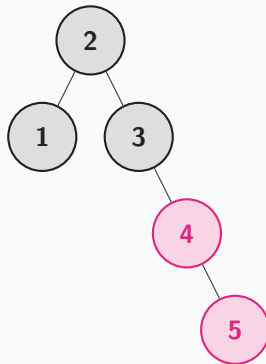
After Insert



Insert 5

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

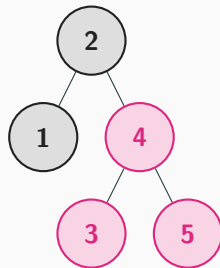
Violation — Two RED in a row!



Insert 5

- Right child of 4
- Insert as **RED** (default)
- Uncle (node 1) is **BLACK**
- **CASE 3**
Uncle is **BLACK** — rotate & recolor!
- Left rotate at node 3 → 4 moves up

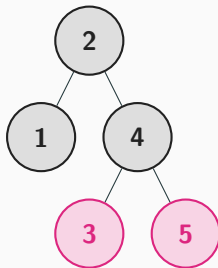
After Left Rotation



Insert 5

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

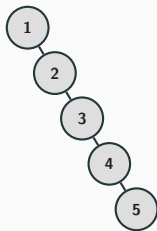
After Recolor



BST vs. Red-Black Tree

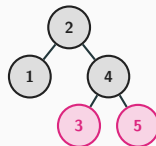
Inserting $\{1, 2, 3, 4, 5\}$ in order

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!

Deletion is even more... interesting!

Deleting a **RED** node

Deleting a **BLACK** node

Deletion is even more... interesting!

Deleting a **RED** node

Deleting a **BLACK** node

- No problem!

Deletion is even more... interesting!

Deleting a **RED** node

- No problem!
- Just remove it

Deleting a **BLACK** node

Deletion is even more... interesting!

Deleting a RED node

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

Deleting a BLACK node

Deletion is even more... interesting!

Deleting a RED node

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

Deleting a BLACK node

- Oh boy...

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!

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**

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 is even more... interesting!

Deleting a RED node

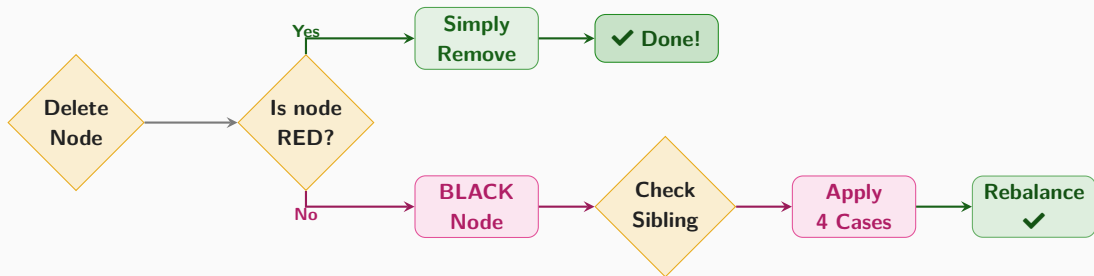
- No problem!
- Just remove it
- **Properties still hold**

Deleting a BLACK node

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

Let's see both cases...

Deletion Decision Flowchart



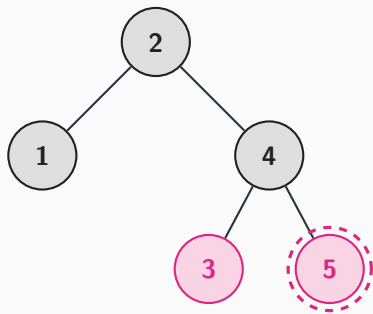
Top path (RED node) = straightforward

Bottom path (BLACK node) = complex

Case 1: Deleting a RED Node

Delete node **5** from the tree

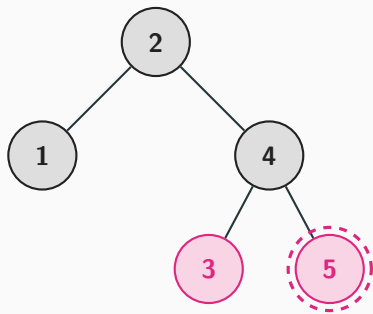
Before



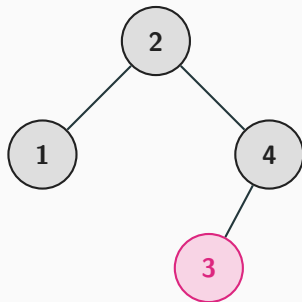
Case 1: Deleting a RED Node

Delete node **5** from the tree

Before



After



Case 1: Deleting a RED Node

Is it done?

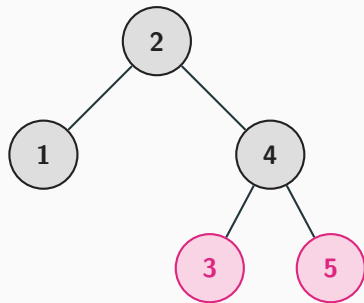
Is it done?

Let's check the black height.

Case 1: Black-Height Stays the Same

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

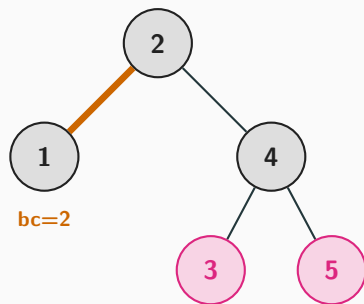
Before (with node 5)



Case 1: Black-Height Stays the Same

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

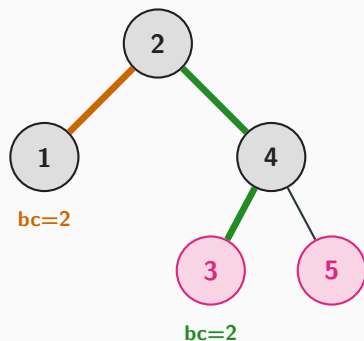
Before (with node 5)



Case 1: Black-Height Stays the Same

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

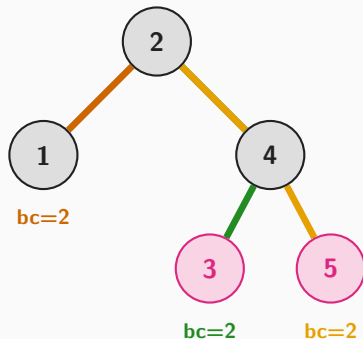
Before (with node 5)



Case 1: Black-Height Stays the Same

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

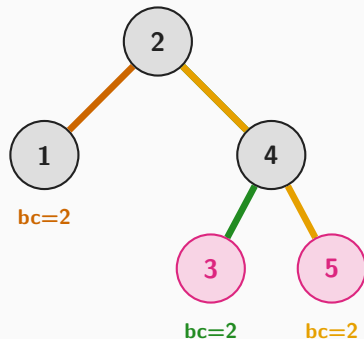
Before (with node 5)



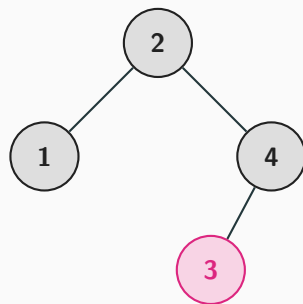
Case 1: Black-Height Stays the Same

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

Before (with node 5)



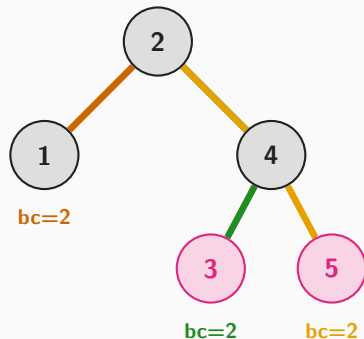
After (node 5 removed)



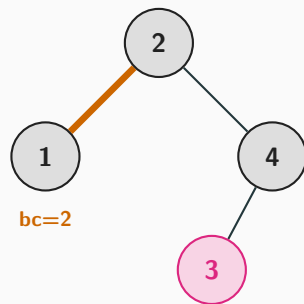
Case 1: Black-Height Stays the Same

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

Before (with node 5)



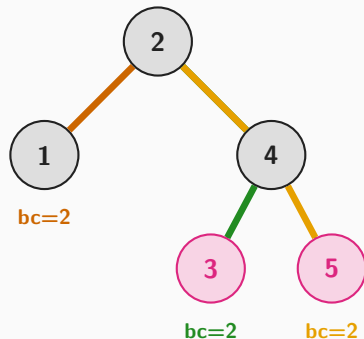
After (node 5 removed)



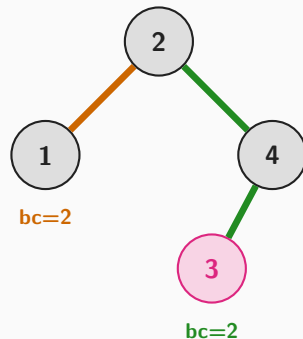
Case 1: Black-Height Stays the Same

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

Before (with node 5)



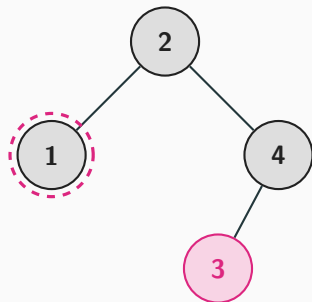
After (node 5 removed)



Case 2: Deleting a BLACK Node

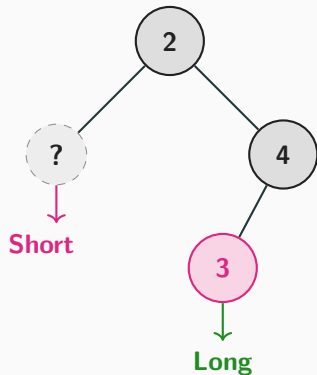
Delete node **1** from the tree

Before deletion:



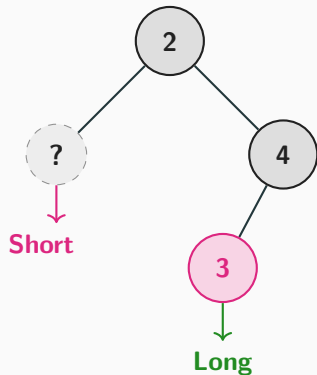
Case 2: After Deleting the BLACK Node

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



Case 2: After Deleting the BLACK Node

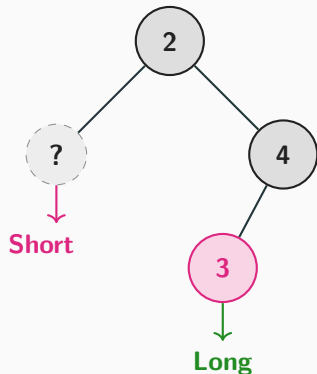
The node is gone - but now we have a **problem**



- Left path is now **shorter**

Case 2: After Deleting the BLACK Node

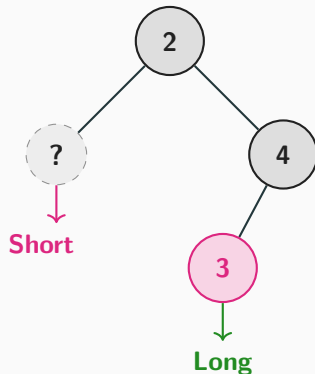
The node is gone - but now we have a **problem**



- Left path is now **shorter**
- Black-height **violated!**

Case 2: After Deleting the BLACK Node

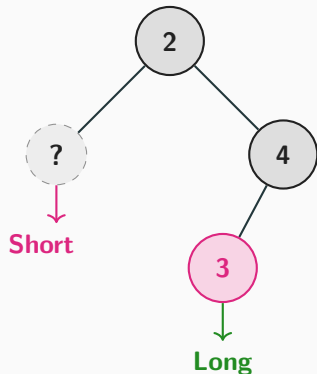
The node is gone - but now we have a **problem**



- 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

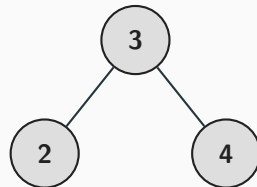
- **Rotate:** Right at 4,
then left at 2

Case 2: The Fix-up

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

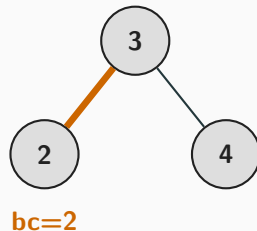
Case 2: The Fix-up

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



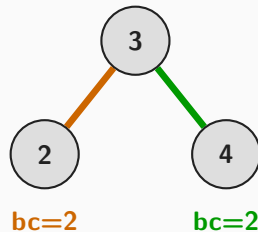
Case 2: The Fix-up

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



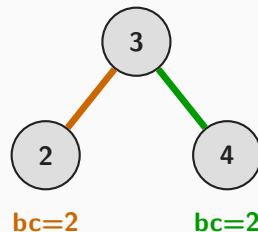
Case 2: The Fix-up

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



Case 2: The Fix-up

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




All paths: $bc = 2$ - Black-height restored!

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

Fixing Double-Black: 4 Cases

When we have a **Double-Black** node,
the fix depends on the **sibling's color and children**.

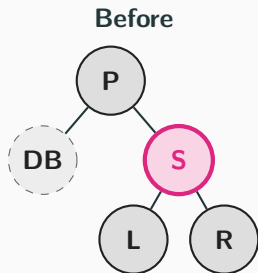
P = Parent **S** = Sibling **L / R** = S's children

 **DB** = Double-Black node

4 cases - let's go through them one by one!

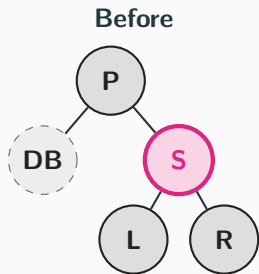
Fix Case 1 of 4: Sibling is RED

The Sibling S is RED



Fix Case 1 of 4: Sibling is RED

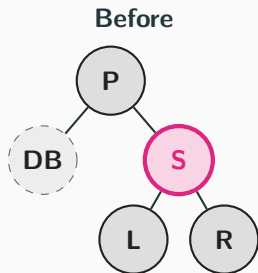
The Sibling S is RED



- **Rotate** P to the left

Fix Case 1 of 4: Sibling is RED

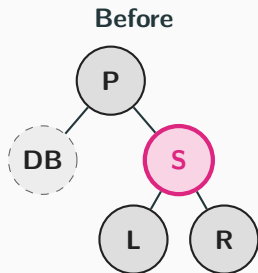
The Sibling S is RED



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

Fix Case 1 of 4: Sibling is RED

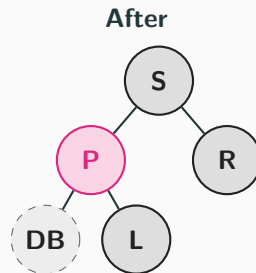
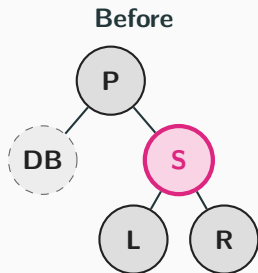
The Sibling S is RED



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

Fix Case 1 of 4: Sibling is RED

The Sibling S is RED

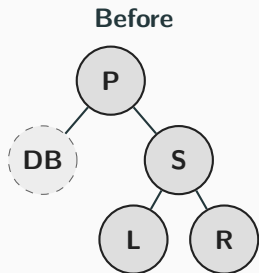


Now apply Case 2, 3, or 4 to DB

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

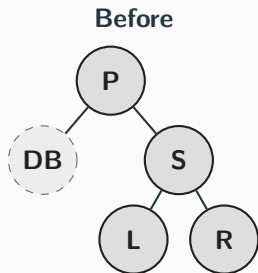
Fix Case 2 of 4: Sibling & Children All BLACK

S and both children are BLACK



Fix Case 2 of 4: Sibling & Children All BLACK

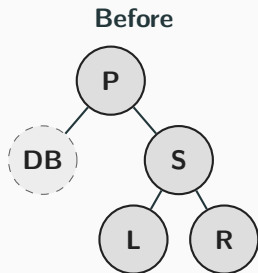
S and both children are BLACK



- Recolor $S \rightarrow \text{Red}$

Fix Case 2 of 4: Sibling & Children All BLACK

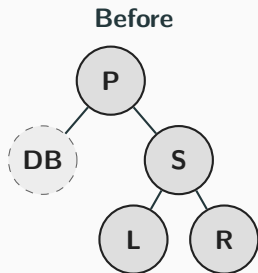
S and both children are BLACK



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

Fix Case 2 of 4: Sibling & Children All BLACK

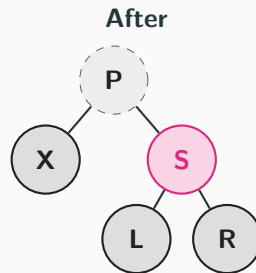
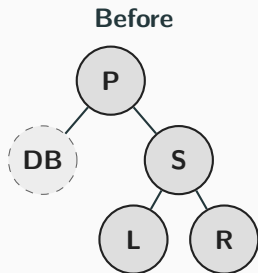
S and both children are BLACK



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

Fix Case 2 of 4: Sibling & Children All BLACK

S and both children are BLACK

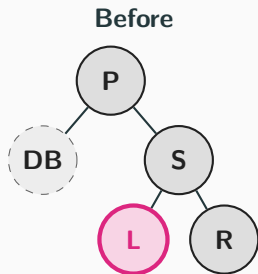


DB pushed to P — continue fixing

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

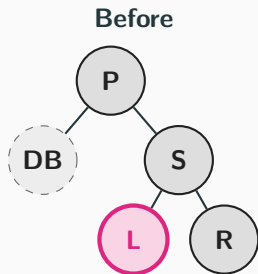
Fix Case 3 of 4: Sibling's Left Child is RED

S is Black, S's Left child is RED



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

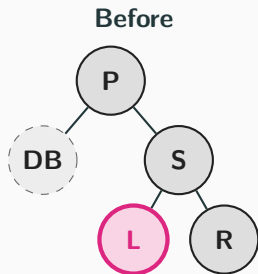
S is Black, S's Left child is RED



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

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

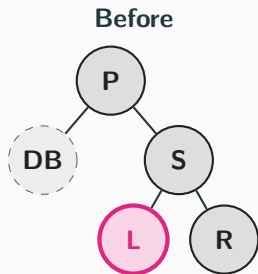
S is Black, S's Left child is RED



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

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

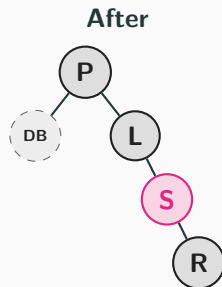
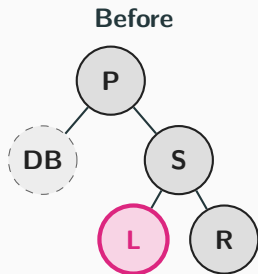
S is Black, S's Left child is RED



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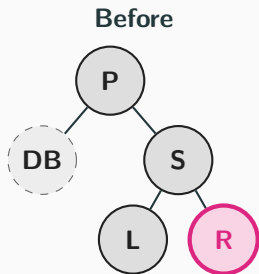


Now proceed with Case 4

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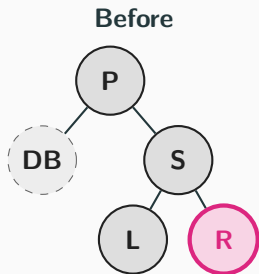
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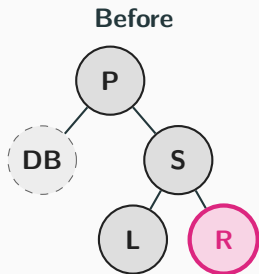
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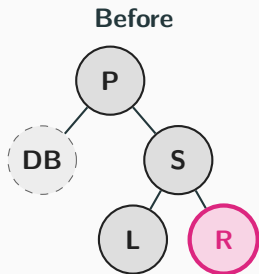
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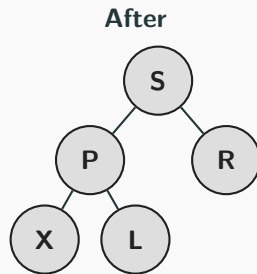
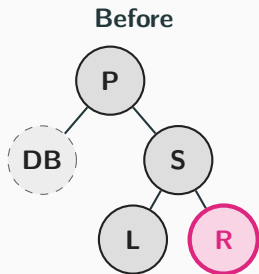
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Double-Black fully resolved!

- Left-rotate at P
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Summary

The cases form a **chain**:



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Goal: Eventually reach Case 4 to fully eliminate Double-Black

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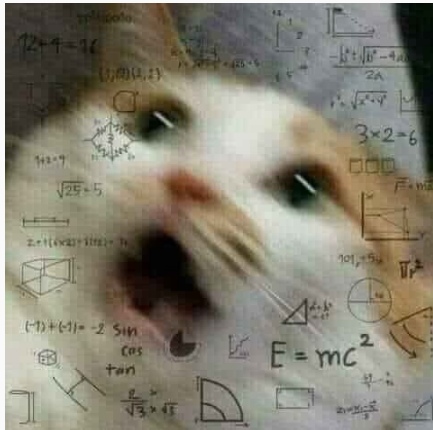
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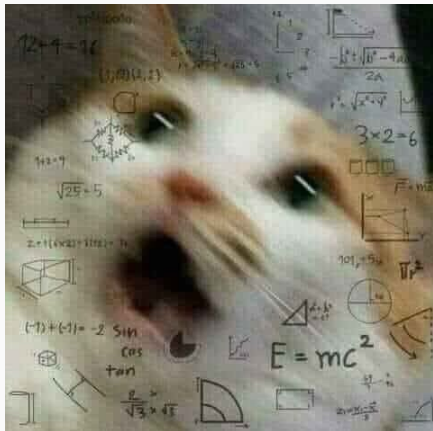
Case 2 may propagate upward; Cases 1 & 3 always lead to Case 4

Too Many Cases?



Confused?

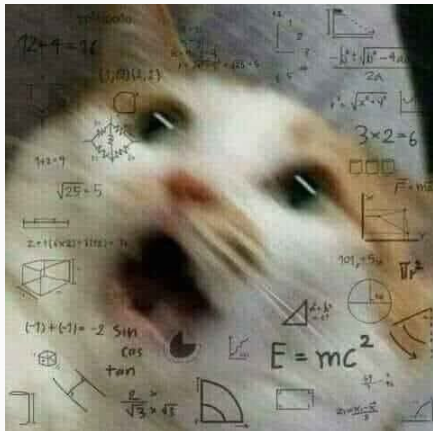
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If this felt like **a lot** at once -
that's because **it is !**

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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.

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What did it actually buy us?

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Let's finally see the payoff.

Rotation Complexity: $O(1)$ Operations

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- Mirror of left rotation

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Key Insight

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

Why Rotations Work: The Magic Behind Balance

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Why Red-Black Trees Work: The Math Behind It

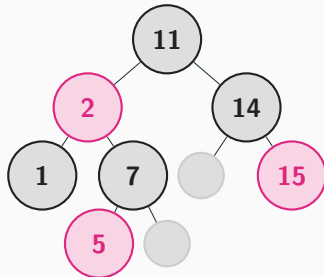
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Black height = 2, Total height = 4

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[squirrel-level efficient]

Why Red-Black Trees Are Space Efficient

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[squirrel-level efficient]

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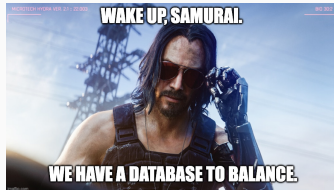
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- RBTs: Keanu Reeves of data structures - always reliable!



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

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Not too fast, not too slow,
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Perfect Balance

Like coffee - balanced and
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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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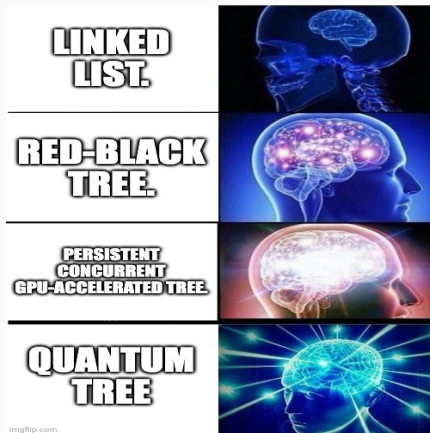
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Remember

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

Thank a red-black tree! ♡

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