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Data structures and algorithms

Part 9

Searching and Search Trees II

Petr Felkel

Topics

Red-Black tree

- Insert
- Delete

B-Tree

- Motivation
- Search
- Insert
- Delete

Based on:

[Cormen, Leiserson, Rivest: Introduction to Algorithms, Chapter 14 and 19, McGraw Hill, 1990]

[Whitney: CS660 Combinatorial Algorithms, San Diego State University, 1996]

[Frederic Maire: An Introduction to Btrees, Queensland University of Technology, 1998]

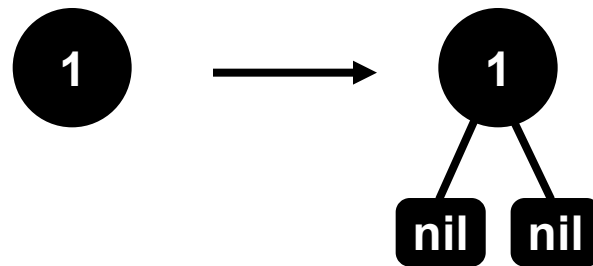
Red-Black tree

Approximately balanced BST

$$h_{RB} \leq 2x h_{BST} \quad (\text{height} \leq 2x \text{ height of balanced tree})$$

Additional bit for COLOR = {red | black}

nil (non-existent child) = pointer to **nil** node



leaf → inner node

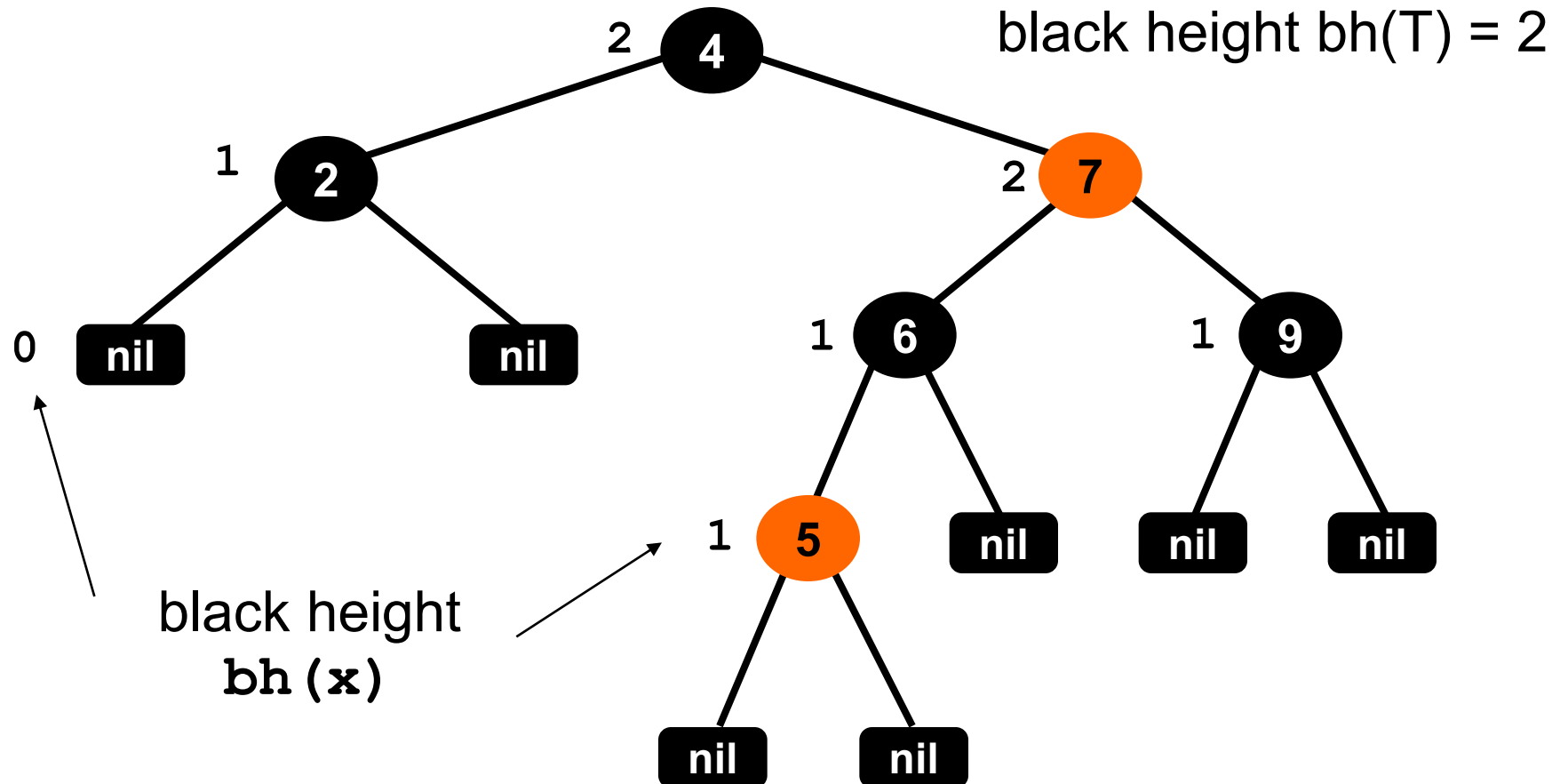
Red-Black tree

A binary search tree is a **red-black** tree if:

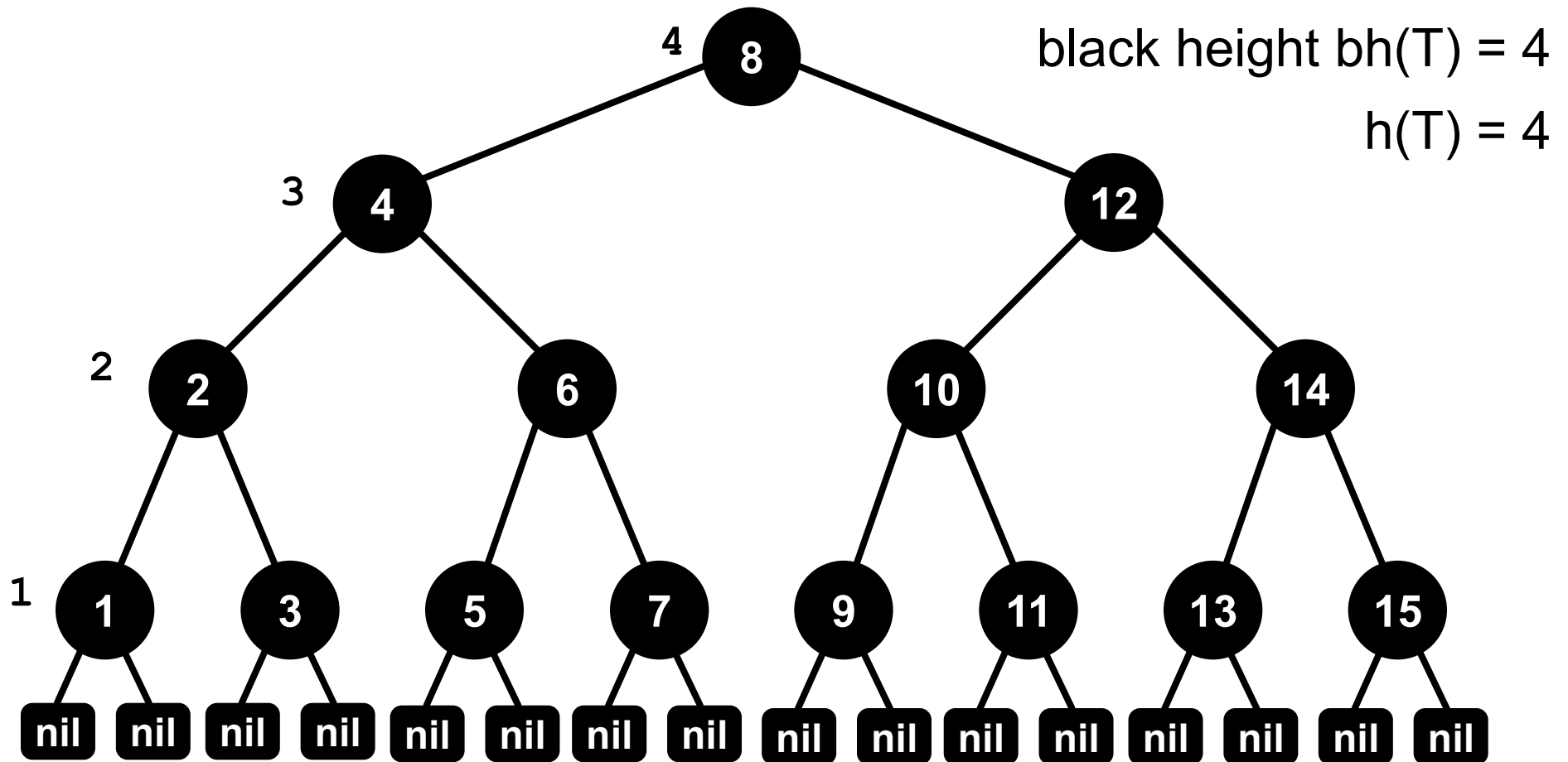
1. Every node is either **red** or **black**
2. Every leaf (nil) is **black**
3. If a node is **red**, then both its children are **black**
4. Every simple path from a node to a descendant leaf contains the same number of **black** nodes
- (5. Root is black)

Black-height $bh(x)$ of a node x is the number of **black** nodes on any path from x to a leaf, not counting x

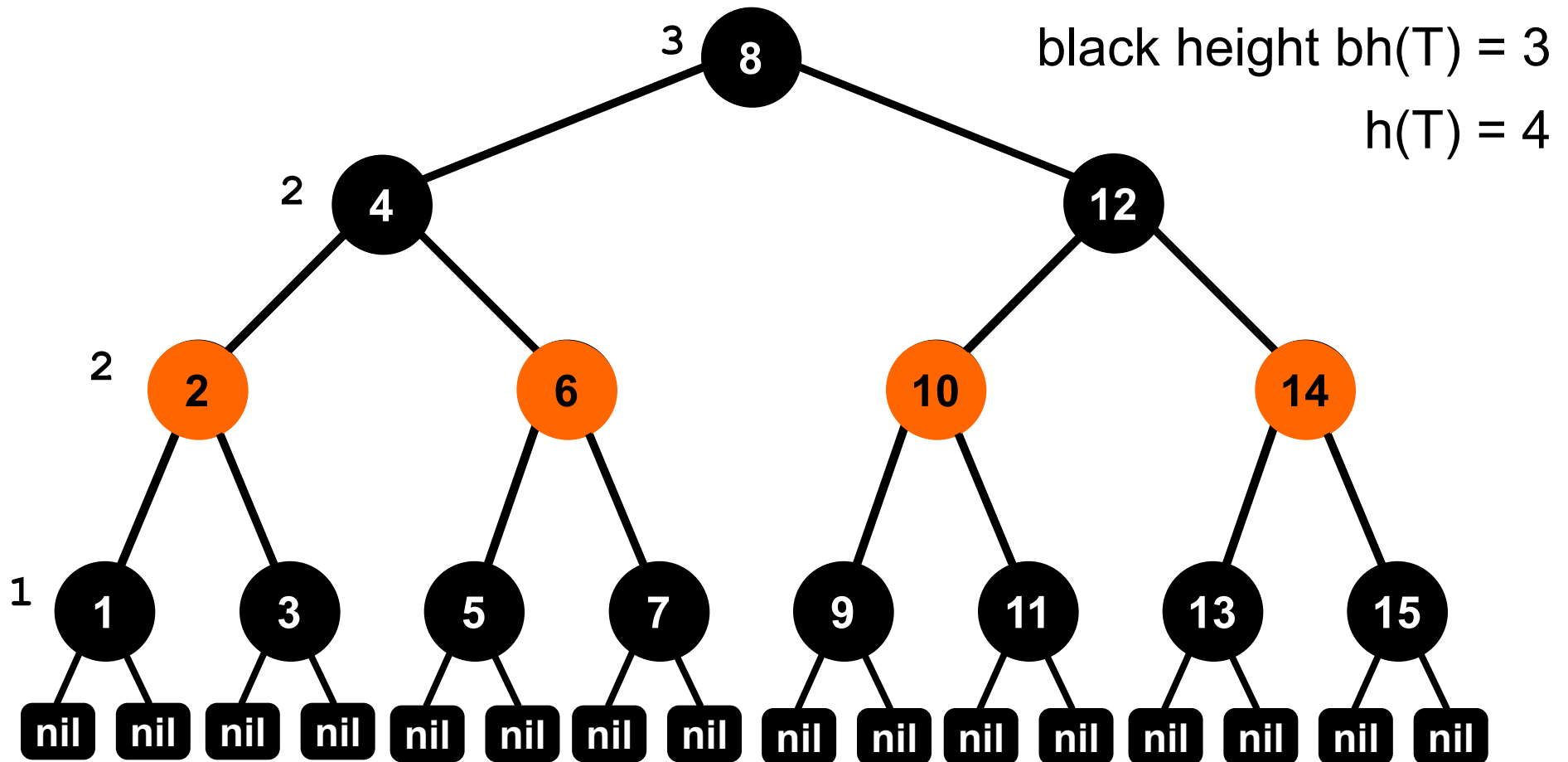
Red-Black tree



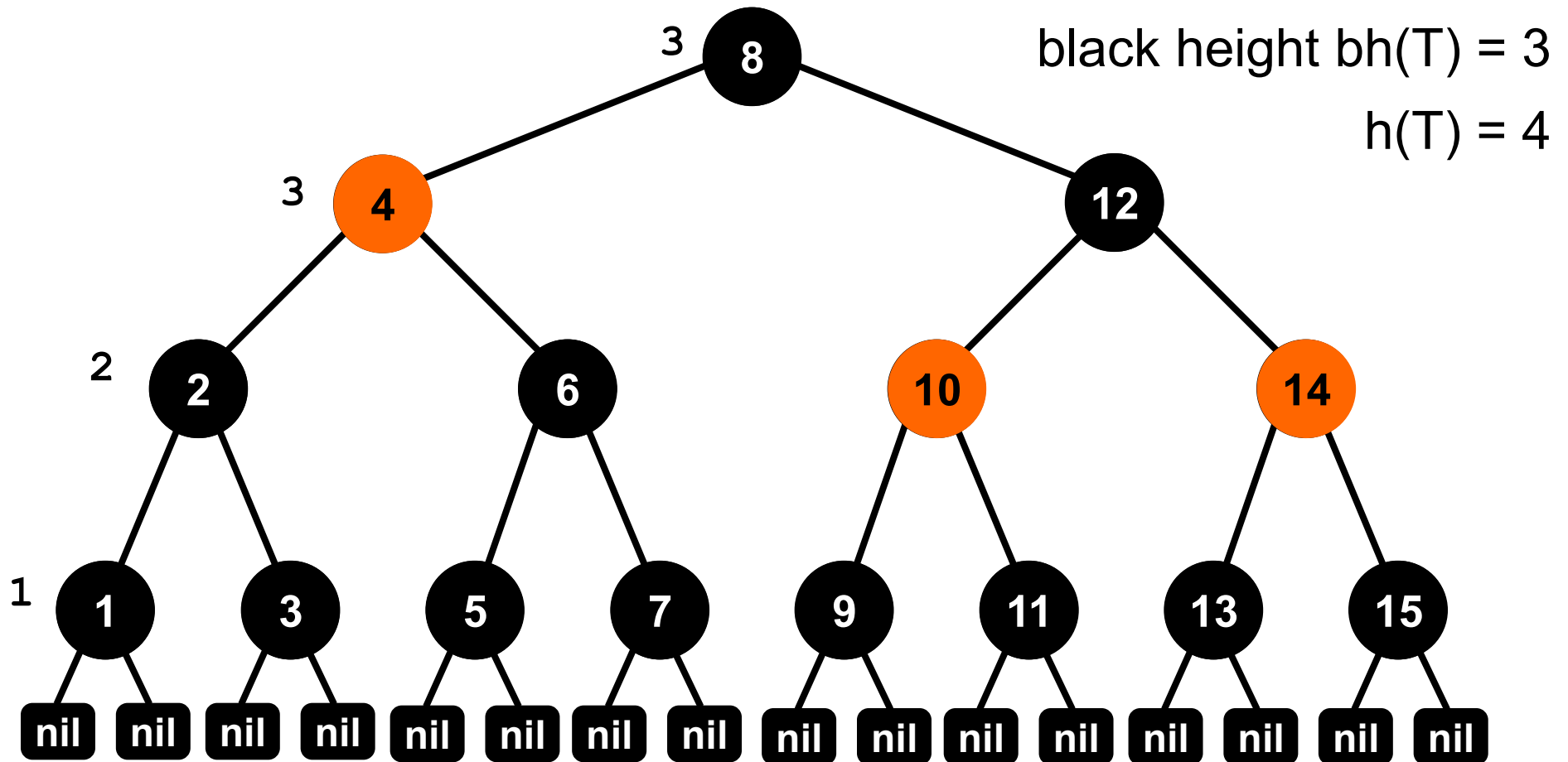
Binary Search Tree -> RB Tree



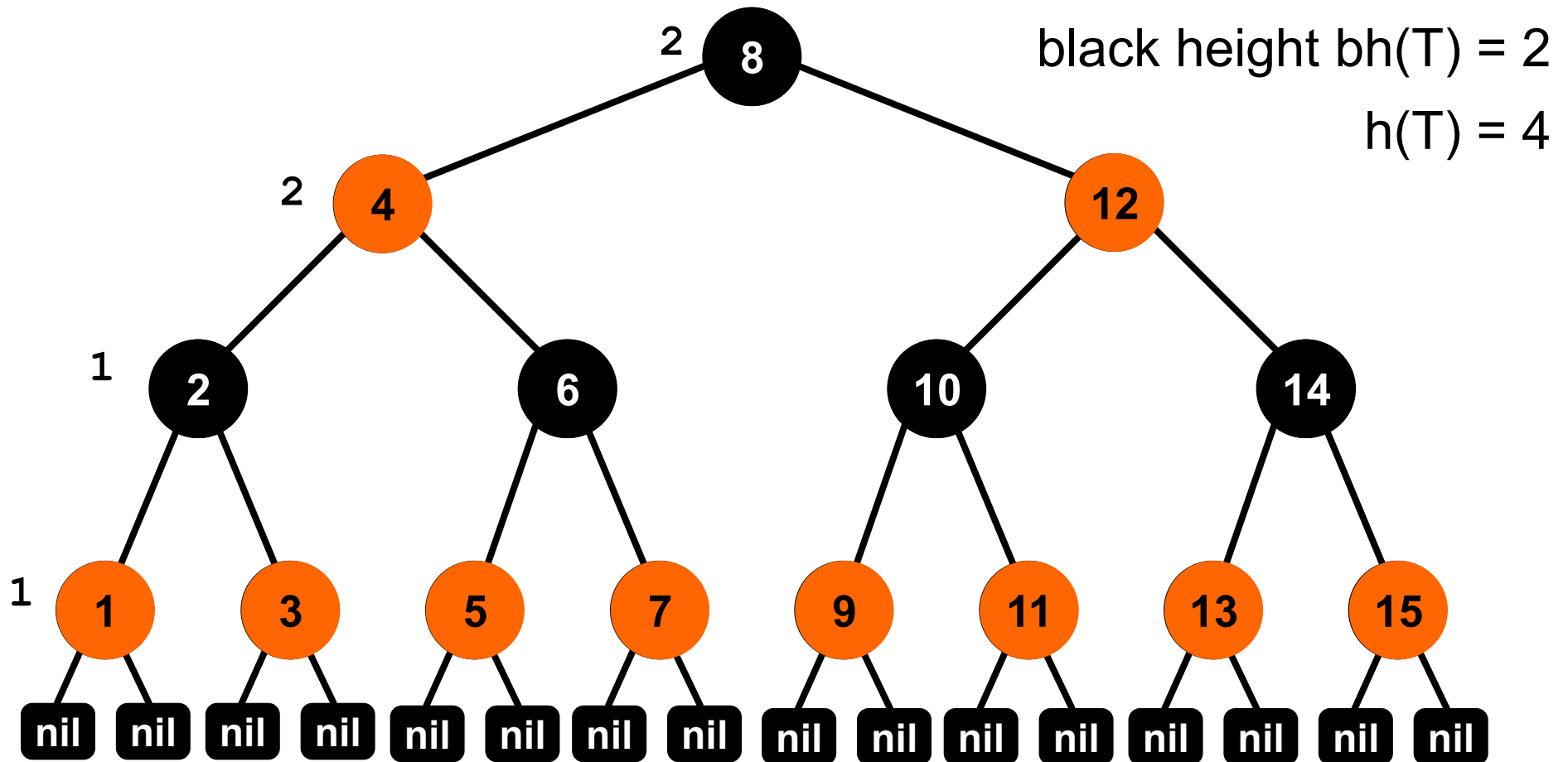
Binary Search Tree -> RB Tree



Binary Search Tree -> RB Tree



Binary Search Tree -> RB Tree



Red-Black tree

Black-height $bh(x)$ of a node x

- is the number of black nodes on any path from x to a leaf, not counting x
- is equal for all paths from x to a leaf
- For given h is $bh(x)$ in the range from $h/2$ to h
 - if $1/2$ of nodes red $\Rightarrow bh(x) \approx 1/2 h(x), h(x) \approx 2 \lg(n+1)$
 - if all nodes black $\Rightarrow bh(x) = h(x) = \lg(n+1) - 1$

Height $h(x)$ of a RB-tree rooted in node x

- is at maximum twice of the optimal height of a balanced tree
- $h \leq 2\lg(n+1)$ $h \in \Theta(\lg(n))$

RB-tree height proof [Cormen, p.264]

A red-black tree with n internal nodes has height h at most $2\lg(n+1)$

Proof: 1. Show that **subtree starting at x contains at least $2^{\text{bh}(x)} - 1$ internal nodes.**

By induction on height of x :

- I. If x is a *leaf*, then $\text{bh}(x) = 0$, $2^{\text{bh}(x)} - 1 = 0$ internal nodes //... nil node
- II. Consider x with height h and two children (with height $h - 1$)
 - x 's children black-height is either $\text{bh}(x) - 1$ or $\text{bh}(x)$ // black or red
 - Ind. hypothesis: x 's children subtree has at least $2^{\text{bh}(x)-1} - 1$ internal nodes
 - So subtree starting at x contains at least $(2^{\text{bh}(x)-1} - 1) + (2^{\text{bh}(x)-1} - 1) + 1 = 2^{\text{bh}(x)} - 1$ internal nodes => proved

2. Let $h =$ height of the tree rooted at x

- min $\frac{1}{2}$ nodes are black on any path to leaf => $\text{bh}(x) \geq h / 2$
- Thus, $n \geq 2^{h/2} - 1 \iff n + 1 \geq 2^{h/2} \iff \lg(n+1) \geq h / 2$
- $h \leq 2\lg(n+1)$

Inserting in Red-Black Tree

Color new node **Red**

Insert it as in the standard BST 

If parent is Black, stop. Tree is a Red-Black tree.

If parent is **Red** (3+3 cases)...

resp.

While x is not root and parent is **Red**

if x 's *uncle* is **Red** then case 1

// propagate red up

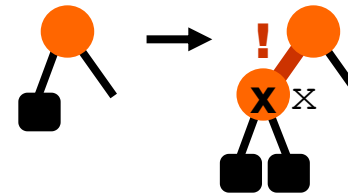
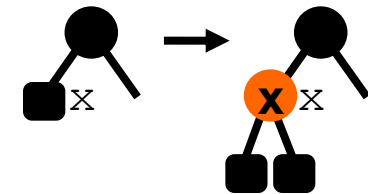
else if x is *Right child* then case 2

// double rotation

case 3

// single rotation

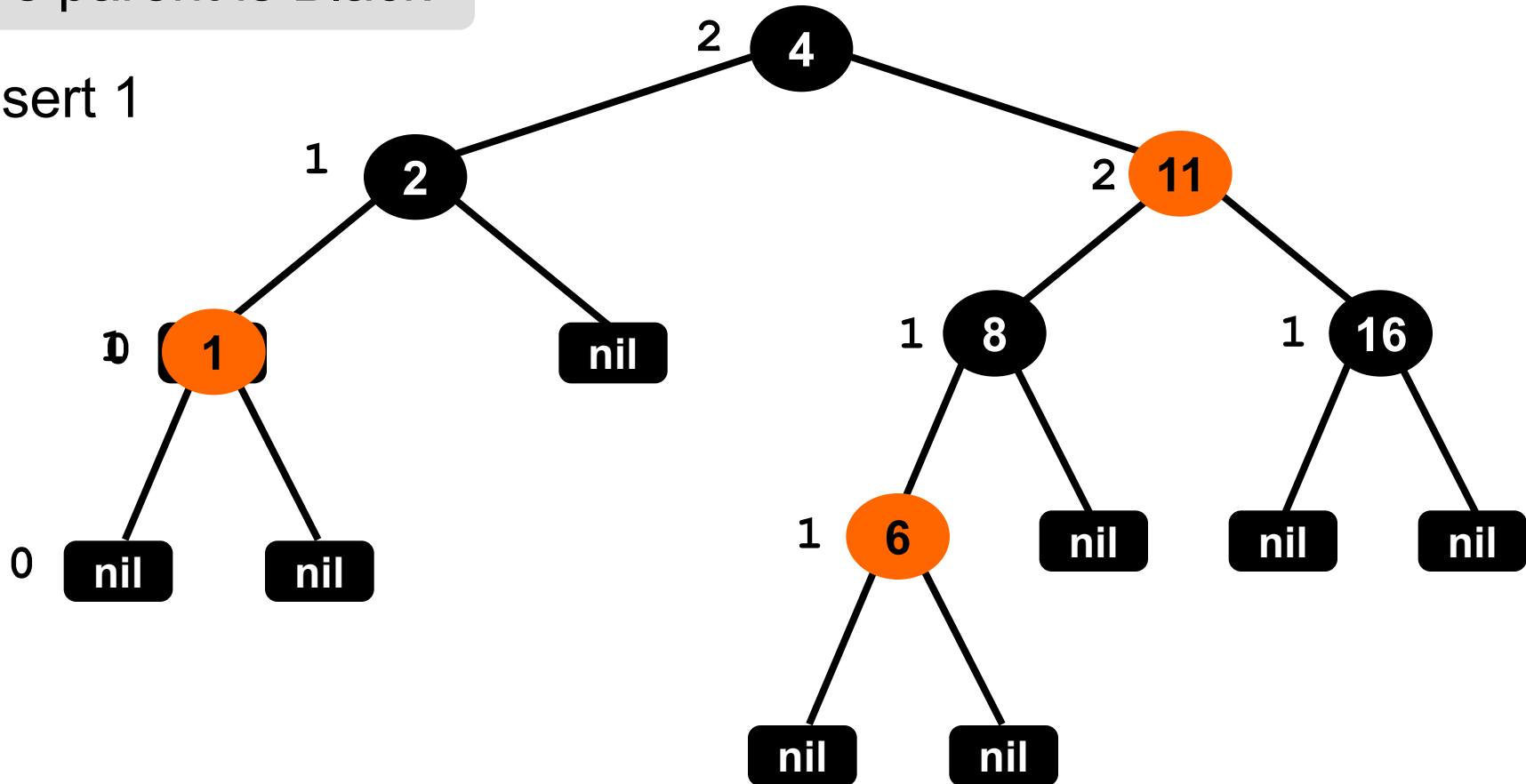
Color root Black



Inserting in Red-Black Tree

x's parent is Black

Insert 1



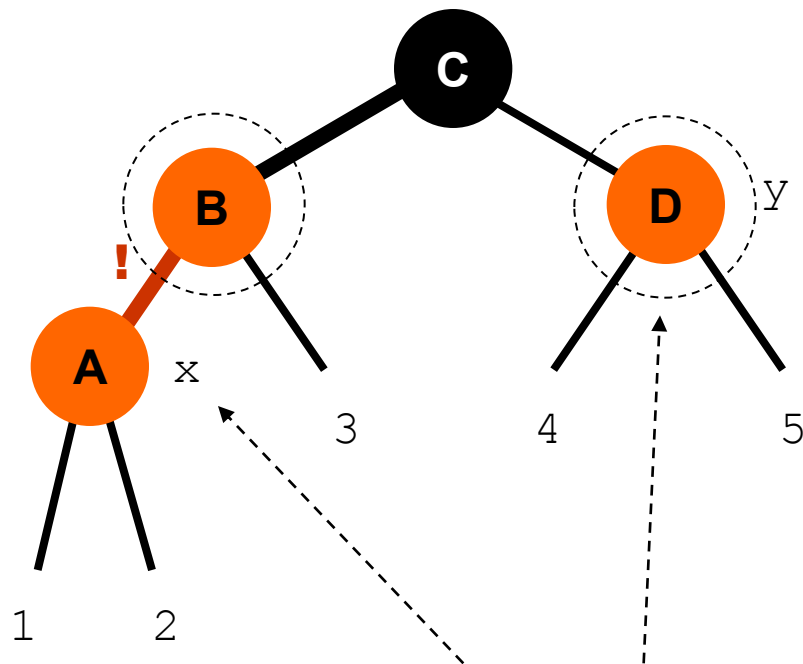
If parent is Black, stop. Tree is a Red-Black tree.

Inserting in Red-Black Tree

x 's parent is Red

x 's uncle y is Red

x is a Left child

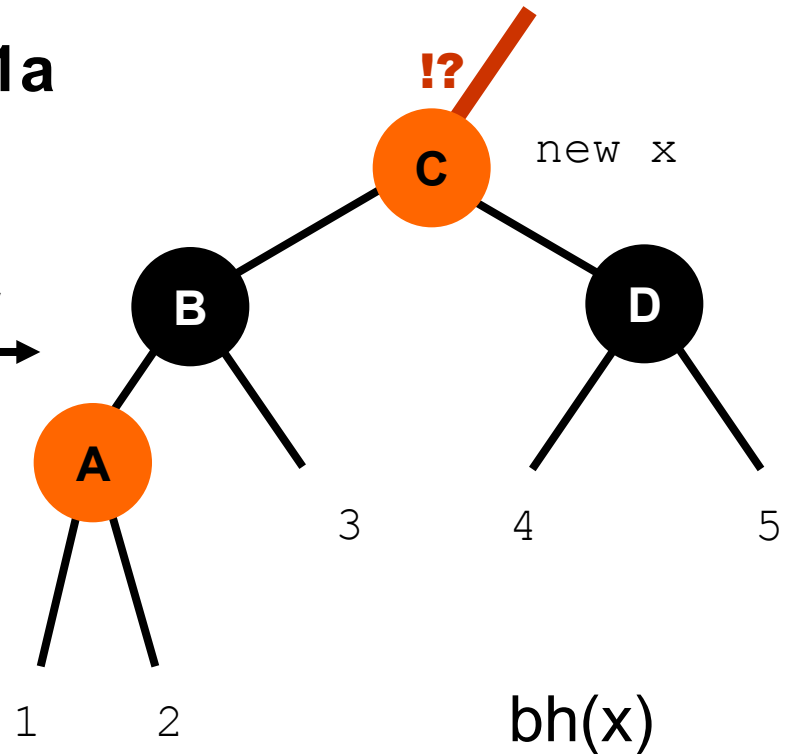


x is node of interest

x 's uncle is Red

Case 1a

Recolor



$bh(x)$
increased by one

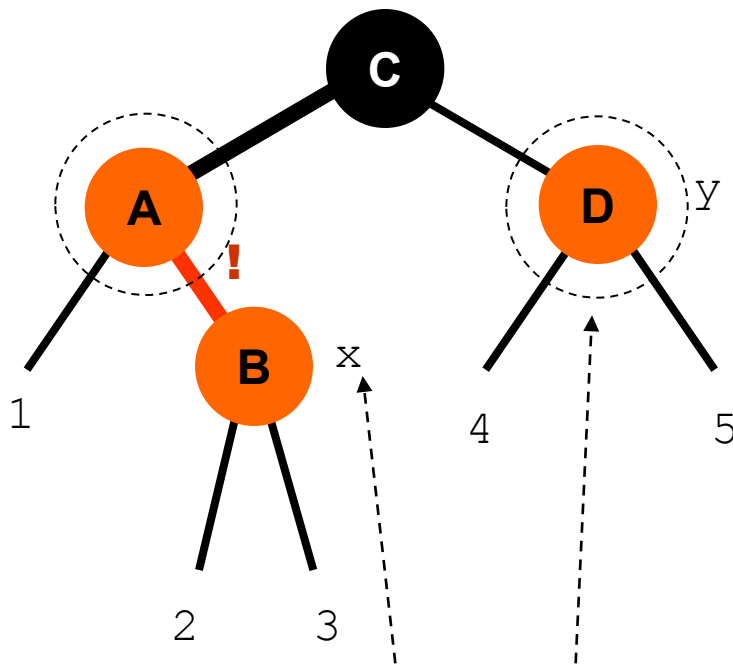
Loop: $x = x.p.p$

Inserting in Red-Black Tree

x's parent is Red

x's uncle y is Red

x is a Right child

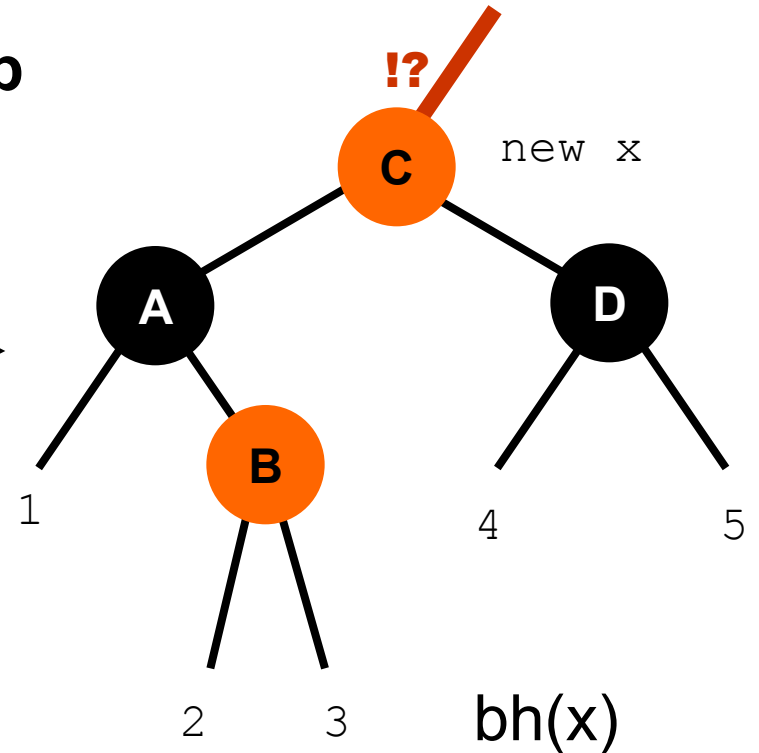


x is node of interest

x's uncle is Red

Case 1b

Recolor



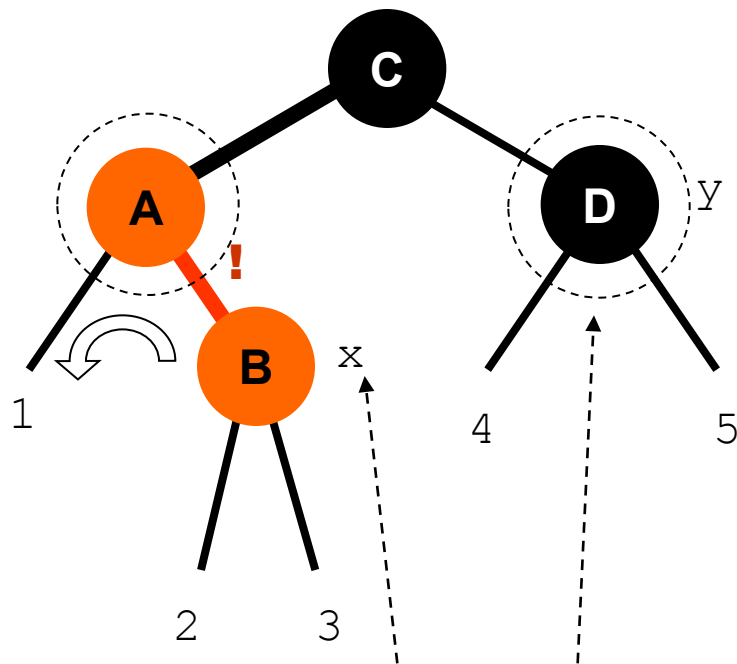
bh(x)
increased by one

Inserting in Red-Black Tree

x 's parent is Red

x 's uncle y is Black

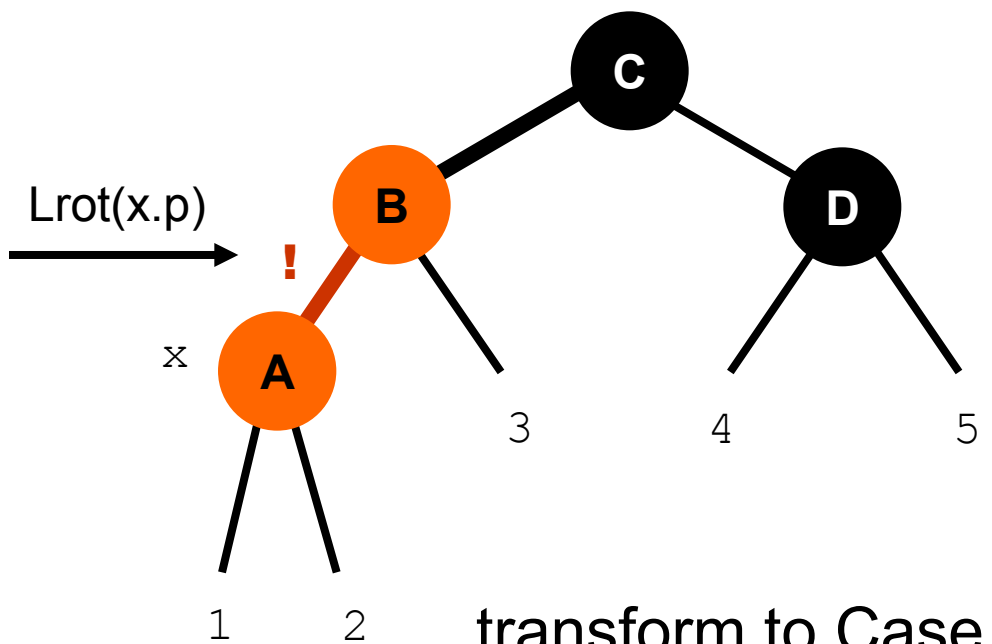
x is a Right child



x is a Right child

x 's uncle is Black

Case 2



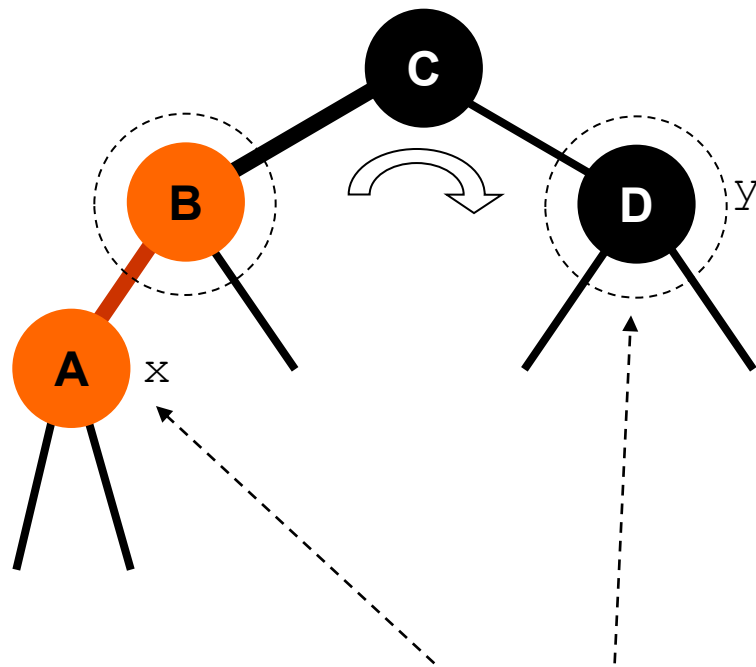
transform to Case 3

Inserting in Red-Black Tree

x 's parent is Red

x 's uncle y is Black

x is a Left child

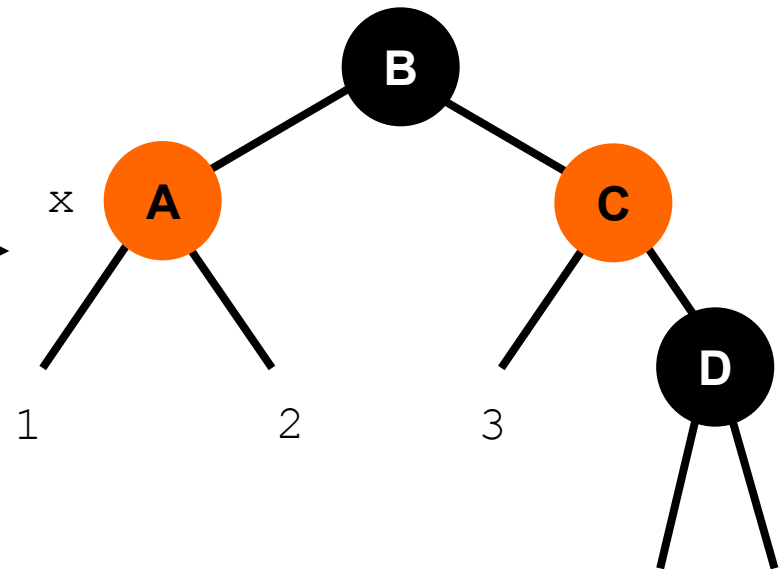


x is a Left child

x 's uncle is Black

Case 3

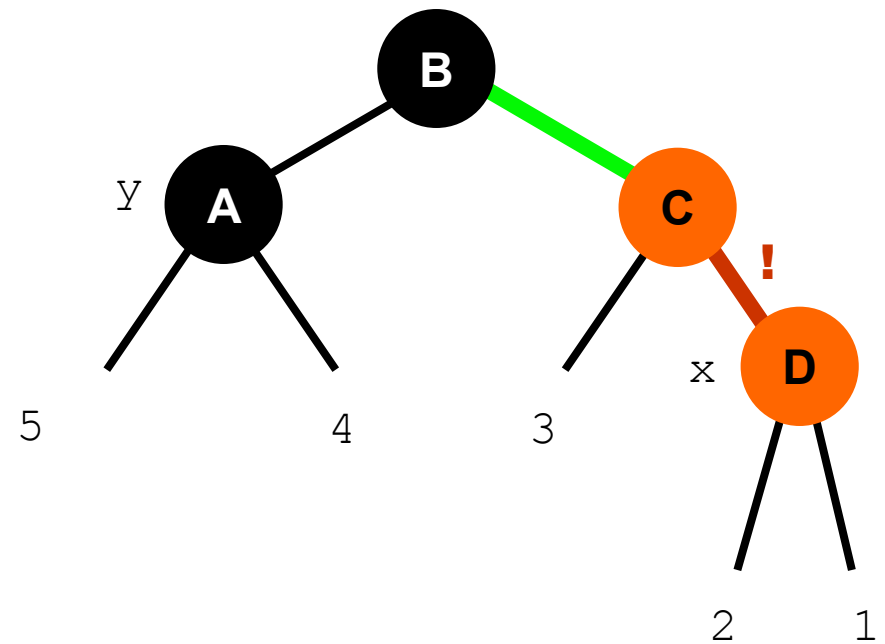
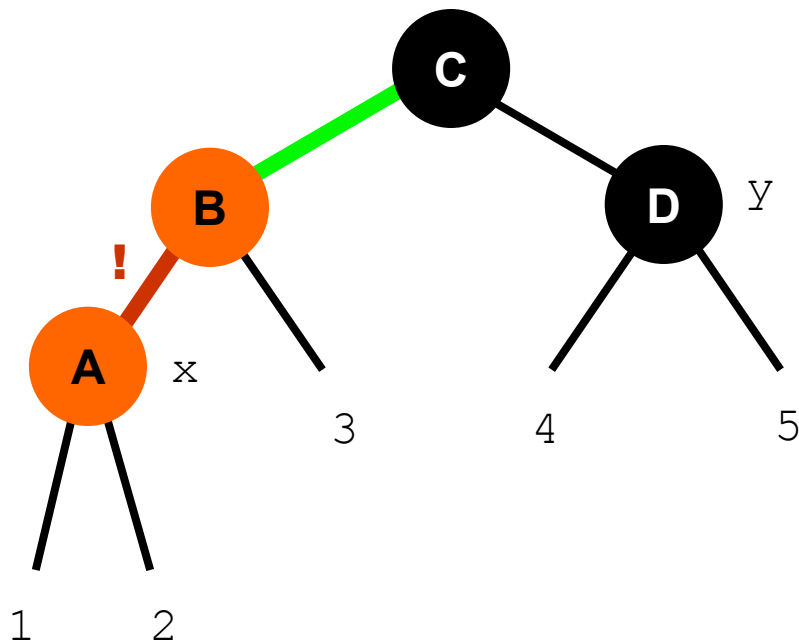
Recolor +
Rrot(x.p.p)



Terminal case, tree
is a Red-Black tree

Inserting in Red-Black Tree

Cases Right from the grandparent
are symmetric



RB-INSERT(T, x)

```

1  TREE-INSERT( $T, x$ )
2   $color[x] \leftarrow RED$ 
3  while  $x \neq root[T]$  and  $color[p[x]] = RED$ 
4      do if  $p[x] = left[p[p[x]]]$ 
5          then  $y \leftarrow right[p[p[x]]]$ 
6              if  $color[y] = RED$ 
7                  then  $color[p[x]] \leftarrow BLACK$ 
8                       $color[y] \leftarrow BLACK$ 
9                       $color[p[p[x]]] \leftarrow RED$ 
10                      $x \leftarrow p[p[x]]$ 
11                 else if  $x = right[p[x]]$ 
12                     then  $x \leftarrow p[x]$ 
13                         LEFT-ROTATE( $T, x$ )
14                  $color[p[x]] \leftarrow BLACK$ 
15                  $color[p[p[x]]] \leftarrow RED$ 
16                 RIGHT-ROTATE( $T, p[p[x]]$ )
17                 else (same as then clause
                        with “right” and “left” exchanged)
18   $color[root[T]] \leftarrow BLACK$ 

```

$p[x]$ = parent of x
 $left[x]$ = left son of x
 y = uncle of x

Red uncle $y \rightarrow$ recolor up

▷ Case 1

▷ Case 1

▷ Case 1

▷ Case 1

▷ Case 2

▷ Case 2

▷ Case 3

▷ Case 3

▷ Case 3

Inserting in Red-Black Tree

Insertion in $O(\log(n))$ time

Requires at most two rotations

DEMO: <http://www.ececs.uc.edu/~franco/C321/html/RedBlack/redblack.html>

(Intuitive, good for understanding)

<http://reptar.uta.edu/NOTES5311/REDBLACK/RedBlack.html>

(little different order of re-coloring and rotations)

Deleting in Red-Black Tree

Find node to delete

Delete node as in a regular BST

Node y to be physically deleted will have at most one child x !!!

If we **delete a Red node**, tree still is a Red-Black tree, **stop**

Assume we **delete a black node**

Let x be the **child of deleted (black) node**


If x is **red**, color it black and stop

while(x is not root) AND (x is black)

 move x with virtual black mark through the tree

 (If x is black, mark it virtually double black )

Deleting in Red-Black Tree

```
while(x is not root) AND ( x is black) {  
    // move x with virtual black mark  through the tree  
    // just recolor or rotate other subtree up (decrease bh in R subtree)  
    if(red sibling)  
        -> Case 1: Rotate right subtree up, color sibling black, and  
                continue in left subtree with new sibling  
    if(black sibling with both black children)  
        -> Case 2: Color sibling red and go up  
    else // black sibling with one or two red children  
        if(red left child) -> Case 3: rotate to surface  
        Case 4: Rotate right subtree up  
}
```

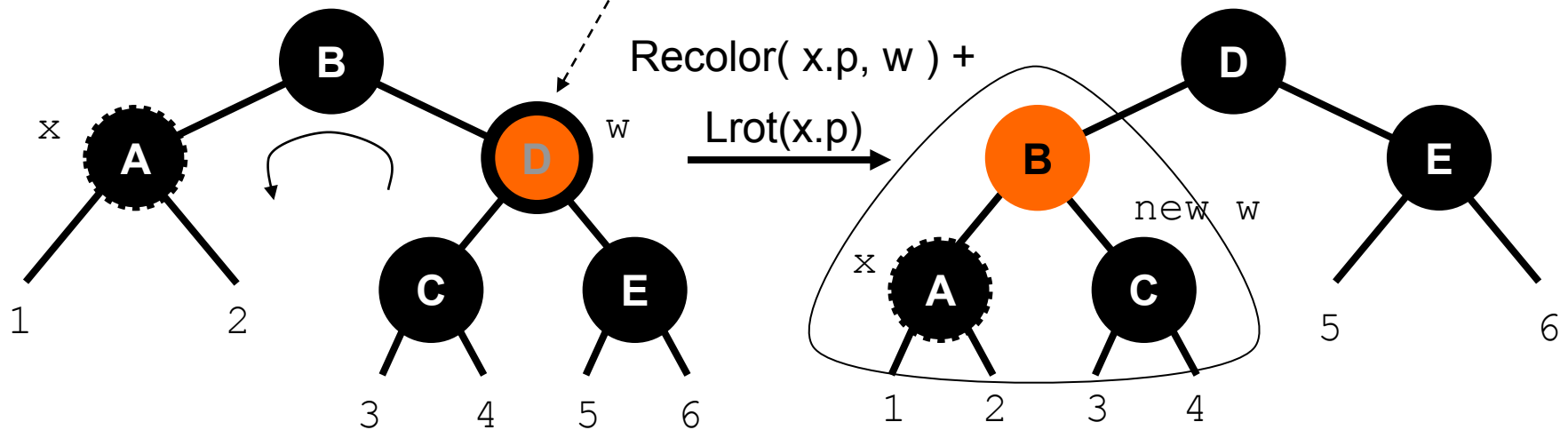
Deleting in R-B Tree - Case 1

x is the child of the physically deleted black node \Rightarrow double black
 x 's sibling w (*sourozenec*) is **red**



(x 's parent MUST be black)

Case 1

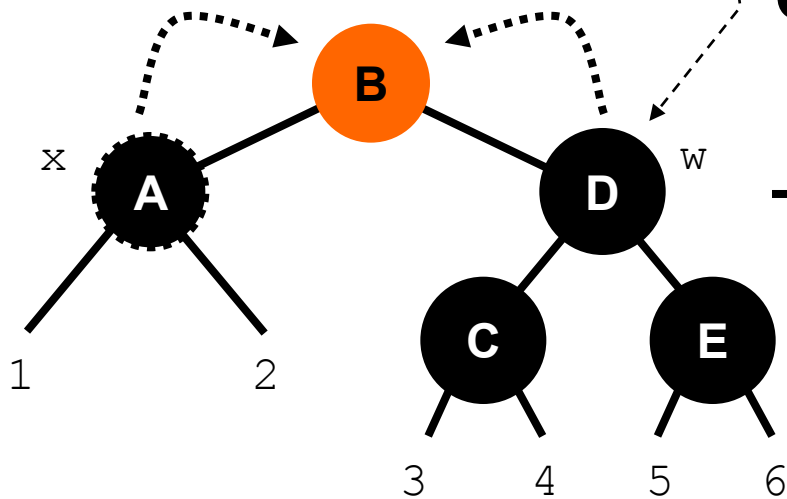


x stays at the same black height

[Possibly transforms to case 2a and terminates – depends on 3,4]

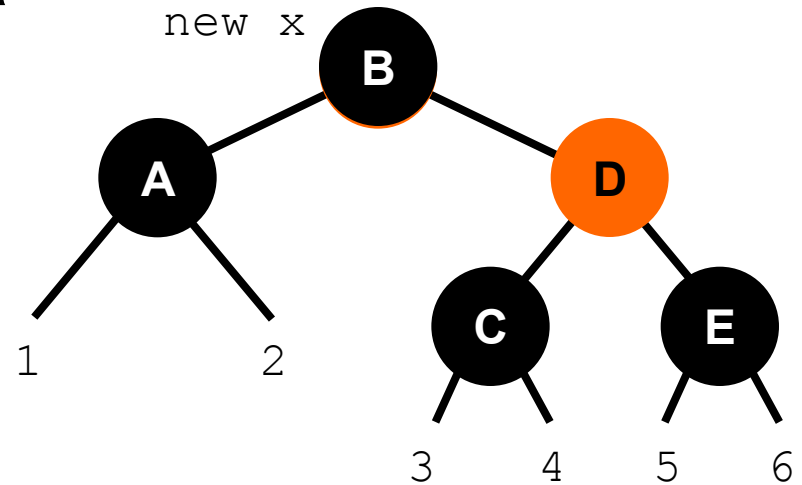
Deleting in R-B Tree - Case 2a

- x's sibling w is black
- x's parent is red
- x's sibling left child is black
- x's sibling right child is black



Case 2a

black up

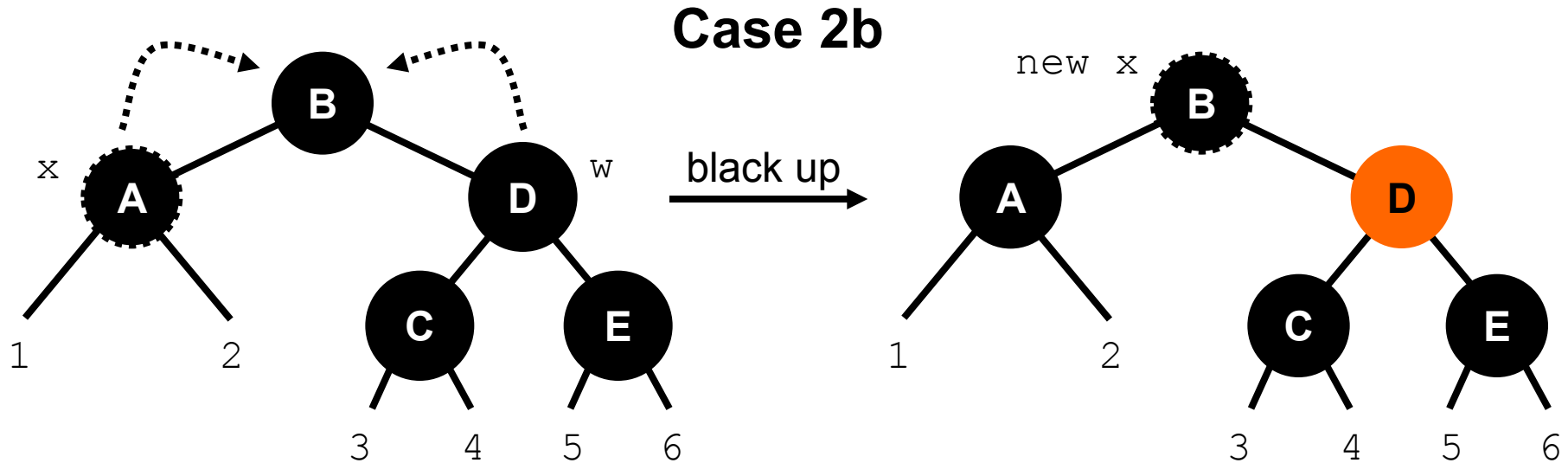


Terminal case, tree is Red-Black tree

stop

Deleting in R-B Tree - Case 2b

- x 's sibling w is black
- x 's parent is black
- x 's sibling left child is black
- x 's sibling right child is black



Decreases x black height by one

Deleting in R-B Tree - Case 3

x 's sibling w is black

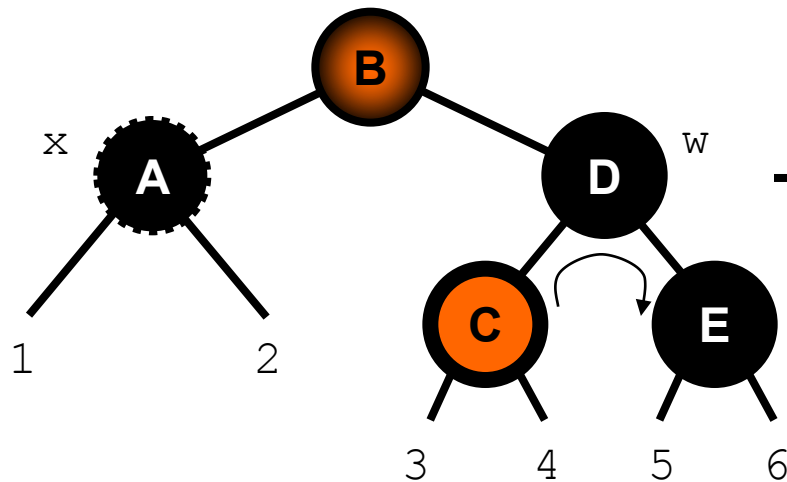
x 's parent is either

x 's sibling left child is red

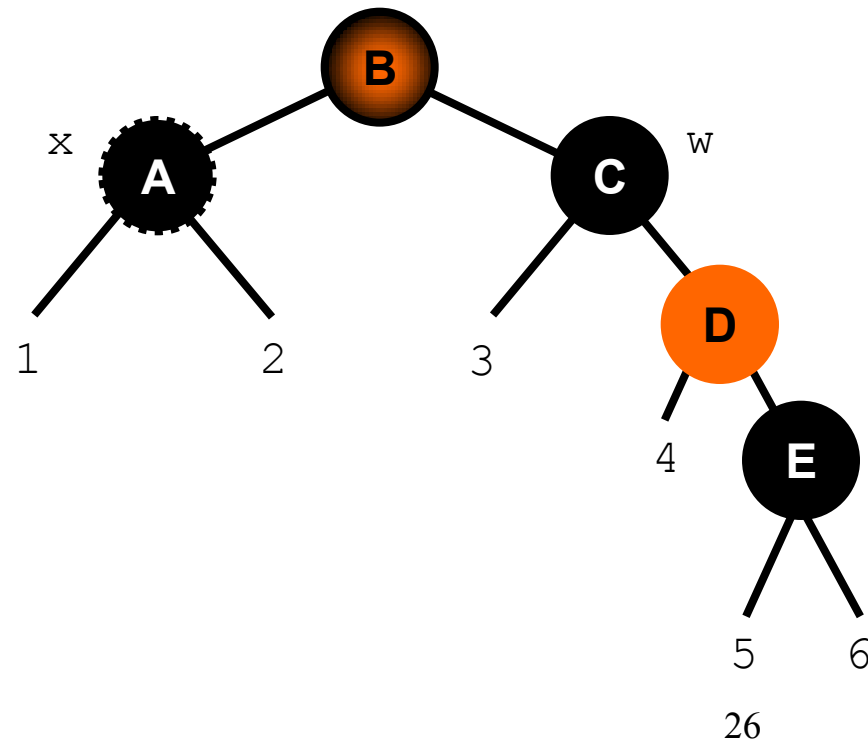
x 's sibling right child is black

// blocks coloring w red

Case 3



$\xrightarrow{\text{Rrot}(w)}$



Transform to case 4

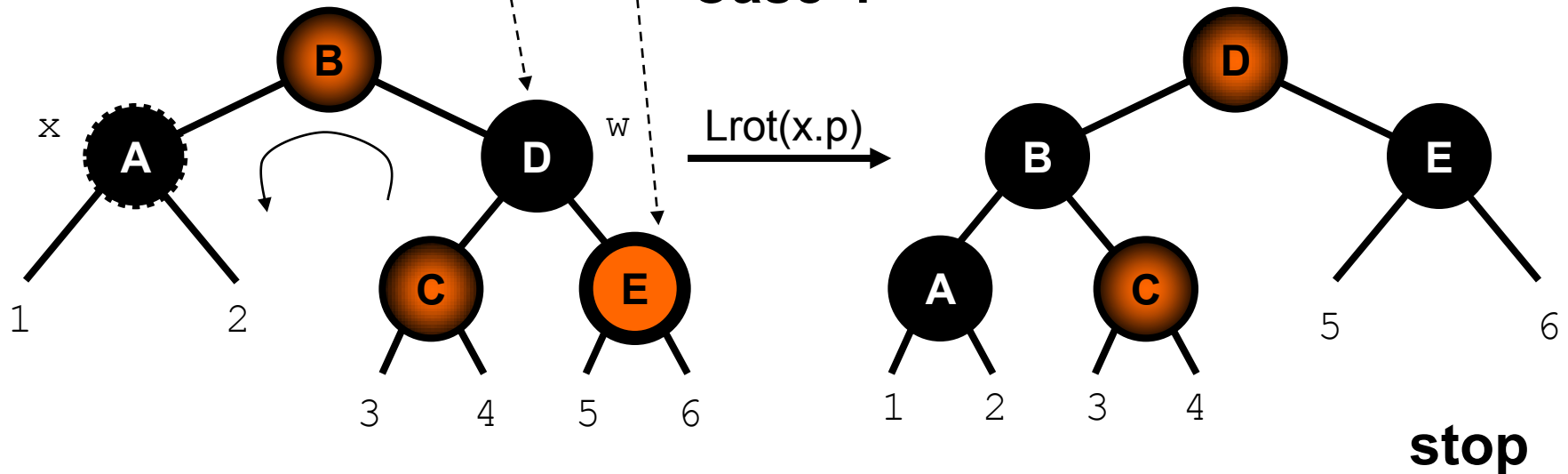
x stays at same black height

Deleting in R-B Tree - Case 4

x's sibling w is black
x's parent is either
x's sibling left child is either
x's sibling right child is red

// blocks coloring w red

Case 4



Terminal case, tree is Red-Black tree

Deleting in Red-Black Tree

RB-DELETE(T, z)

```
1  if left[z] = nil[T] or right[z] = nil[T]
2    then y ← z
3    else y ← TREE-SUCCESSOR(z)
4  if left[y] ≠ nil[T]
5    then x ← left[y]
6    else x ← right[y]
7  p[x] ← p[y]
8  if p[y] = nil[T]
9    then root[T] ← x
10 else if y = left[p[y]]
11       then left[p[y]] ← x
12       else right[p[y]] ← x
13 if y ≠ z
14   then key[z] ← key[y]
15       ▷ If y has other fields, copy them, too.
16 if color[y] = BLACK
17   then RB-DELETE-FIXUP(T, x)
18 return y
```

Notation similar to AVL
 z = *logically* removed
 y = *physically* removed
 x = y 's only son

[Cormen90]

RB-DELETE-FIXUP(T, x)

x = son of removed node

$p[x]$ = parent of x

w = sibling (brother) of x

1 **while** $x \neq \text{root}[T]$ and $\text{color}[x] = \text{BLACK}$

2 **do if** $x = \text{left}[p[x]]$

3 **then** $w \leftarrow \text{right}[p[x]]$

4 **if** $\text{color}[w] = \text{RED}$

5 **then** $\text{color}[w] \leftarrow \text{BLACK}$

▷ Case 1

6 $\text{color}[p[x]] \leftarrow \text{RED}$

▷ Case 1

7 LEFT-ROTATE($T, p[x]$)

▷ Case 1

8 $w \leftarrow \text{right}[p[x]]$

▷ Case 1

9 **if** $\text{color}[\text{left}[w]] = \text{BLACK}$ and $\text{color}[\text{right}[w]] = \text{BLACK}$

10 **then** $\text{color}[w] \leftarrow \text{RED}$

▷ Case 2

11 $x \leftarrow p[x]$

▷ Case 2

12 **else if** $\text{color}[\text{right}[w]] = \text{BLACK}$

13 **then** $\text{color}[\text{left}[w]] \leftarrow \text{BLACK}$

▷ Case 3

14 $\text{color}[w] \leftarrow \text{RED}$

▷ Case 3

15 RIGHT-ROTATE(T, w)

▷ Case 3

16 $w \leftarrow \text{right}[p[x]]$

▷ Case 3

17 $\text{color}[w] \leftarrow \text{color}[p[x]]$

▷ Case 4

18 $\text{color}[p[x]] \leftarrow \text{BLACK}$

▷ Case 4

19 $\text{color}[\text{right}[w]] \leftarrow \text{BLACK}$

▷ Case 4

20 LEFT-ROTATE($T, p[x]$)

▷ Case 4

21 $x \leftarrow \text{root}[T]$

▷ Case 4

22 **else** (same as **then** clause

with “right” and “left” exchanged)

23 $\text{color}[x] \leftarrow \text{BLACK}$

R subtree up
Check L

Recolor
Black up
Go up

inner R-
subtree up

R subtree up
stop

[Cormen90]

Deleting in R-B Tree

Delete time is $O(\log(n))$

At most three rotations are done

Which BS tree is the best? [Pfaff 2004]

It is data dependent

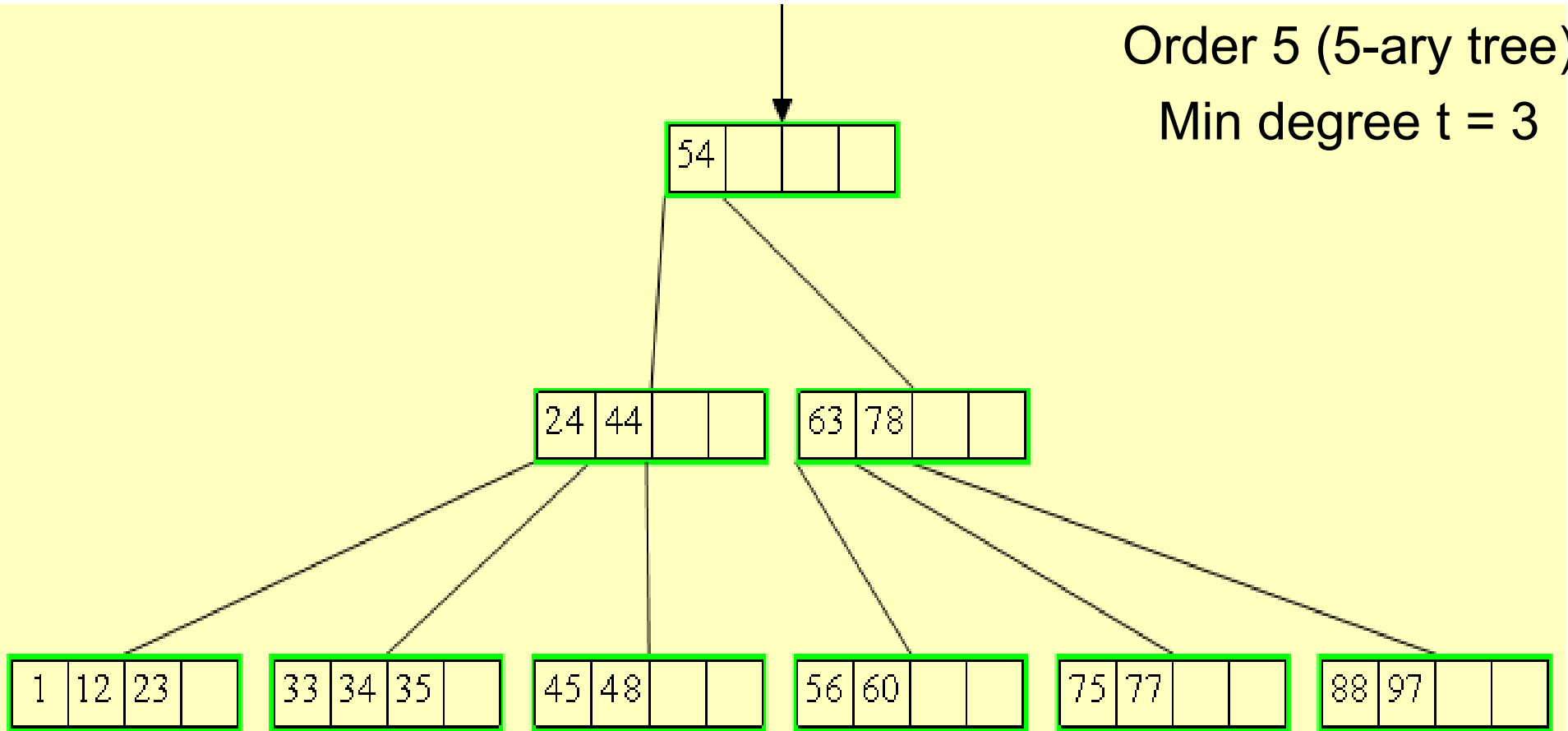
- For random sequences
 - => use *unsorted tree*, no waste time for rebalancing
- For mostly random ordering with occasional runs of sorted order
 - => use *red-black trees*
- For insertions often in a sorted order and
 - later accesses tend to be random => AVL trees
 - later accesses are sequential or clustered => splay trees
 - self adjusting trees,
 - update each search by moving searched element to the root



B-tree as BST on disk

B-tree

Order 5 (5-ary tree)
Min degree $t = 3$



Based on [Cormen] and [Maire]

B-tree

1. Motivation
2. Multiway search tree
3. B-tree
4. Search
5. Insert
6. Delete

B-tree

Motivation

- Large data do not fit into operational memory -> disk
- Time for disk access is limited by HW
(Disk access = Disk-Read, Disk-Write)
- Disk access is MUCH slower compared to instruction
 - 1 disk access ~ 13 000 000 instructions!!!!
 - Number of disk accesses dominates the computational time

DISK : 16 ms
Seek 8ms + rotational
delay 7200rpm 8ms

Instruction:
800 MHz 1,25ns

B-tree

Motivation

Disk access = Disk-Read, Disk-Write

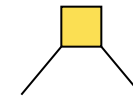
- Disk divided into blocks
(512, 2048, 4096, 8192 bytes)
- Whole block transferred

- Design a *multiway search tree*
- Each node fits to one disk block

B-tree

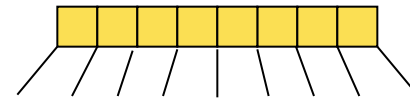
Multiway search tree

= a generalization of Binary search tree



($m=2$)

Each node has at most m children



($m>2$)

Internal node with n keys has $n+1$ successors, $n < m$

(except root)

Leaf nodes with no successors

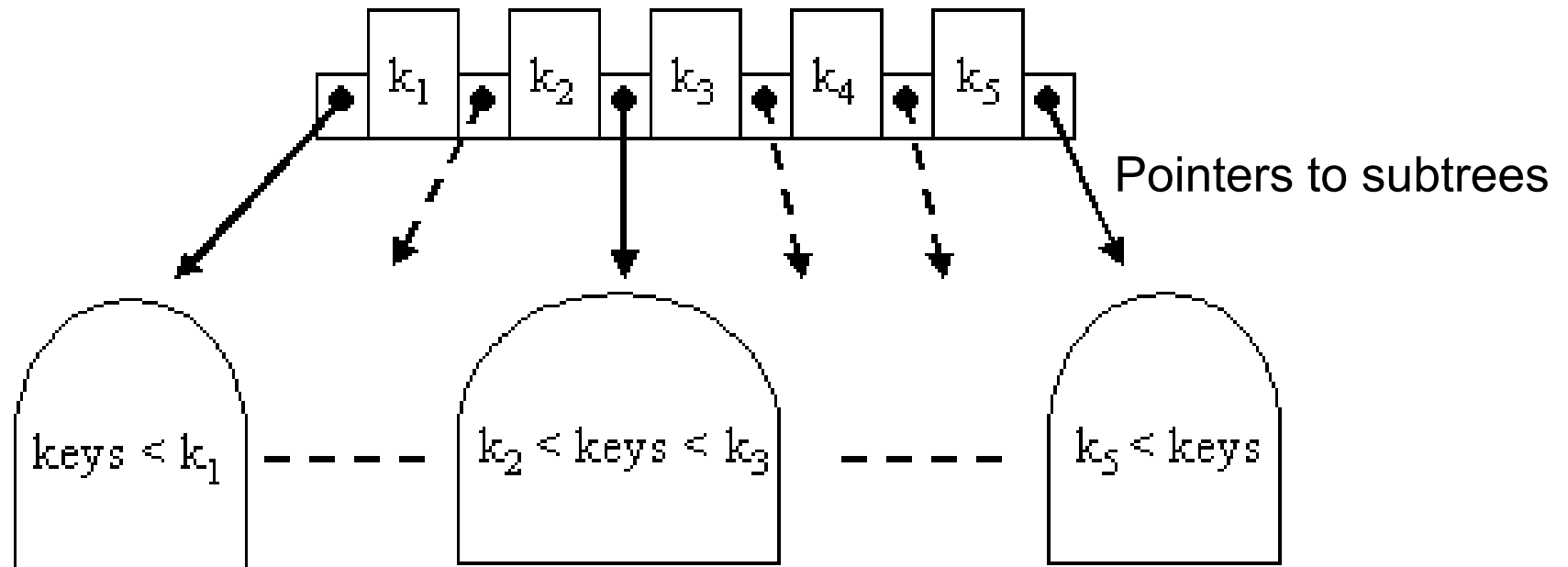
Tree is ordered %

Keys in nodes separates the ranges in subtrees %

B-tree

Multiway search tree – internal node

Keys in internal node separate the ranges of keys in subtrees



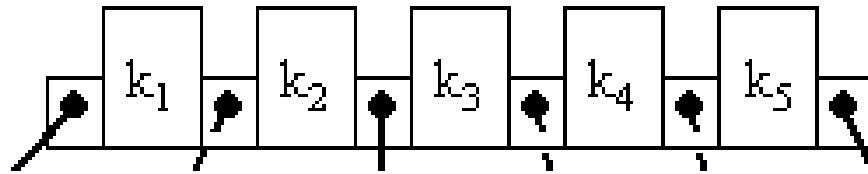
$$k_1 < k_2 < \dots < k_5$$

© Frederic Maire, QUT

B-tree

Multiway search tree – leaf node

Leaves have no subtrees and do not use pointers



Leaves have no pointers to subtrees

$$k_1 < k_2 < \dots < k_5$$

© Frederic Maire, QUT

B-tree

B-tree

= of order m is an m -way search tree, such that

- All **leaves** have the same height (B-tree is balanced)
- All **internal nodes** are constrained to have
 - at least $m/2$ non-empty children and (precisely later)
 - at most m non-empty children
- The **root** can have 0 or between 2 to m children
 - 0 - leaf
 - m - a **full node**

B-tree

B-tree – problems with notation

Different authors use different names

- Order m B-tree
 - Maximal number of children
 - Maximal number of keys (No. of children - 1)
 - Minimal number of keys
- Minimum degree t
 - Minimal number of children [Cormen]

B-tree

B-tree – problems with notation

Relation between minimal and maximal number of children also differs

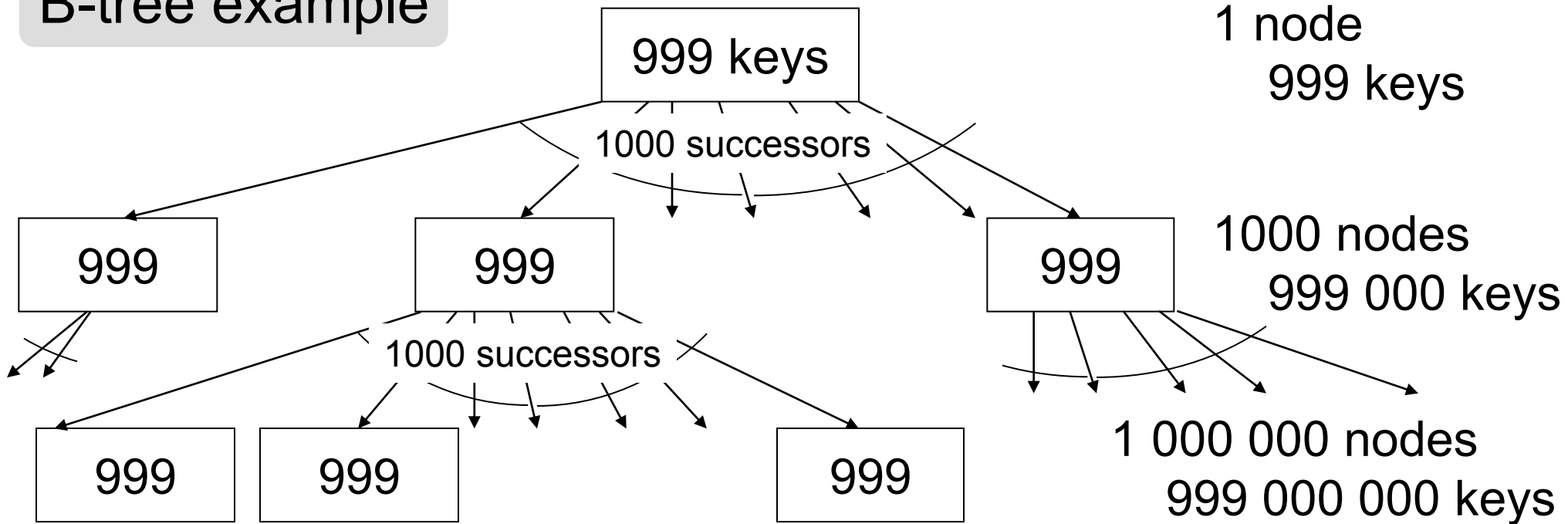
For minimal number t of children

Maximal number m of children is

- $m = 2t - 1$ simple B-tree,
multiphase update strategy
- $m = 2t$ optimized B-tree,
singlephase update strategy

B-tree

B-tree example



B-tree of order $m=1000$ of height 2 contains

1 001 001 nodes ($1+1000 + 1\ 000\ 000$)

999 999 999 keys ~ one billion keys (1 miliarda klíčů)

B-tree

B-tree node fields

n ... number of keys k_i stored in the node $n < m$.

Node with $n = m-1$ is a **full-node**

k_i ... n keys, stored in non-decreasing order

$$k_1 \leq k_2 \leq \dots \leq k_n$$

leaf ... boolean value, true for leaf, false for internal node

c_i ... $n+1=m$ pointers to successors (undefined for leaves)

Keys k_i separate the keys in subtree:

For $keys_j$ in the subtree with root k_j holds

$$keys_1 \leq k_1 \leq keys_2 \leq k_2 \leq \dots \leq k_n \leq keys_{n+1}$$

B-tree

B-tree algorithms

- Search
- Insert
- Delete

B-tree search

Similar to BST tree search

Keys in nodes sequentially or binary search

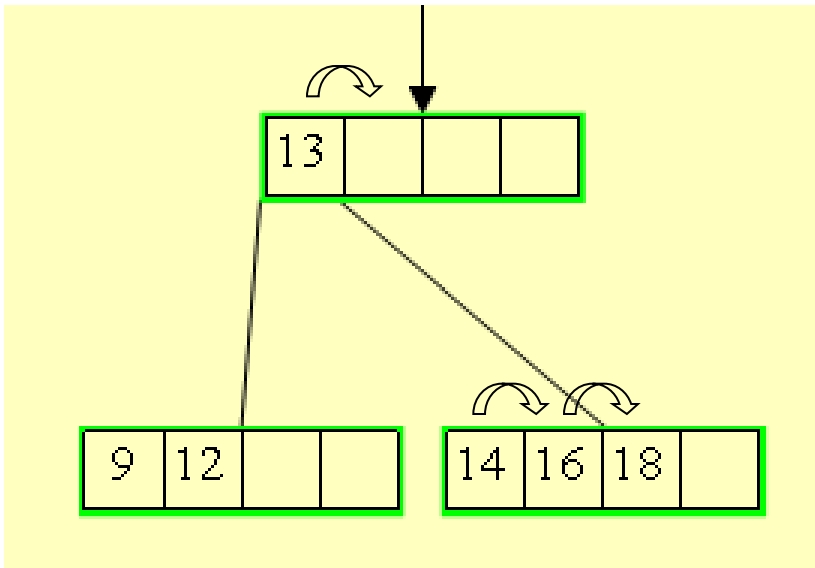
Input: pointer to tree root and a key k

Output: an ordered pair (y, i) , node y and index i
such that $y.k[i] = k$
or NIL, if k not found

B-tree search

Search 17

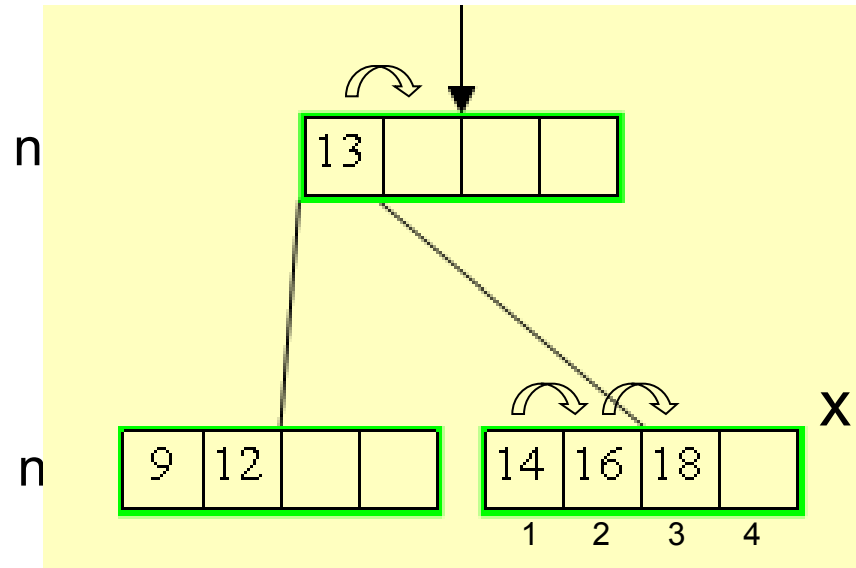
17



17 not found => return NIL

Search 18

18



18 found => return (x, 3)

B-tree search

```
B-treeSearch(x, k)
```

```
  i ← 1
```

```
  while i ≤ x.n and k > x.k[i]           // sequential search
```

```
    do i ← i+1
```

```
  if i ≤ x.n and k = x.k[i]
```

```
    return (x, i)                       // pair: node & index
```

```
  if x.leaf
```

```
    then return NIL
```

```
    else
```

```
      Disk-Read(x.c[i]) // tree traversal
```

```
      return B-treeSearch(x.c[i], k)
```

B-tree search

B-treeSearch complexity

Using tree order m

Number of disk pages read is

$$O(h) = O(\log_m n)$$

Where h is tree *height* and

m is the tree order

n is number of tree nodes

Since num. of keys $x.n < m$, the while loop takes $O(m)$

and

total time is **$O(m \log_m n)$**

B-tree search

B-treeSearch complexity

Using minimum degree t

Number of disk pages read is

$$O(h) = O(\log_t n)$$

Where h is tree *height* and

t is the minimum degree of B-tree

n is number of tree nodes

Since num. of keys $x.n < 2t$, the while loop takes $O(t)$

and

total time is **$O(t \log_t n)$**

B-tree update strategies

Two principal strategies

1. Multiphase strategy

“solve the problem, when appears” $m=2t-1$ children

2. Single phase strategy [Cormen]

“avoid the future problems” $m = 2t$ children

Actions:

Split full nodes

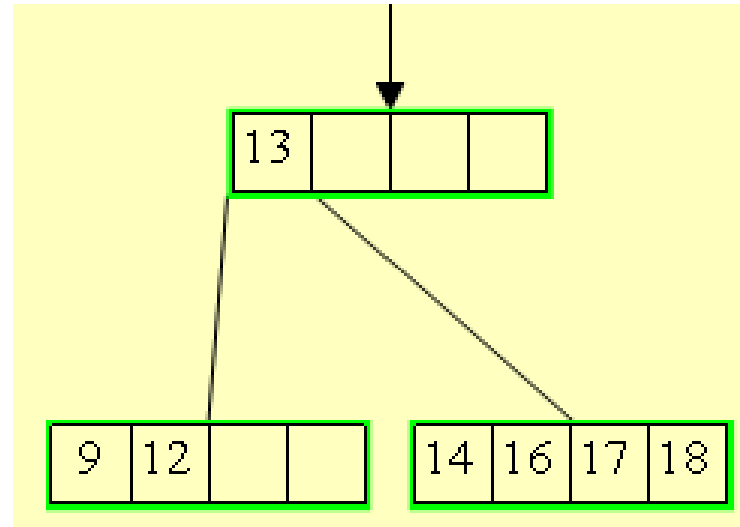
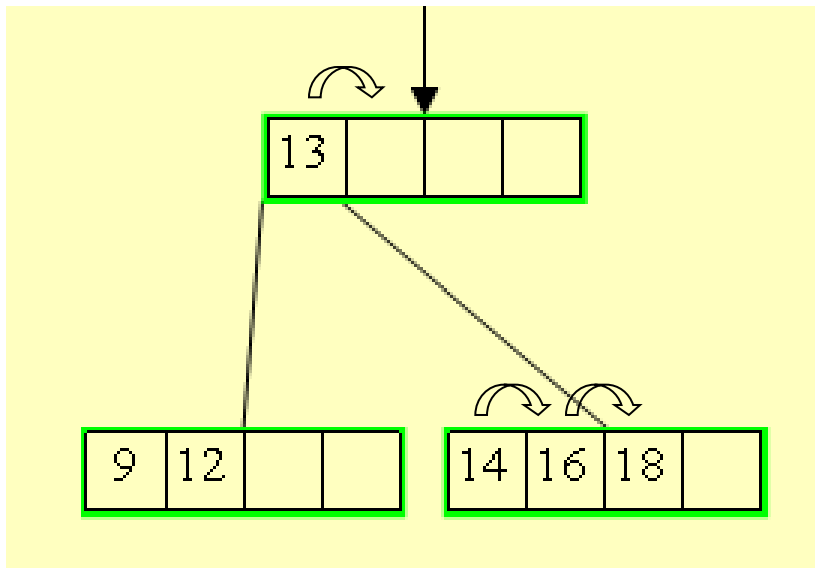
Merge nodes with less than minimum entries

B-tree insert - 1. Multiphase strategy

Insert to a **non-full** node

Insert 17

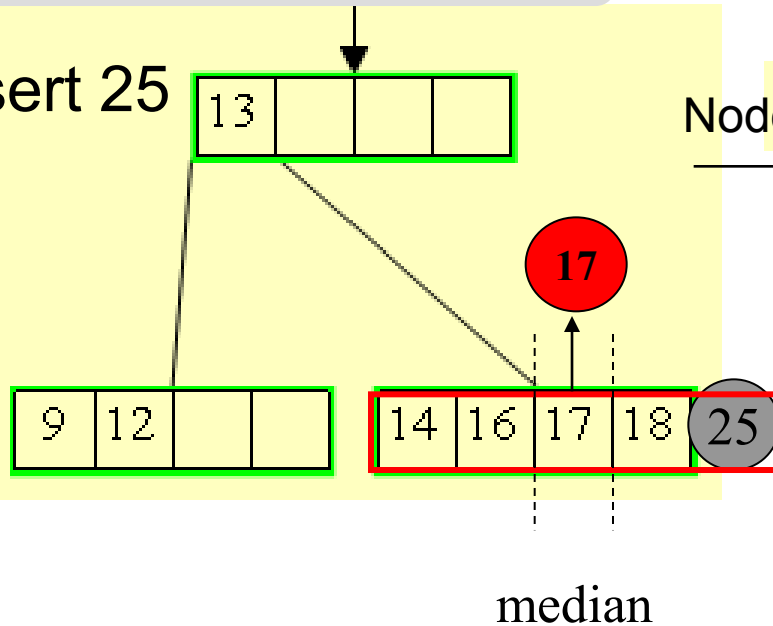
17



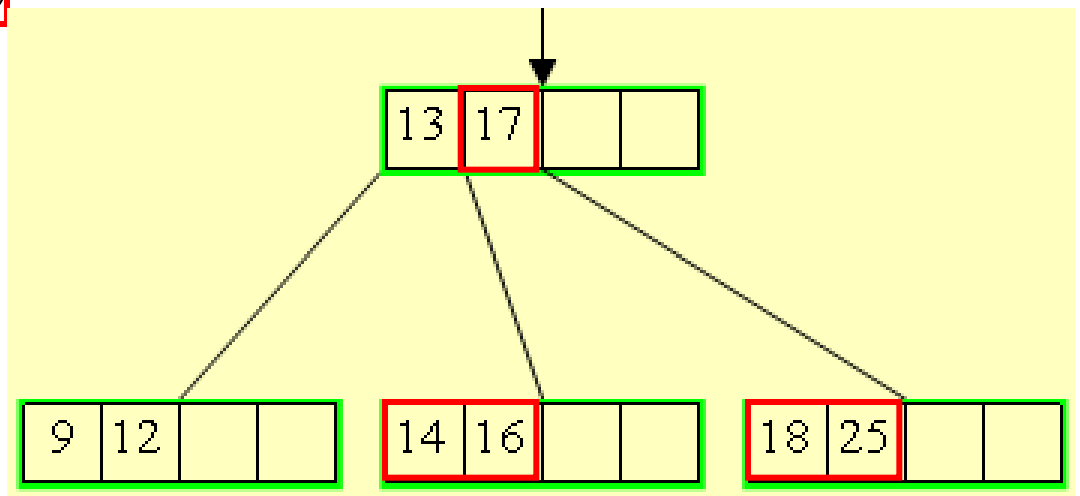
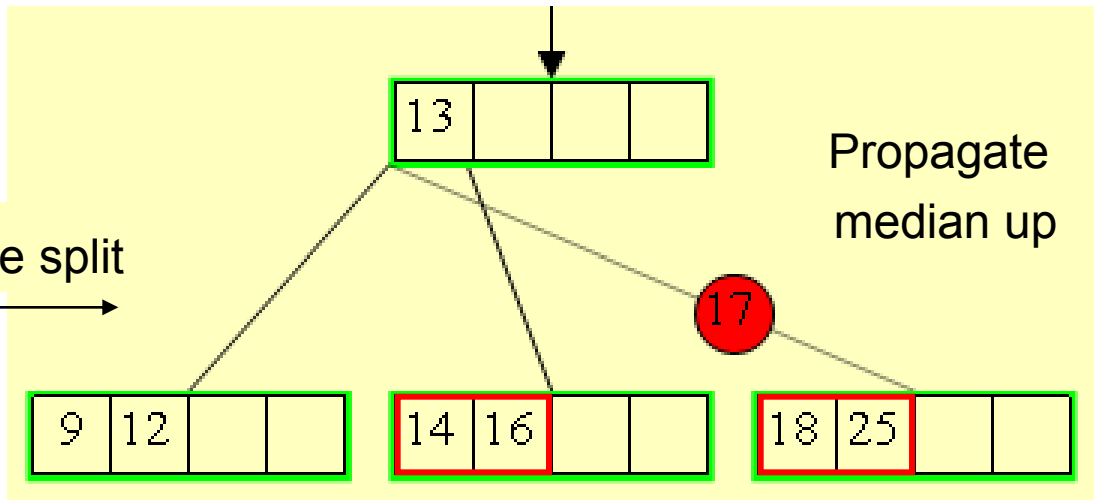
B-tree insert - 1. Multiphase strategy

Insert to a full node

Insert 25



Node split



1. Multiphase strategy
"solve the problem, when appears"

B-tree insert - 1. Multiphase strategy

Insert (x, T) - pseudocode

x ...key, T ...tree

Find the leaf for x

Top down phase

If not full, insert x and stop

while (current_node full) (node overflow)

find median (in keys in the node after insertion of x)

split node into two

Bottom-up phase

promote median up as new x

current_node = parent of current_node or new root

Insert x and stop

B-tree insert - 2. Singlephase strategy

Principle: “avoid the future problems”

Top down phase only

- Split the full node with $2t-1$ keys when enter
- It creates space for future medians from the children
- No need to go bottom-up

- Splitting of
 - Root \Rightarrow tree grows by one
 - Inner node or leaf \Rightarrow parent gets median key

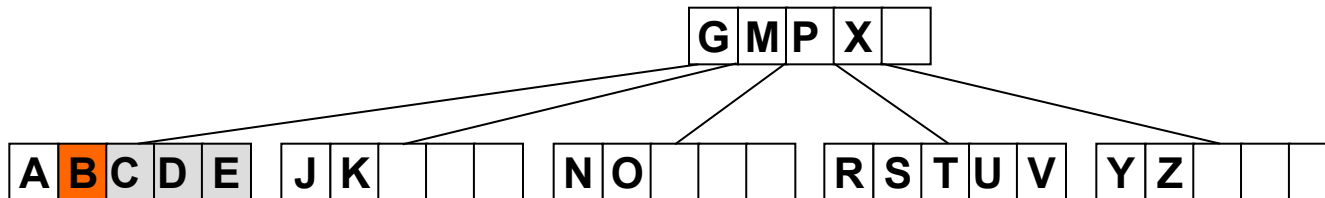
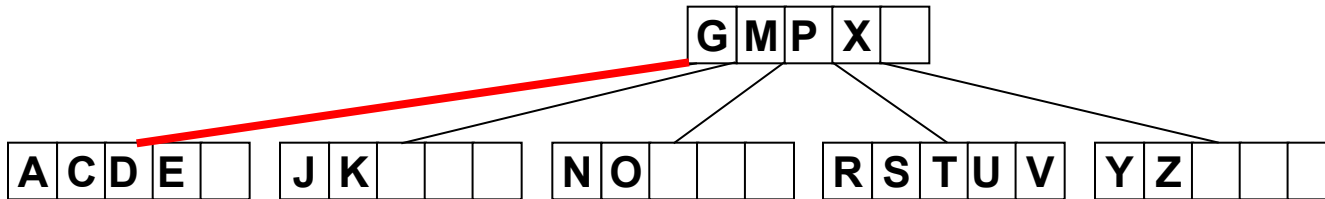
B-tree insert - 2. Singlephase strategy

Insert to a **non-full** node

$m = 2t = 6$ children

$m-1$ keys = odd max number

Insert B

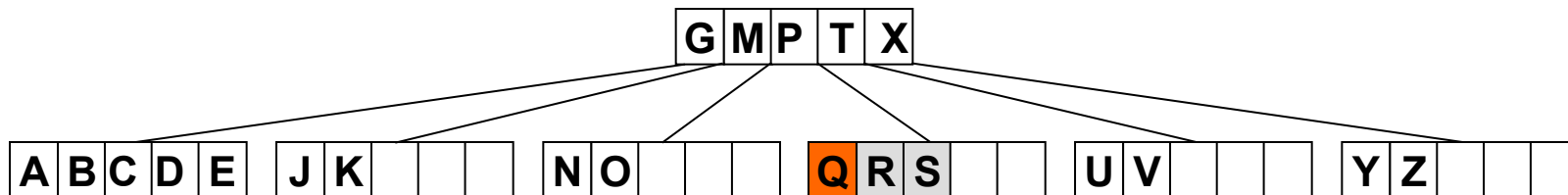
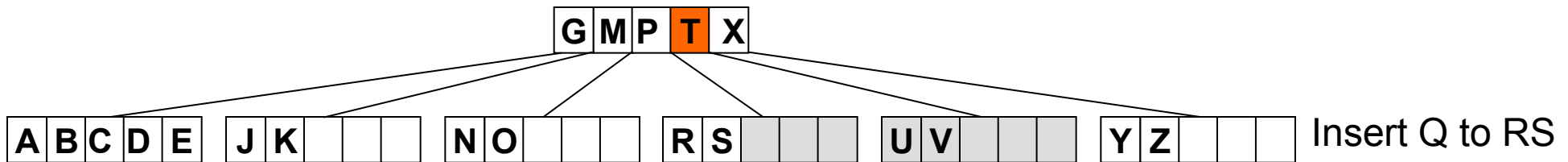
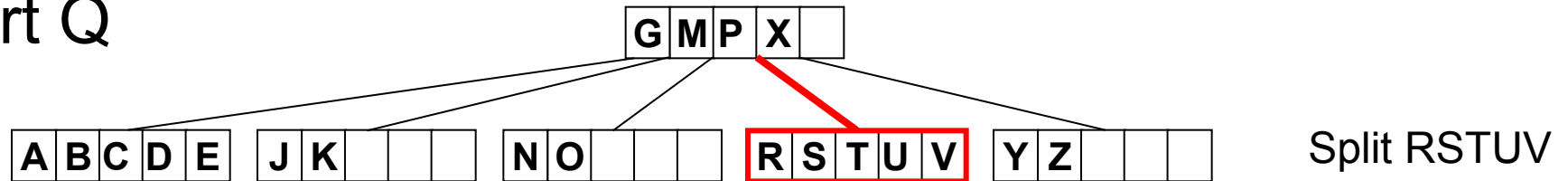


B-tree insert - 2. Singlephase strategy

1 new node

Splitting a passed **full node** and insert to a **not full** node

Insert Q

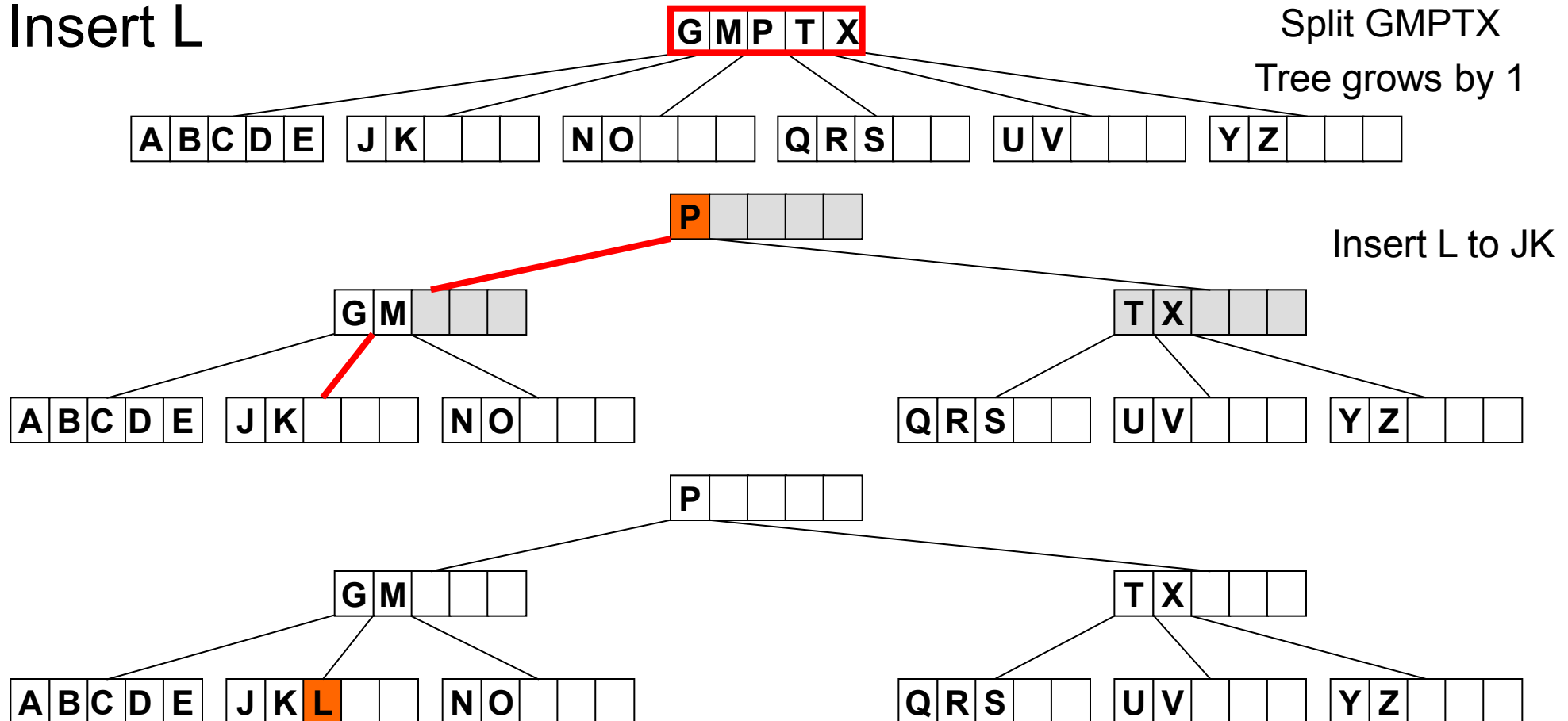


B-tree insert - 2. Singlephase strategy

2 new nodes

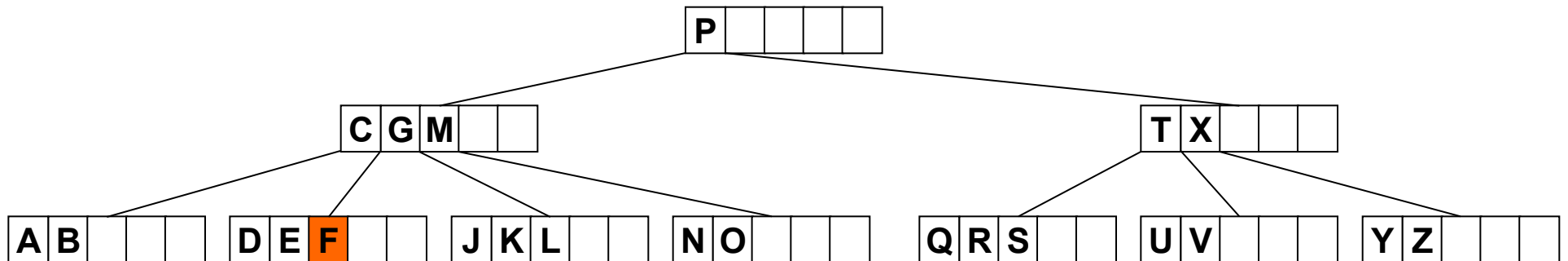
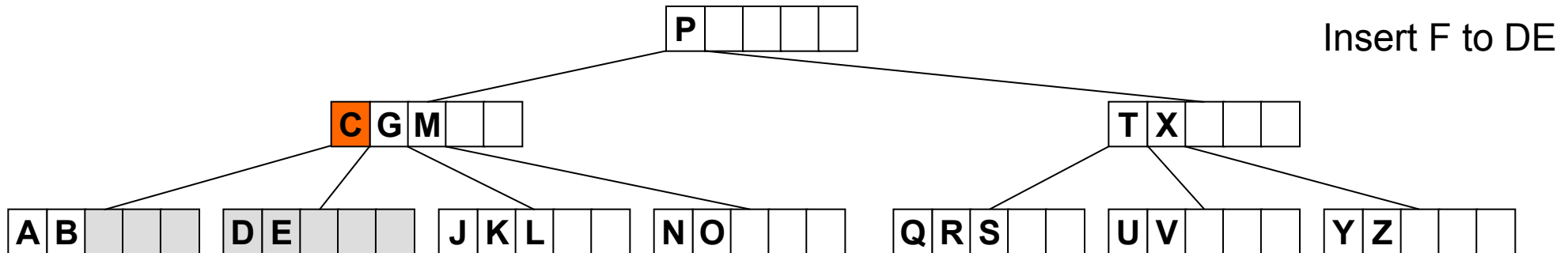
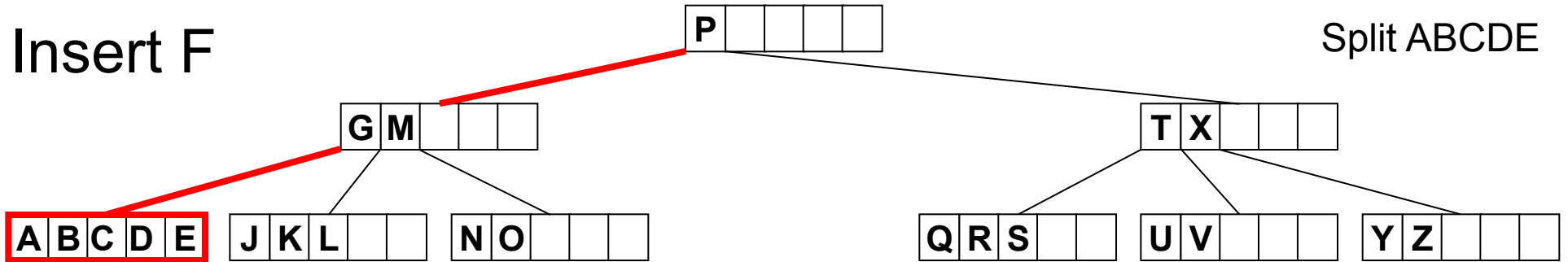
Splitting a passed **full root** and insert to a **not full** node

Insert L



B-tree insert - 2. Singlephase strategy

Insert F



B-tree insert - 2. Singlephase strategy

Insert (x, T) - pseudocode

Top down phase only

While searching the leaf x

x ...key, T... tree

if (node full)

 find median (in keys in the full node only)

 split node into two

 insert median to parent (there is space)

Insert x and stop

B-tree delete

Delete (x, btree) - principles

- Search for value to delete
- Entry is in **leaf**
 - is simple to delete. Do it. Corrections of number of elements later...
- Entry is in **Inner node**
 - It serves as separator for two subtrees
 - swap it with predecessor(x) or successor(x)
 - and delete in leaf

Leaf in detail

if leaf had more than minimum number of entries
delete x from the leaf and STOP

else

redistribute the values to correct and delete x in leaf
(may move the problem up to the parent,
problem stops by root, as it has no minimum number of entries)

Multipass strategy only

B-tree delete

Node has less than minimum entries

- Look to siblings left and right
- If one of them has more than minimum entries

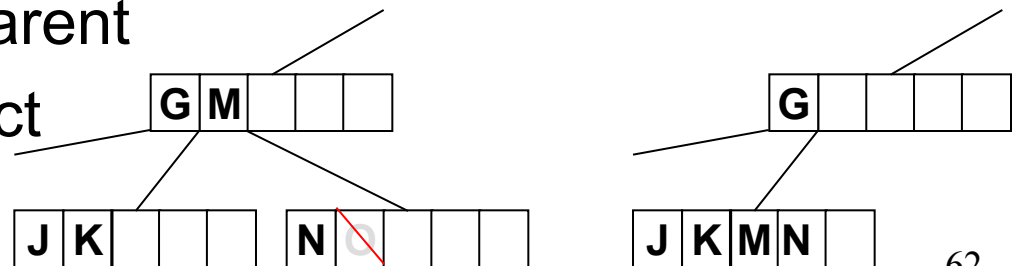
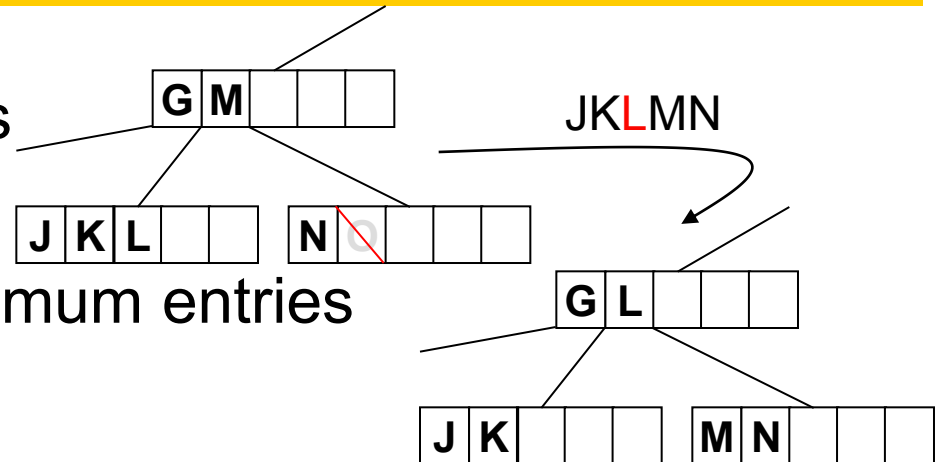
- Take some values from it
- Find new median in the sequence:

(sibling values – separator- node values)

- Make new median a separator (store in parent)

- Both siblings are on minimum

- Collapse node – separator – sibling to one node
- Remove separator from parent
- Go up to parent and correct



B-tree delete

Delete (x, btree) - pseudocode

Multipass strategy only

if (x to be removed is not in a leaf)

 swap it with successor(x)

currentNode = leaf

while (currentNode underflow)

 try to redistribute entries from an immediate
 sibling into currentNode via its parent

if (impossible) then merge currentNode with a
 sibling and one entry from the parent

 currentNode = parent of currentNode

Maximum height of B-tree

$$h \leq \log_{\lceil m/2 \rceil} ((n+1)/2)$$

half node used for k,
half of children

Gives the upper bound to number of disk accesses

See [Maire] or [Cormen] for details

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