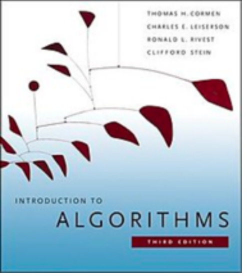

Introduction to Algorithms
11. Augmenting Data Structures

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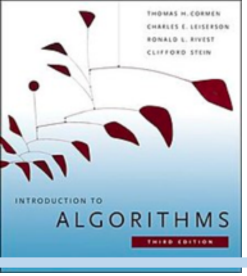


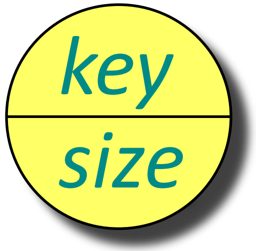
Dynamic order statistics

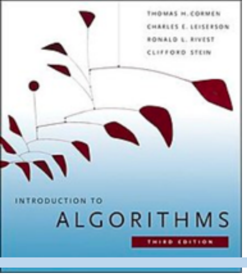
OS-SELECT(i, S): returns the ith smallest element in the dynamic set S.

OS-RANK(x, S): returns the rank of $x \in S$ in the sorted order of S's elements.

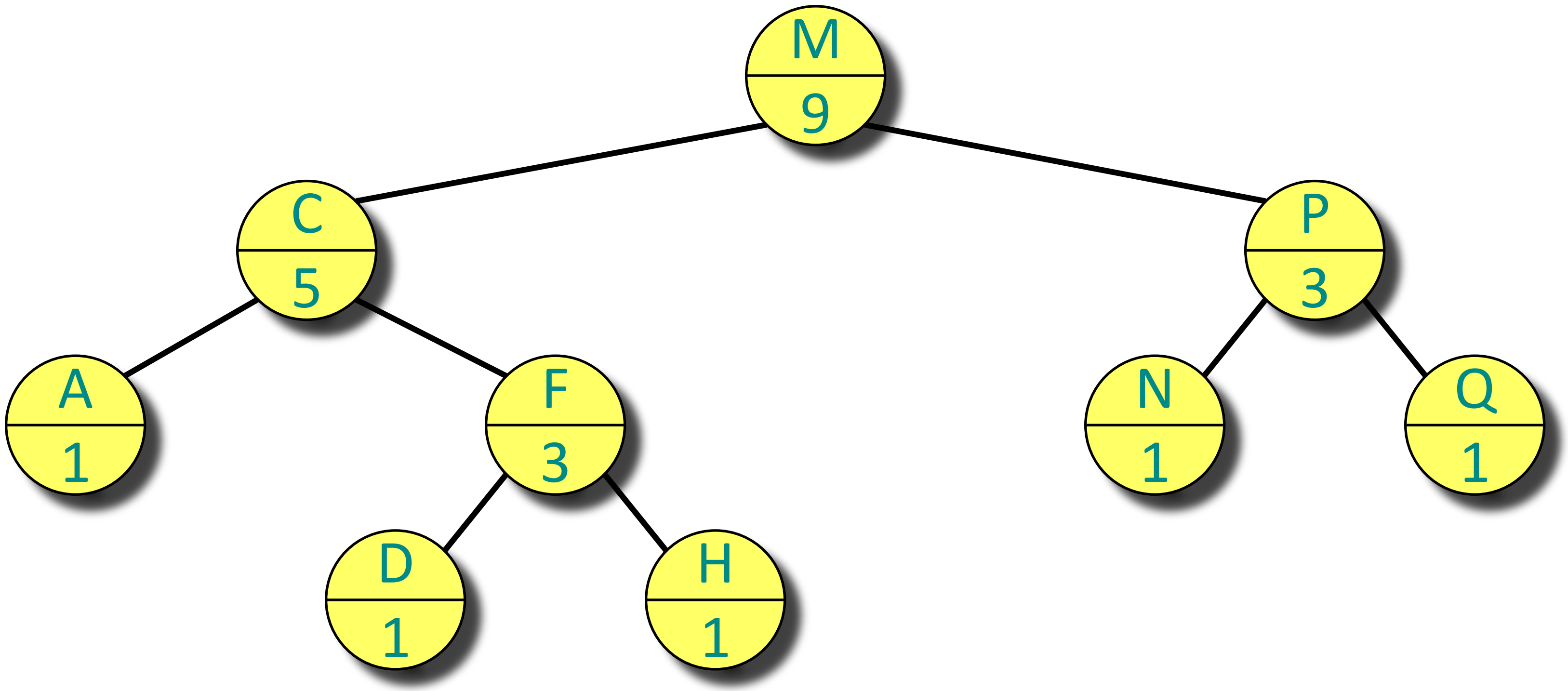
IDEA: Use a red-black tree for the set S, but keep subtree sizes in the nodes.

Notation for nodes:

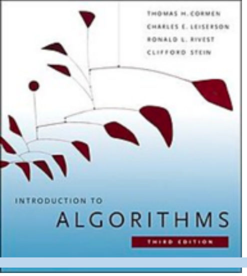




Example of an OS-tree



$$size[x] = size[left[x]] + size[right[x]] + 1$$



Selection

Implementation trick: Use a ***sentinel*** (dummy record) for NIL such that *size*[NIL] = 0.

OS-SELECT(x, i) ⊳ ith smallest element in the subtree rooted at x

    $k \leftarrow size[left[x]] + 1$ ⊳ k = rank(x)

    if $i = k$ **then return** x

    if $i < k$

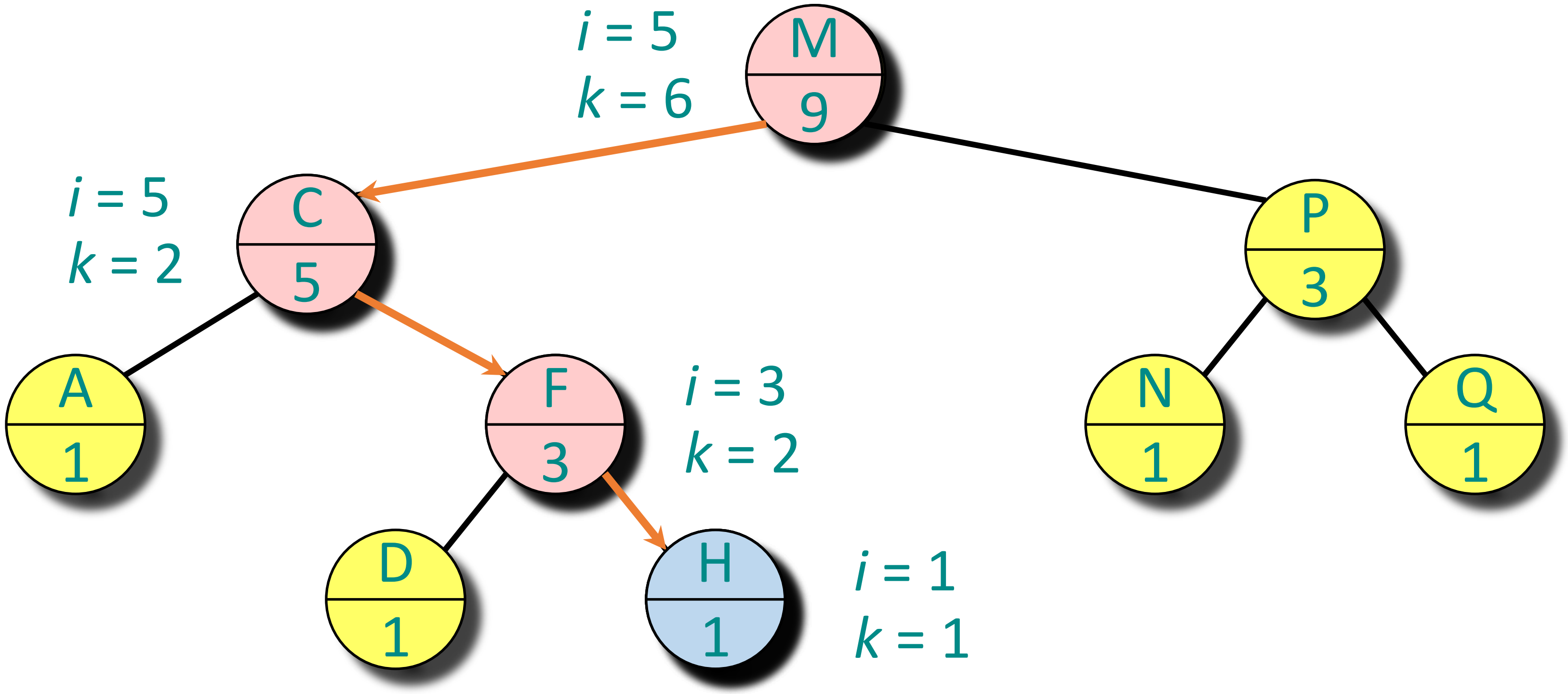
        then return OS-SELECT($left[x]$, i)

        else return OS-SELECT($right[x]$, $i - k$)

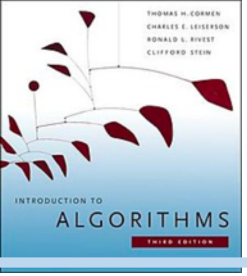
(OS-RANK is in the textbook.)

Example

OS-SELECT(*root*, 5)



Running time = $O(h) = O(\lg n)$ for red-black trees.



Data structure maintenance

Q. Why not keep the ranks themselves in the nodes instead of subtree sizes?

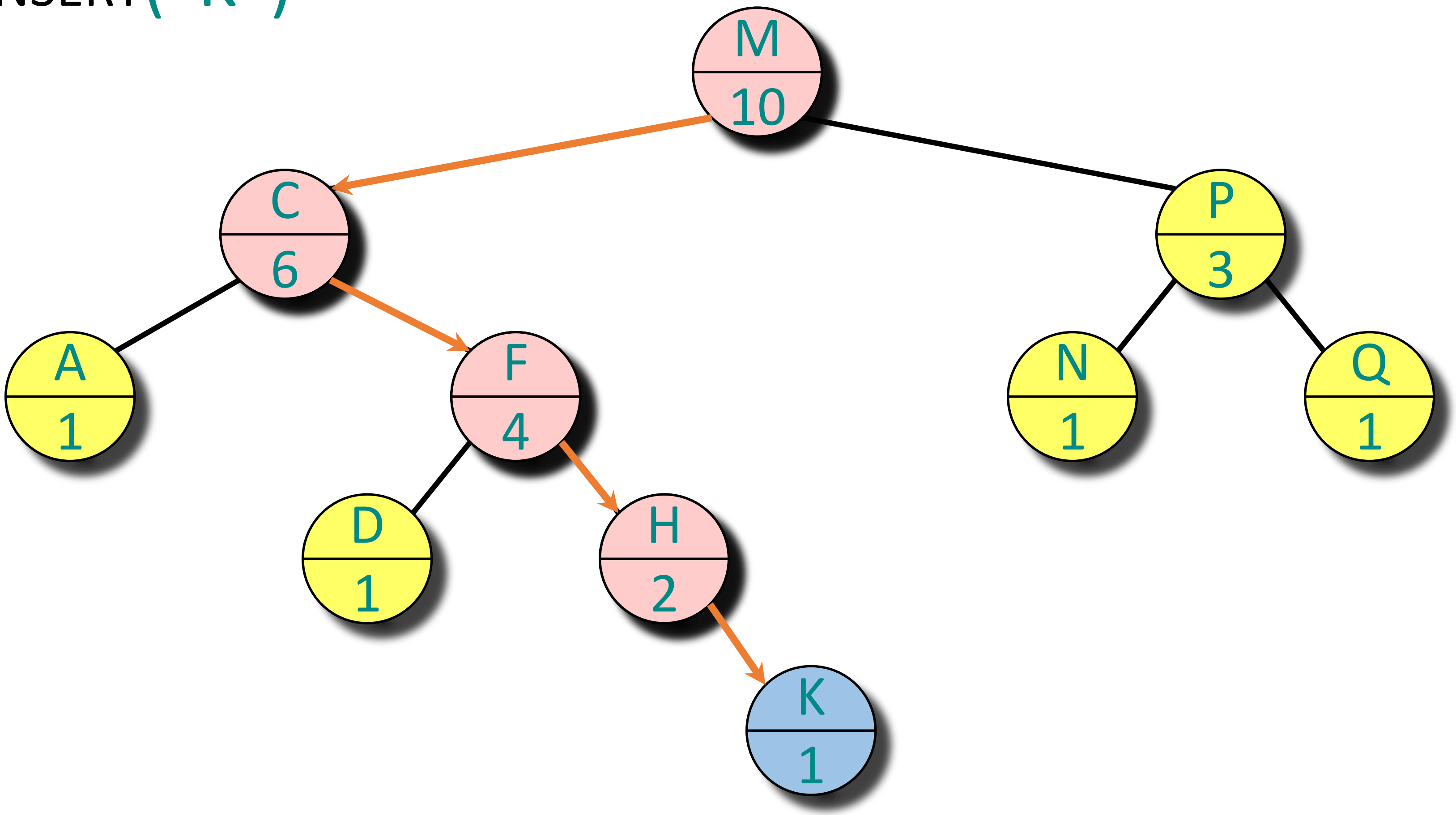
A. They are hard to maintain when the red-black tree is modified.

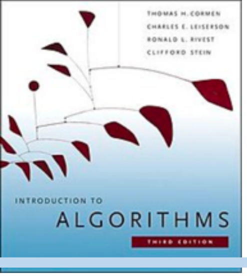
Modifying operations: INSERT and DELETE.

Strategy: Update subtree sizes when inserting or deleting.

Example of insertion

INSERT(“K”)



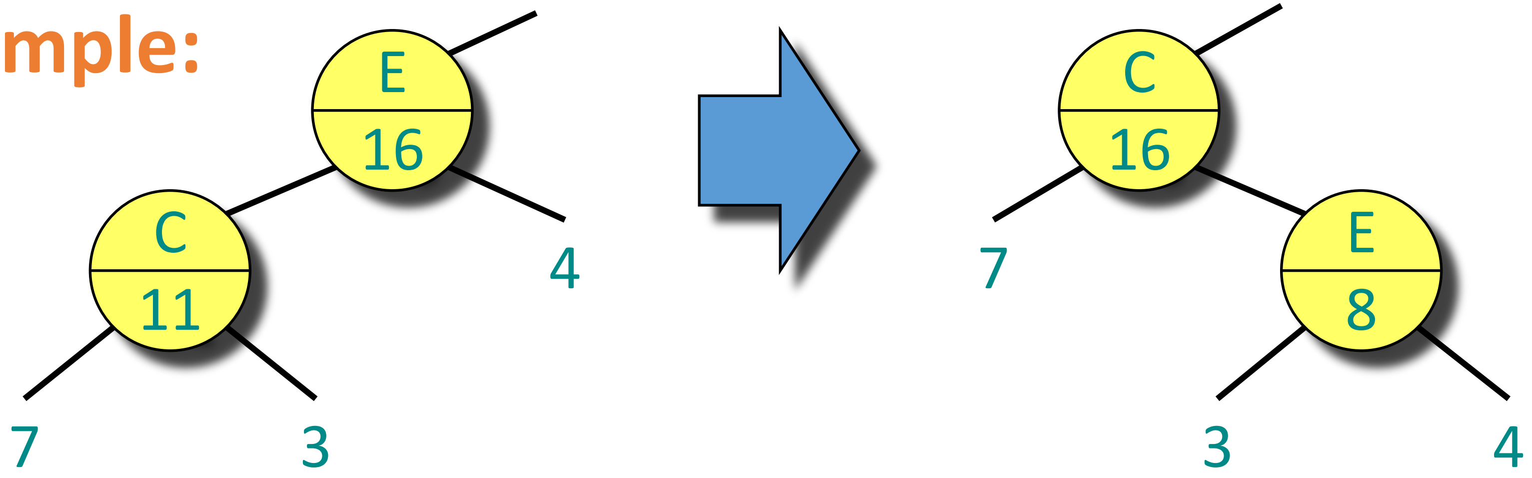


Handling rebalancing

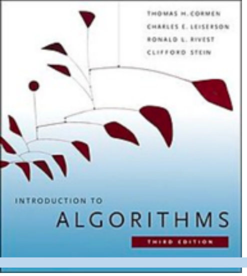
Don’t forget that RB-INSERT and RB-DELETE may also need to modify the red-black tree in order to maintain balance.

- *Recolorings*: no effect on subtree sizes.
- *Rotations*: fix up subtree sizes in $O(1)$ time.

Example:



$\therefore$ RB-INSERT and RB-DELETE still run in $O(\lg n)$ time.

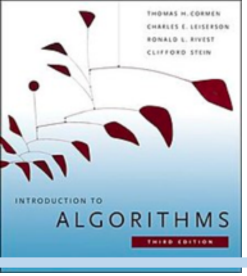


Data-structure augmentation

Methodology: (*e.g., order-statistics trees*)

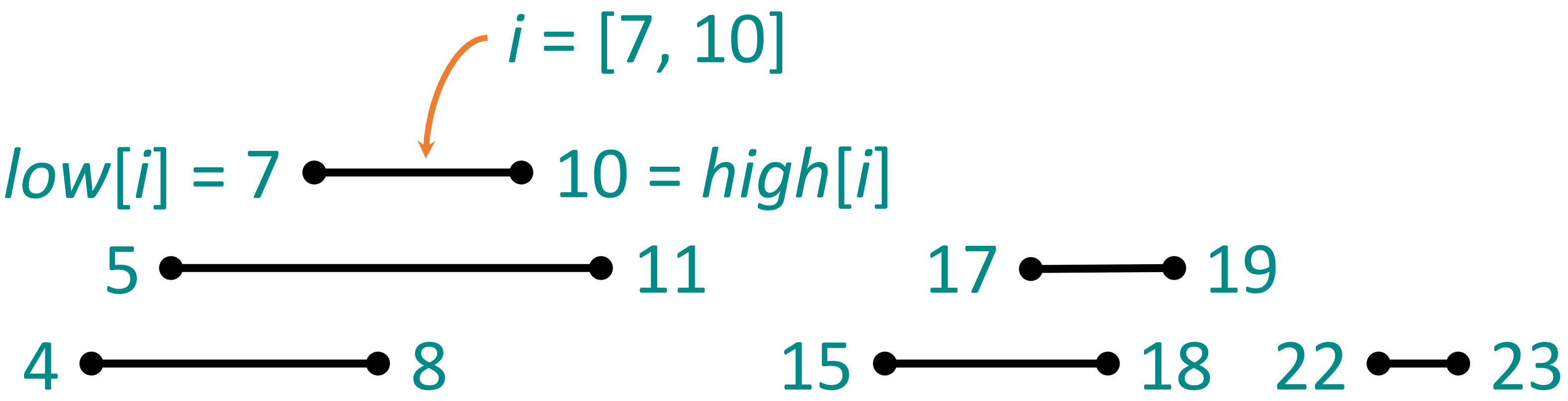
1. Choose an underlying data structure (*red-black trees*).
2. Determine additional information to be stored in the data structure (*subtree sizes*).
3. Verify that this information can be maintained for modifying operations (*RB-Insert, RB-Delete — don’t forget rotations*).
4. Develop new dynamic-set operations that use the information (*OS-Select and OS-Rank*).

These steps are guidelines, not rigid rules.

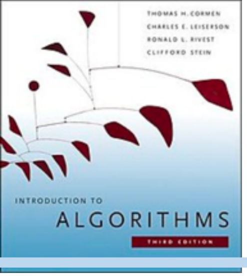


Interval trees

Goal: To maintain a dynamic set of intervals, such as time intervals.

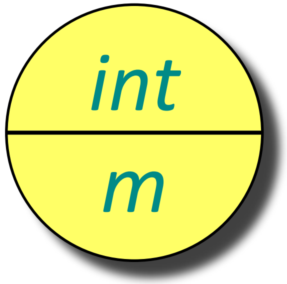


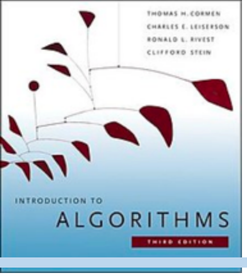
Query: For a given query interval *i*, find an interval in the set that overlaps *i*.



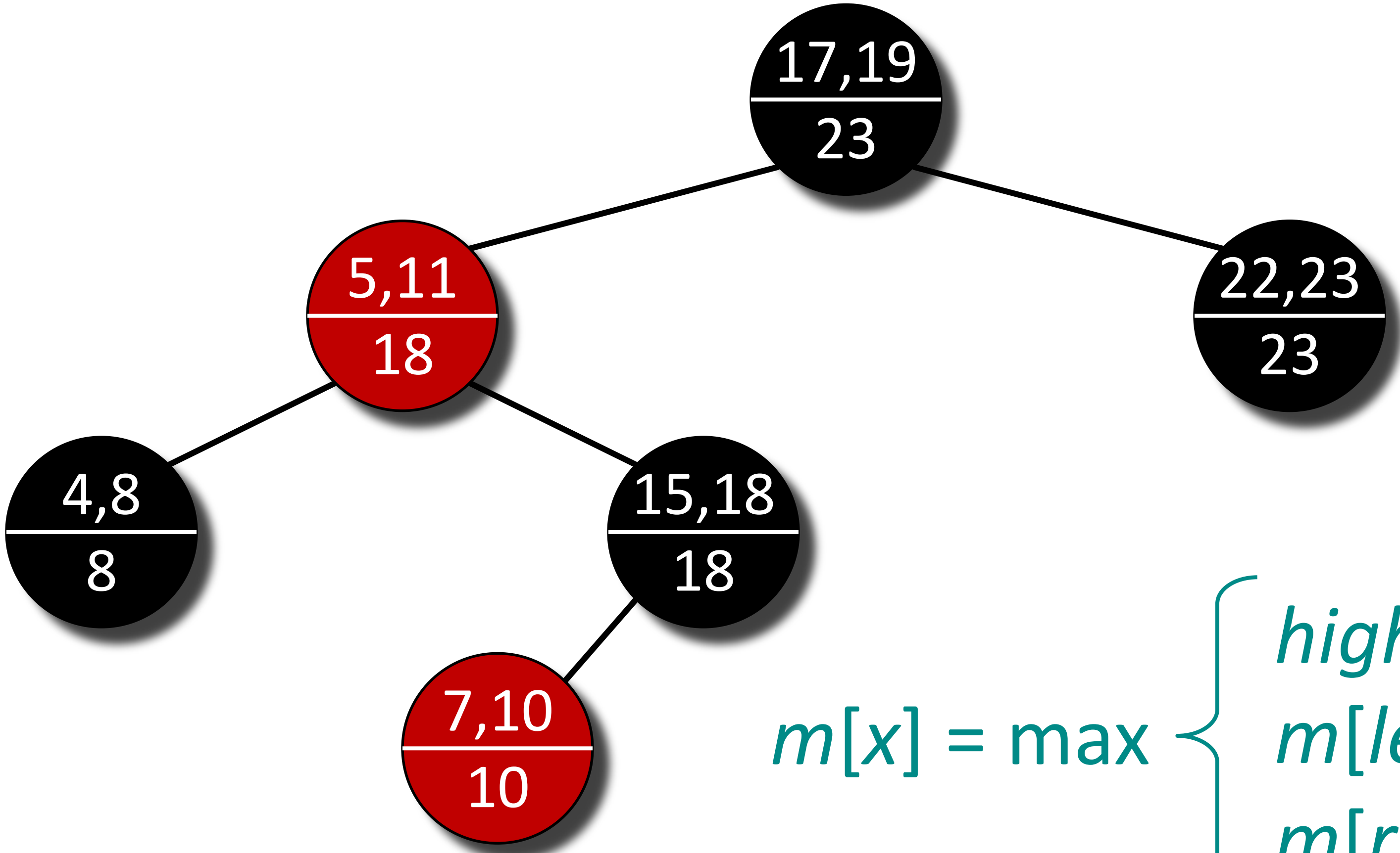
Following the methodology

1. *Choose an underlying data structure.*
   - Red-black tree keyed on low (left) endpoint.
2. *Determine additional information to be stored in the data structure.*
   - Store in each node *x* the largest value *m*[*x*] in the subtree rooted at *x*, as well as the interval *int*[*x*] corresponding to the key.





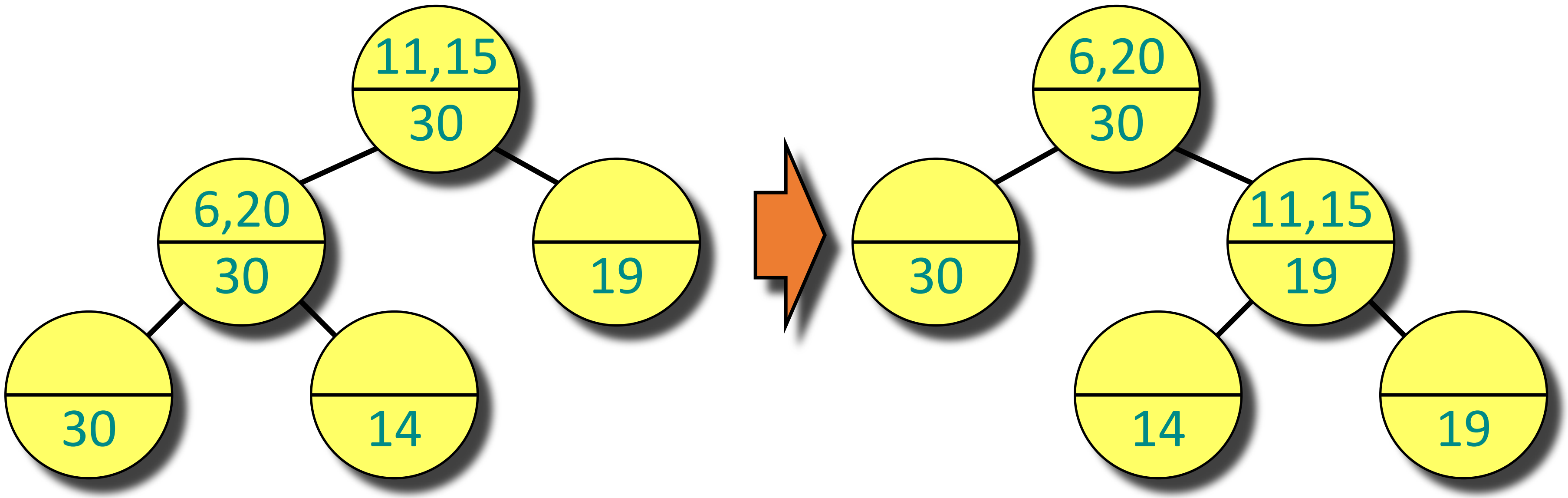
Example interval tree



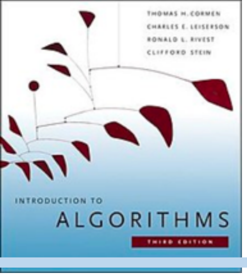
$$m[x] = \max \begin{cases} high[int[x]] \\ m[left[x]] \\ m[right[x]] \end{cases}$$

Modifying operations

3. *Verify that this information can be maintained for modifying operations.*
   - INSERT: Fix *m*'s on the way down.
   - Rotations — Fixup = $O(1)$ time per rotation:



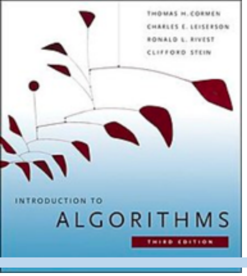
Total INSERT time = $O(\lg n)$; DELETE similar.



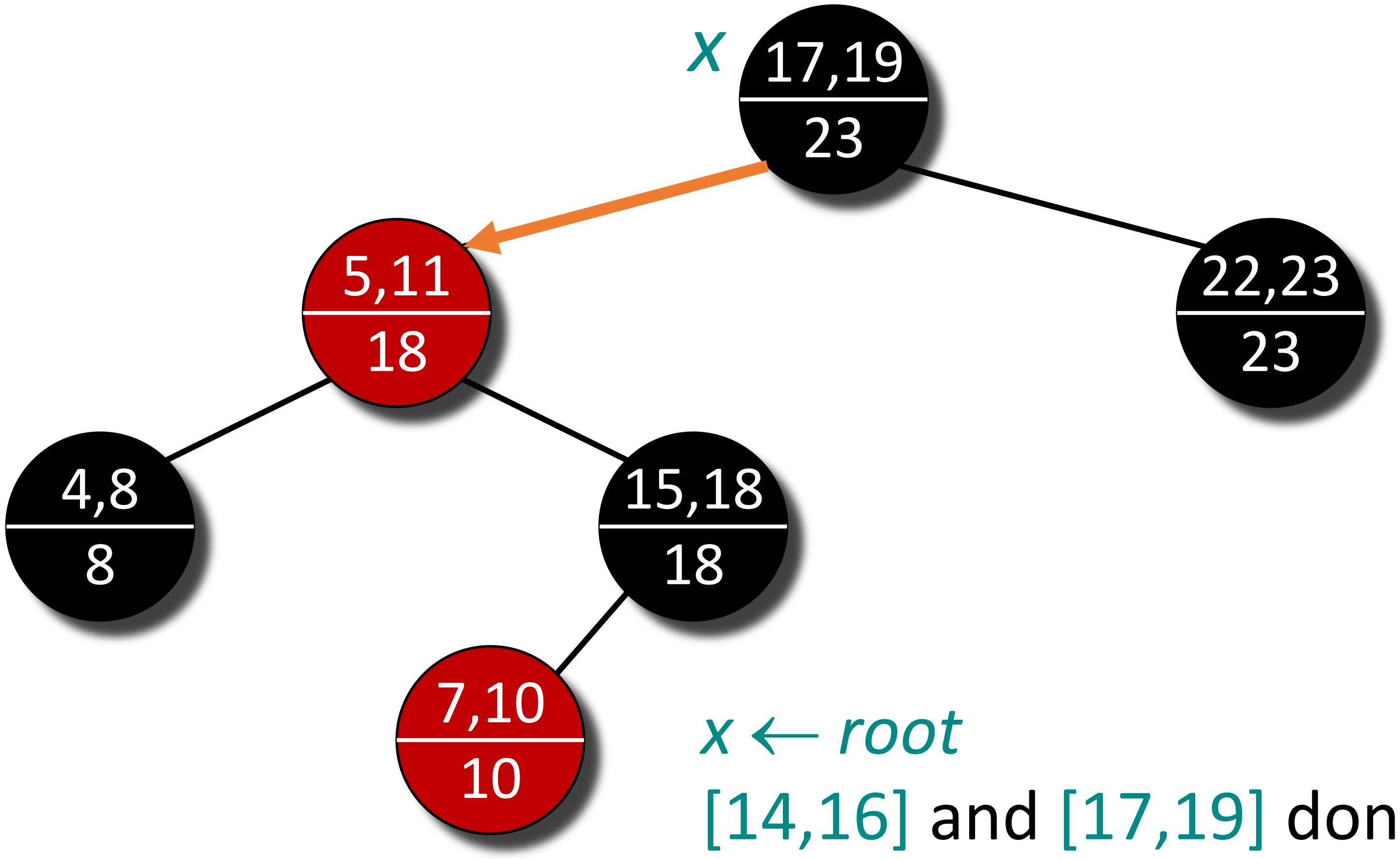
New operations

4. Develop new dynamic-set operations that use the information.

```
INTERVAL-SEARCH(i)
    x ← root
    while x ≠ NIL and (low[i] > high[int[x]]
                          or low[int[x]] > high[i])
        do ⊳ i and int[x] don't overlap
            if left[x] ≠ NIL and low[i] ≤ m[left[x]]
                then x ← left[x]
                else x ← right[x]
    return x
```



Example 1: INTERVAL-SEARCH([14,16])

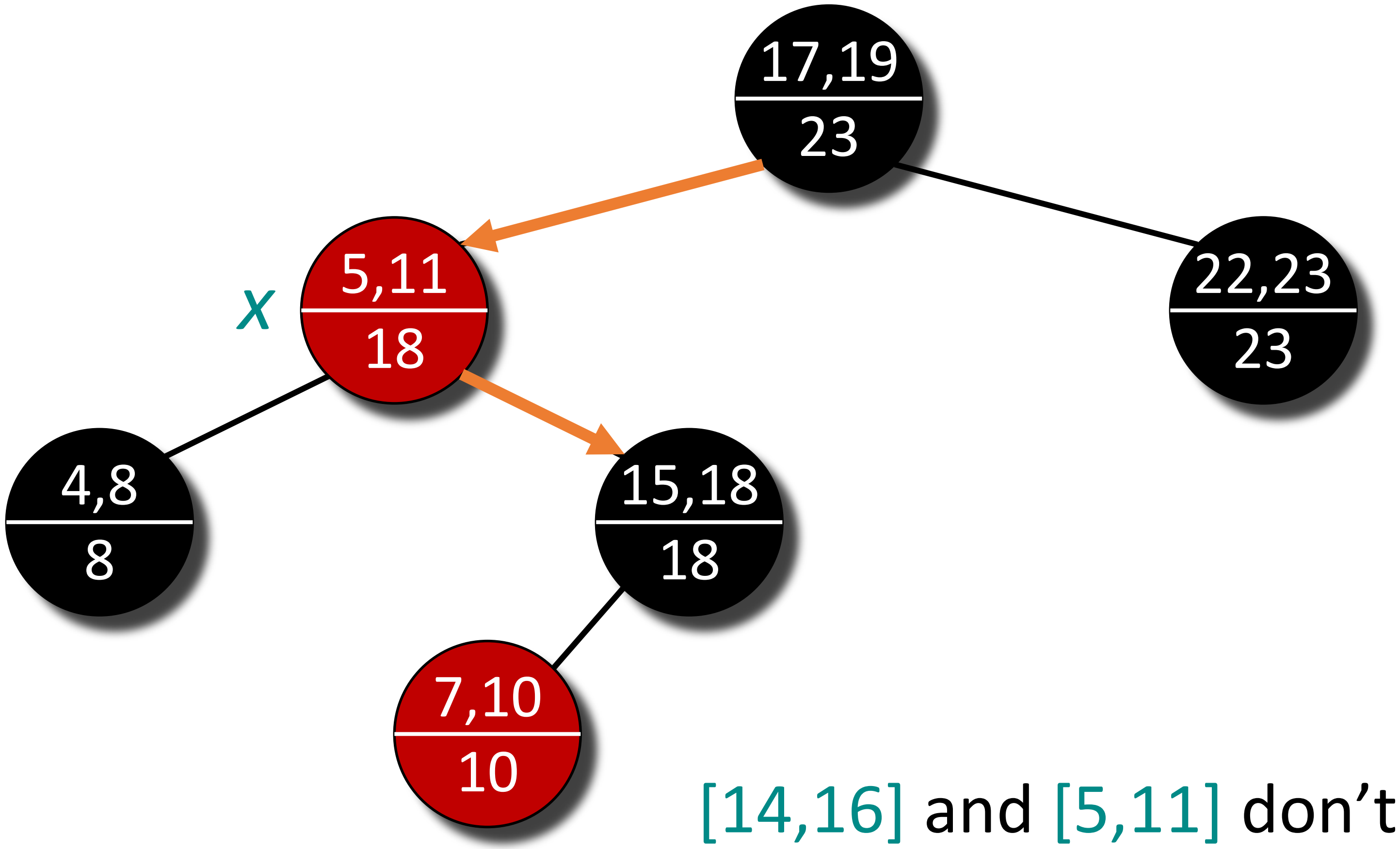


$x \leftarrow root$

[14,16] and [17,19] don't overlap

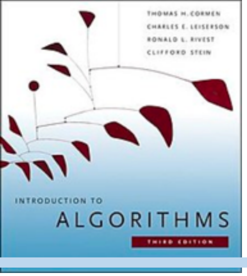
$14 \leq 18 \Rightarrow x \leftarrow left[x]$

Example 1: INTERVAL-SEARCH([14,16])



[14,16] and [5,11] don’t overlap

$14 > 8 \Rightarrow x \leftarrow right[x]$



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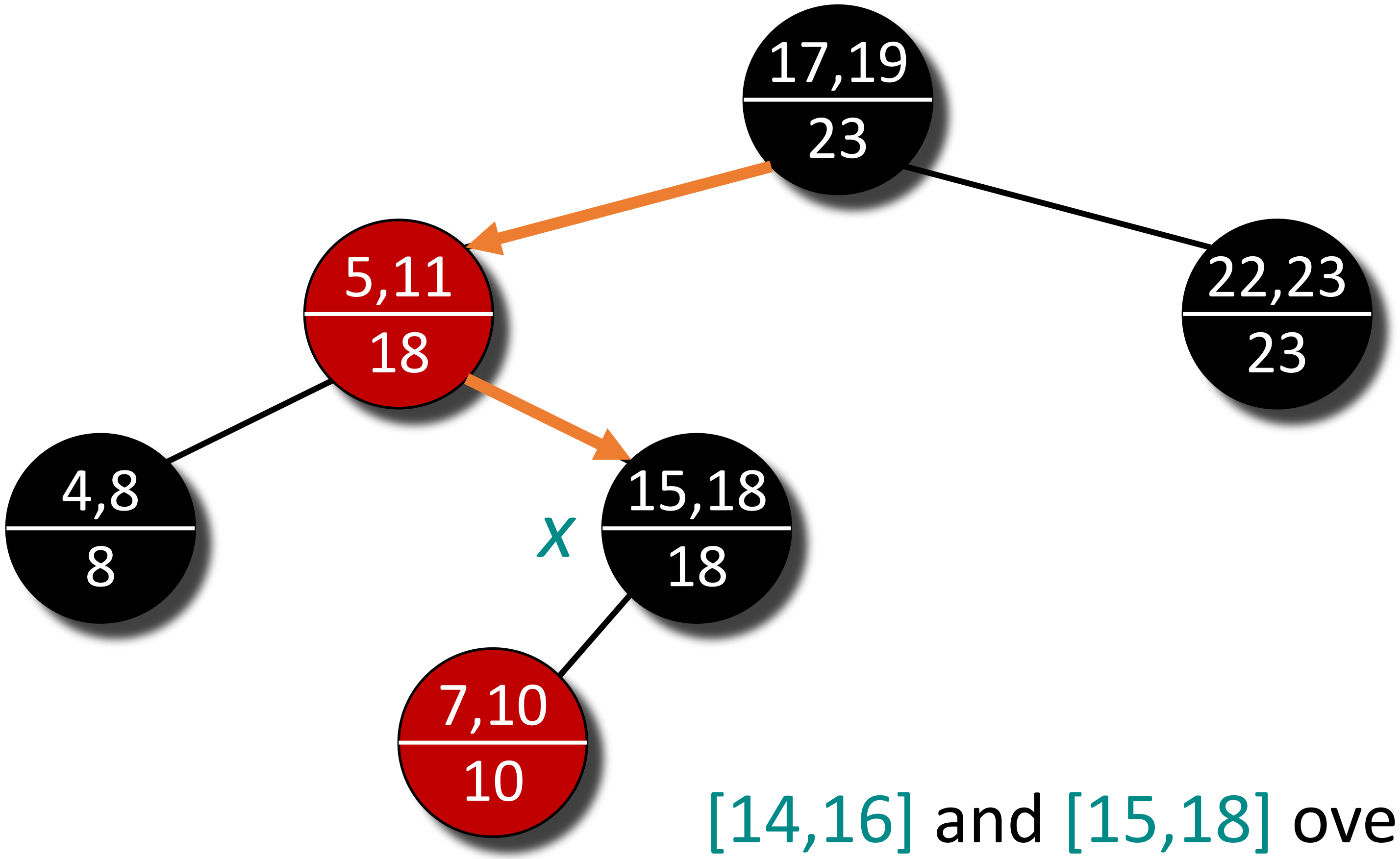
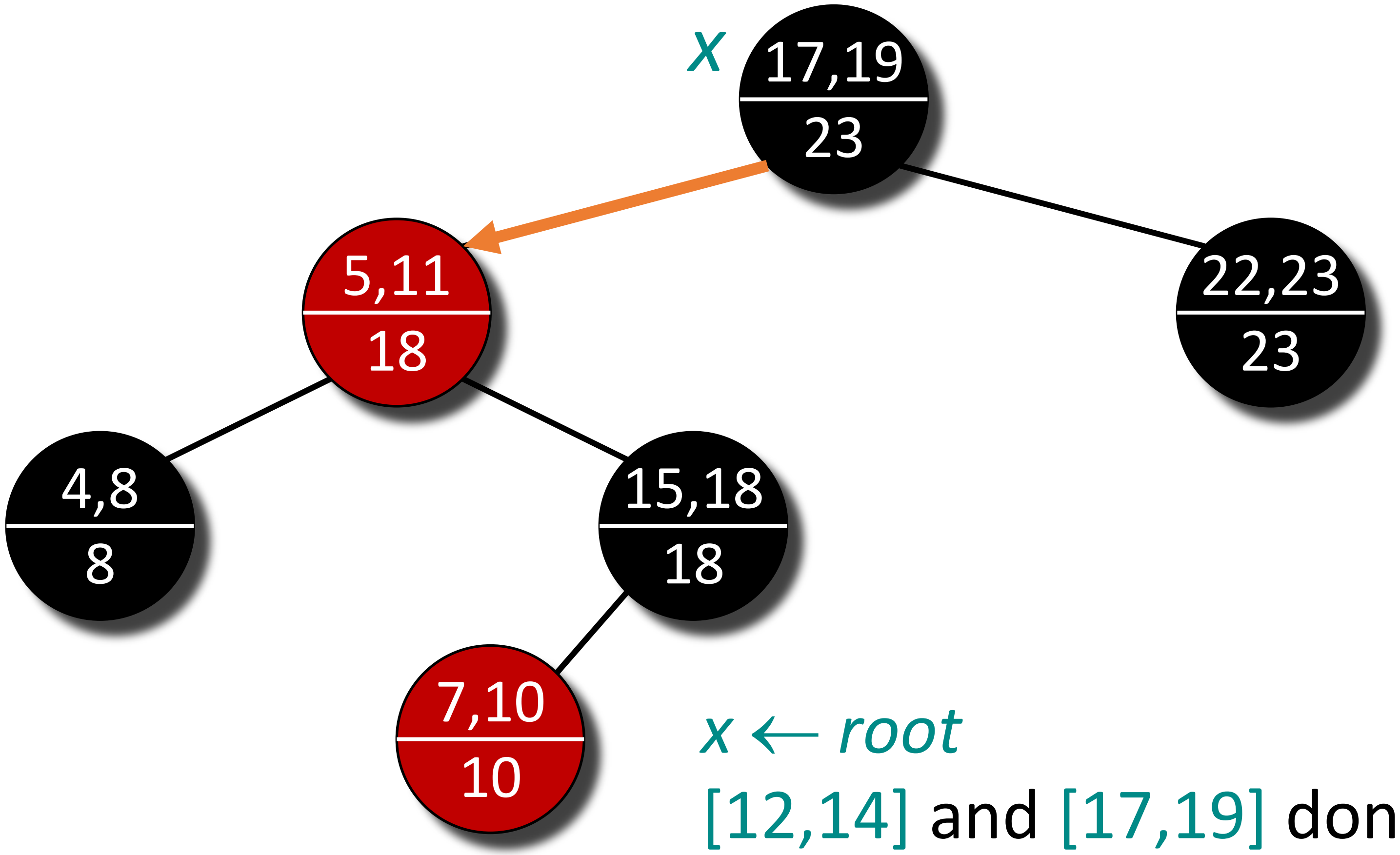


[14,16] and [15,18] overlap

return [15,18]

Example 2: INTERVAL-SEARCH([12,14])



$x \leftarrow root$

[12,14] and [17,19] don't overlap

$12 \leq 18 \Rightarrow x \leftarrow left[x]$

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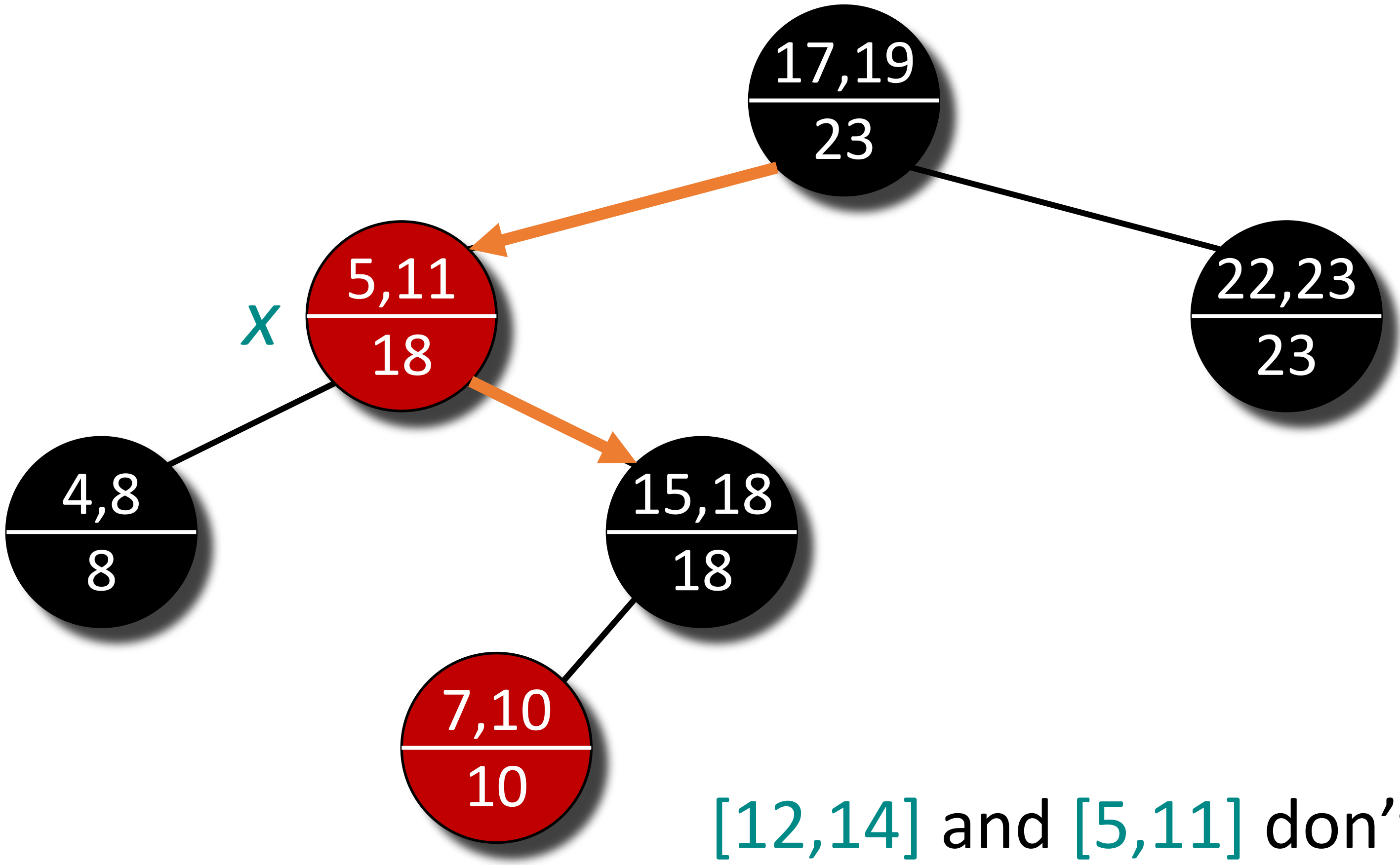
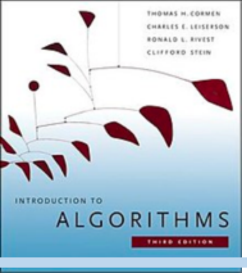


[12,14] and [5,11] don't overlap

$12 > 8 \Rightarrow x \leftarrow right[x]$



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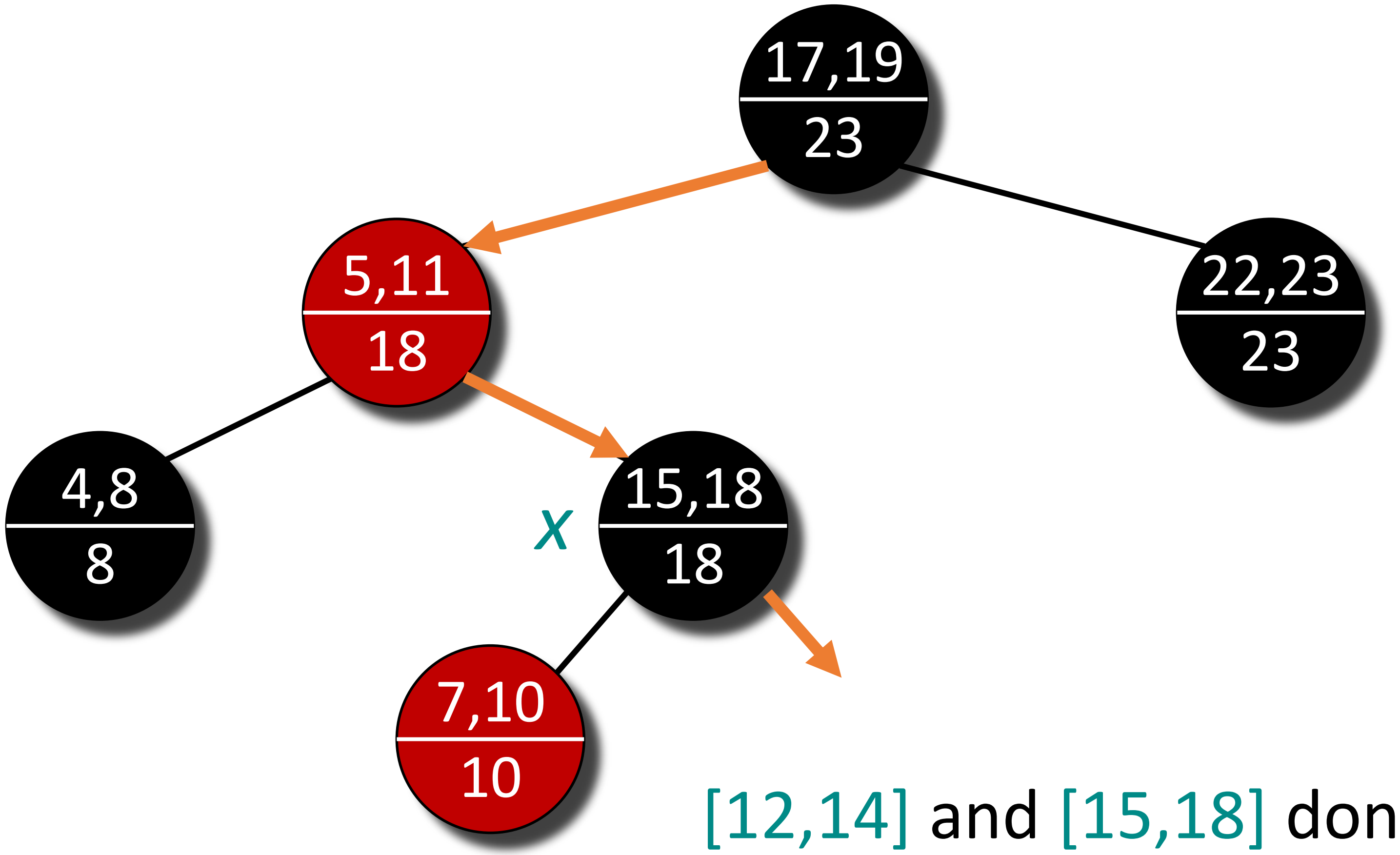
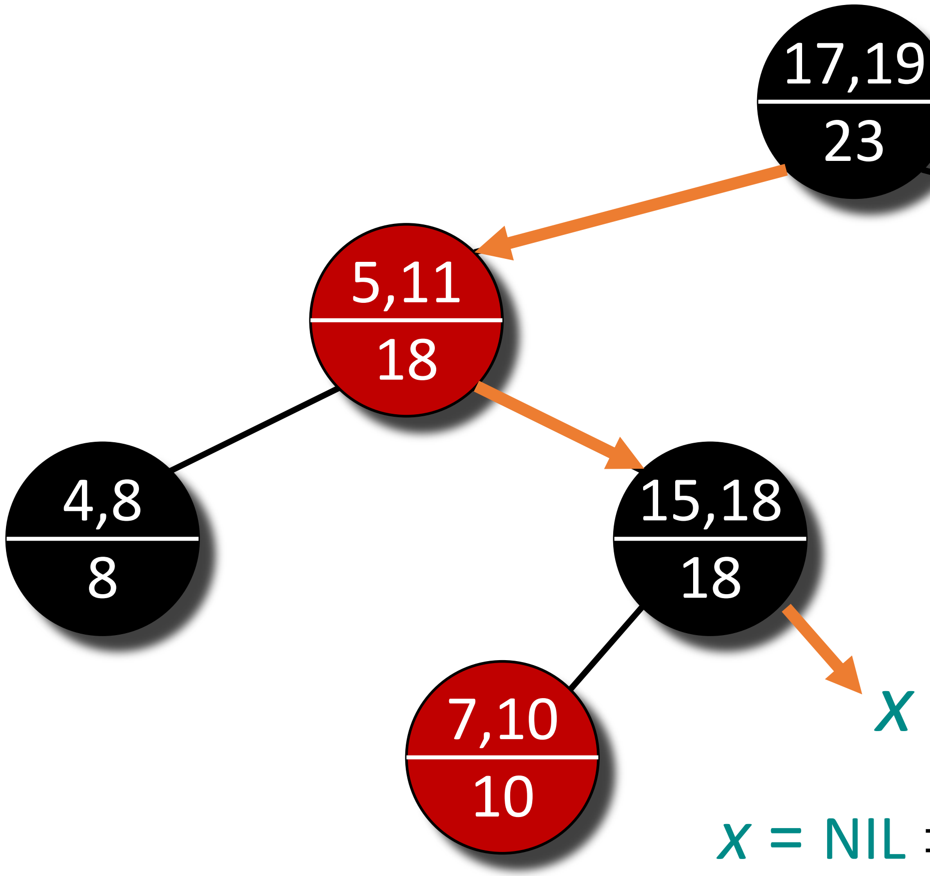


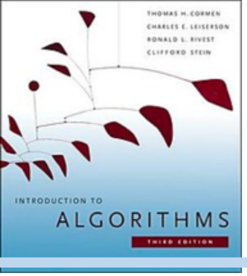
[12,14] and [15,18] don't overlap

$12 > 10 \Rightarrow x \leftarrow \mathit{right}[x]$

Example 2: INTERVAL-SEARCH([12,14])



x = NIL $\Rightarrow$ no interval that overlaps [12,14] exists



Analysis

Time = $O(h)$ = $O(\lg n)$, since INTERVAL-SEARCH does constant work at each level as it follows a simple path down the tree.

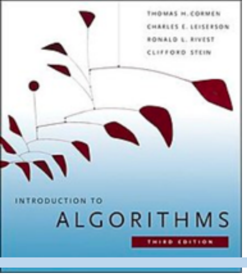
List *all* overlapping intervals:

- Search, list, delete, repeat.
- Insert them all again at the end.

Time = $O(k \lg n)$, where k is the total number of overlapping intervals.

This is an ***output-sensitive*** bound.

Best algorithm to date: $O(k + \lg n)$.



Correctness

Theorem. Let L be the set of intervals in the left subtree of node x, and let R be the set of intervals in x's right subtree.

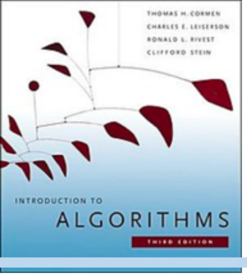
- If the search goes right, then

$$\{ i' \in L : i' \text{ overlaps } i \} = \emptyset.$$

- If the search goes left, then

$$\{i' \in L : i' \text{ overlaps } i \} = \emptyset$$
$$\Rightarrow \{i' \in R : i' \text{ overlaps } i \} = \emptyset.$$

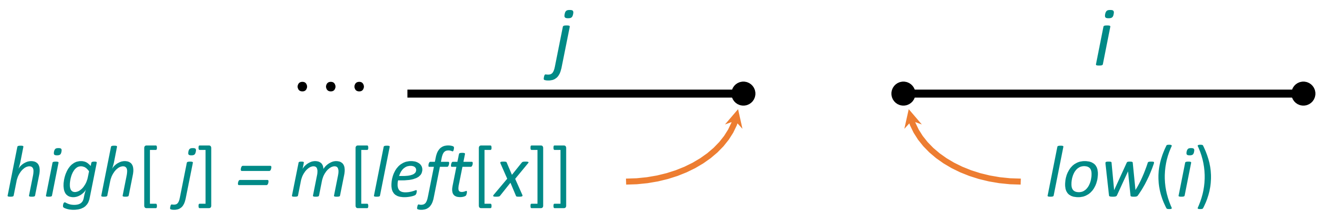
In other words, it's always safe to take only 1 of the 2 children: we'll either find something, or nothing was to be found.



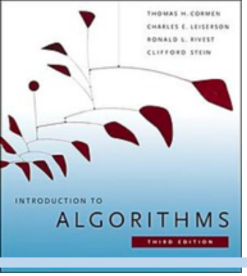
Correctness proof

Proof. Suppose first that the search goes right.

- If *left*[*x*] = NIL, then we're done, since $L = \emptyset$.
- Otherwise, the code dictates that we must have *low*[*i*] > *m*[*left*[*x*]]. The value *m*[*left*[*x*]] corresponds to the high endpoint of some interval $j \in L$, and no other interval in L can have a larger high endpoint than *high*[*j*].



- Therefore, $\{i' \in L : i' \text{ overlaps } i\} = \emptyset$.

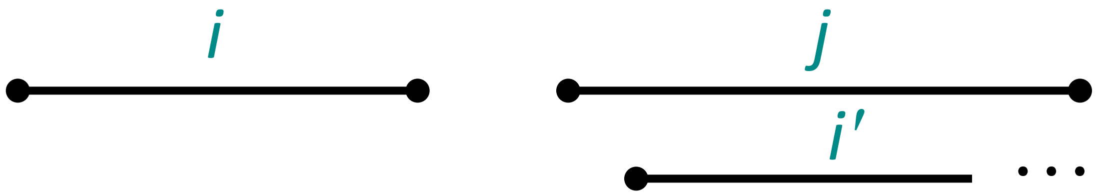


Proof (continued)

Suppose that the search goes left, and assume that

$$\{i' \in L : i' \text{ overlaps } i\} = \emptyset.$$

- Then, the code dictates that $low[i] \leq m[left[x]] = high[j]$ for some $j \in L$.
- Since $j \in L$, it does not overlap i, and hence $high[i] < low[j]$.
- But, the binary-search-tree property implies that for all $i' \in R$, we have $low[j] \leq low[i']$.
- But then $\{i' \in R : i' \text{ overlaps } i\} = \emptyset$. $\square$



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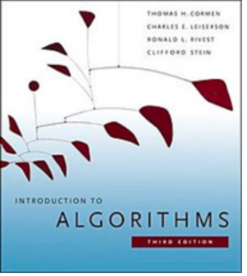
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