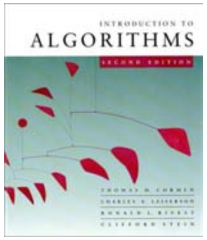

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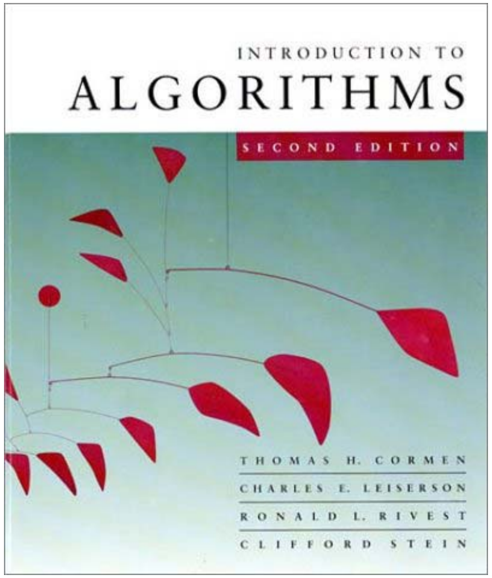
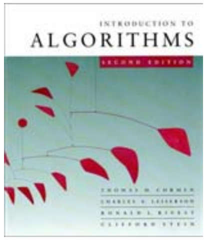


Red-black trees

Carola Wenk

Slides courtesy of Charles Leiserson with small changes by Carola Wenk

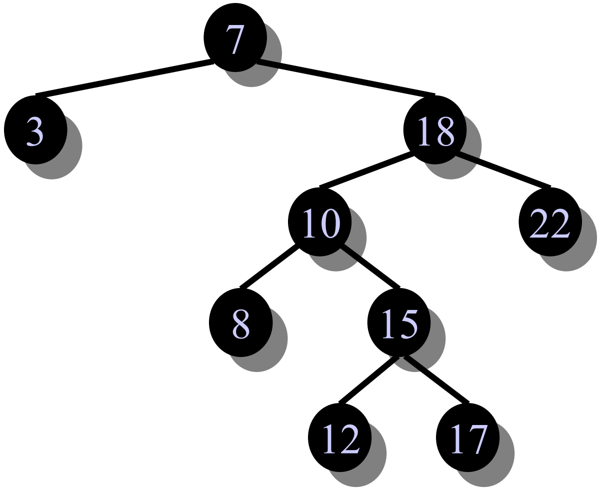


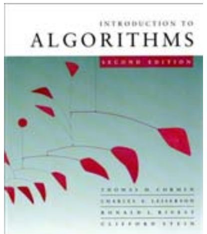
Search Trees

- A binary search tree is a binary tree. Each node stores a key. The tree fulfills the **binary search tree property**:

For every node x holds:

- $left(x) \leq x$, if x's left child $left(x)$ exists
- $x \leq right(x)$, if x's right child $right(x)$ exists

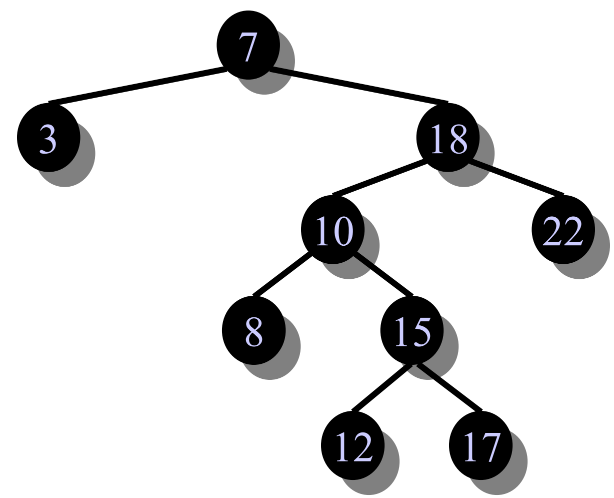


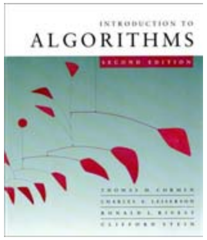


Search Trees

Different variants of search trees:

- Balanced search trees (guarantee height of *log n* for *n* elements)
- *k*-ary search trees (such as B-trees, 2-3-trees)
- Search trees that store the keys only in the leaves, and store additional split-values in the internal nodes



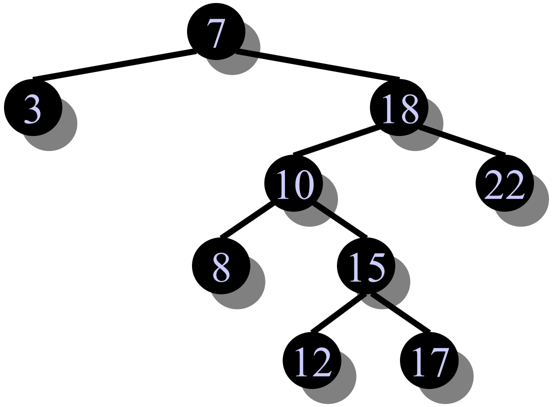


ADT Dictionary / Dynamic Set

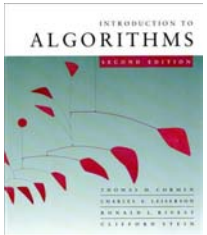
Abstract data type (ADT) Dictionary (also called Dynamic Set):

A data structure which supports operations

- Insert
- Delete
- Find



Using **balanced binary search trees** we can implement a dictionary data structure such that each operation takes $O(\log n)$ time.

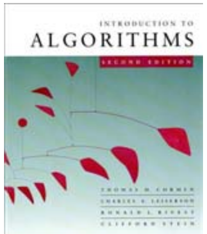


Balanced search trees

Balanced search tree: A search-tree data structure for which a height of $O(\log n)$ is guaranteed when implementing a dynamic set of n items.

Examples:

- AVL trees
- 2-3 trees
- 2-3-4 trees
- B-trees
- Red-black trees

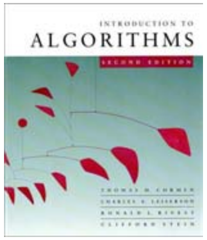


Red-black trees

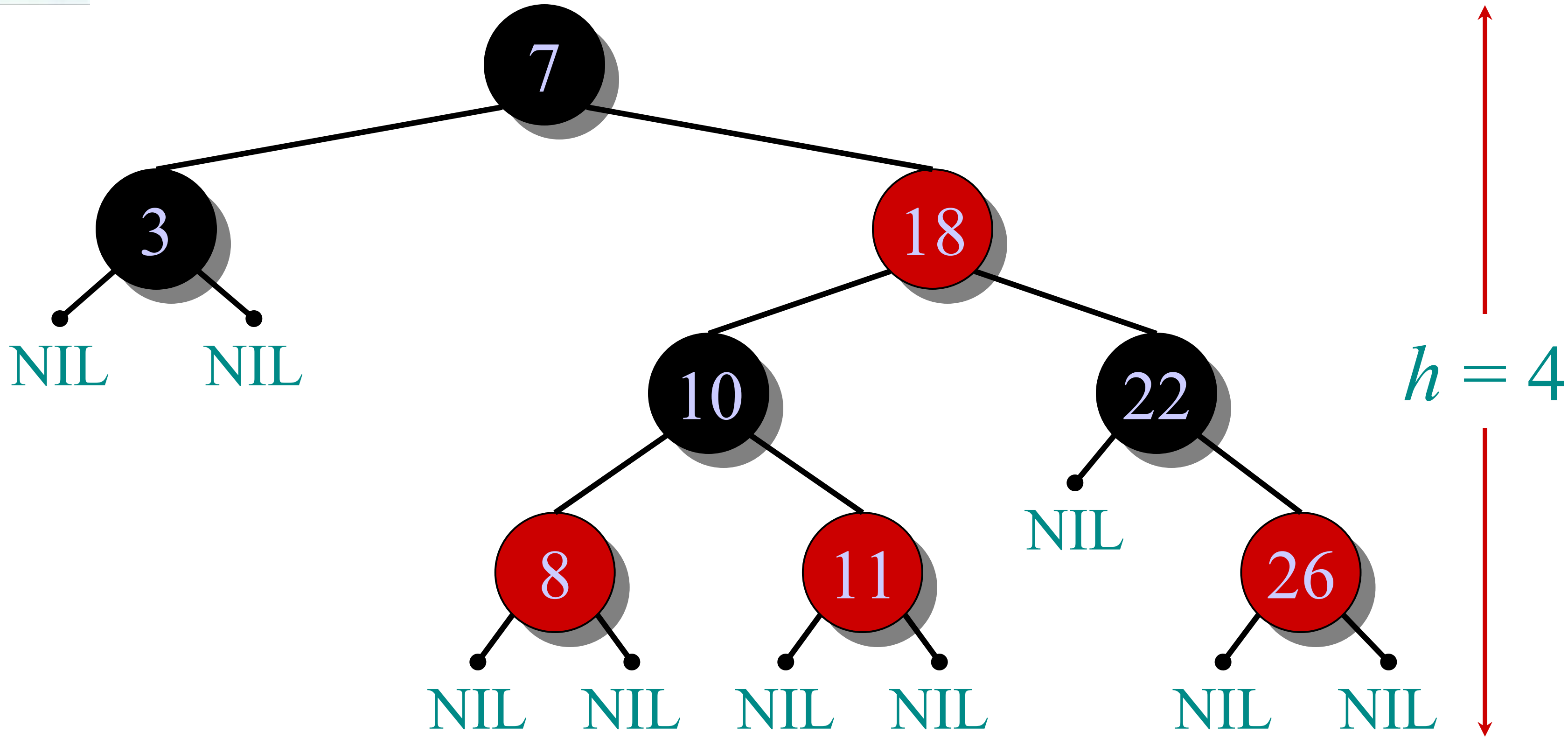
This data structure requires an extra one-bit color field in each node.

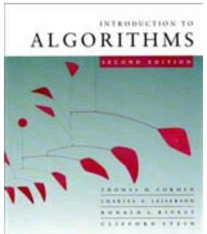
Red-black properties:

1. Every node is either red or black.
2. The root is black.
3. The leaves (NIL's) are black.
4. If a node is red, then both its children are black.
5. All simple paths from any node x, excluding x, to a descendant leaf have the same number of black nodes = black-height(x).



Example of a red-black tree





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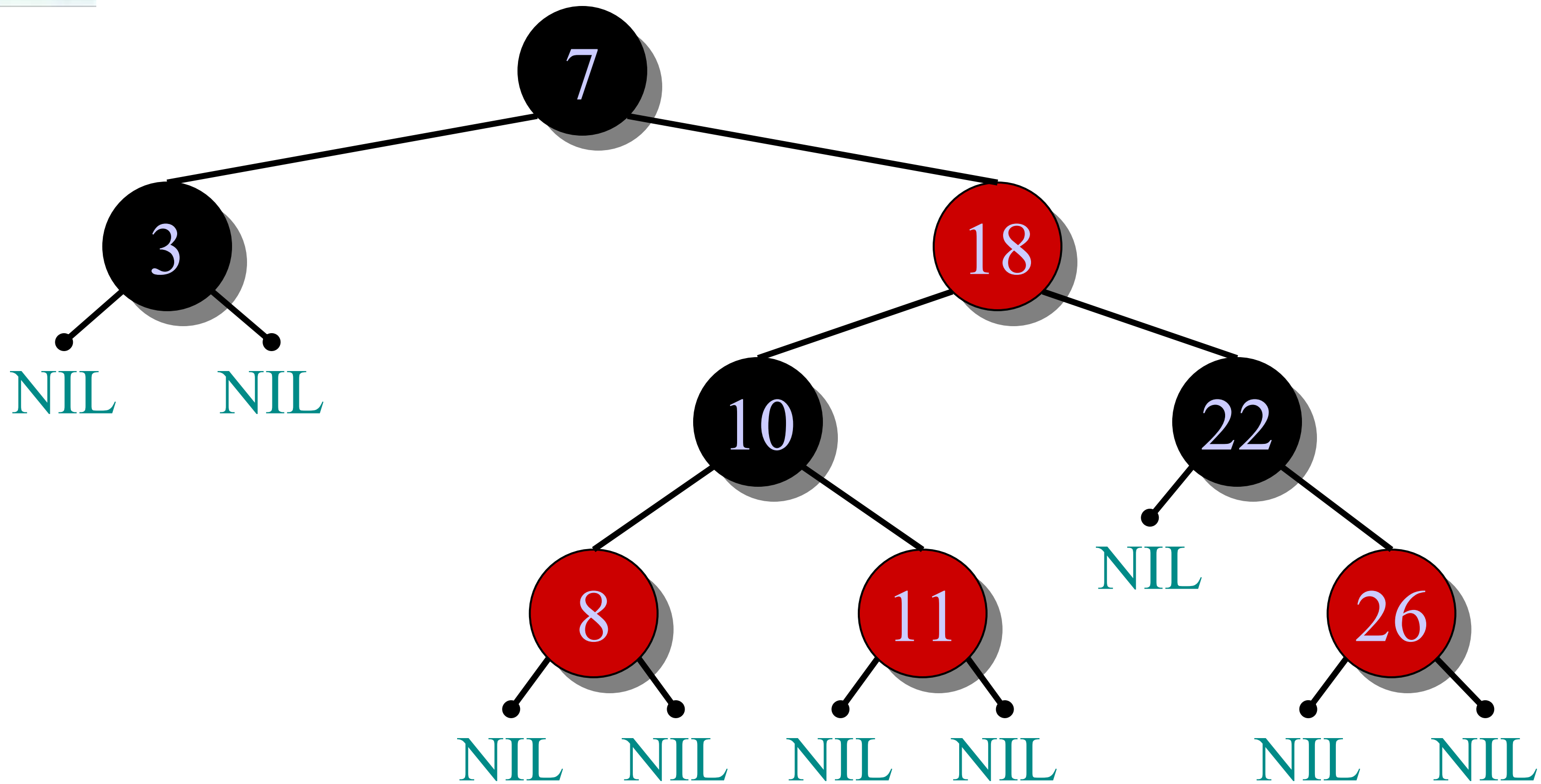

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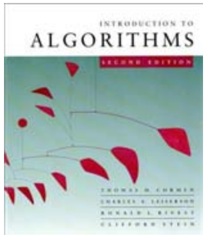

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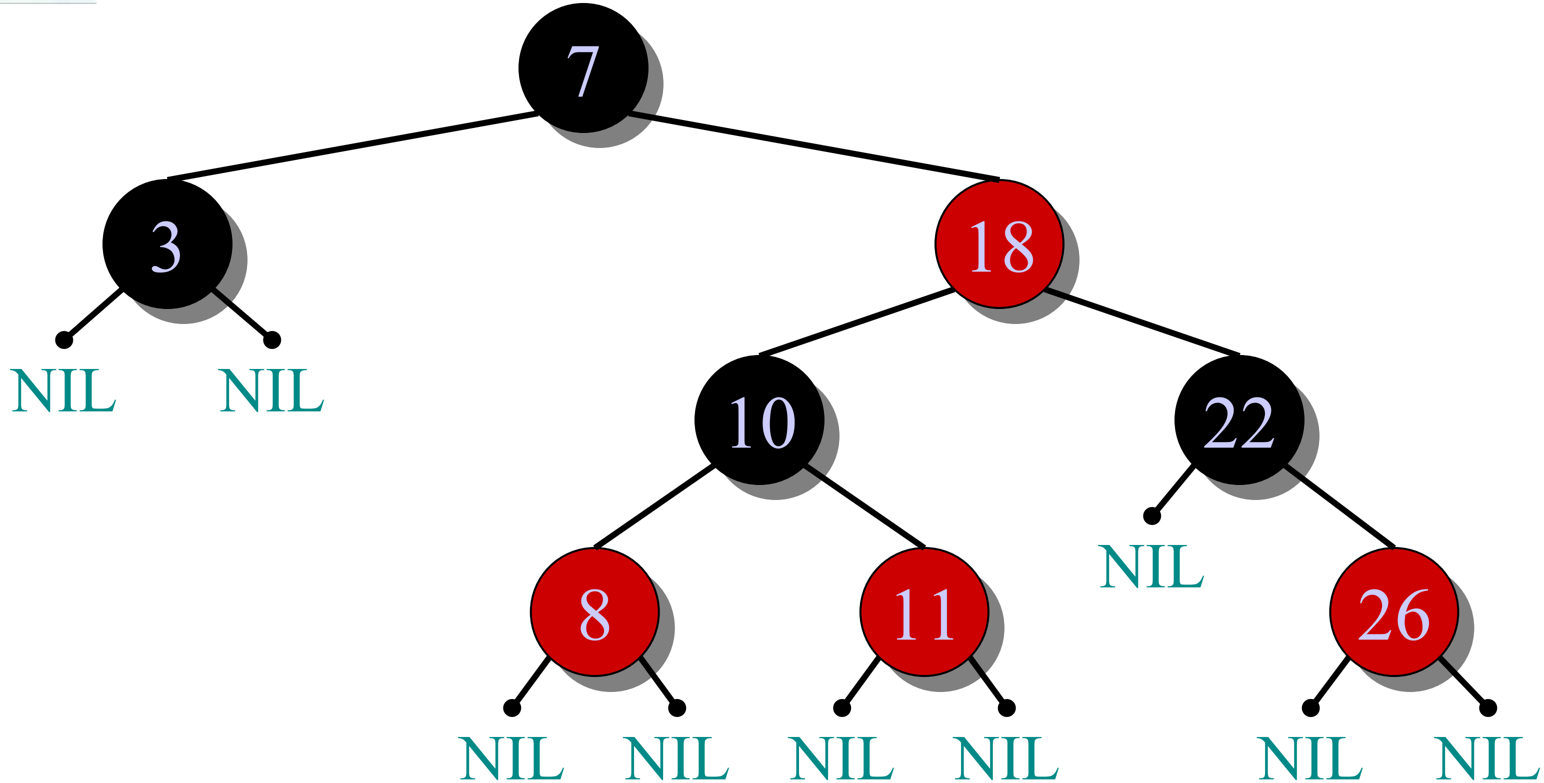
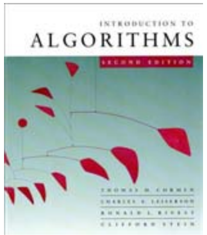


2., 3. The root and leaves (NIL's) are black.



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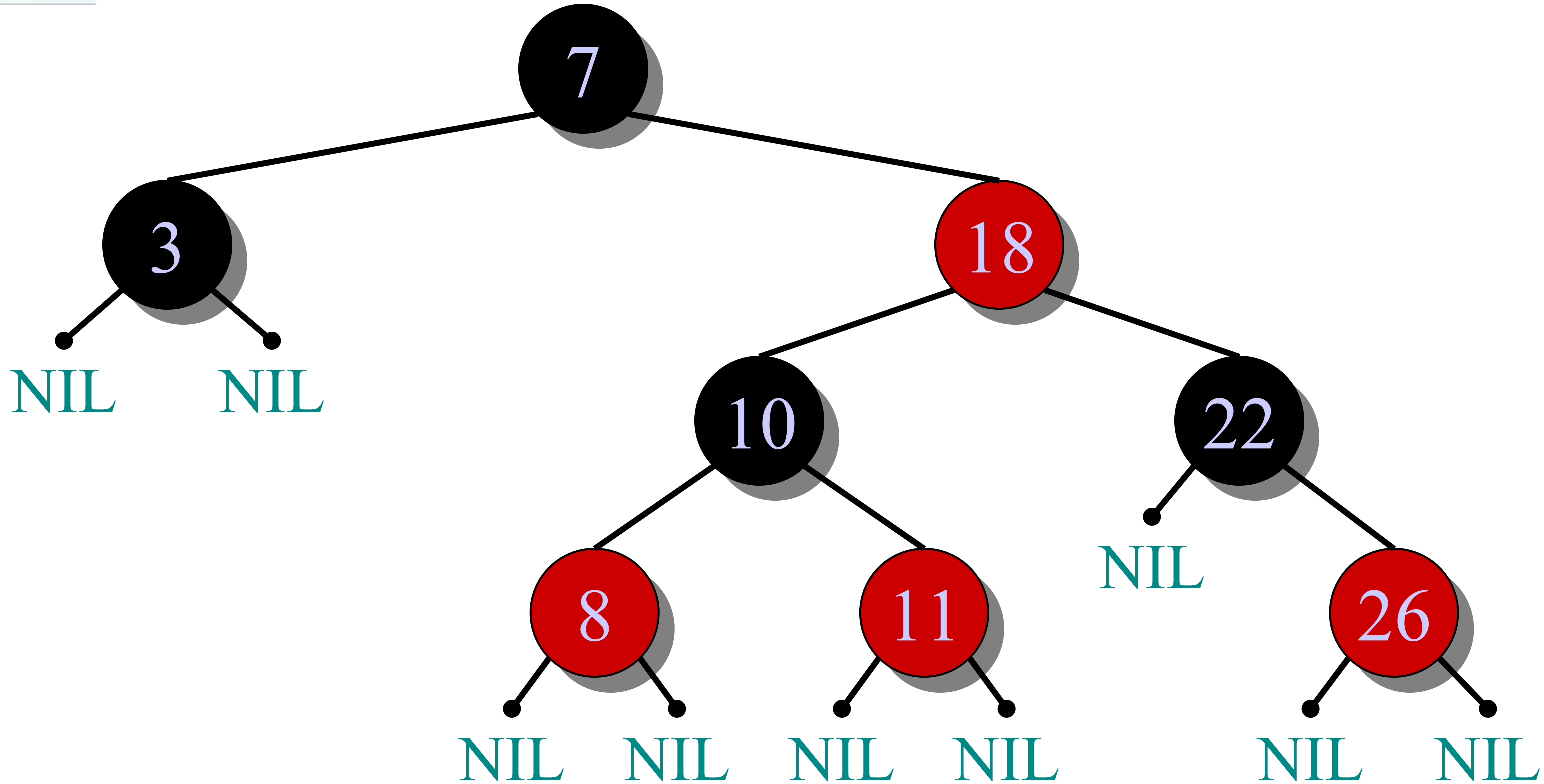

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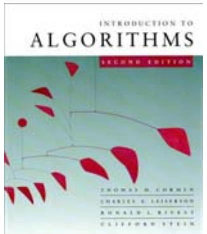

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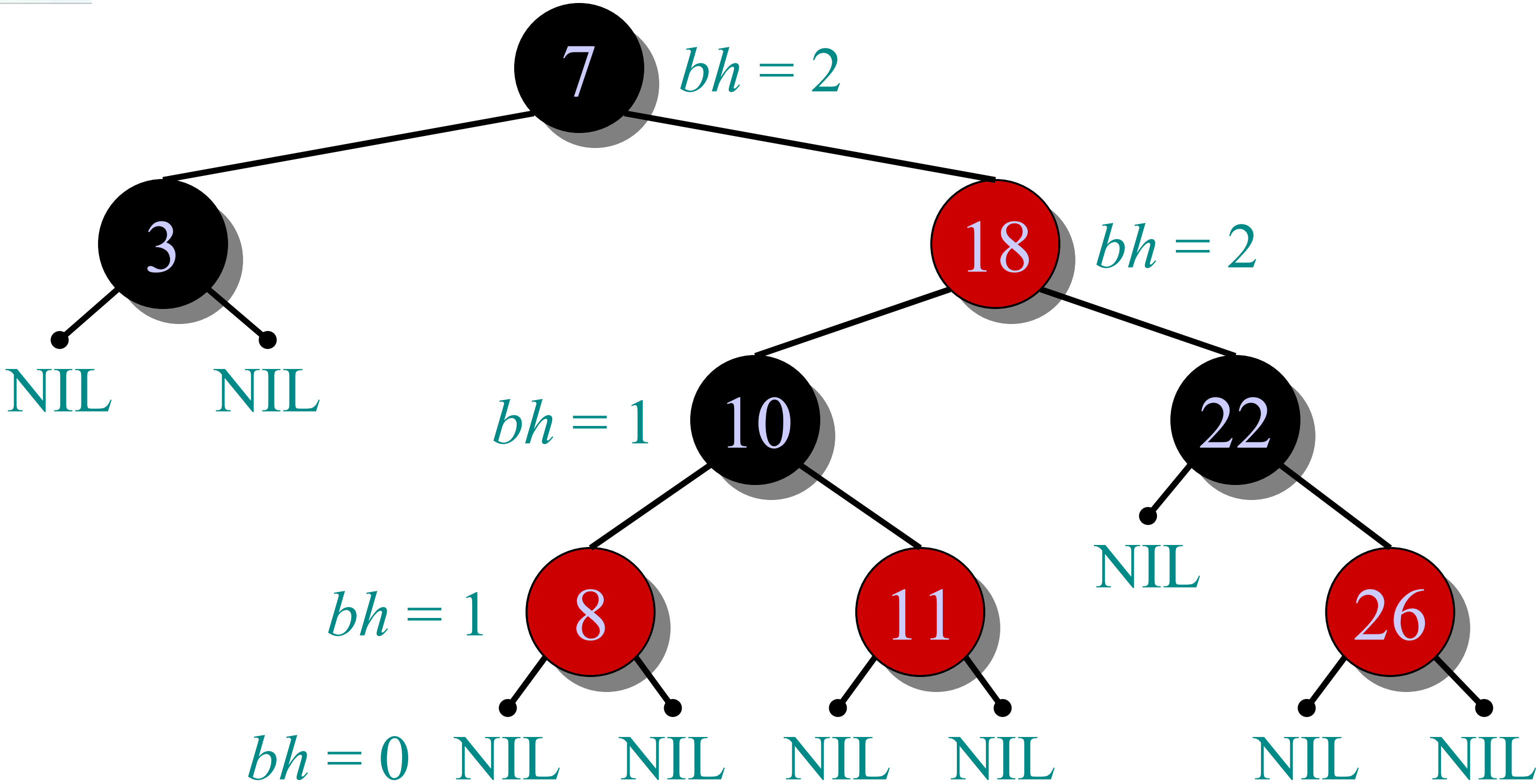

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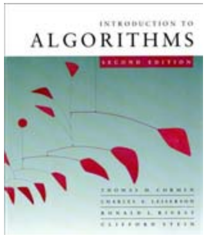


Height of a red-black tree

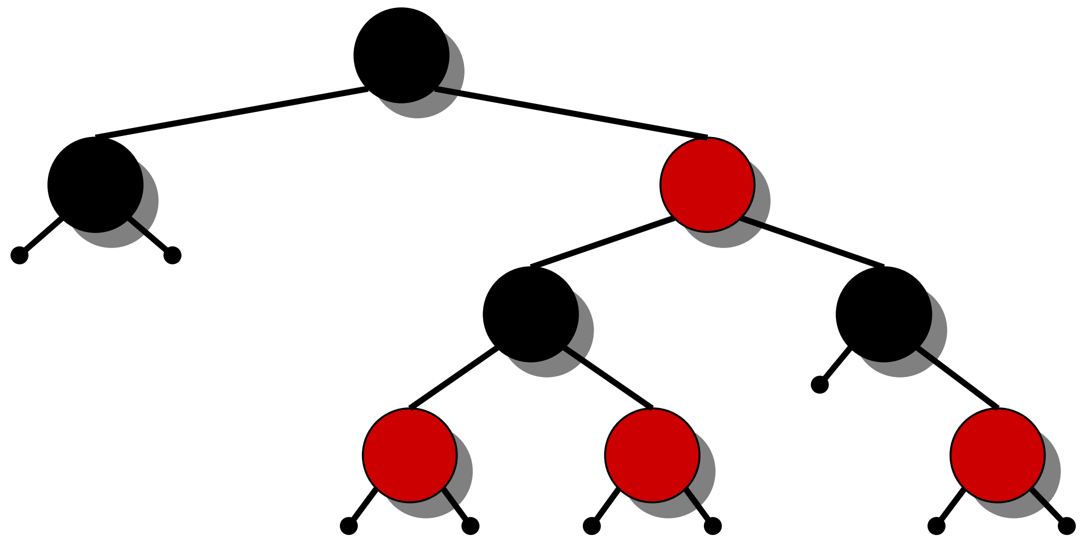
Theorem. A red-black tree with n keys has height

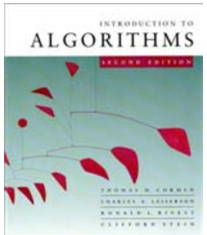
$$h \le 2 \log(n + 1).$$

Proof. (The book uses induction. Read carefully.)

INTUITION:

- Merge red nodes into their black parents.





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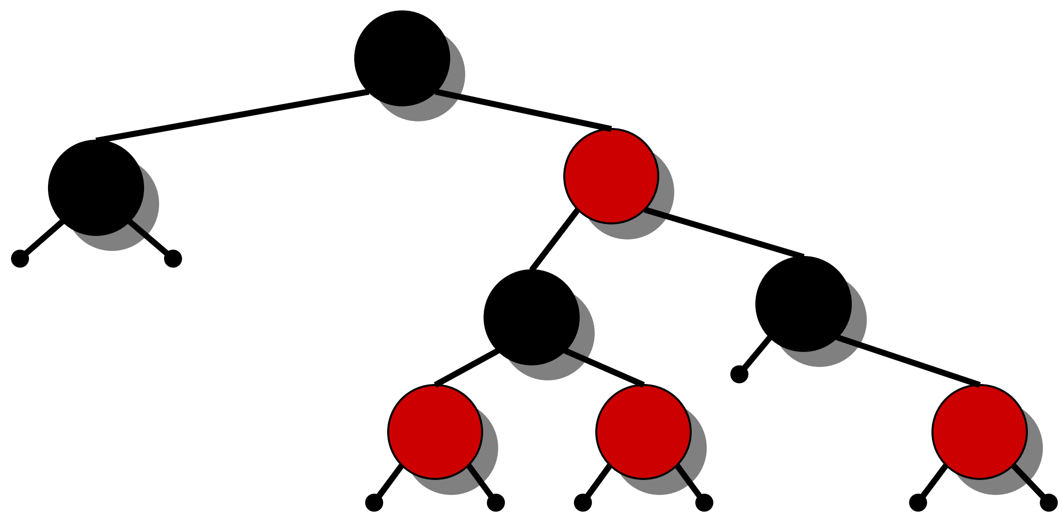

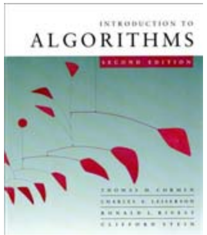

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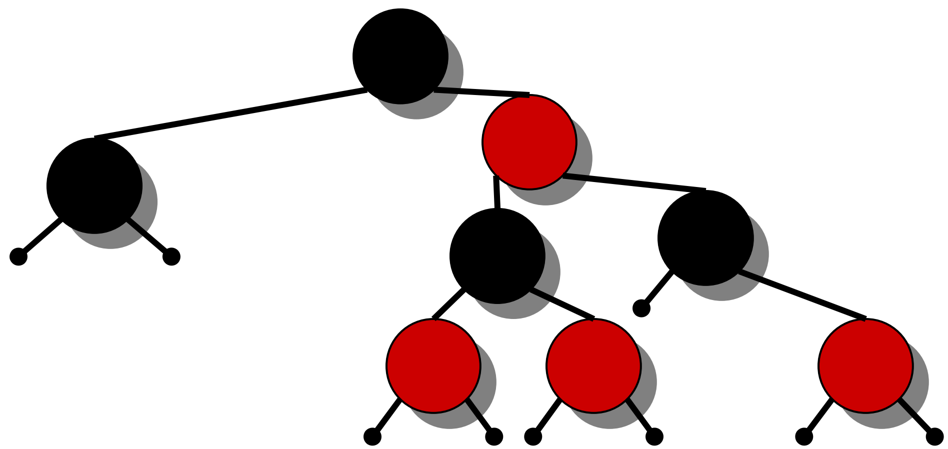

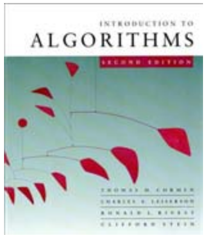

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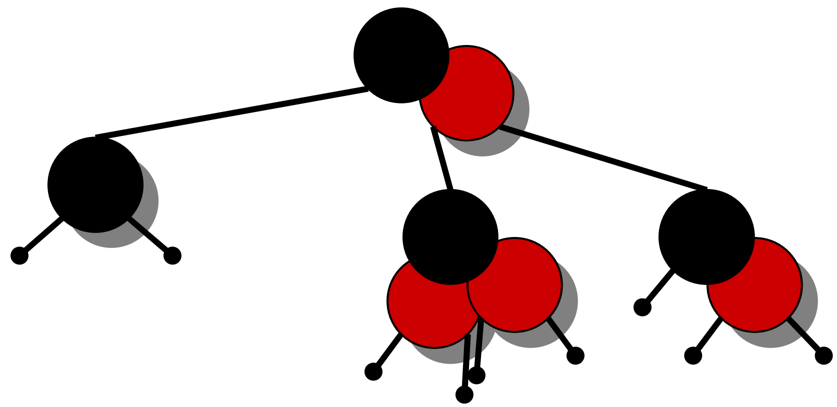

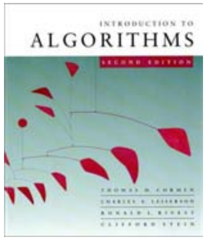

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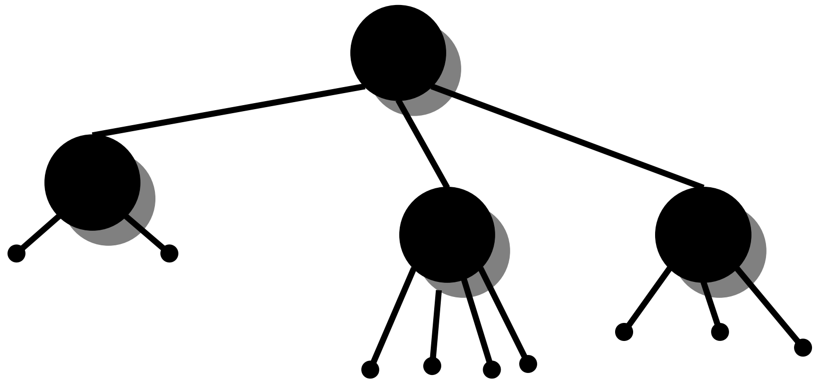

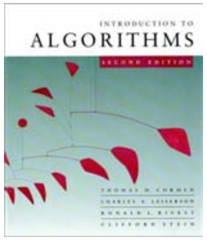

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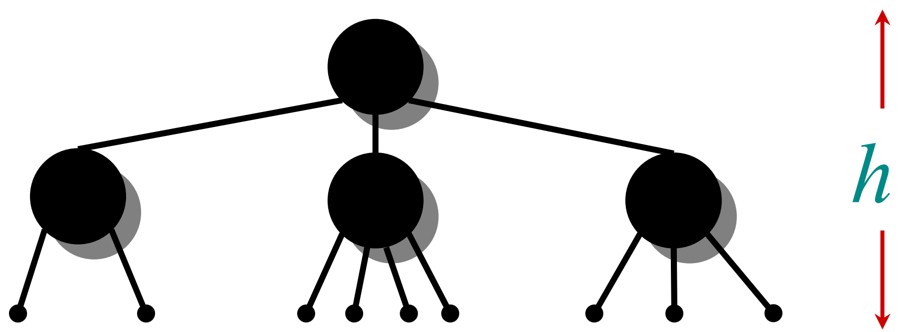
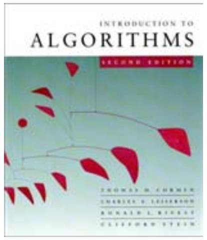
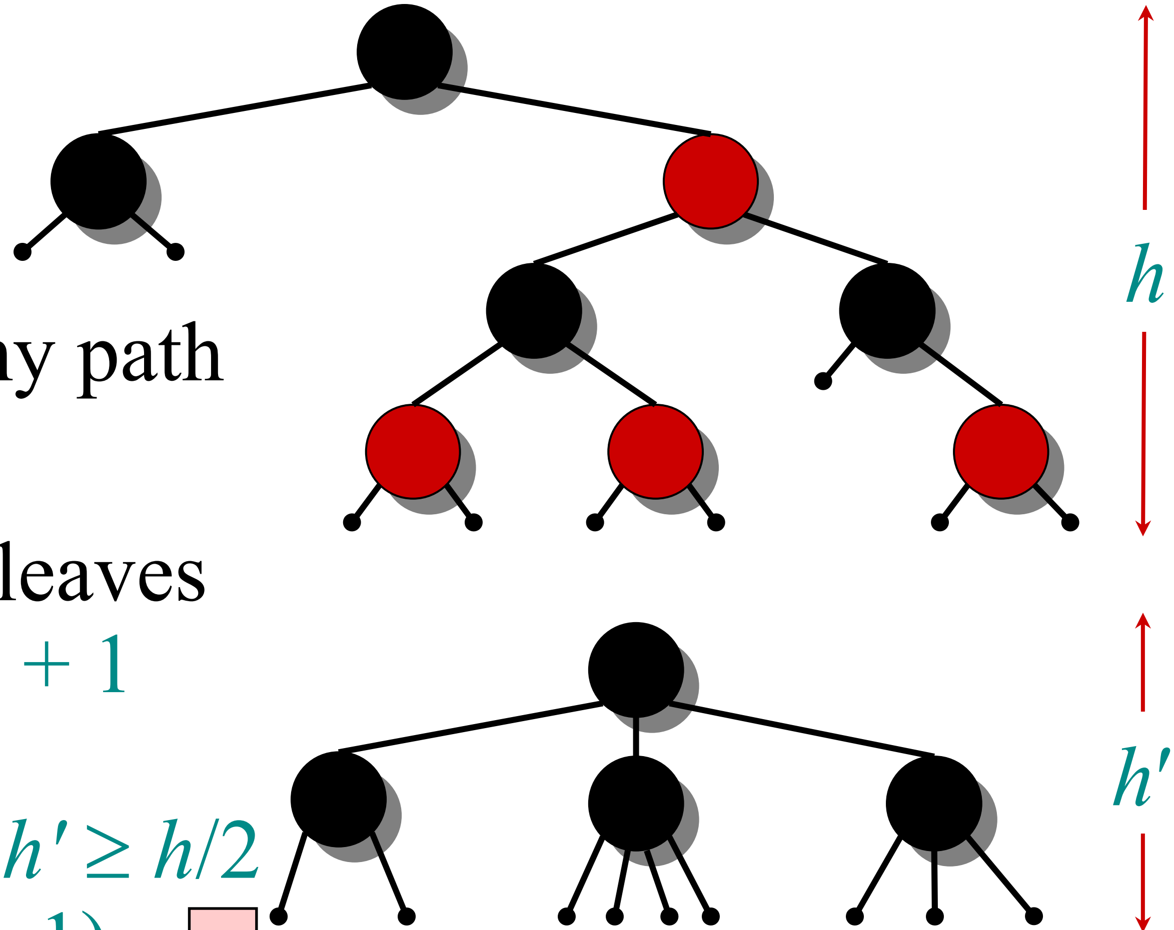


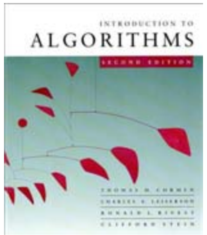
- This process produces a tree in which each node has 2, 3, or 4 children.
- The 2-3-4 tree has uniform depth h' of leaves.



Proof (continued)

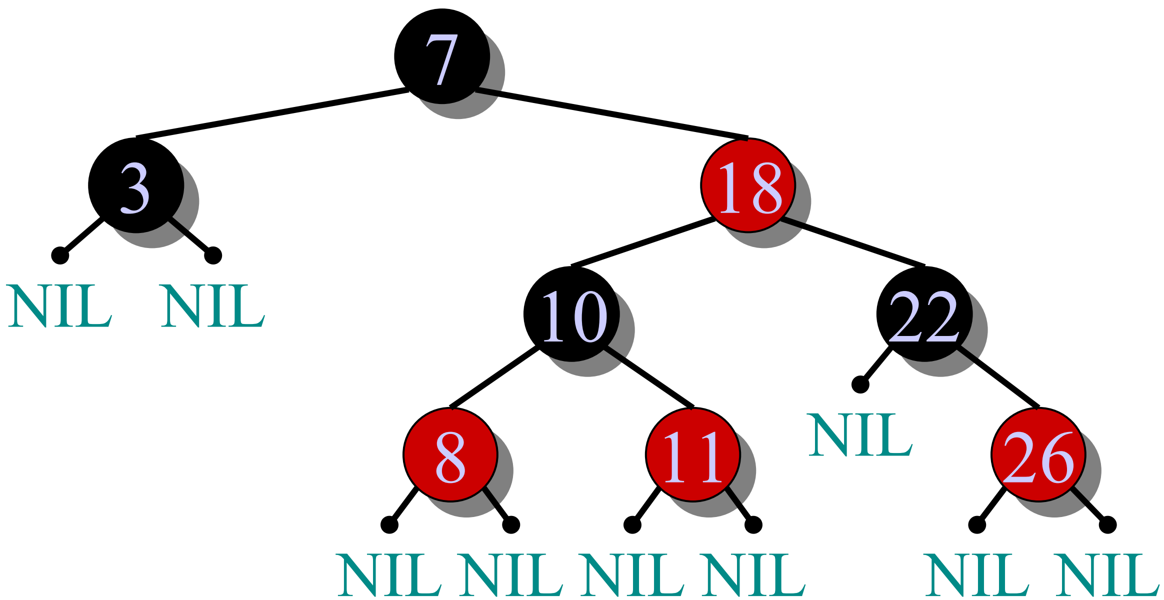
- We have $h' \geq h/2$, since at most half the leaves on any path are red.
- The number of leaves in each tree is $n + 1$
  $\Rightarrow n + 1 \geq 2^{h'}$
  $\Rightarrow \log(n + 1) \geq h' \geq h/2$
  $\Rightarrow h \leq 2 \log(n + 1)$. ∎

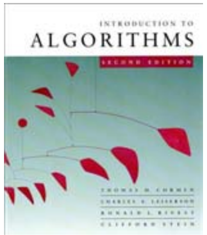




Query operations

Corollary. The queries SEARCH, MIN, MAX, SUCCESSOR, and PREDECESSOR all run in $O(\log n)$ time on a red-black tree with n nodes.

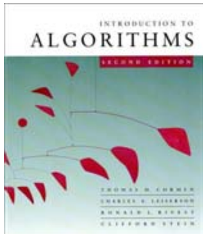




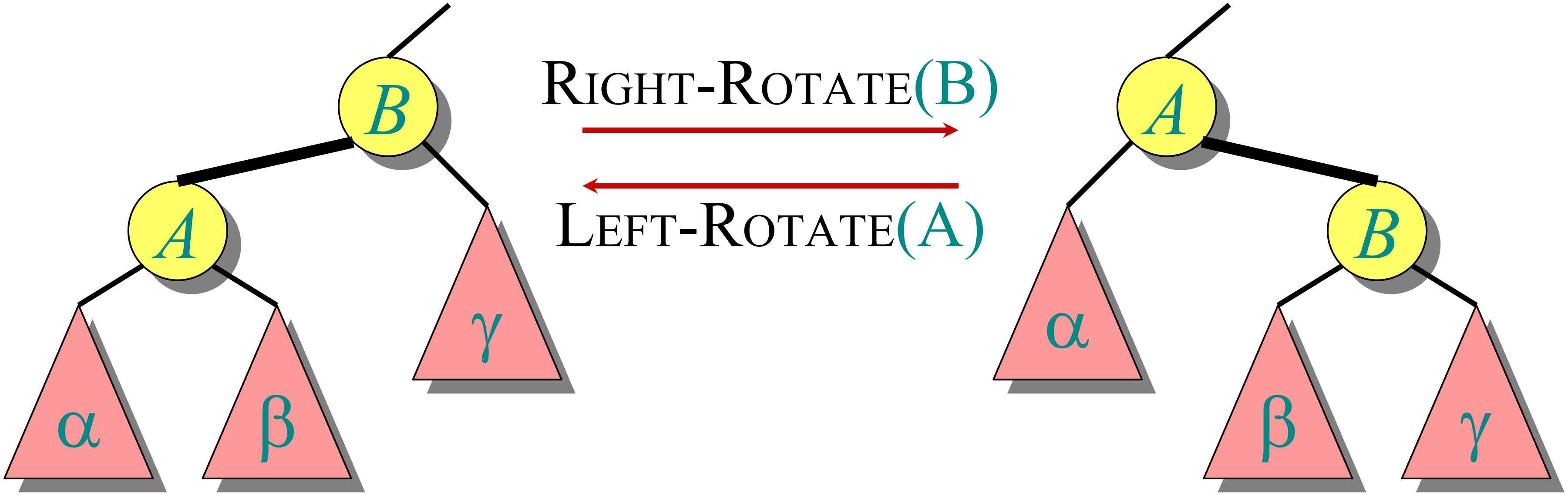
Modifying operations

The operations INSERT and DELETE cause modifications to the red-black tree:

1. the operation itself,
2. color changes,
3. restructuring the links of the tree via ***“rotations”***.

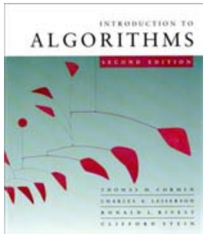


Rotations



- Rotations maintain the inorder ordering of keys:

  $a \in \alpha, b \in \beta, c \in \gamma \;\Rightarrow\; a \le A \le b \le B \le c.$
- Rotations maintain the binary search tree property
- A rotation can be performed in $O(1)$ time.



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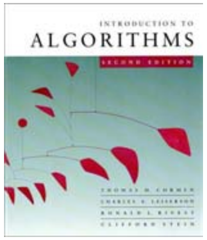
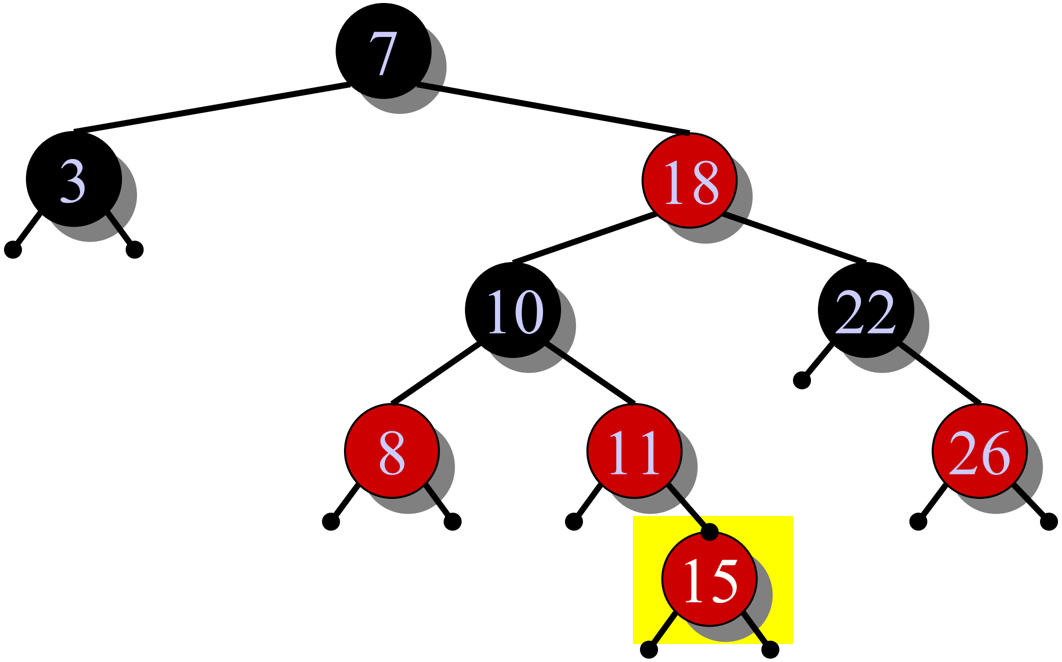


Insertion into a red-black tree

IDEA: Insert x in tree. Color x red. Only red-black property 4 might be violated. Move the violation up the tree by recoloring until it can be fixed with rotations and recoloring.

Example:

- Insert x =15.



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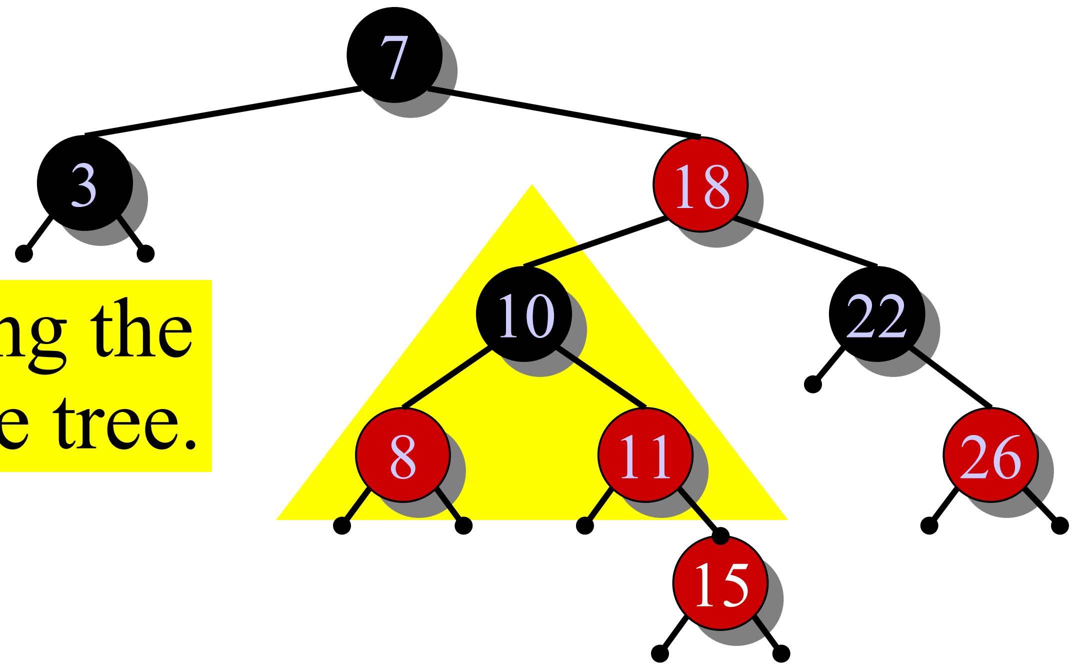

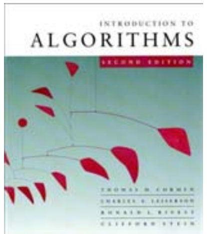

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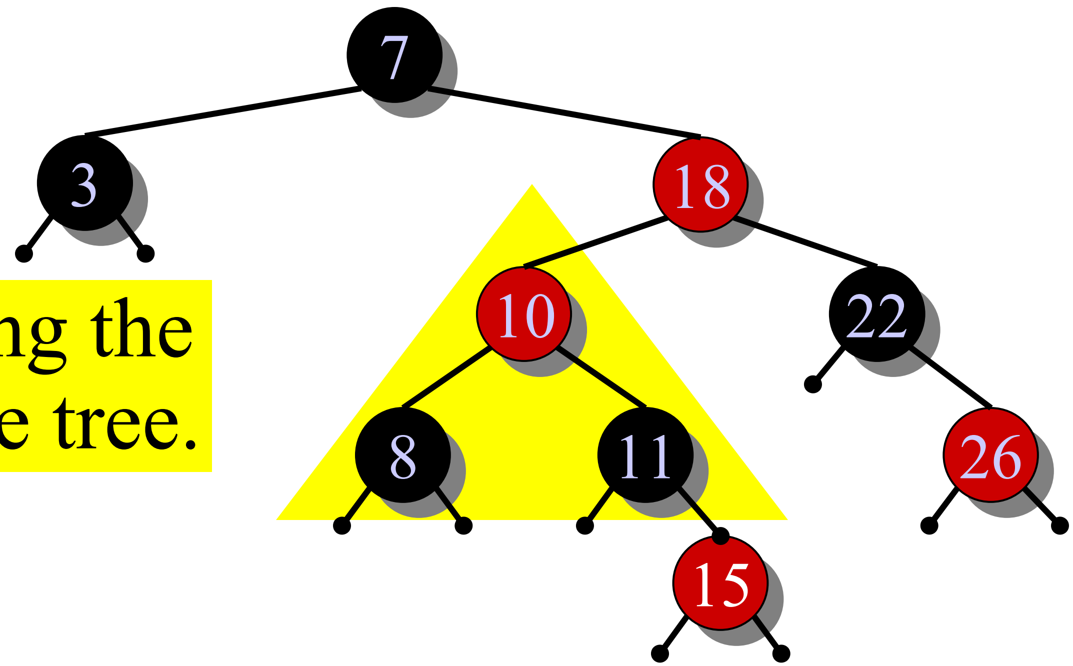

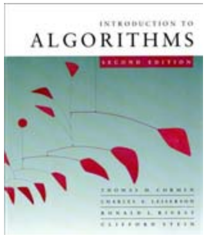

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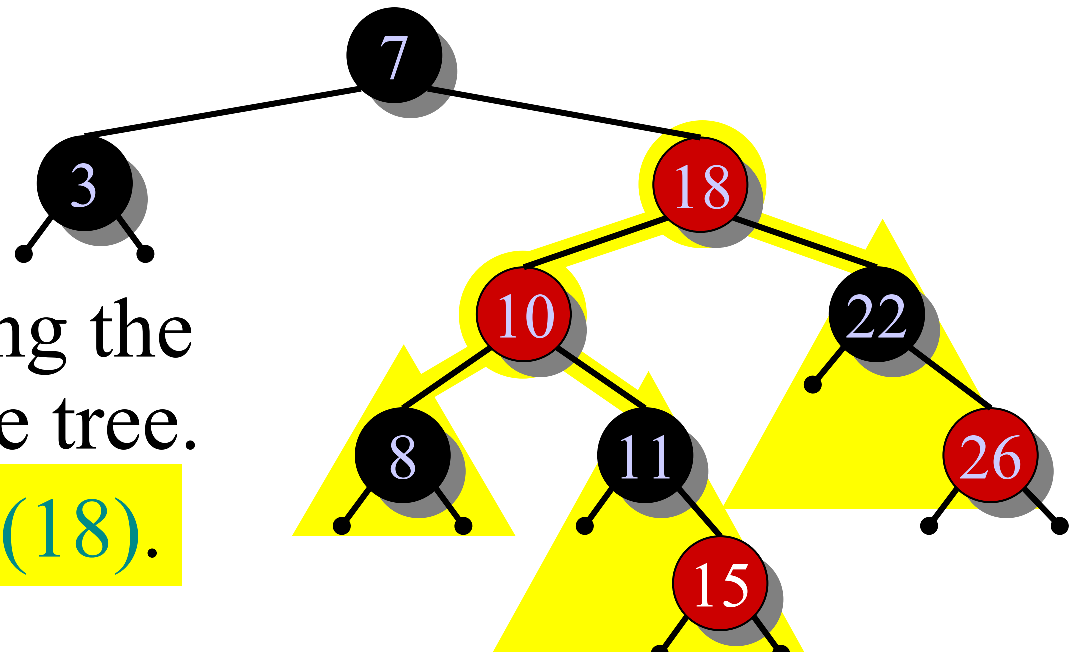
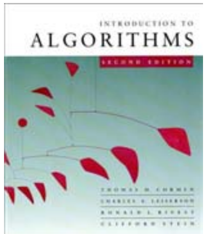
- RIGHT-ROTATE(18).





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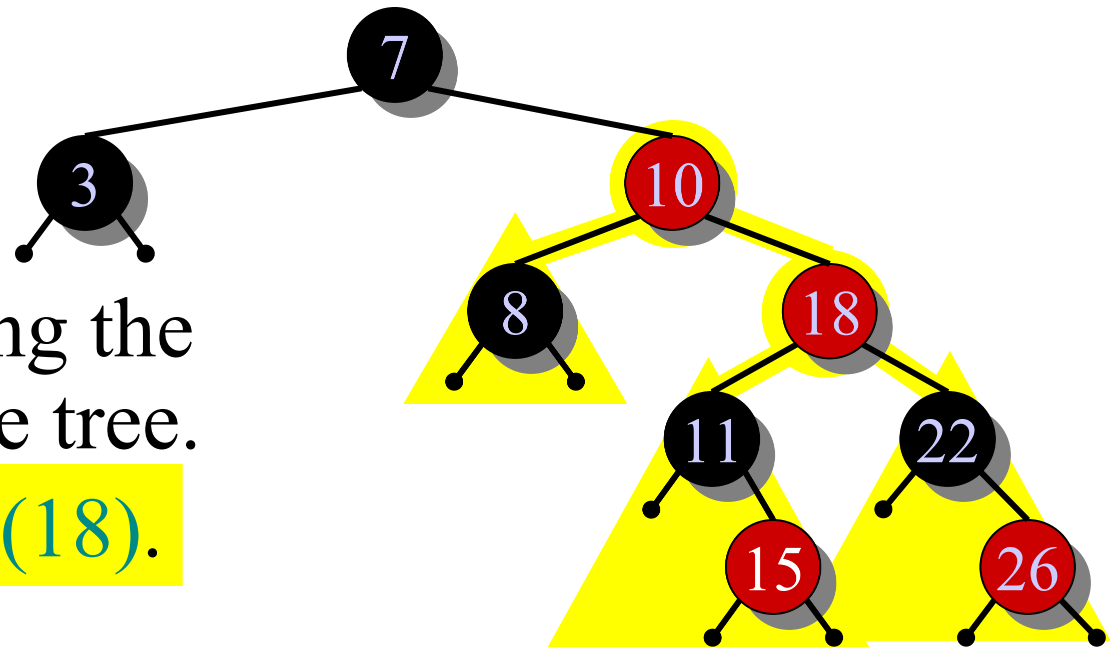

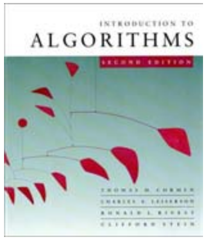

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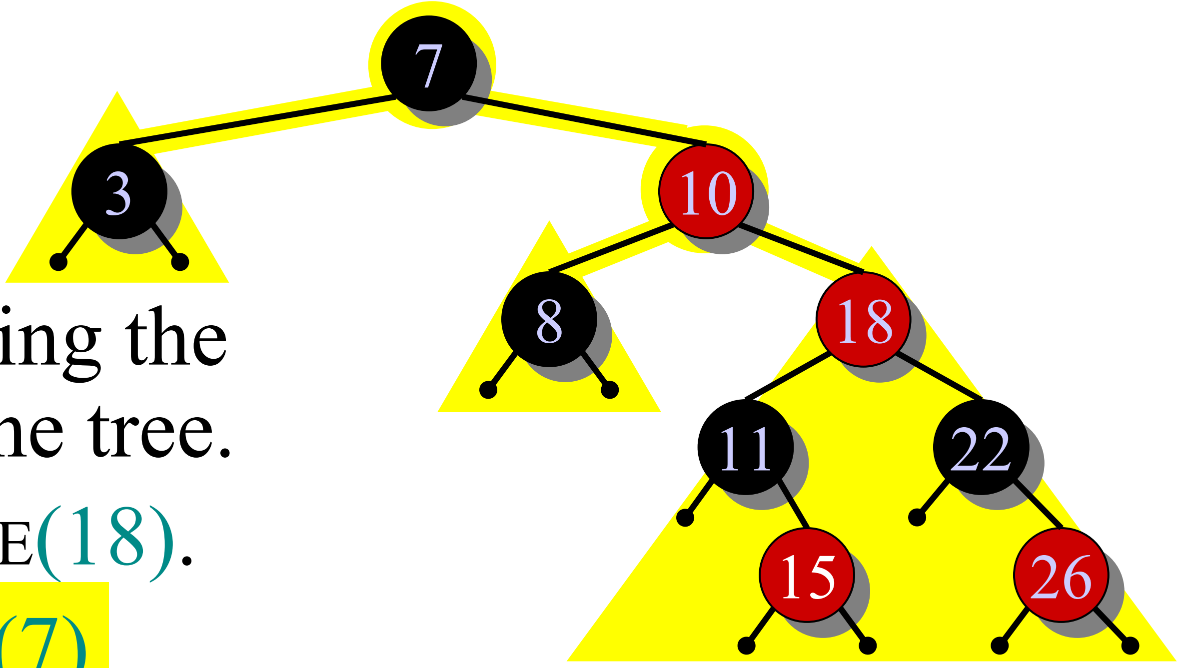

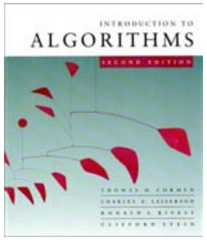

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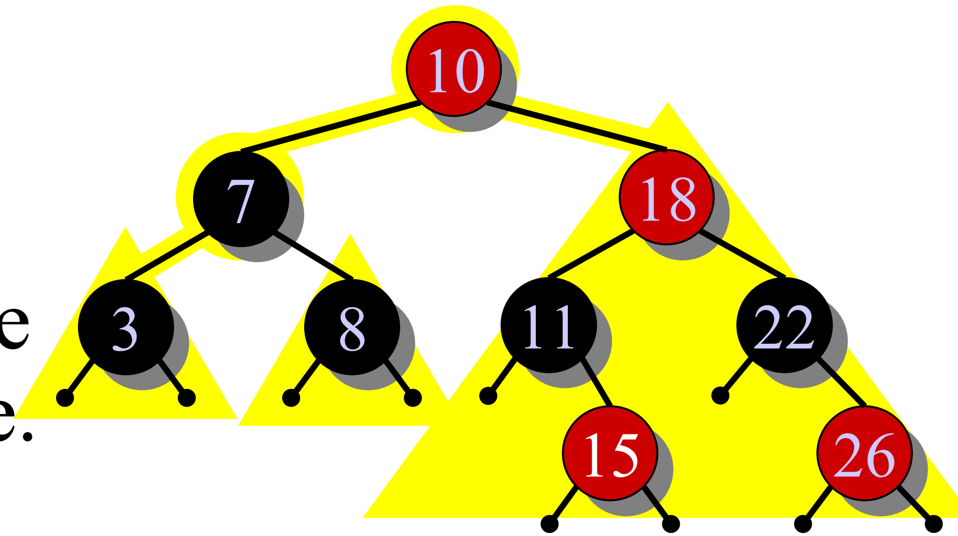

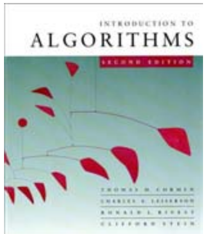

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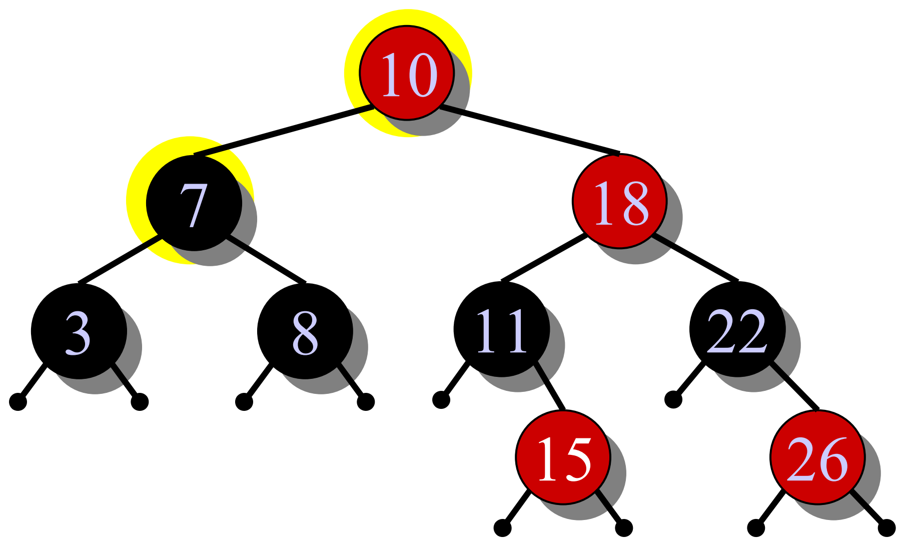

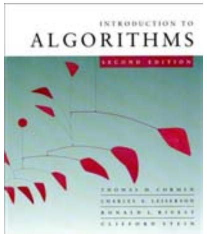

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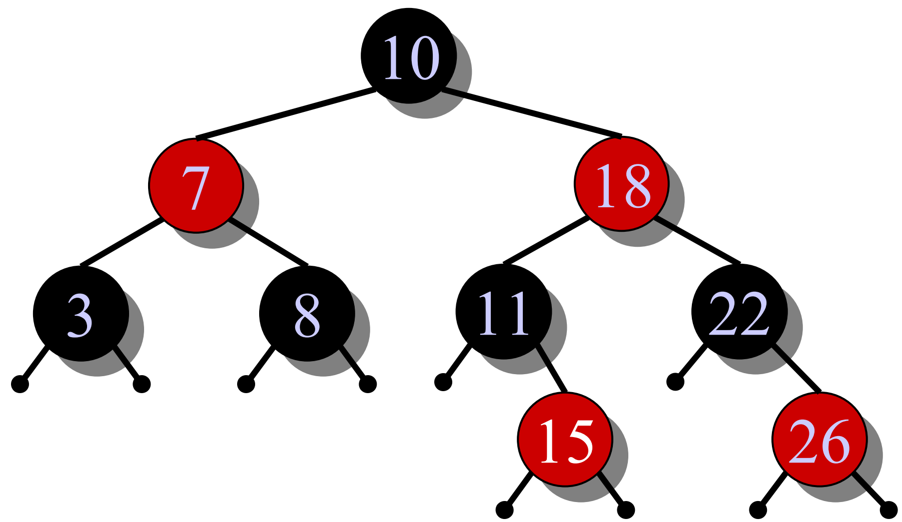
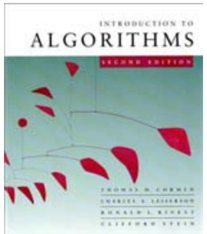
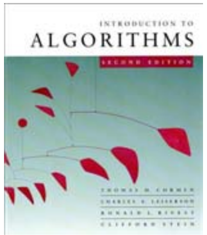
- LEFT-ROTATE(7) and recolor.



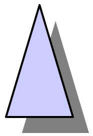


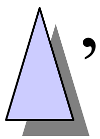
Pseudocode

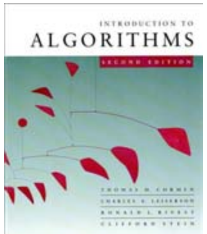
```
RB-INSERT(T, x)
    TREE-INSERT(T, x)
    color[x] ← RED      ▷ only RB property 4 can be violated
    while x ≠ root[T] and color[p[x]] = RED
        do if p[x] = left[p[p[x]]
            then y ← right[p[p[x]]          ▷ y = aunt/uncle of x
                 if color[y] = RED
                  then 〈Case 1〉
                  else  if x = right[p[x]]
                          then 〈Case 2〉   ▷ Case 2 falls into Case 3
                        〈Case 3〉
            else 〈"then" clause with "left" and "right" swapped〉
    color[root[T]] ← BLACK
```



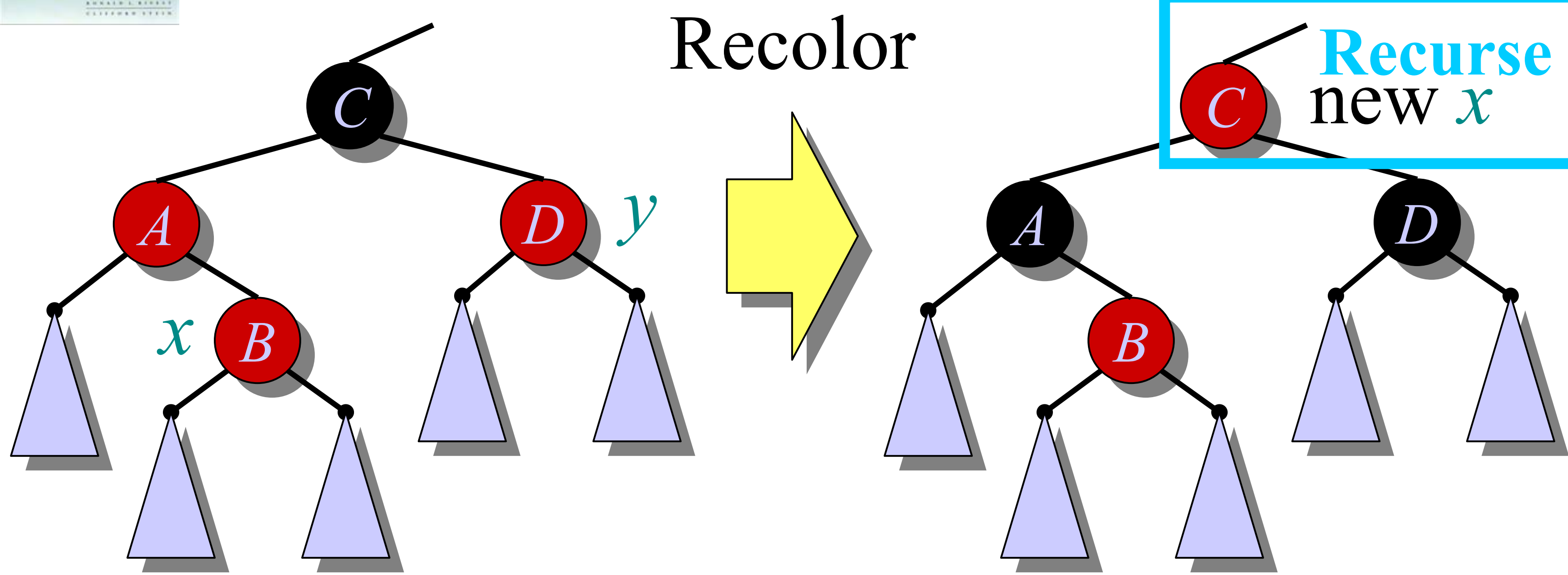
Graphical notation

Let  denote a subtree with a black root.

All ’s have the same black-height.



Case 1



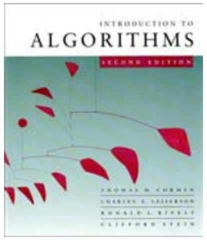
(Or, *A*'s children are swapped.)

$p[x] = left[p[p[x]]$

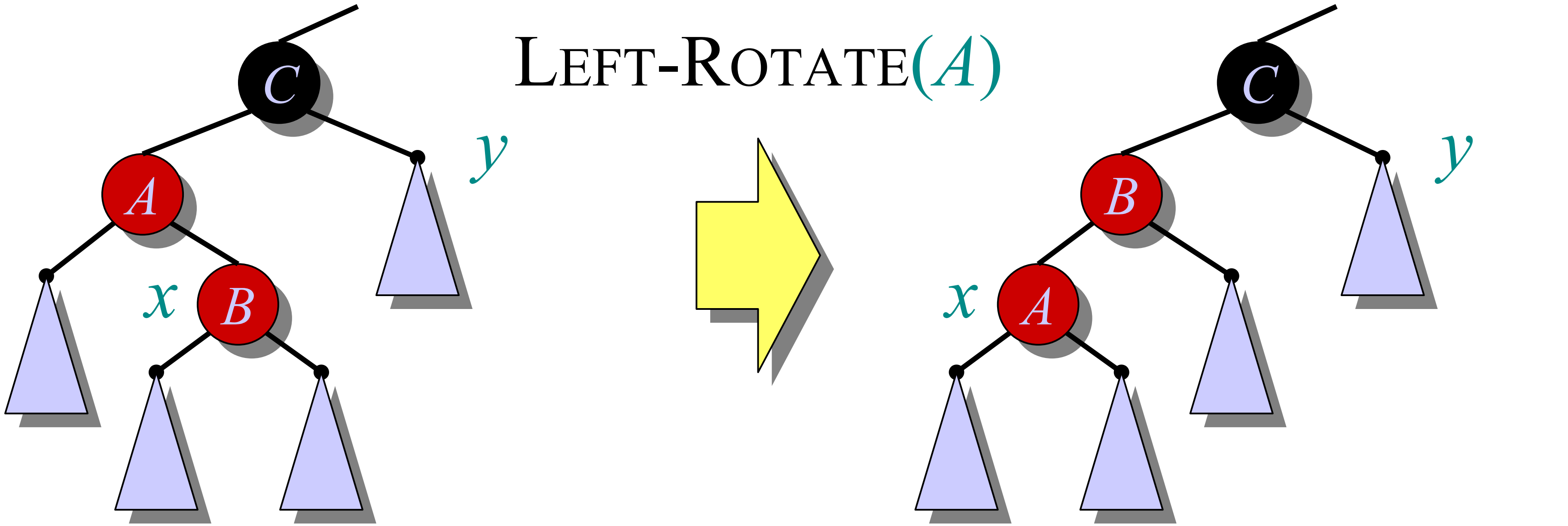
$y = right[p[p[x]]$

$color[y] = \text{RED}$

Push *C*'s black onto *A* and *D*, and recurse, since *C*'s parent may be red.



Case 2



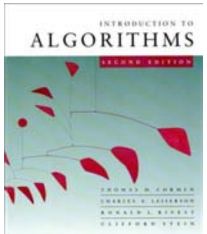
$p[x] = left[p[p[x]]$

$y = right[p[p[x]]$

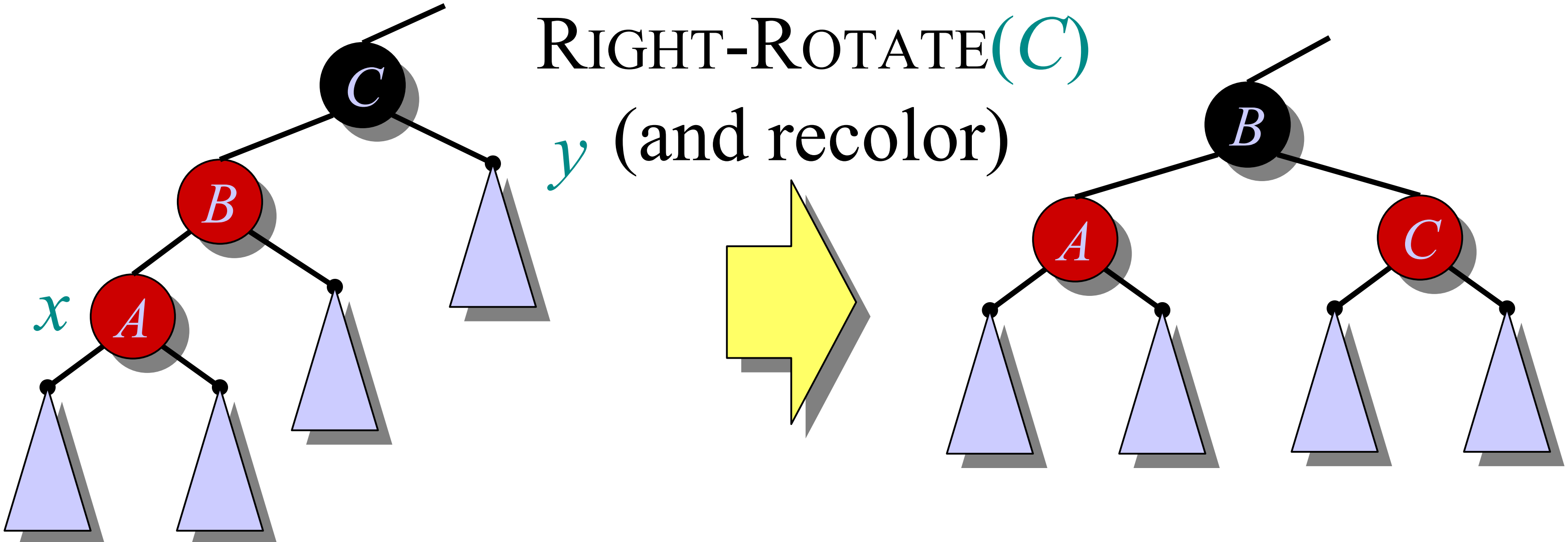
$color[y] = \text{BLACK}$

$x = right[p[x]]$

Transform to Case 3.



Case 3



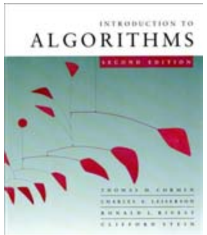
Done! No more violations of RB property 4 are possible.

$p[x] = left[p[p[x]]$

$y = right[p[p[x]]$

$color[y] = \text{BLACK}$

$x = left[p[x]]$

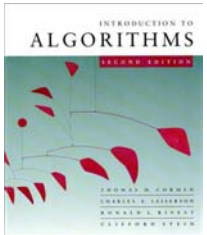


Analysis

- Go up the tree performing Case 1, which only recolors nodes.
- If Case 2 or Case 3 occurs, perform 1 or 2 rotations, and terminate.

Running time: $O(\log n)$ with $O(1)$ rotations.

RB-DELETE — same asymptotic running time and number of rotations as RB-INSERT (see textbook).



Pseudocode (part II)

else ⟨**"then"** clause with "*left*" and "*right*" swapped⟩

▷ $p[x] = right[p[p[x]]$

then $y \leftarrow left[p[p[x]]$ ▷ y = aunt/uncle of x

if $color[y] = \text{RED}$

then ⟨**Case 1'**⟩

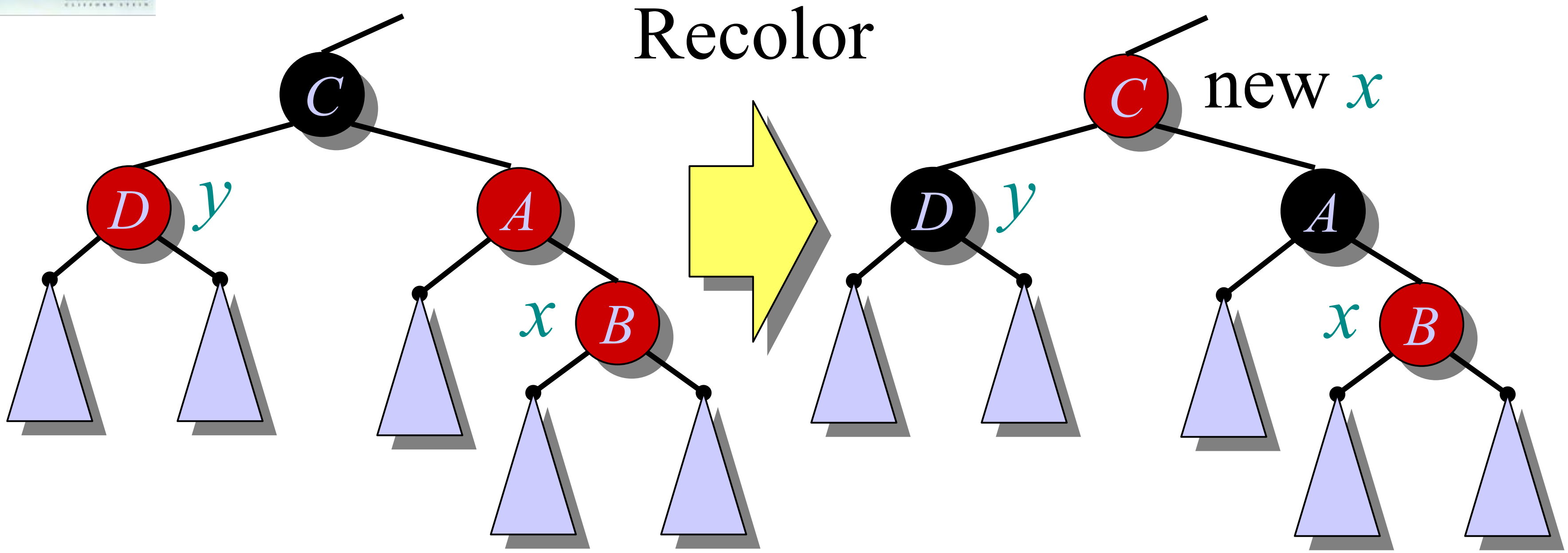
else if $x = left[p[x]]$

then ⟨**Case 2'**⟩ ▷ Case 2' falls into Case 3'

⟨**Case 3'**⟩

$color[root[T]] \leftarrow \text{BLACK}$

Case 1’



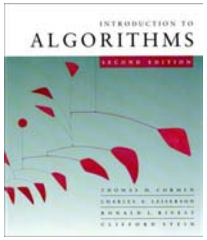
(Or, *A*’s children are swapped.)

$p[x] = right[p[p[x]]]$

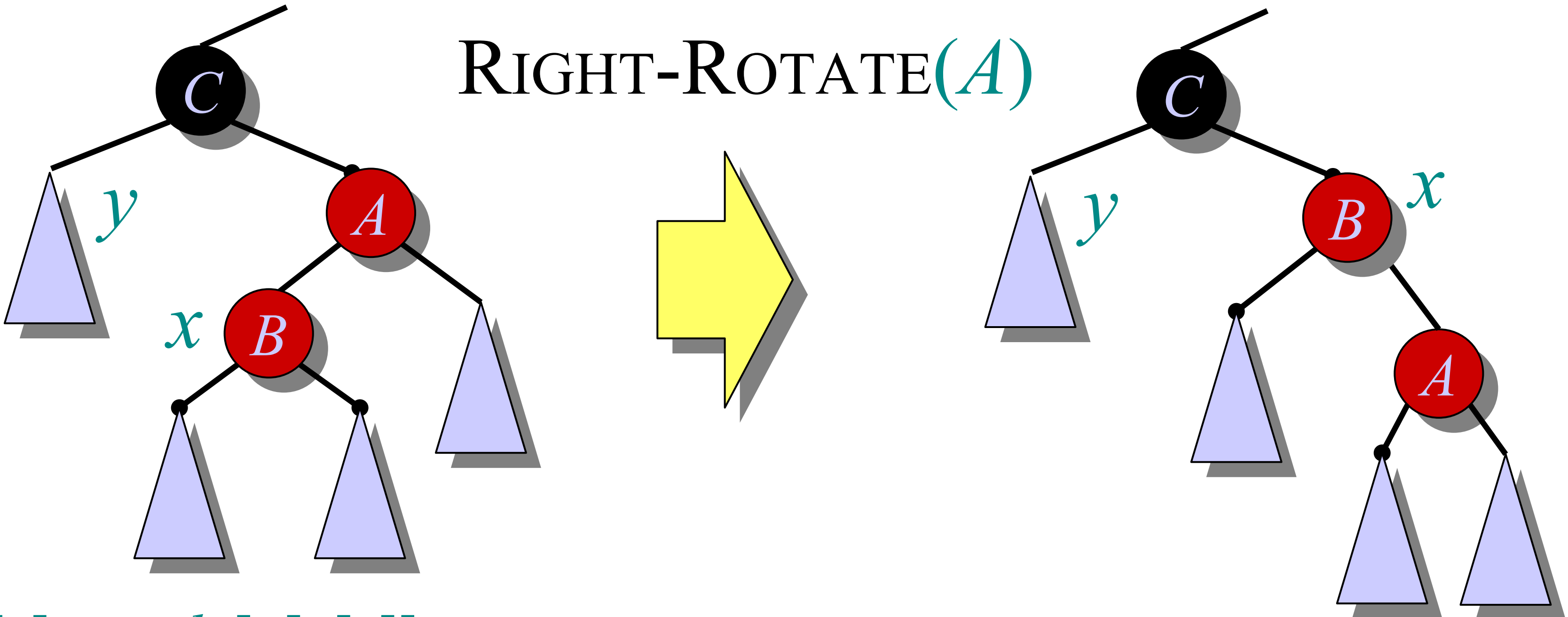
$y = left[p[p[x]]]$

$color[y] = \text{RED}$

Push *C*’s black onto *A* and *D*, and recurse, since *C*’s parent may be red.



Case 2’



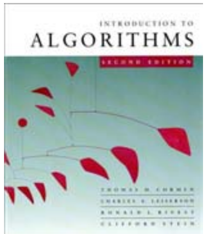
$p[x] = right[p[p[x]]$

$y = left[p[p[x]]$

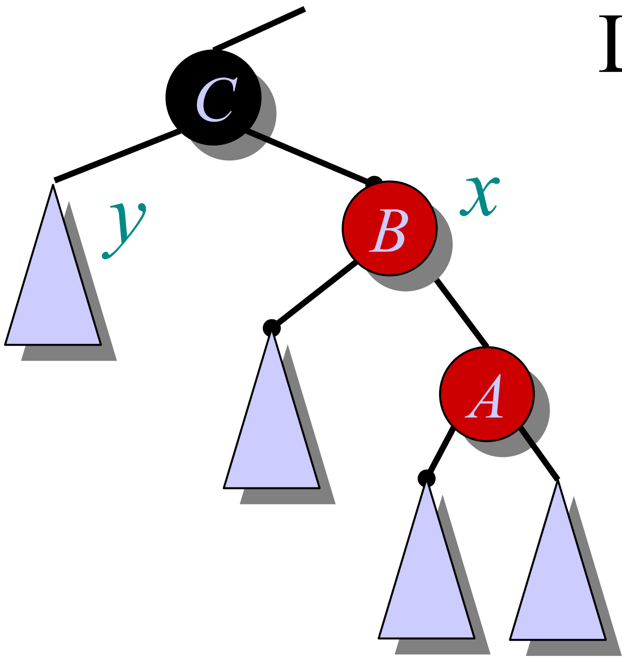
$color[y] =$ BLACK

$x = left[p[x]]$

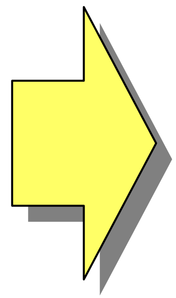
Transform to Case 3’.

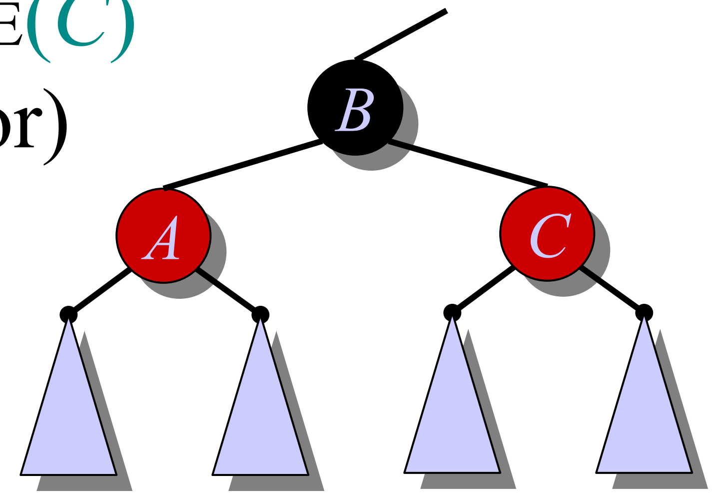


Case 3’



LEFT-ROTATE(C)
(and recolor)





$p[x] = right[p[p[x]]$

$y = left[p[p[x]]$

$color[y] = \text{BLACK}$

$x = right[p[x]]$

Done! No more violations of RB property 4 are possible.