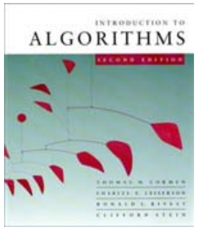
CS 5633 -- Spring 2006



B-trees

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

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

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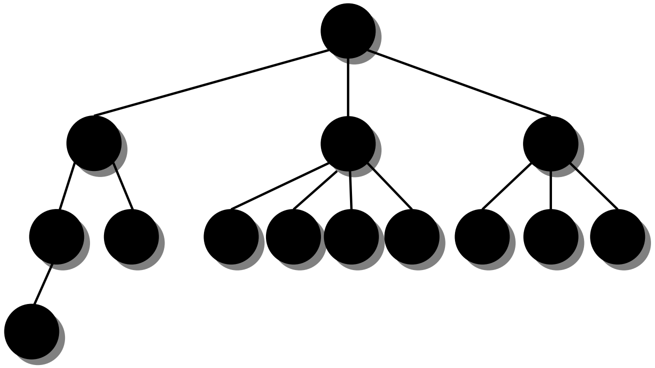
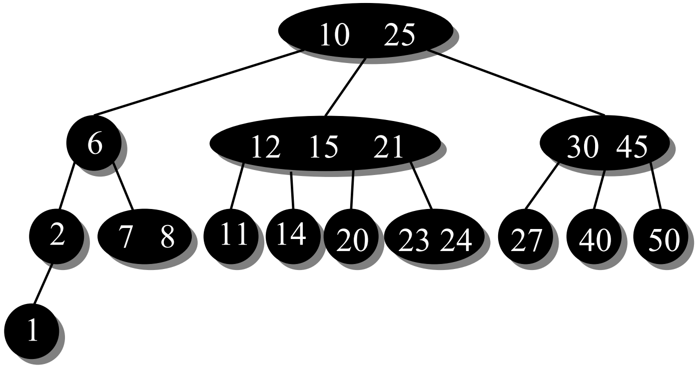
Example of a 4-ary tree



Example of a 4-ary search tree

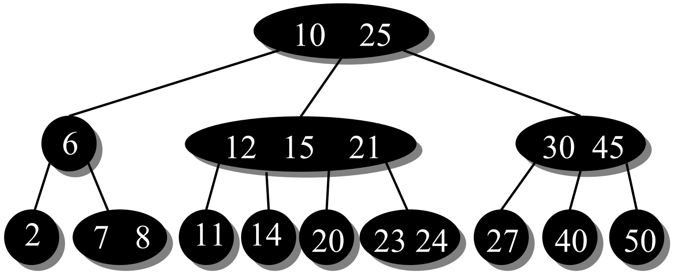


B-tree

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

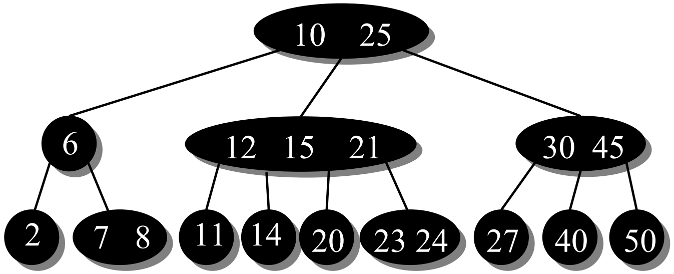
1. T is a $(2k)$-ary search tree
2. Every node, except the root, stores at least k-1 keys
   (every internal non-root node has at least k children)
3. The root must store at least one key
4. All leaves have the same depth

B-tree with k=2



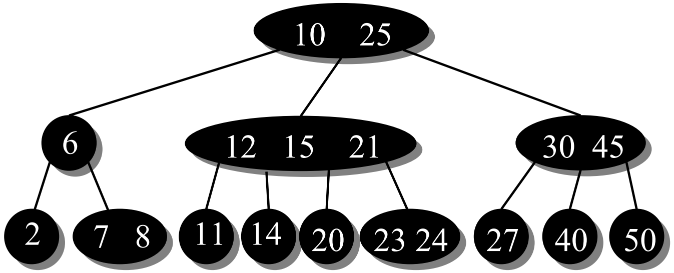
1. T is a $(2k)$-ary search tree

B-tree with k=2



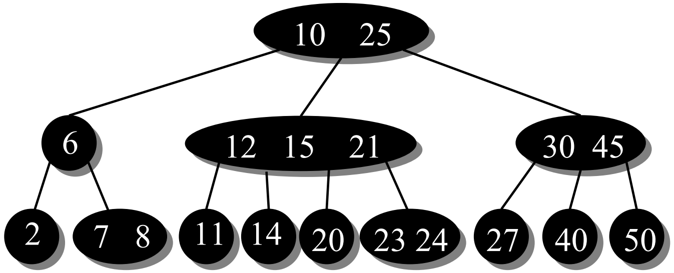
2. Every node, except the root, stores at least k-1 keys

B-tree with k=2



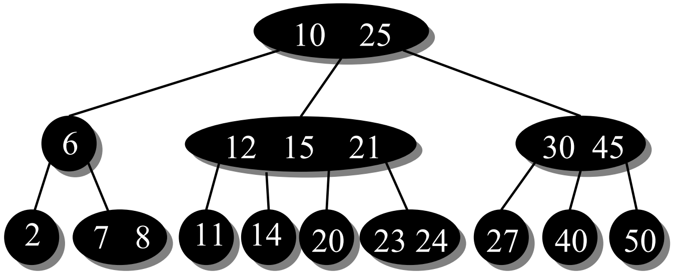
3. The root must store at least one key

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: A B-tree with minimum degree $k \geq 2$ which stores n keys has height h at most

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

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

level 1 level 3

level 0 level 2

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

□

B-tree search

```
B-TREE-SEARCH($x$,$key$)
    $i \leftarrow 1$
    while $i \le \#keys\ of\ x$ and $key > i$-th key of $x$
        do $i \leftarrow i+1$
    if $i \le \#keys\ of\ x$ 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

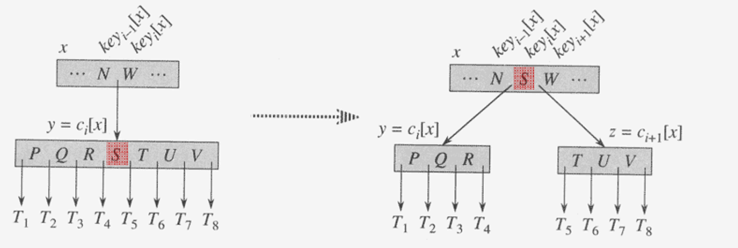
B-tree insert

- 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)

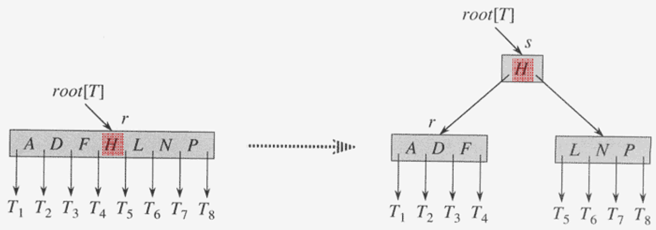
has $2k$-1 keys

- Split full node y 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 $k = 4$



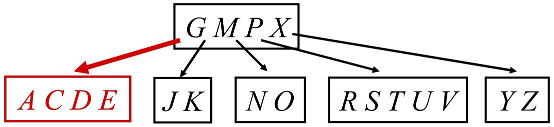
B-TREE-INSERT(*T*,*key*)

```
r = root[T]
if (# keys in r) = 2k-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)
```

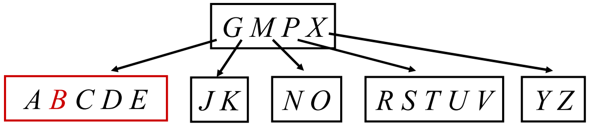
B-TREE-INSERT-NONFULL(*x*,*key*)

```
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)
        B-TREE-INSERT-NONFULL(c,k)
```

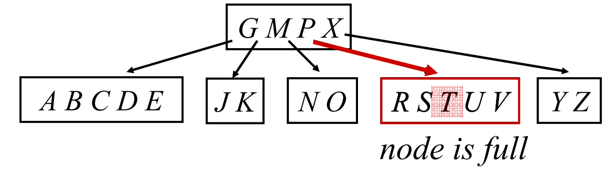
Insert example (k=3)



- Insert *B*:



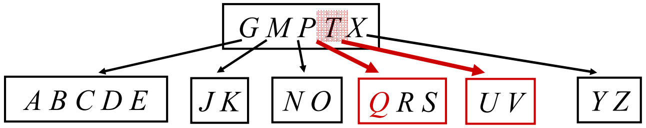
Insert example (*k*=3) -- cont.


G M P X

A B C D E | J K | N O | R S T U V | Y Z

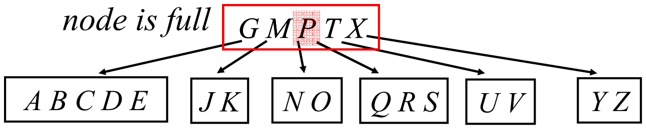
node is full

- Insert *Q*:


G M P T X

A B C D E | J K | N O | Q R S | U V | Y Z

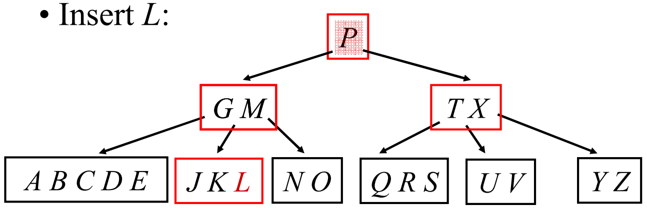
Insert example (*k*=3) -- cont.


node is full

G M P T X

A B C D E | J K | N O | Q R S | U V | Y Z

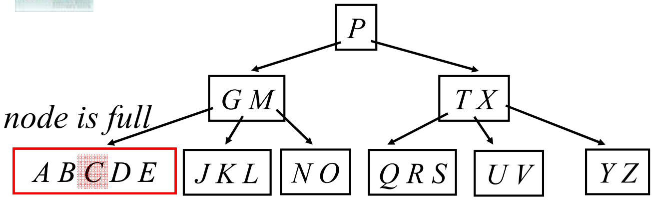
- Insert *L*:


P

G M | T X

A B C D E | J K L | N O | Q R S | U V | Y Z

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

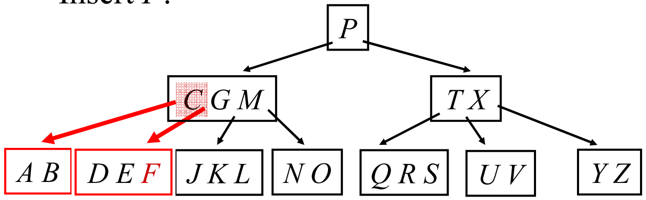

P

G M | T X

node is full

A B C D E | J K L | N O | Q R S | U V | Y Z

- Insert *F*:


P

C G M | T X

A B | D E F | J K L | N O | Q R S | U V | Y Z

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