Brief Guide to Red-Black Trees

What they are

How they are implemented

Red-Black Trees (RBTs)

Self-balancing binary search trees

Assuredly fast search, insertion, deletion

History

Adelson-Velsky & Landis (AVL tree) (1962) 

Bayer (Symmetric binary B-trees) (1972) 

Guibas & Sedgewick (RB trees) (1978) 

Sedgewick (Left-leaning RB trees) (2008) 

Complexity (for n data items)

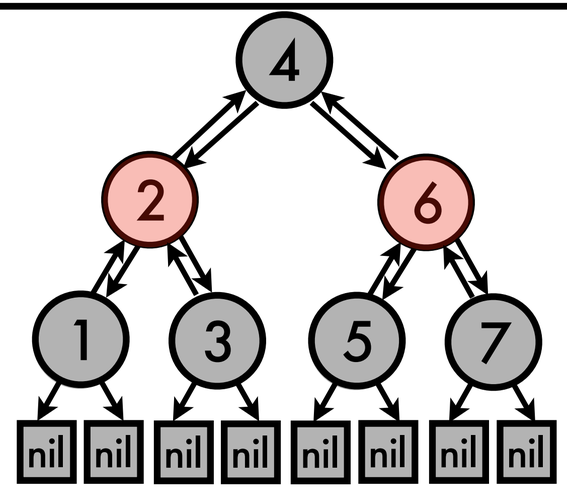
By balancing, red-black trees guarantee speed

Worst case: search, insert, delete $\rightarrow O(\log n)$

Storage of red-black trees: $\Theta(n)$

Suits Abstract Data Types | Set | Map

Applications: Container libraries (C++, Java) | Linux CFS



If node has no child, points to a special `nil` node

- treated as black
- simplify logic
- omitted from diagrams

Red-black tree: a Binary Search Tree where each node also has a colour (which can be **red** or **black**)

Approximately balanced: Tree height is $\Theta(\log n)$

References/Notes/Image credits:
https://en.wikipedia.org/wiki/Red%E2%80%93black_tree
(AVL Trees) G. M. Adelson-Velsky and E. M. Landis, "An algorithm for the organization of information", Doklady Akademii Nauk (1962)
(G. M. Adelson-Velsky) https://www.math.toronto.edu/askold/2014-UMN-4-e-Adelson-.pdf
(E. Landis) https://opc.mfo.de/detail?photo_id=2447
R. Bayer, "Symmetric binary B-trees: Data structure and maintenance algorithms", Acta informatica (1972)
(R. Bayer) https://www.computerhope.com/people/rudolf_bayer.htm
L. Guibas and R. Sedgewick, "A dichromatic framework for balanced trees", SFCS (1978)
(L. Guibas) https://geometry.stanford.edu/member/guibas/
(R. Sedgewick) https://sedgewick.io/
(Red-Black Trees) T. Cormen et al., "Introduction to algorithms", Chap 13.1, MIT press, (2022)
(Linux CFS) https://en.wikipedia.org/wiki/Completely_Fair_Scheduler

Red-Black Tree Properties

Five key properties of Red-Black Trees (CLRS)

RBTs are Binary Search Trees with:

Property 1 Every node is **red** or **black**

Property 2 The root node is **black**

Property 3 Every leaf node (nil node) is **black**

Property 4 If a node is **red**, both of its children are **black**

Property 5 Starting from any node, all simple paths down to leaf nodes hold the same number of **black** nodes

Tree height (h) is $\Theta(\log n)$

By **Property 5** all root-leaf paths have the same number of **black** nodes

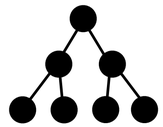
By **Property 4** **red** nodes have **black** children

$\Longrightarrow$ longest path, $h_{\max} \leq 2 \cdot$ shortest path, $h_{\min}$

Note: complete binary tree has $n = 2^{h+1} - 1$ nodes

- $h = 0$, $n = 1$

$h = 1$, $n = 3$



$h = 2$, $n = 7$

$$\Longrightarrow 2^{h_{\min}+1} - 1 \leq n \leq 2^{h_{\max}+1} - 1$$

$$\Longrightarrow h_{\min} \leq \log(n+1) - 1 \leq h_{\max} \leq 2 \cdot h_{\min}$$

$$\Longrightarrow h_{\min} = \Theta(\log n)$$

Key "balanced tree" result

$$h_{\min} \leq h_{\max} \leq 2 \cdot h_{\min} \Longrightarrow h_{\max} = \Theta(\log n)$$

$\Longrightarrow$ Min, Max, Search, Successor, Predecessor, $O(\log n)$

References:
(CLRS) T. Cormen et al., "Introduction to algorithms", Chap 13.1, MIT press, (2022)
(Proof of tree height) L. Arge and M. Lagoudakis, CPS 230 lecture notes, https://courses.cs.duke.edu/cps130/fall02/fall02lectures/lecture18/long_redblack.pdf (2002)

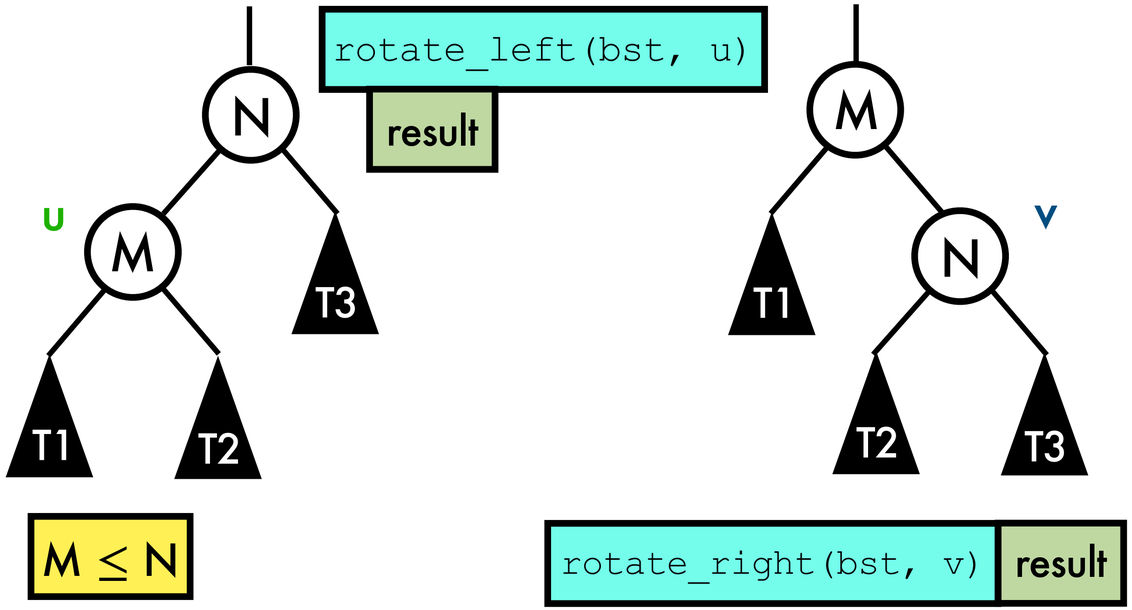
Rotation Operations

The rotation operation

Rotations restructure a tree locally without

breaking the Binary Search Tree Property

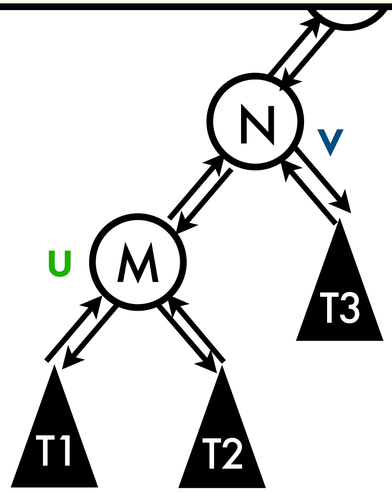
Rotations change links (not colours) at $O(1)$ cost



References:
(Rotations) L. Arge and M. Lagoudakis, CPS 230 lecture notes, https://courses.cs.duke.edu/cps130/fall02/fall02lectures/lecture18/long_redblack.pdf (2002)
(rotation logic/comments based on CLRS) T. Cormen et al., "Introduction to algorithms", Chap 13.2, MIT press (2022)
Python code snippet reference for rotate_left - https://blog.boot.dev/python/red-black-tree-python/

Rotate_left implementation in Python

```
def rotate_left(self, u): # self is BST instance
    v = u.right
    u.right = v.left
    if v.left != self.nil:
        v.left.parent = u
    v.parent = u.parent
    if u.parent is None:
        self.root = v
    elif u.parent.left == u:
        u.parent.left = v
    else:
        u.parent.right = v
    v.left, u.parent = u, v
```



Why Are Rotations Useful?

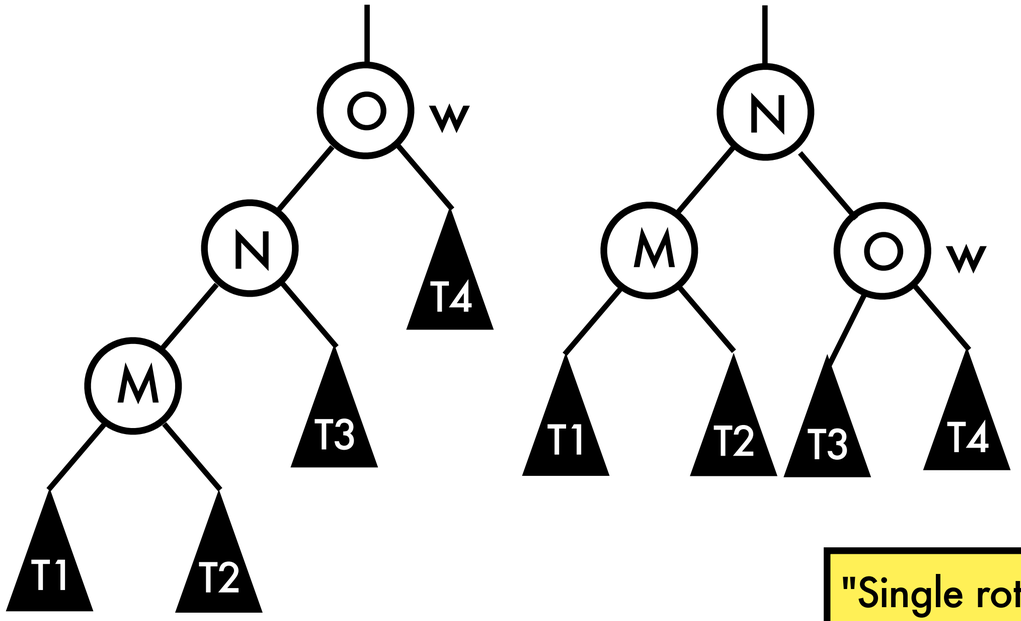
The benefits of rotation

When too many nodes are on a single path,

rotation distributes them to neighbour paths

This restores balance in the tree

It preserves the Binary Search Tree Property

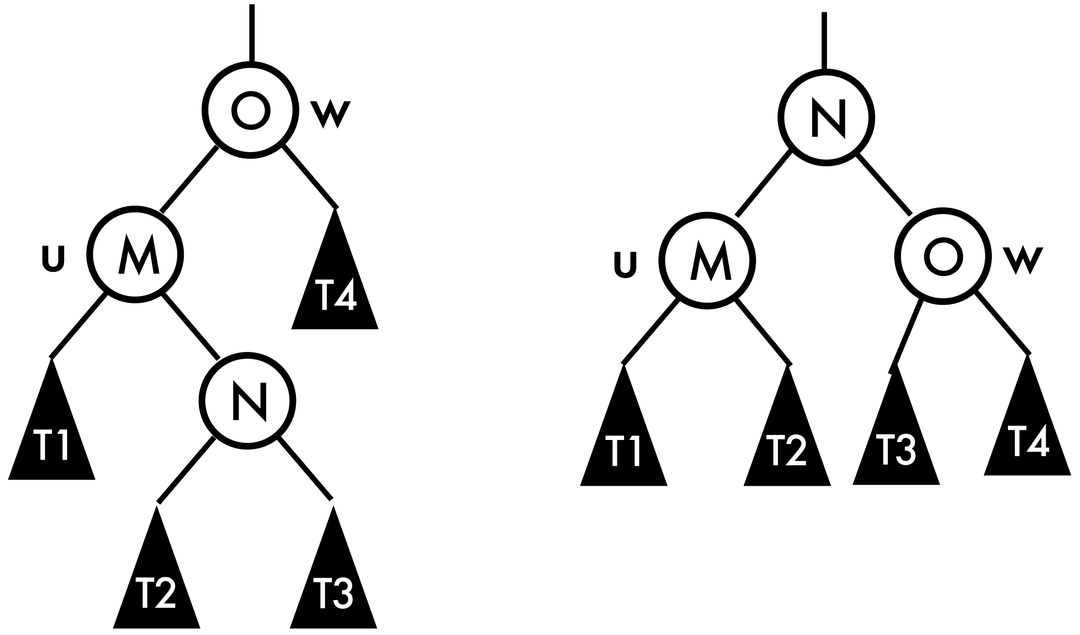


"Single rotation"

`rotate_right(bst, w)` — Produces more balanced structure

Double rotations

If we have a chain with both a left child and a right child, then a "double rotation" is needed



Function calls: `rotate_left(bst, u)` `rotate_right(bst, w)`

References:
(Rotations) L. Arge and M. Lagoudakis, CPS 230 lecture notes, https://courses.cs.duke.edu/cps130/fall02/fall02lectures/lecture18/long_redblack.pdf (2002)

Red-Black Tree Insertion

Insertion overview

Initially, RBT insertion is the same as BST insertion

What colour should the inserted node be?

We have two options: **red** or **black**

If we colour the inserted node **red** and its parent is **red**, we violate Property 4

If we colour the inserted node **black**, the extra black node will violate Property 5

Strategy: fix problem locally with rotations and recolouring

"Escalate" further issues up the tree

"Management strategy"

Tree height is $\Theta(\log n)$ so fixing is $O(\log n)$

Total Red-Black Tree insertion $O(\log n)$

Insertion - handling cases

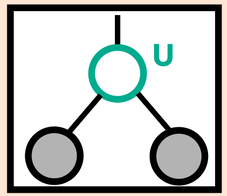
Red-black tree insertion involves patiently handling several cases

Precursor: whenever we have a RBT violation,

the node has **black** children

True after inserts (nils are **black**)

Also true further up the tree



Case 1 u has a black parent

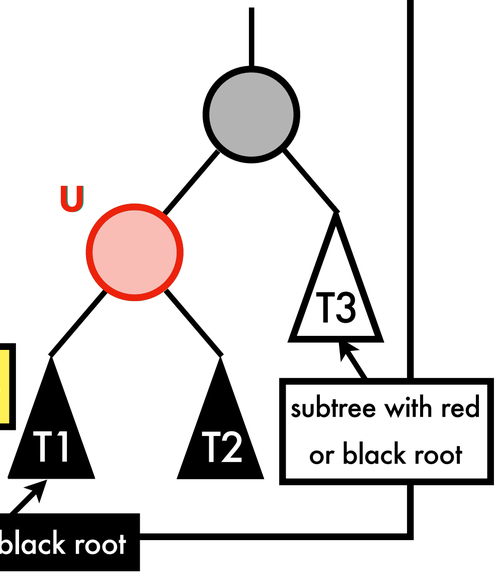
Simply colour node u **red**:

u is not the root Property 2

Only **black** children Property 4

No extra **black** nodes Property 5

Problem is fixed locally



Reference:
(Rotations) L. Arge and M. Lagoudakis, CPS 230 lecture notes, https://courses.cs.duke.edu/cps130/fall02/fall02lectures/lecture18/long_redblack.pdf (2002)

Red-Black Tree Insertion Cont.

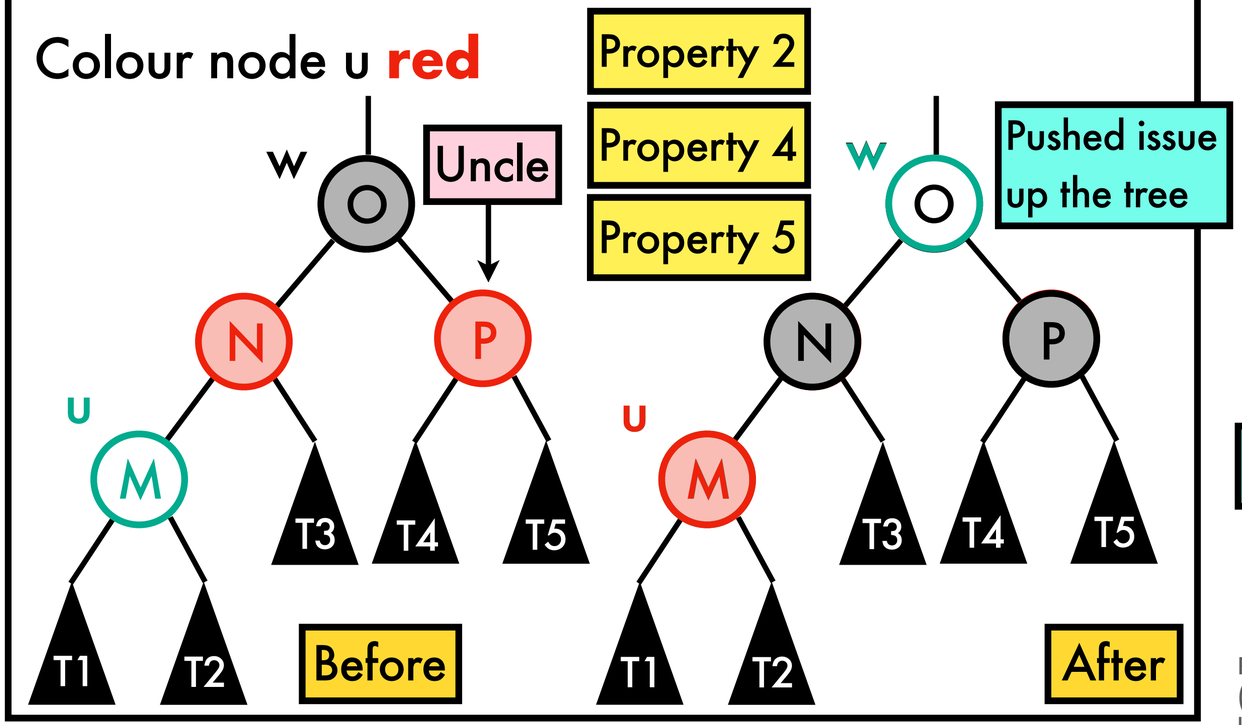
Parent of u is red

When parent of (u) is **red**, the steps depend on colour of its parent's sibling (its "uncle")

Case 2 (u) has **red** parent, **red** uncle

Push **black** colour of w down to each child

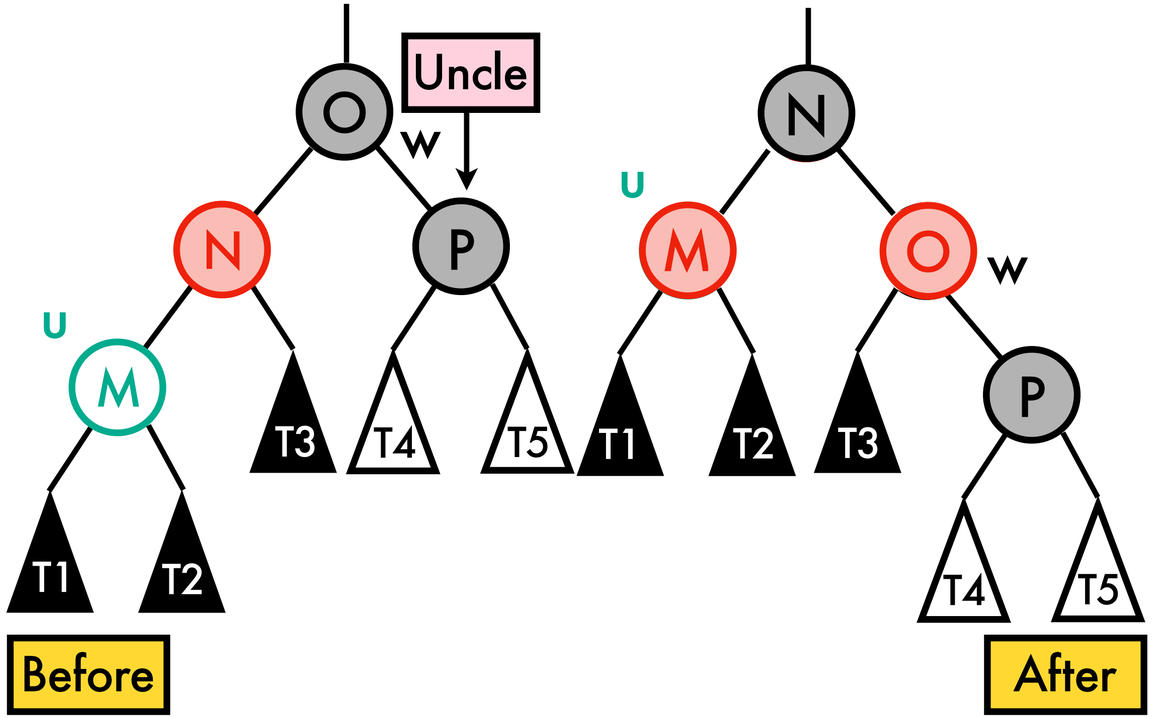
Colour node u **red**



Parent of u is red

Case 3 (u) has **red** parent, **black** uncle

Case 3a (u) is away from its uncle



`rotate_right(bst, w)` | u → red | u.parent → black | w → red

Problem is fully fixed (no further escalation)

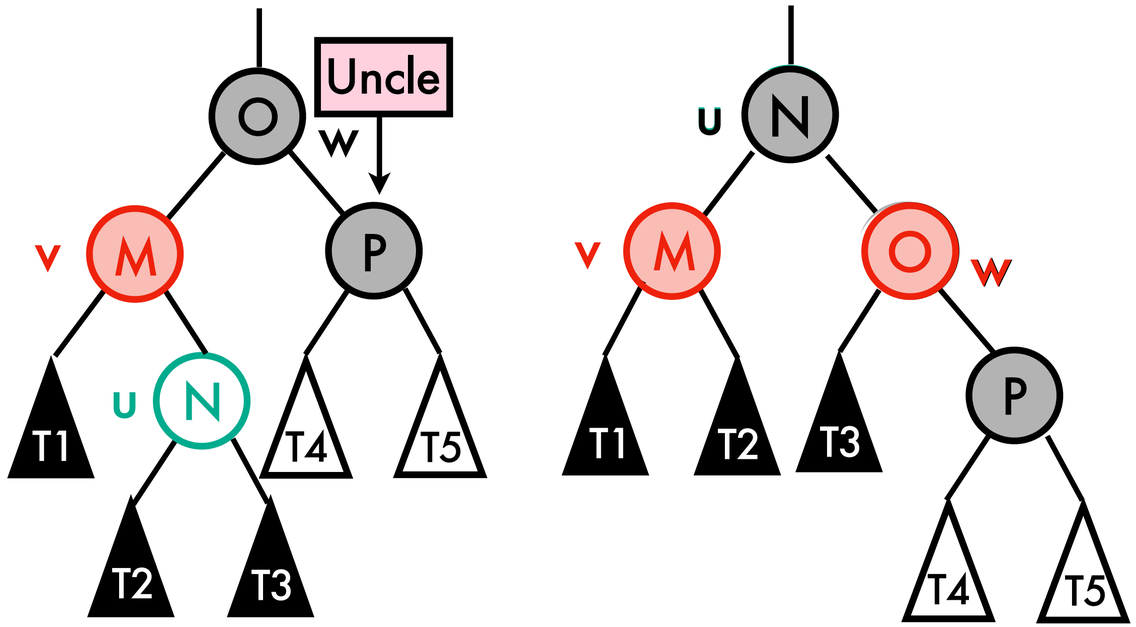
Reference:
(Rotations) L. Arge and M. Lagoudakis, CPS 230 lecture notes, https://courses.cs.duke.edu/cps130/fall02/fall02lectures/lecture18/long_redblack.pdf (2002)

Red-Black Tree Insertion Cont.

Parent of u is red

Case 3 (u) has **red** parent, **black** uncle

Case 3b (u) is towards its uncle



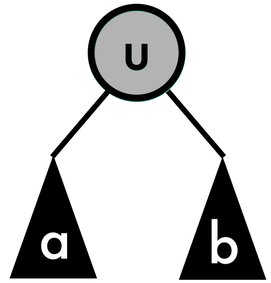
Before `rotate_left(bst, v)` After

`rotate_right(bst, w)` u → black w →red

Problem is fully fixed (no further escalation)

u has no parent

Case 4 (u) has no parent



Colour node u **black**

Property 2 Property 5

Problem is fully fixed (no further escalation)

Red-Black Tree Deletion

Deletion overview

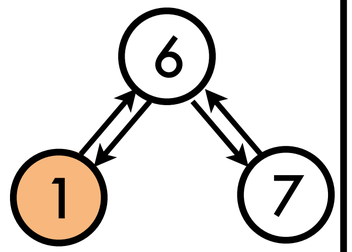
We build on top of Binary Search Tree deletion

Red-Black Tree deletion is $O(\log n)$

It is also quite complicated to implement

Shifting subtrees

```
def shift_nodes(self, old, new):
    if not old.parent:
        self.root = new
    elif old == old.parent.left:
        old.parent.left = new
    else:
        old.parent.right = new
    new.parent = old.parent
```



Reference:
T. Cormen et al., "Introduction to algorithms", Chap 13.4, MIT press (2022)

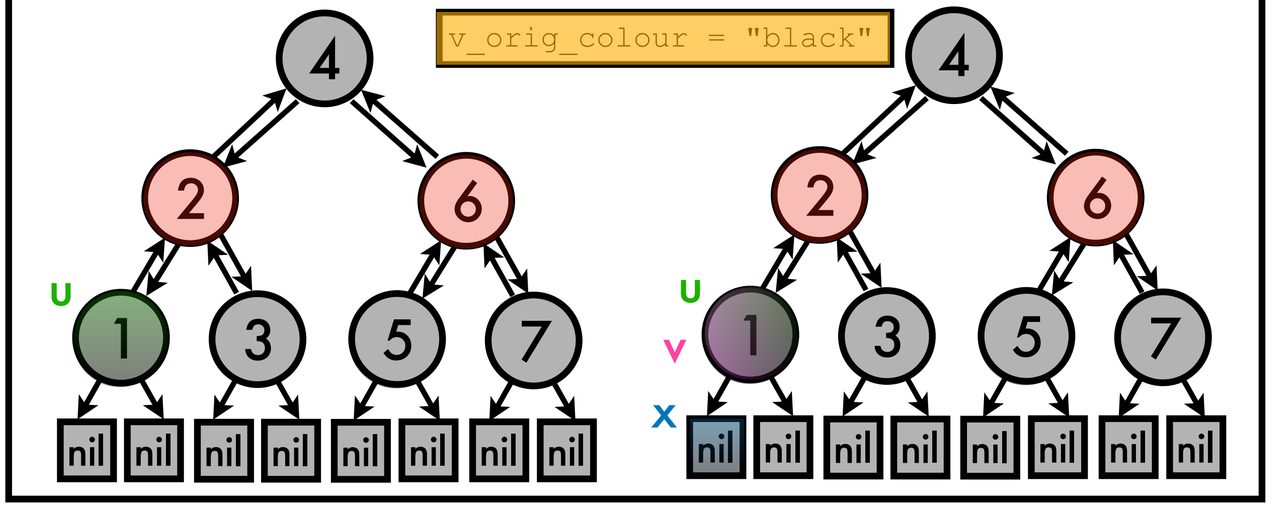
Red-Black Tree Deletion

```
def delete(self, u):  # self is an instance of a red-black tree
    v = u  # assign v to the node to be deleted
    v_orig_colour = v.colour  # track v's original colour
    if u.left == self.nil:  # u's left child is nil
        x = u.right
        shift_nodes(self, u, x)  # shift up x into u's place
    elif u.right == self.nil:  # u's right child is nil
        x = u.left
        shift_nodes(self, u, x)  # shift up x into u's place
    else:  # u has two children
        v = minimum(u.right)
        v_orig_colour = v.colour
        x = v.right
        if v != u.right:
            shift_nodes(self, v, v.right)
            v.right = u.right
            v.right.parent = v
        else:
            x.parent = v
        shift_nodes(self, u, v)
        v.left = u.left
        v.left.parent = v
        v.colour = u.colour
if v_orig_colour == "black":
    fix_delete_violations(self, x)
```

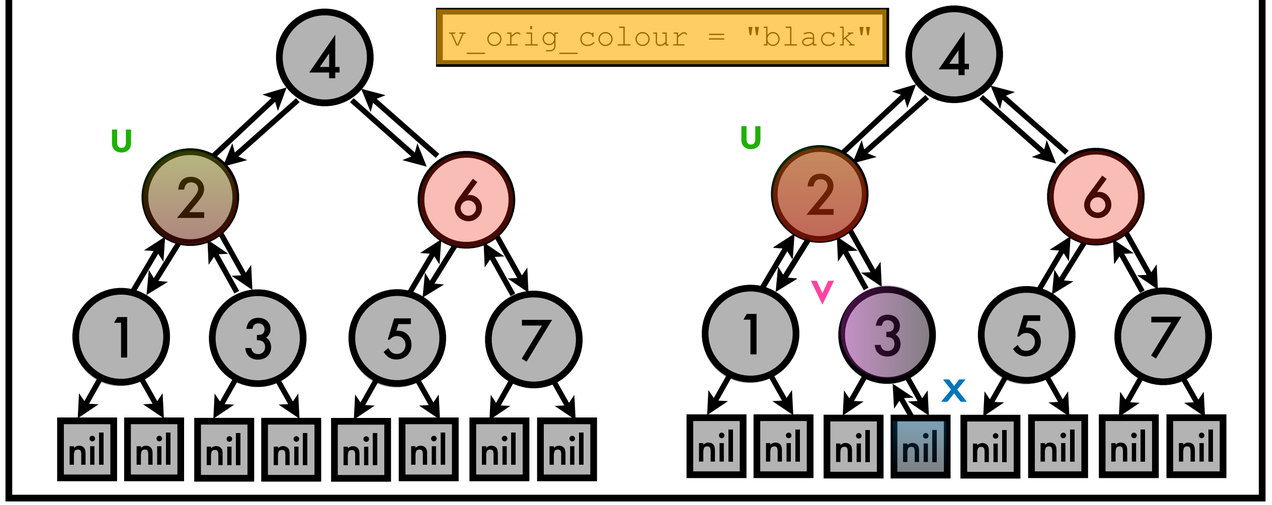
If `v_orig_color` was red:

- v wasn't the root — Property 2
- no red nodes have become neighbours — Property 4
- num black nodes on paths haven't changed — Property 5

u's left child is nil (right case is symmetric)



u has two children



Reference:
Code adapted from T. Cormen et al., "Introduction to algorithms", Chap 13.4, MIT press (2022)

Fixing RBT Violations

Double black and red-and-black nodes

Moving node v breaks **Property 5**

(and possibly also **Property 2** and **Property 4**)

Trick: when v is moved we add "additional black" onto x (the node that takes its place)

x is now **"double black"** or **"red-and-black"**

Until we resolve this, we break **Property 1**

To fix, `fix_delelete_violations` handles cases

```
def fix_delete_violations(self, x):  # self is RBT instance
    while x != self.root and x.colour == "black":
        x = handle_cases(self, x)
    x.colour = "black"
```

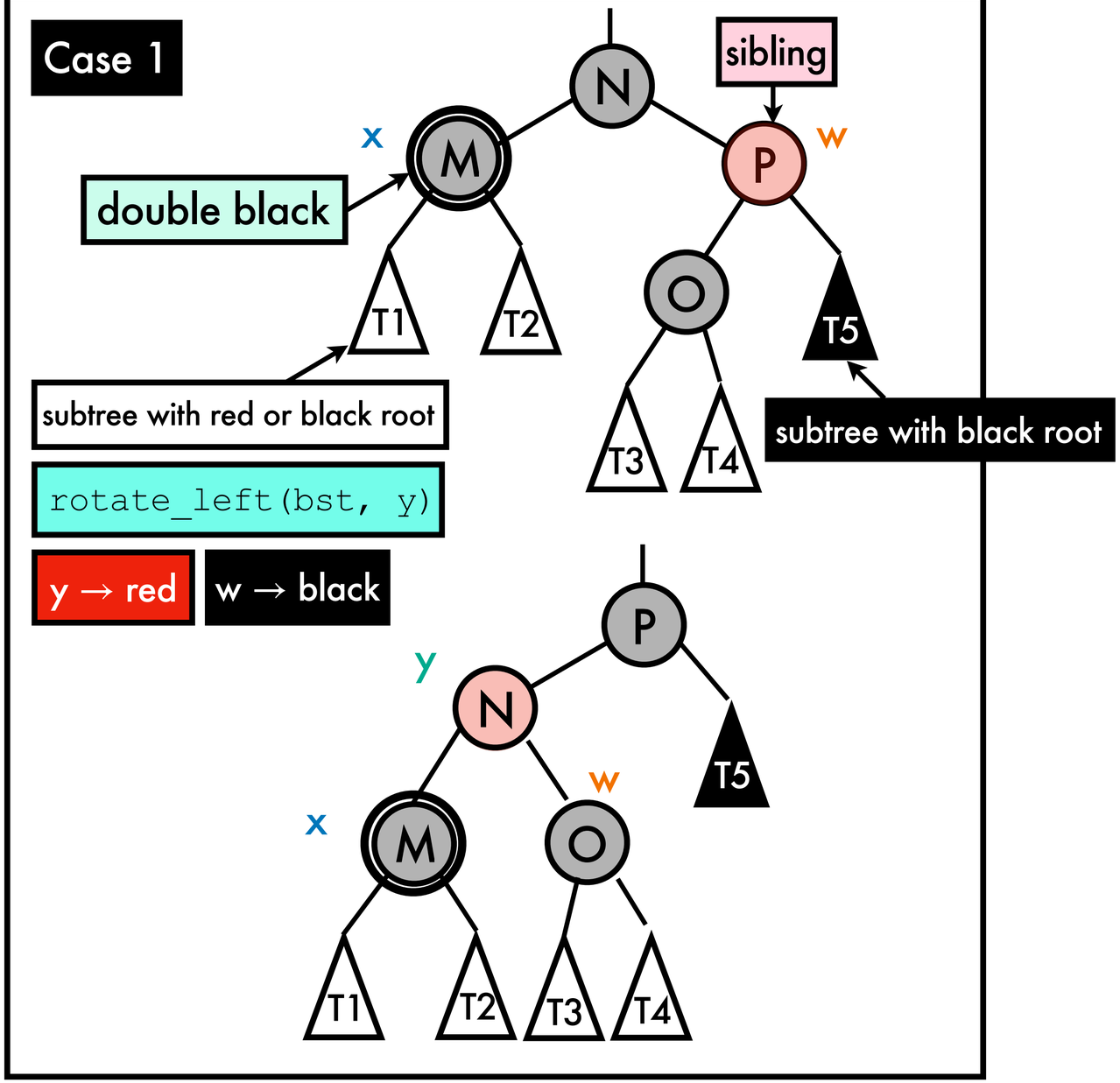
in while loop, x is double black

Cases depend on the colour of x's sibling w

Focus on x as left child (right child is symmetric)

w (x's sibling) is red

Case 1

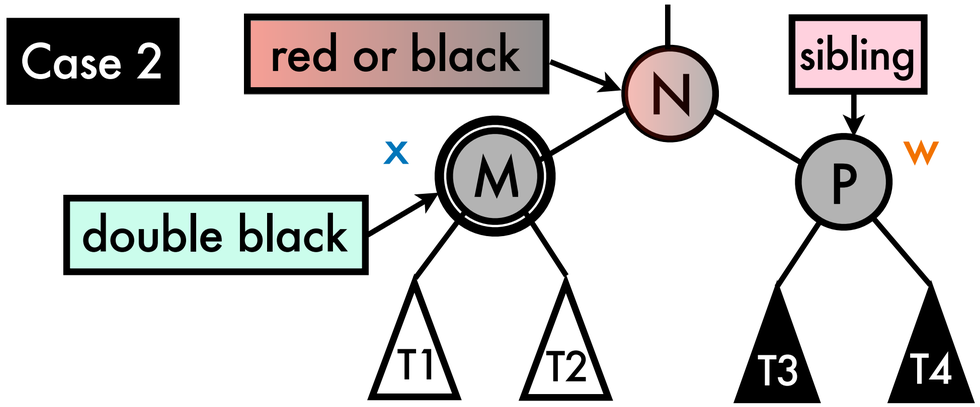


Reference:
T. Cormen et al., "Introduction to algorithms", Chap 13.4, MIT press (2022)

Fixing RBT Violations

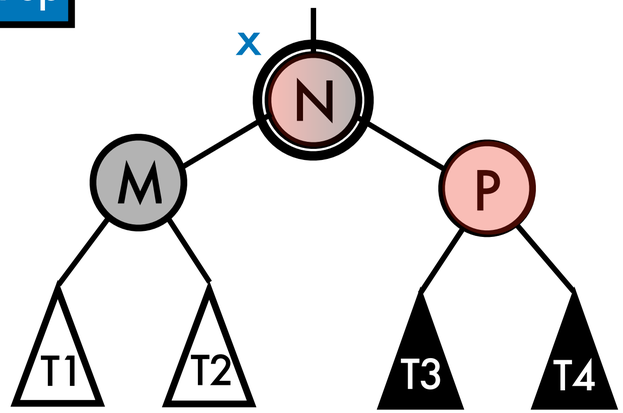
w (x's sibling) is black, w's children are black

Case 2



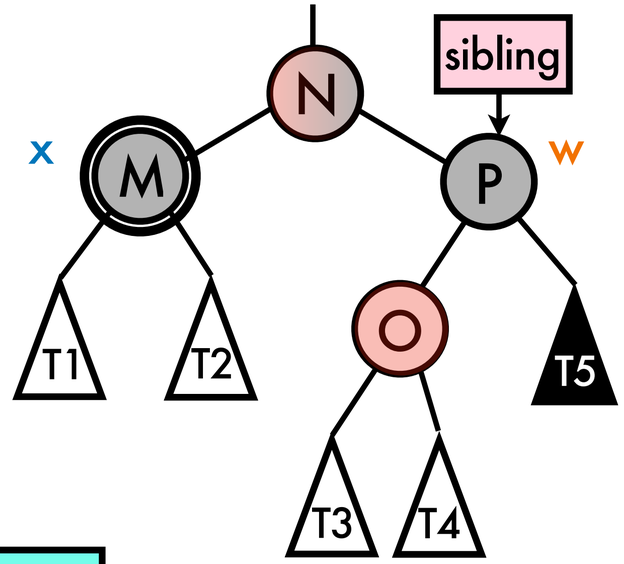
w → red

Move x up



w is black with red left and black right child

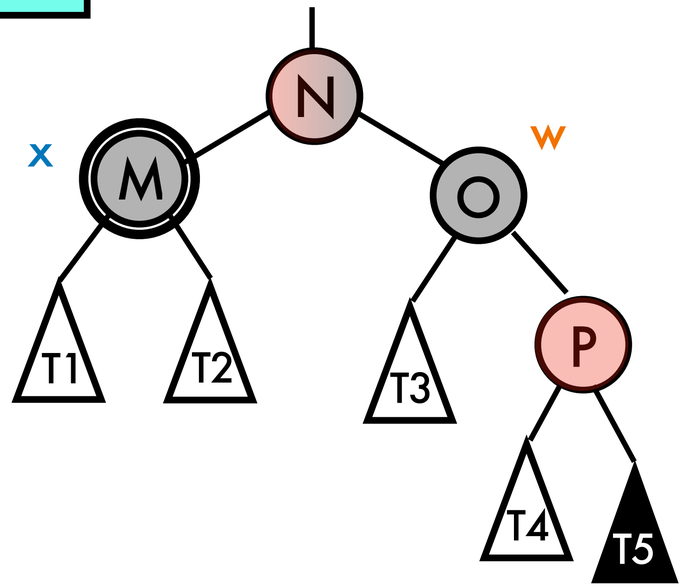
Case 3



`rotate_right(bst, w)`

w → red

w.parent → black

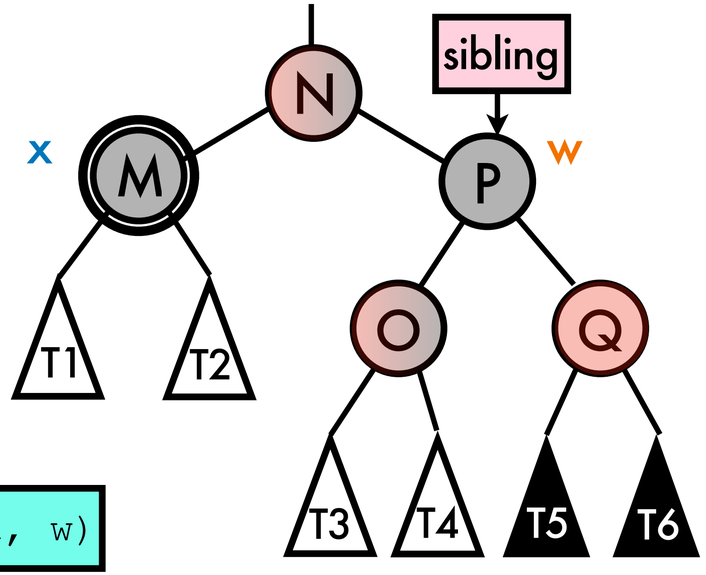


Reference:
T. Cormen et al., "Introduction to algorithms", Chap 13.4, MIT press (2022)

Fixing RBT Violations

w is black and w's right child is red

Case 4



`rotate_left(bst, w)`

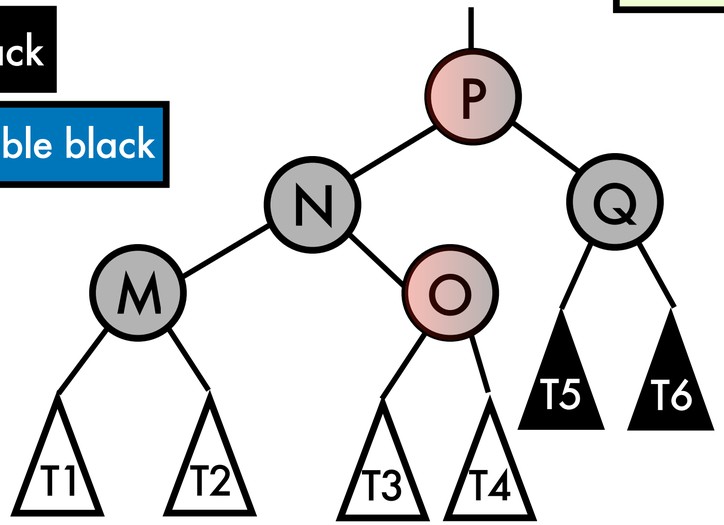
w.right → black

w → w.left's colour

x = root

w.left → black

Remove double black



Case flow

Case 1 → Case 2 → resolves (x red-and-black)

Case 1 → Case 3

Case 1 → Case 4

Case 2 → Case 2 → loops at most $O(\log n)$ times

Case 3 → Case 4

Case 4 → resolves (x set to root)

All paths through case handling are $O(\log n)$

$\Longrightarrow$ `fix_delete_violations()` is $O(\log n)$

$\Longrightarrow$ Red-Black Tree deletion is $O(\log n)$

Reference:
T. Cormen et al., "Introduction to algorithms", Chap 13.4, MIT press (2022)