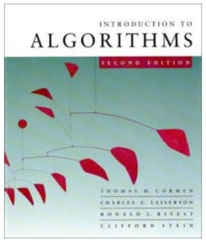
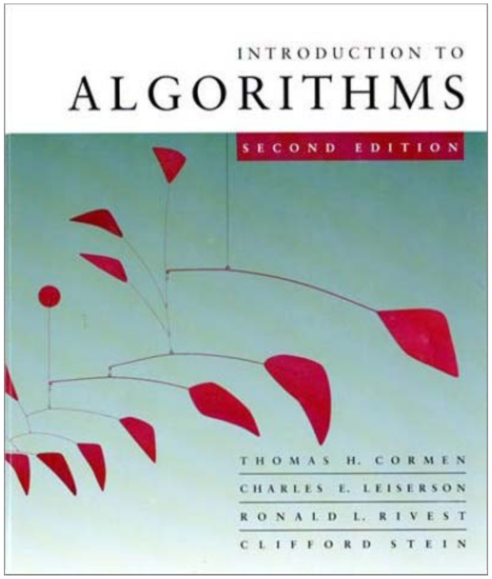
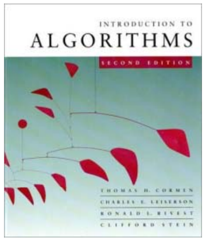


CS 3343 -- Fall 2011



B-trees

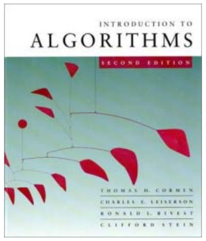
Carola Wenk



External memory dictionary

Task: Given a large amount of data that does not fit into main memory, process it into a dictionary data structure

- Need to minimize number of disk accesses
- With each disk read, read a whole block of data
- Construct a balanced search tree that uses one disk block per tree node
- Each node needs to contain more than one key

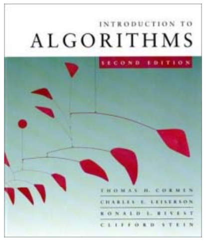


k-ary search trees

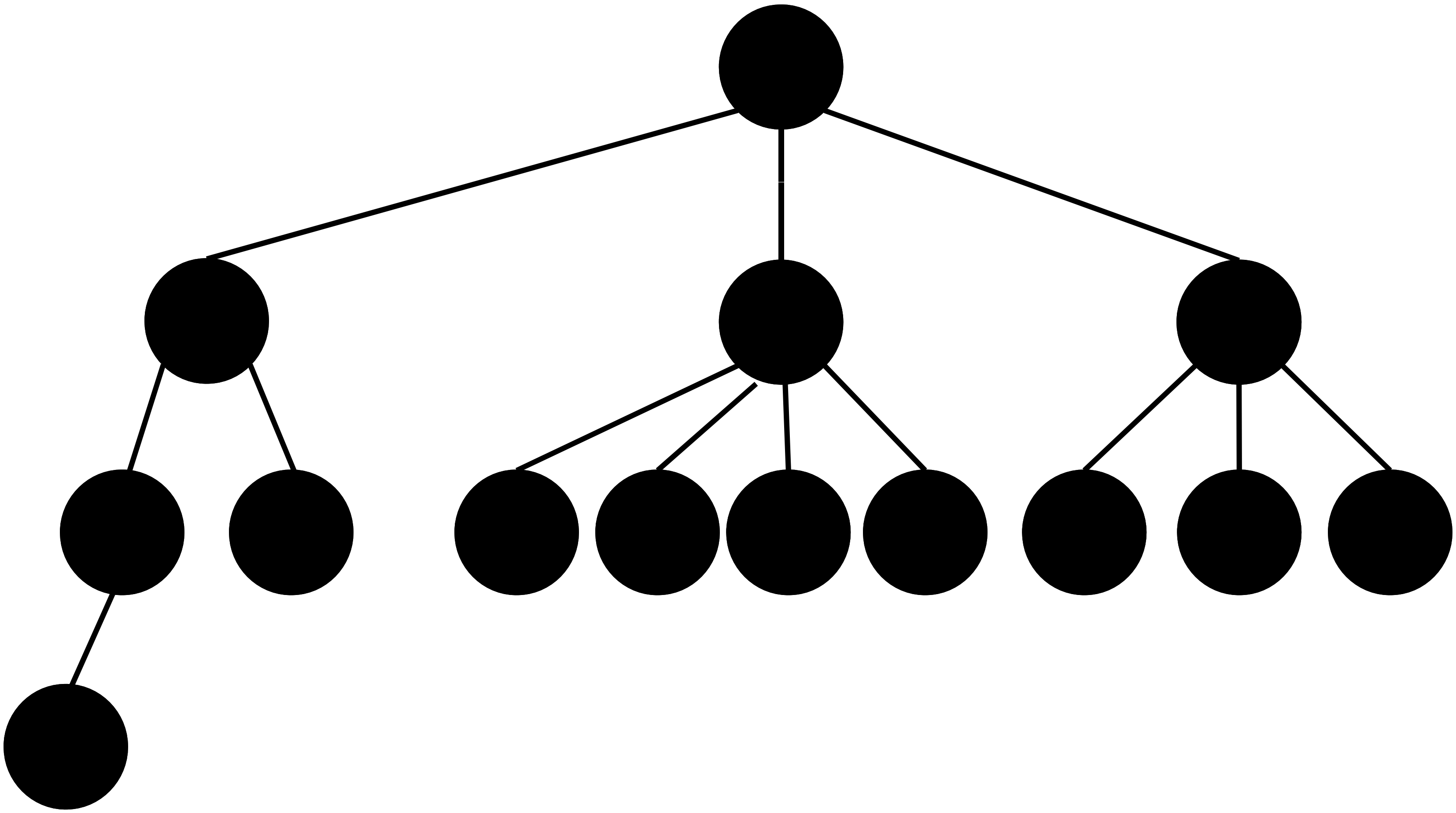
A ***k*-ary search tree** T is defined as follows:

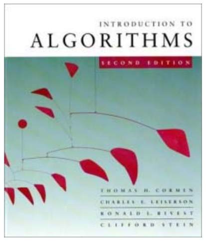
- For each node *x* of T:
  - *x* has at most *k* children (i.e., T is a *k*-ary tree)
  - *x* stores an ordered list of pointers to its children, and an ordered list of keys
  - For every internal node: #keys = #children-1
  - *x* fulfills the search tree property:

  keys in subtree rooted at *i*-th child $\leq$ *i*-th key $<$ keys in subtree rooted at $(i+1)$-st child

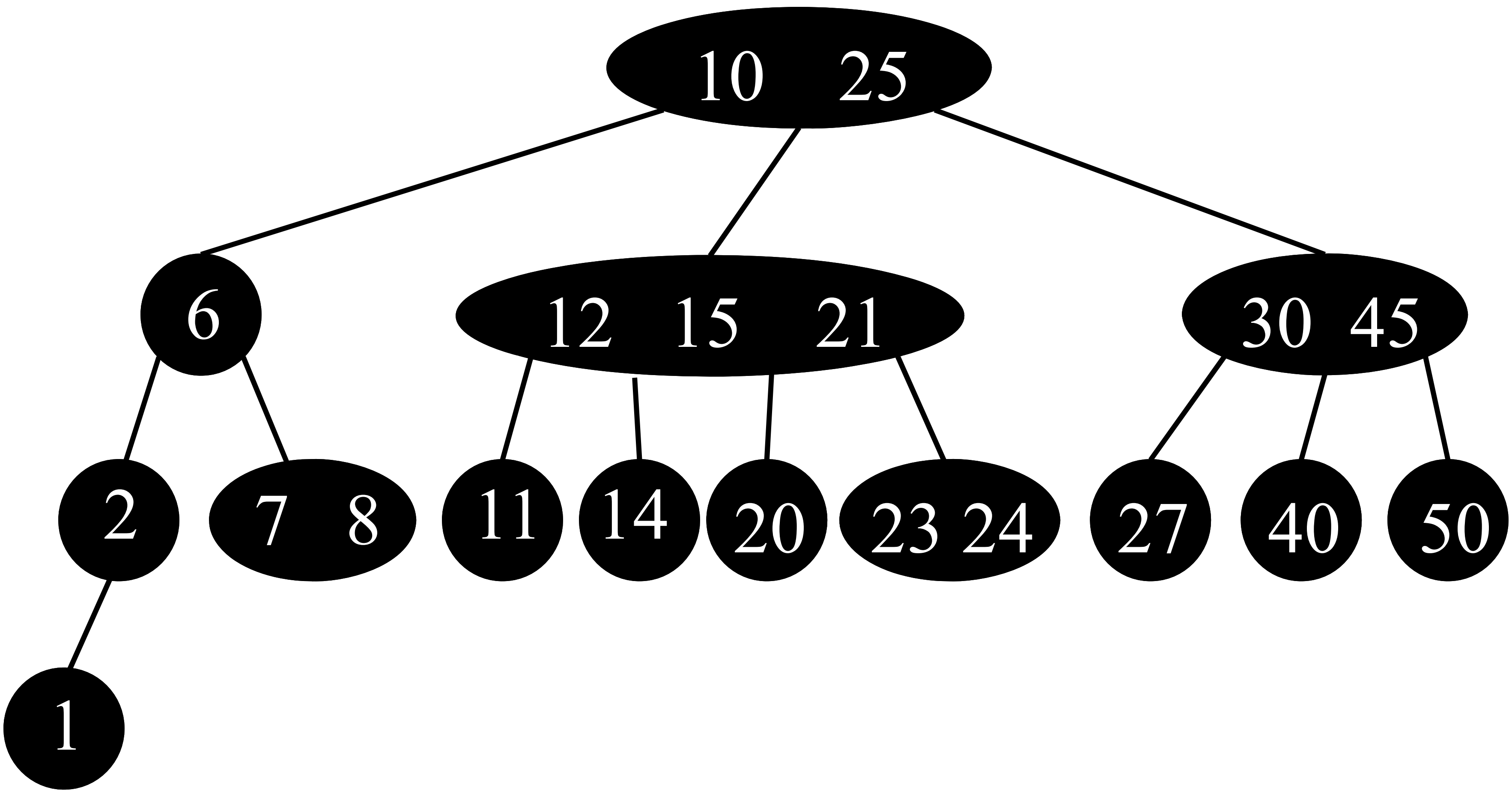


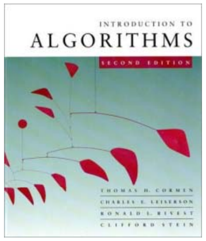
Example of a 4-ary tree





Example of a 4-ary search tree

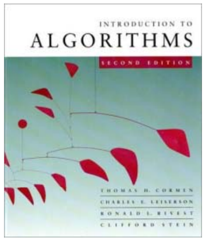




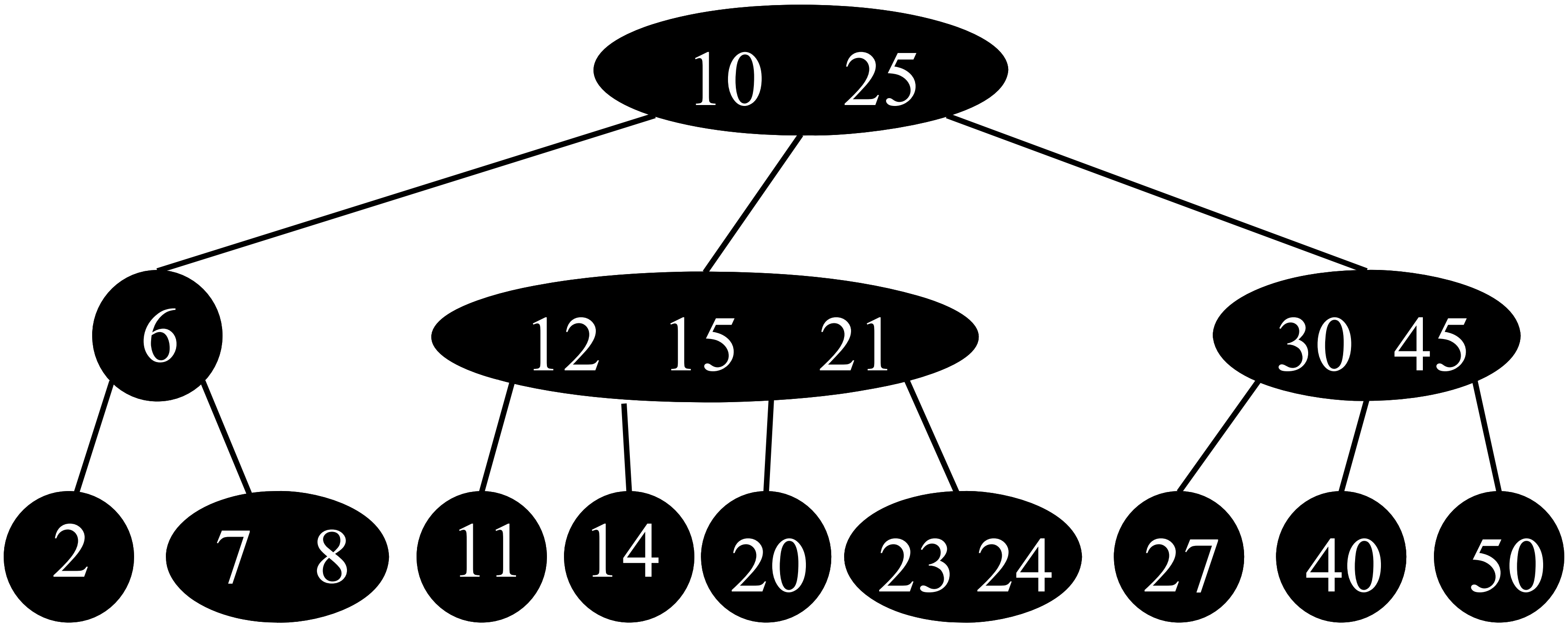
B-tree

A ***B*-tree** T with **minimum degree** $k \geq 2$ is defined as follows:

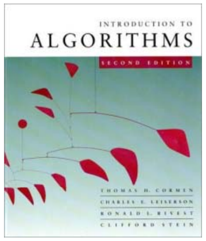
1. T is a $(2k)$-ary search tree
2. Every node, except the root, stores at least k-1 keys
   (every internal non-root node has at least k children)
3. The root must store at least one key
4. All leaves have the same depth



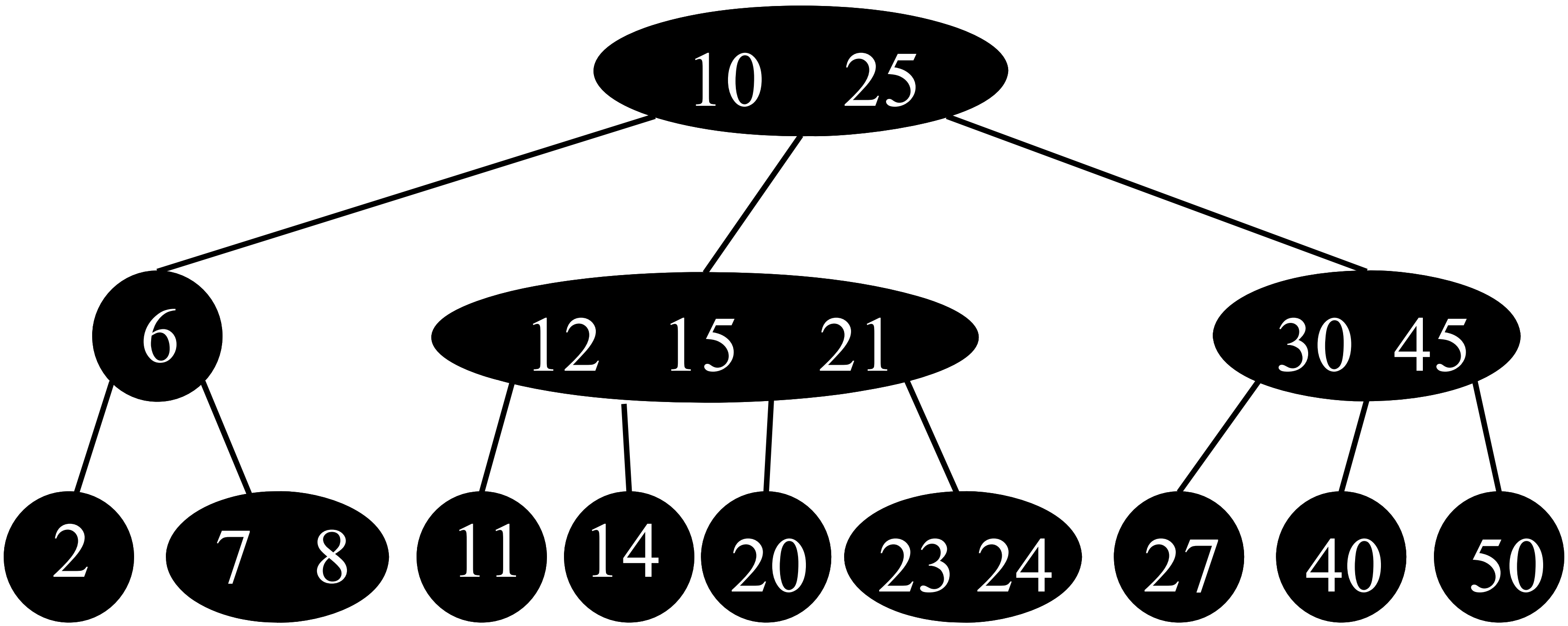
B-tree with k=2



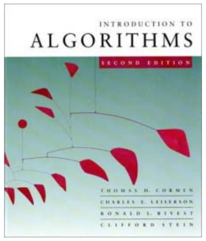
1. T is a $(2k)$-ary search tree



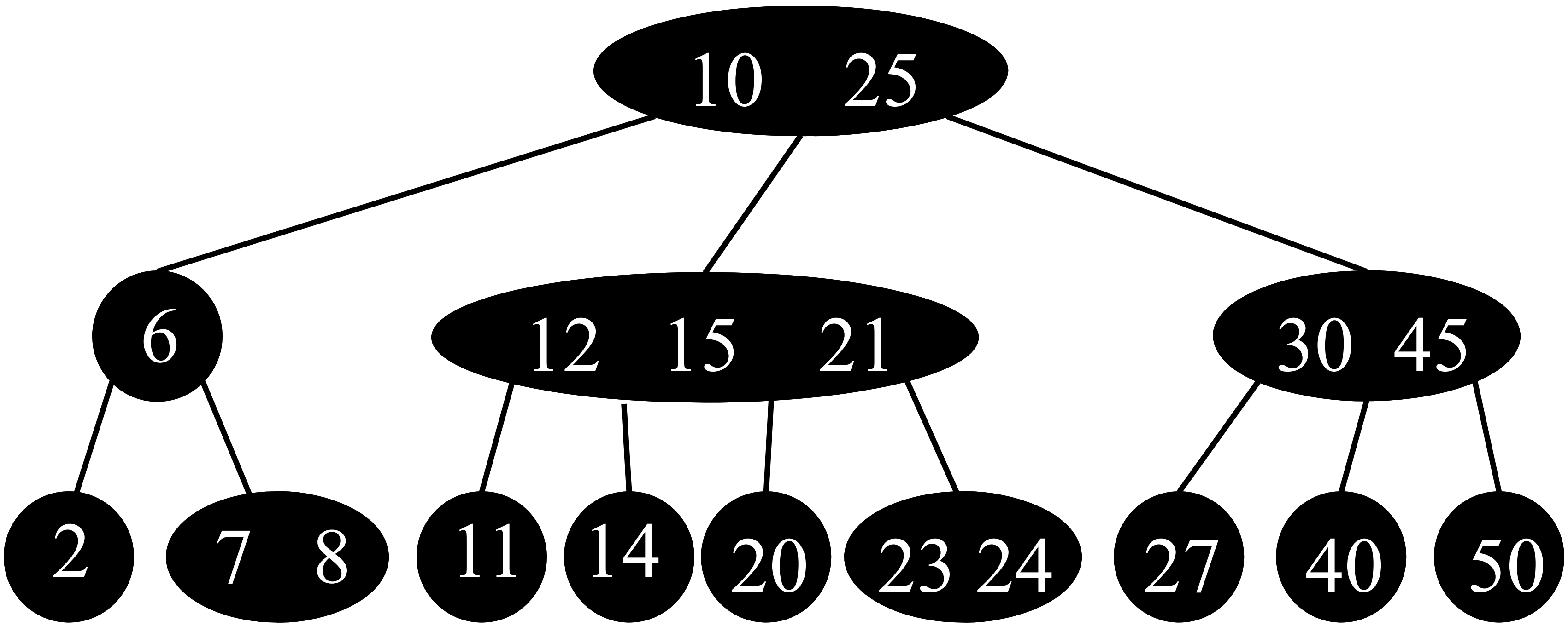
B-tree with k=2



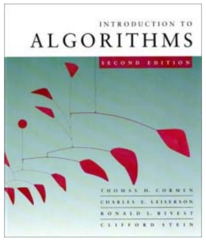
2. Every node, except the root, stores at least k-1 keys



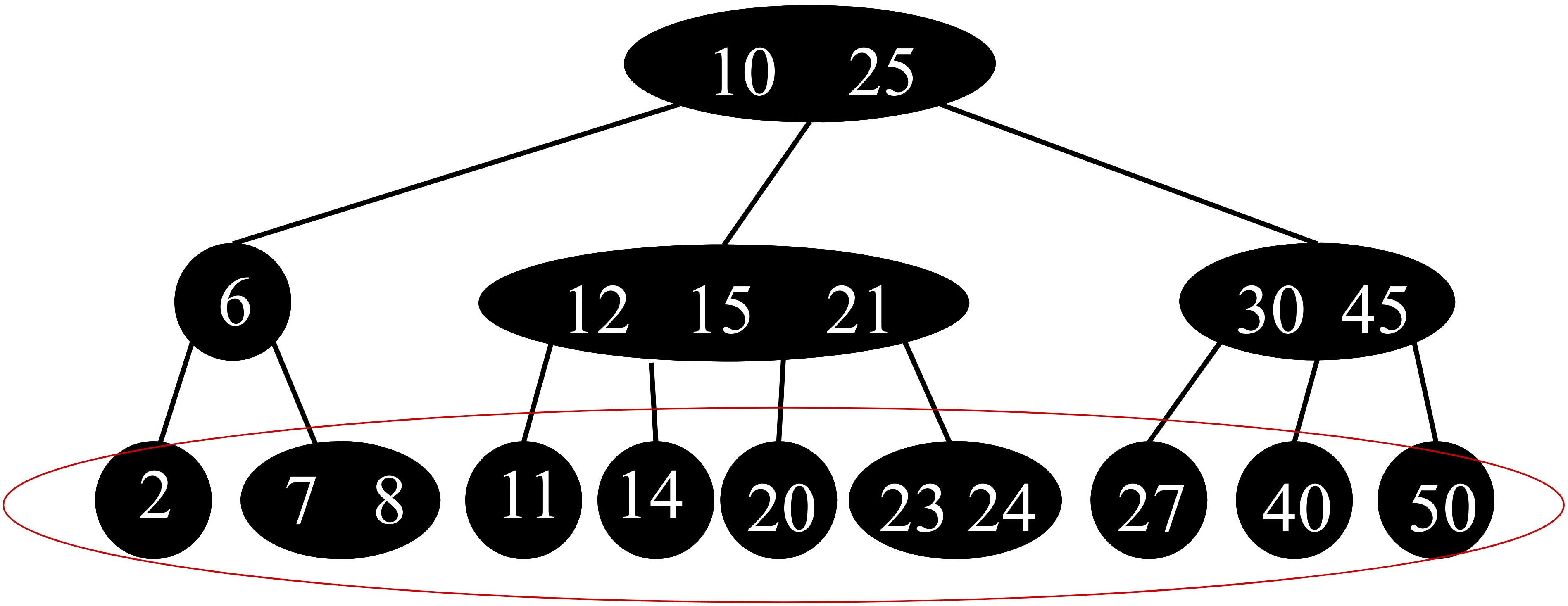
B-tree with *k*=2



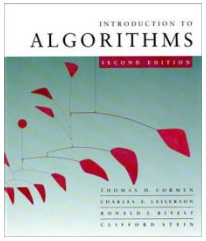
3. The root must store at least one key



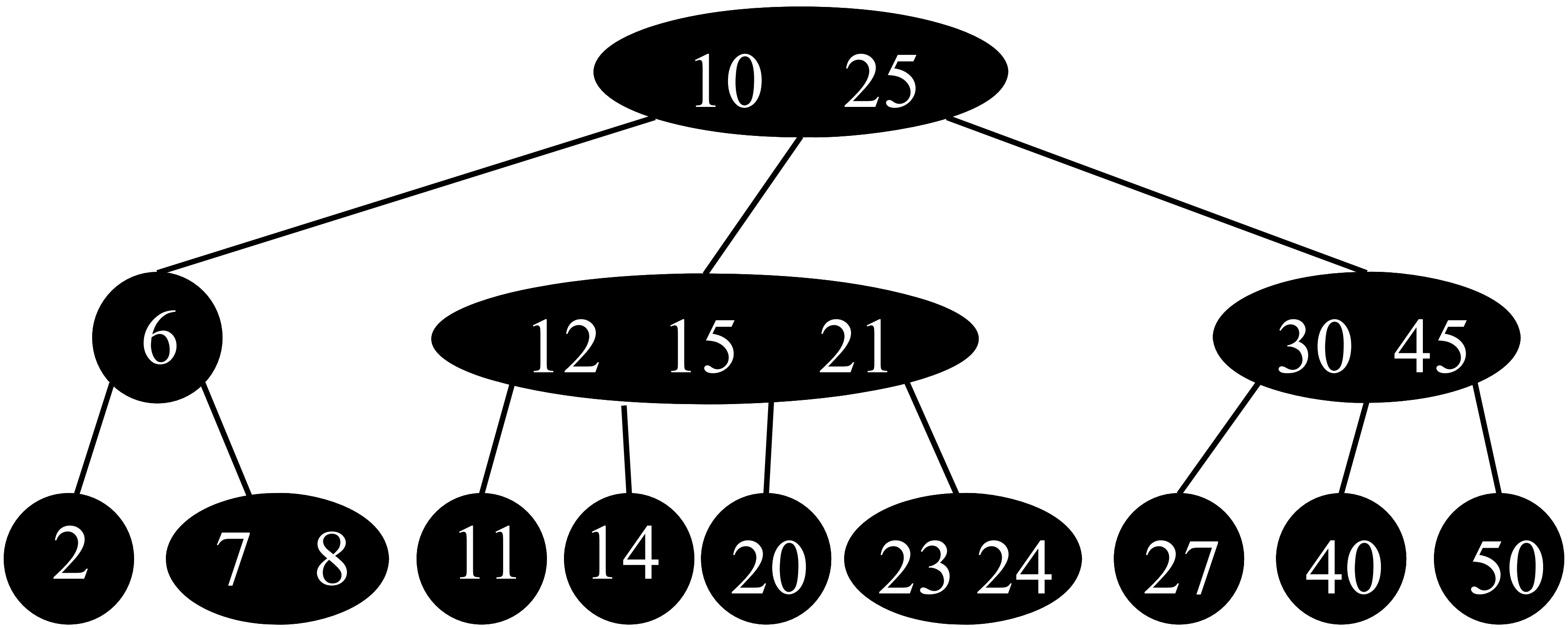
B-tree with *k*=2



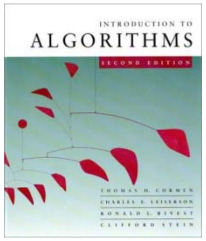
4. All leaves have the same depth



B-tree with *k*=2



Remark: This is a (2,3,4)-tree.



Height of a B-tree

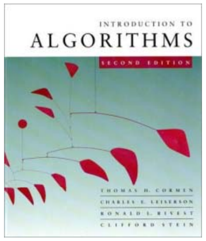
Theorem: For a B-tree with minimum degree $k \geq 2$ which stores n keys has height h holds:

$$h \leq \log_k (n+1)/2$$

Proof: #nodes $\geq 1+2+2k+2k^2+\ldots+2k^{h-1}$

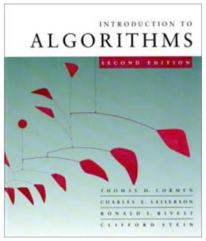
level 0, level 1, level 2, level 3

$$n = \#\text{keys} \geq 1+(k-1)\sum_{i=0}^{h-1} 2k^i = 1+2(k-1)\cdot \frac{k^h-1}{k-1} = 2k^h-1$$



B-tree search

```
B-TREE-SEARCH(x,key)
    i ← 1
    while i≤#keys of x and key > i-th key of x
        do  i ← i+1
    if i≤#keys of x and key = i-th key of x
        then return (x,i)
    if x is a leaf
        then return NIL
    else b=DISK-READ(i-th child of x)
        return B-TREE-SEARCH(b,key)
```

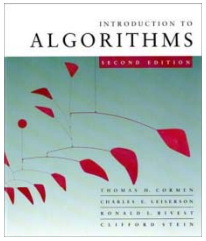


B-tree search runtime

- $O(k)$ per node
- Path has height $h = O(\log_k n)$
- CPU-time: $O(k \log_k n)$

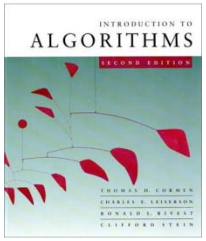
- Disk accesses: $O(\log_k n)$

  disk accesses are more expensive than CPU time



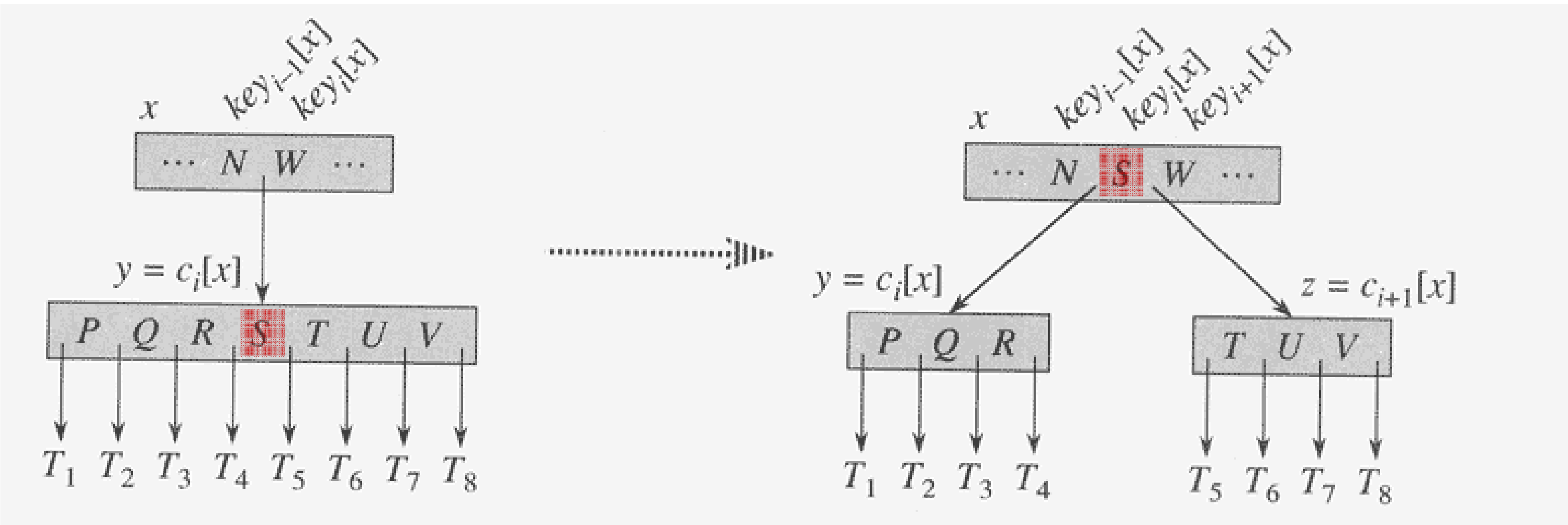
B-tree insert

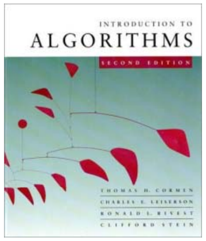
- There are different insertion strategies. We just cover one of them
- Make one pass down the tree:
  - The goal is to insert the new *key* into a leaf
  - Search where *key* should be inserted
  - **Only descend into non-full nodes:**
    - If a node is full, split it. Then continue descending.
    - **Splitting of the root node is the only way a B-tree grows in height**



B-TREE-SPLIT-CHILD(x,i,y)

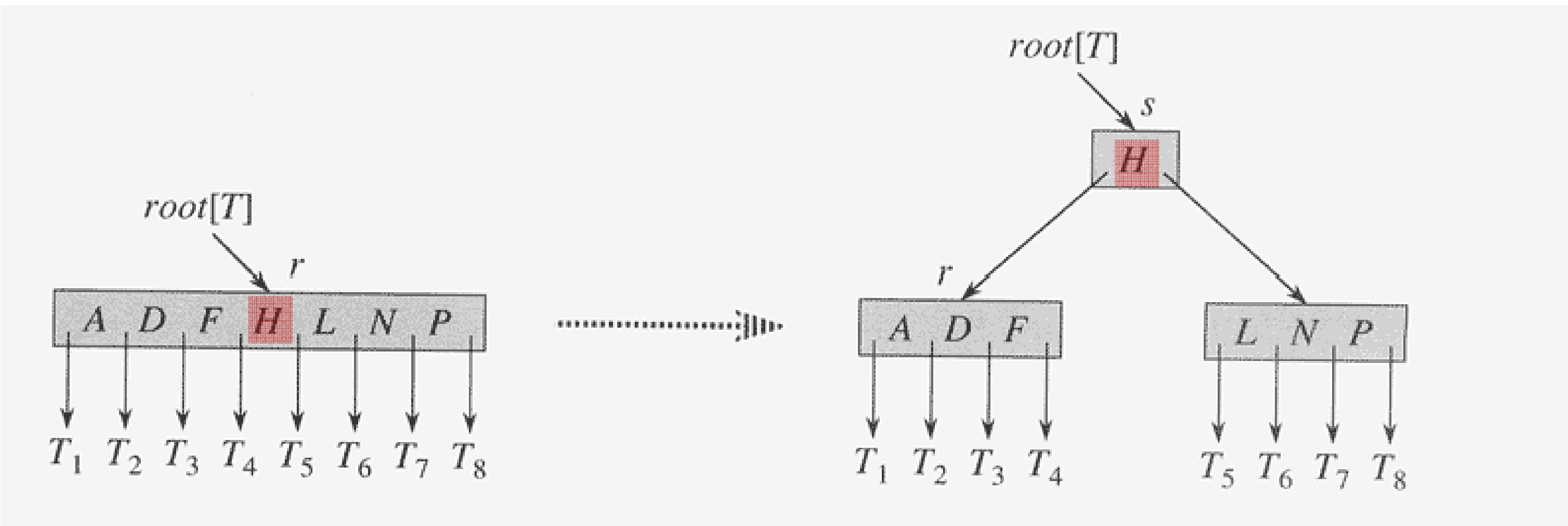
- Split full node y (has $2k$-1 keys) into two nodes y and z of k-1 keys
- Median key S of y is moved up into y's parent x
- Example below for $k = 4$

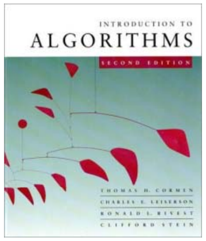




Split root: B-TREE-SPLIT-CHILD(*s*,*1*,*r*)

- The **full** root node *r* is split in two.
- A new root node *s* is created
- *s* contains the median key H of *r* and has the two halves of *r* as children
- Example below for $k = 4$





B-TREE-INSERT(*T*,*key*)

r = root[*T*]

if (# keys in *r*) = 2*k*-1 // root *r* is full

  //insert new root node:

  s ← ALLOCATE-NODE()

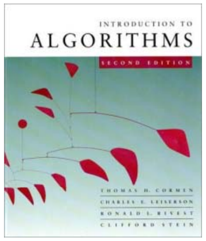
  root[*T*] ← s

  // split old root *r* to be two children of new root *s*

  B-TREE-SPLIT-CHILD(*s*,1,*r*)

  B-TREE-INSERT-NONFULL(*s*,*key*)

else B-TREE-INSERT-NONFULL(*r*,*key*)



B-TREE-INSERT-NONFULL(*x*,*key*)

if *x* is a leaf **then**

  insert *key* at the correct (sorted) position in *x*

  DISK-WRITE(*x*)

else

  find child *c* of *x* which by the search tree property should contain *key*

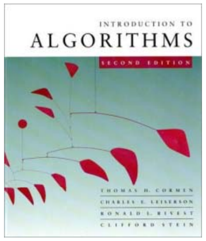
  DISK-READ(*c*)

  if *c* is full **then** // *c* contains $2k$-1 keys

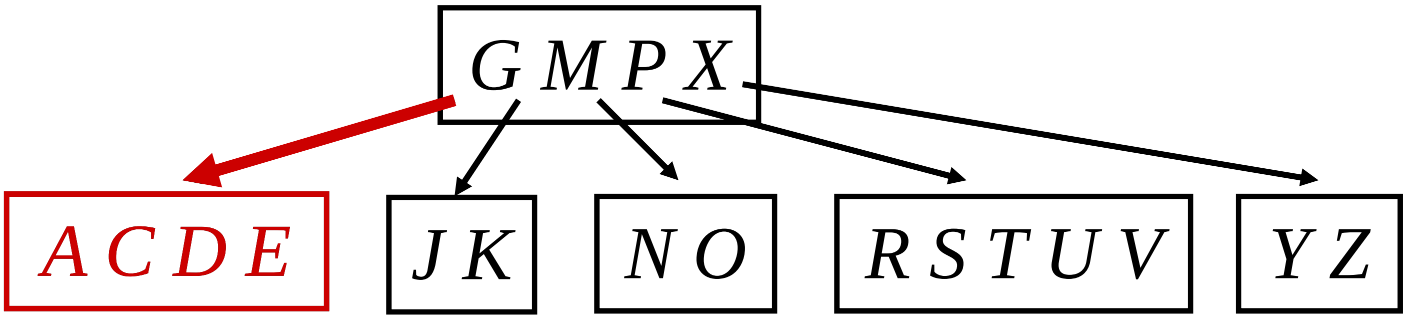
    B-TREE-SPLIT-CHILD(*x*,*i*,*c*)

    c=child of *x* which should contain *key*

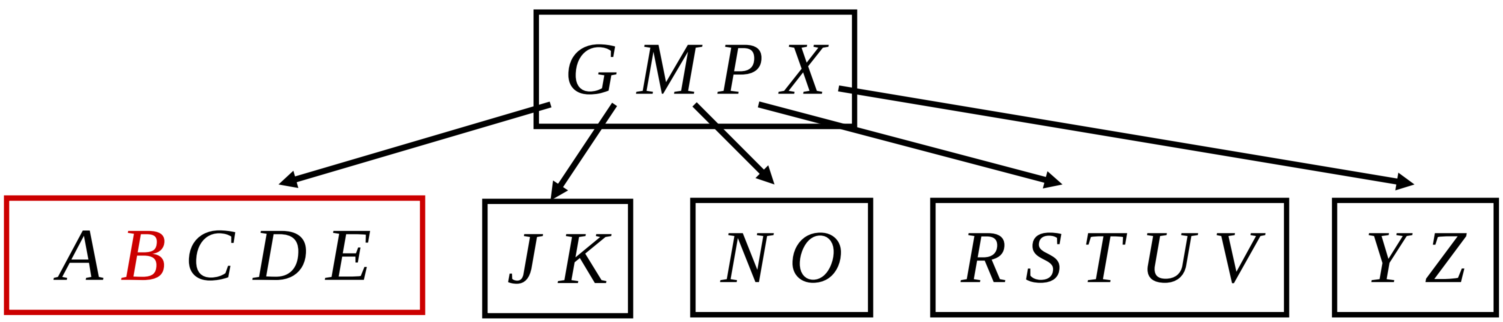
  B-TREE-INSERT-NONFULL(*c*,*key*)

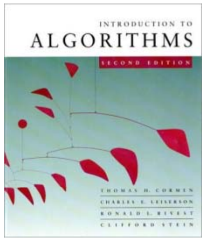


Insert example (k=3)

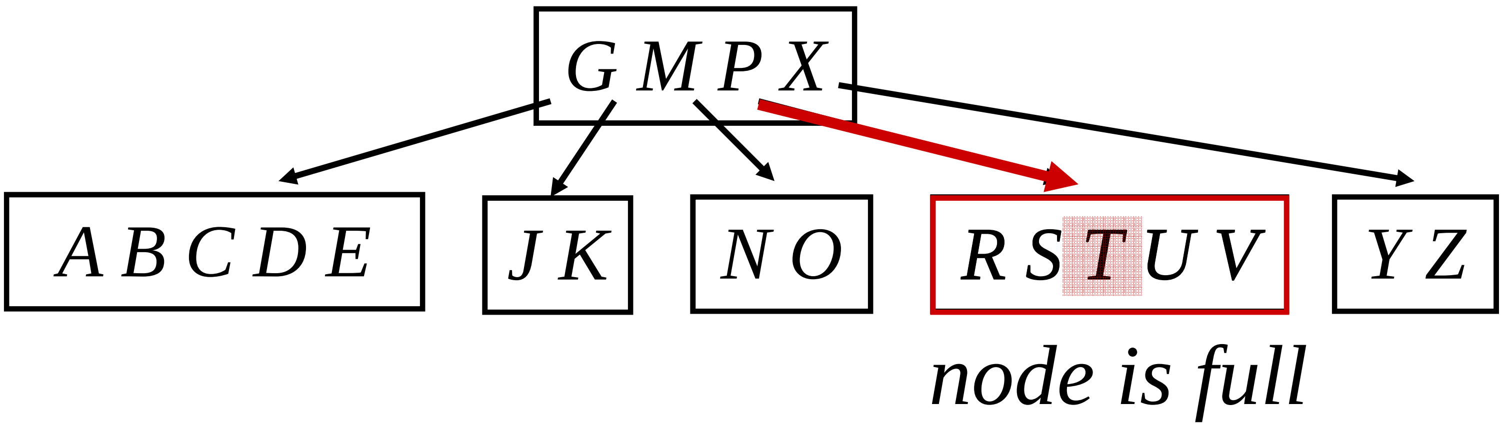


- Insert *B*:

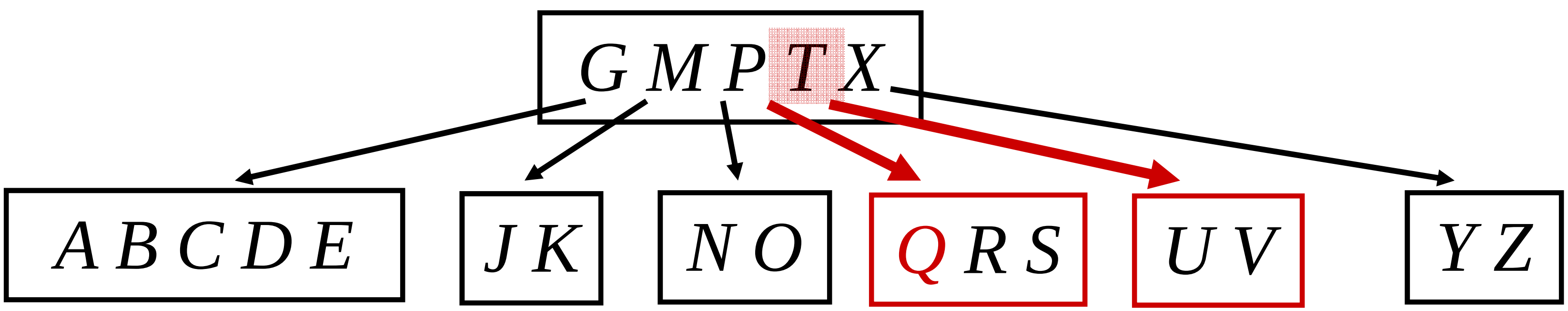


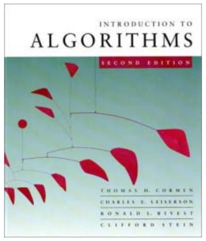


Insert example ($k=3$) -- cont.

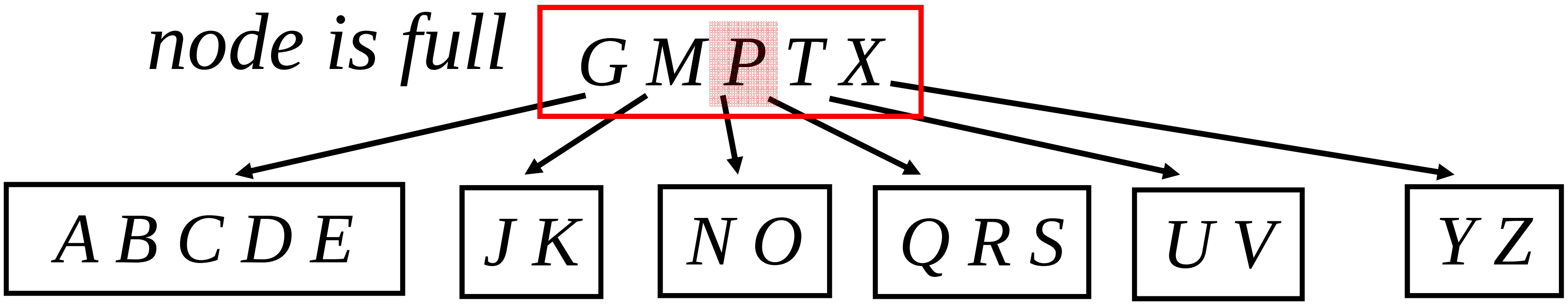


- Insert *Q*:

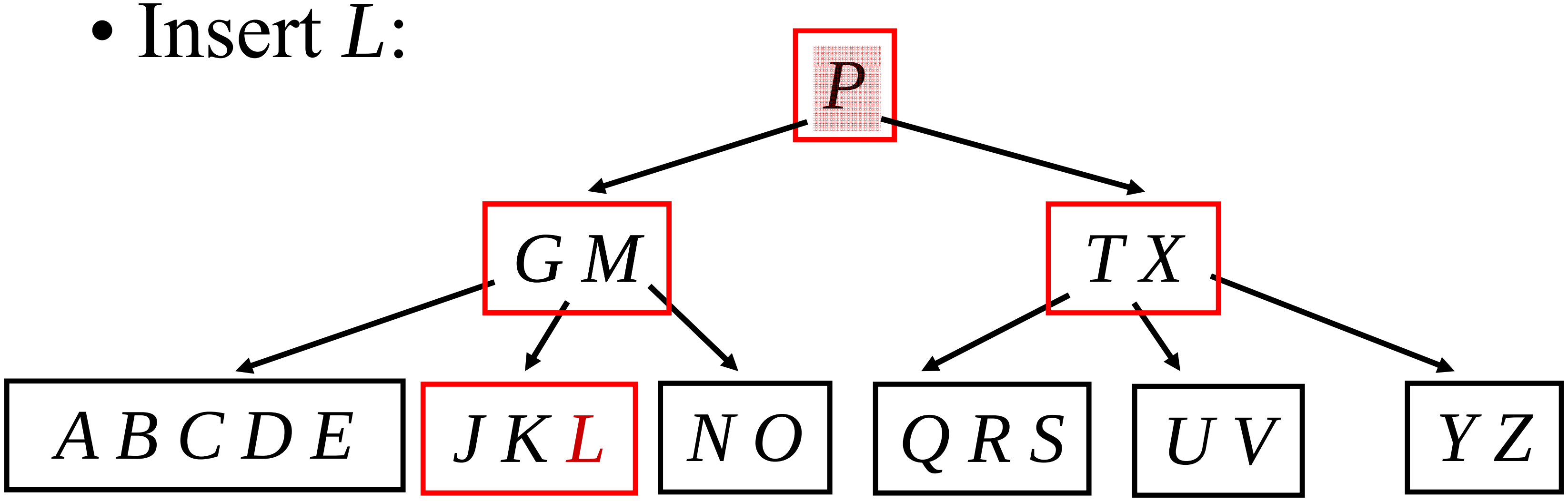


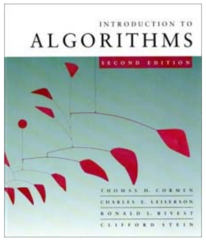


Insert example (k=3) -- cont.

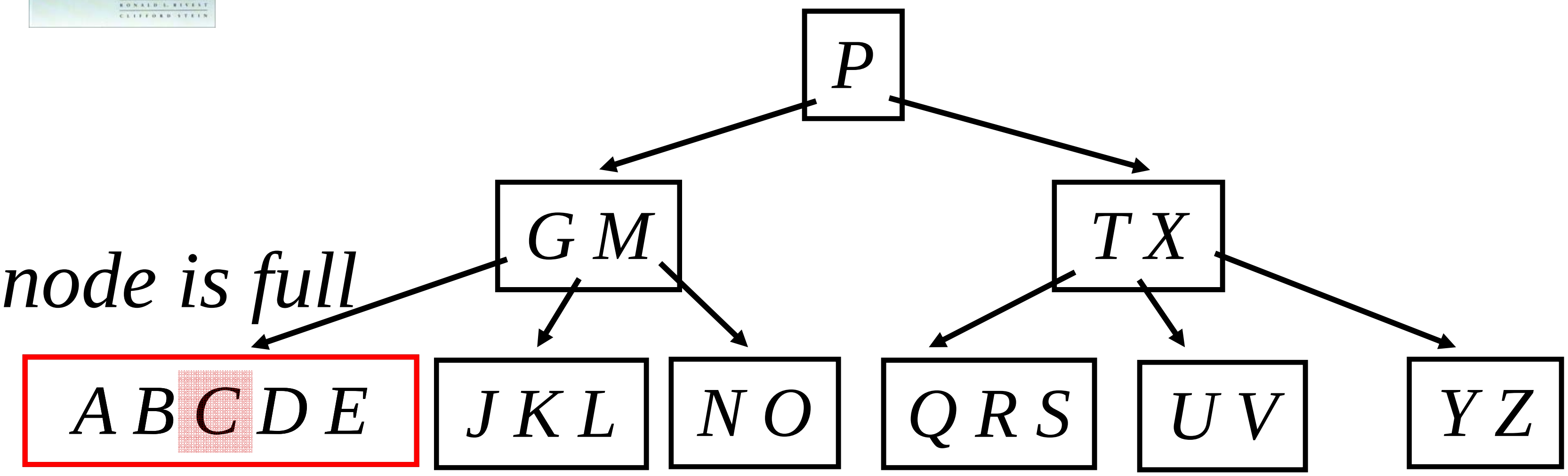


- Insert *L*:

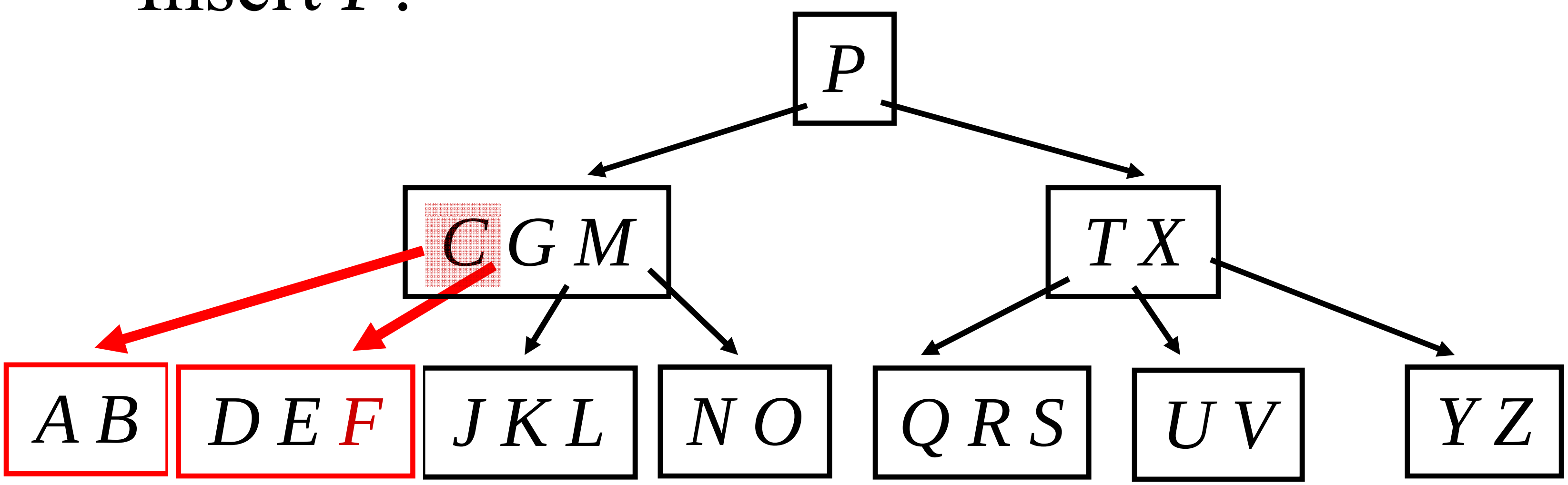


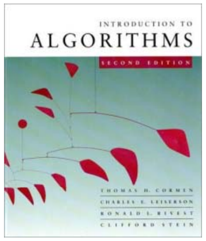


Insert example (k=3) -- cont.



- Insert *F*:



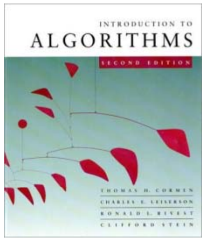


Runtime of B-TREE-INSERT

- *O(k)* runtime per node
- Path has height $h = O(\log_k n)$
- CPU-time: $O(k \log_k n)$

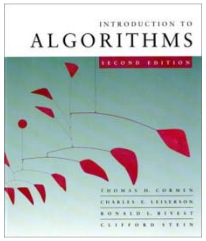
- Disk accesses: $O(\log_k n)$

  disk accesses are more expensive than CPU time



Deletion of an element

- Similar to insertion, but a bit more complicated; see book for details
- If sibling nodes get not full enough, they are **merged** into a single node
- Same complexity as insertion



B-trees -- Conclusion

- B-trees are balanced $2k$-ary search trees
- The **degree** of each node is **bounded from above and below** using the parameter k
- All leaves are at the same height
- **No rotations** are needed: During insertion (or deletion) the balance is maintained by node **splitting** (or node **merging**)
- The tree grows (shrinks) in height only by splitting (or merging) the root