

B-Trees

ΚΟ8 Δομές Δεδομένων και Τεχνικές Προγραμματισμού

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Searching on disks

- So far we have assumed that our data are stored in memory
- What about storing data on a **disk**?
 - **Example**: databases
- **Disk access** can be at least 100,000 to 1,000,000 slower
 - Goal: **minimize disk accesses**
- Also: data is read in **blocks**
 - Eg 512 or 1024 bytes
 - Reading 1 byte is the same as **reading a whole block**

2

B-Trees

We can easily generalize 2-3 / 2-4-trees:

- A **B-tree** of order m is an m -way search tree with 2 extra properties
- **Size property**
 - Any node contains between $\lceil \frac{m}{2} \rceil - 1$ and $m - 1$ values
 - **Internal** nodes with n values have exactly $n + 1$ children
 - The **root is excluded** from this rule
- **Depth property**
 - All **leaves** have the **same depth** (lie on the same level)

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B-Trees

- We select m so that the **whole B-tree node** fits in a block
 - We read “multiple nodes” for the “price” of one
 - Fewer disk accesses than reading multiple nodes of a BST / AVL / ...
- Such trees are **balanced**
 - $h = O(\log n)$
 - Proof: exercise
- 2-3 and 2-4-trees are B-trees of order 3 and 4
- Generalize even more: require between a and b children
 - for some $2 \leq a \leq \frac{(b+1)}{2}$

4

ADT Set using BTree, types

```
// Κόμβος του set, περιέχει μία μόνο τιμή. Κάθε btree_node έχει πολλά
struct set_node {
    Pointer value;           // Η τιμή του κόμβου.
    BTreeNode owner;        // Ο btree_node στον οποίο ανήκει αυτό το
};

// Το struct btree_node είναι ο κόμβος ενός B-Δέντρου.
struct btree_node {
    int count;               // Αριθμός στοιχείων
    BTreeNode parent;       // Πατέρας
    BTreeNode children[MAX_CHILDREN + 1]; // Παιδιά
    SetNode set_nodes[MAX_VALUES + 1];    // Δεδομένα (μέσα σε set)
};

// Υλοποιούμε τον ADT Set μέσω B-Tree, οπότε το struct set είναι ένα
struct set {
    BTreeNode root;         // Η ρίζα του δέντρου
    int size;               // Μέγεθος, για αποδοτικό set_size
    CompareFunc compare;    // Διάταξη
    DestroyFunc destroy_value; // Συνάρτηση που καταστρέφει ένα στοι
```

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Insertion in a B-tree

- Same as for 2-3 and 2-3-4-trees
 - Search for the value
 - Insert at a leaf
- In case of an overflow ($m + 1$ children)
 - Split it into two nodes of $m/2$ children each
 - Move the separator value (median) to the parent

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Insert example, $m = 5$

0

7

Insert example, $m = 5$

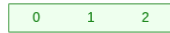
0

1

Inserting 1

7

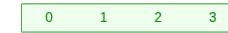
Insert example, $m = 5$



Inserting 2

7

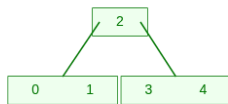
Insert example, $m = 5$



Inserting 3

7

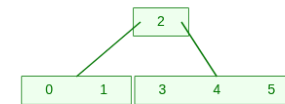
Insert example, $m = 5$



Inserting 4: overflow, 2 moves to a new root

7

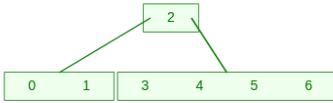
Insert example, $m = 5$



Inserting 5

7

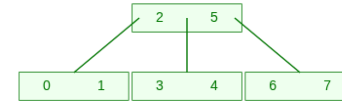
Insert example, $m = 5$



Inserting 6

7

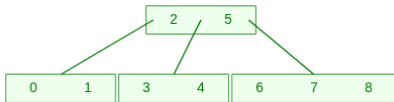
Insert example, $m = 5$



Inserting 7: overflow, 5 moves up

7

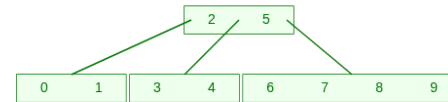
Insert example, $m = 5$



Inserting 8

7

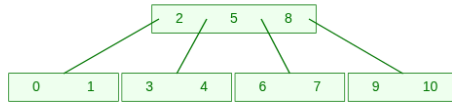
Insert example, $m = 5$



Inserting 9

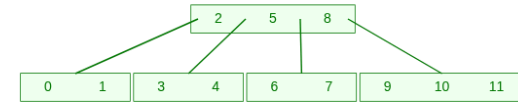
7

Insert example, $m = 5$



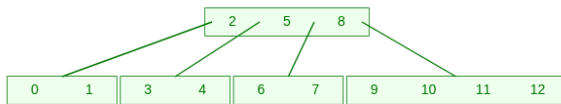
Inserting 10: overflow, 8 moves up

Insert example, $m = 5$



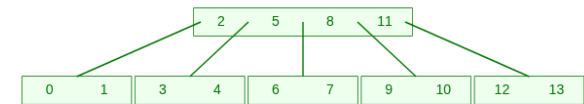
Inserting 11

Insert example, $m = 5$



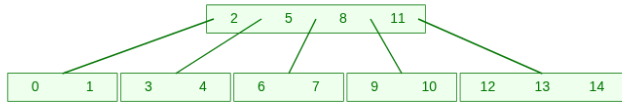
Inserting 12

Insert example, $m = 5$



Inserting 13: overflow, 11 moves up

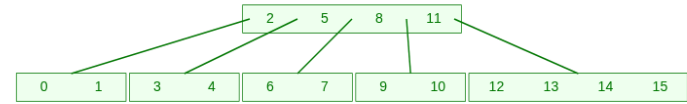
Insert example, $m = 5$



Inserting 14

7

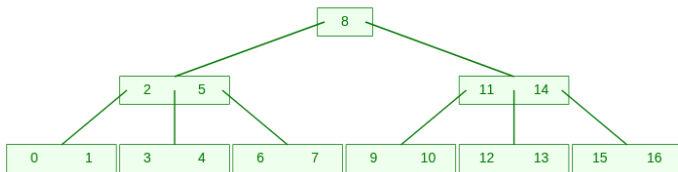
Insert example, $m = 5$



Inserting 15

7

Insert example, $m = 5$



Inserting 16: overflow, 14 moves up, creating a new overflow

7

Code

- As always, the code is in `lecture-code`
 - `modules/UsingBTree/ADTSet.c`
- We only highlight some parts here

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Code, node_insert

```
BTreeNode node_insert(BTreeNode root, CompareFunc compare, Pointer va
// [απλός κώδικας για την περίπτωση κενού δέντρου]

// Εύρεση του κόμβου στον οποίο πρέπει να γίνει insert
int index;
BTreeNode node = node_find(root, compare, value, &index);
if (index != -1) { // Υπάρχει ήδη η τιμή
    node->set_nodes[index]->value = value;
    return root;
}

// Εύρεση της θέσης που πρέπει να μπει το value
for (index = 0;
    index < node->count && compare(value, node->set_nodes[index]
    index++);

node_add_value(node, set_node_create(value), index);

if (node->count > MAX_VALUES) // overflow
    split(node, compare);

// Επιστρέφουμε τη ρίζα, μπορεί να έχει δημιουργηθεί νέα
return root->parent != NULL ? root->parent : root;
}
```

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Code, split

```
// Καλείται όταν ο κόμβος node έχει υπερχειλήσει, τον χωρίζει σε 2 κό
// Στέλνει τη μεσαία από τις τιμές του κόμβου node στον πατέρα του.

static void split(BTreeNode node, CompareFunc compare) {
    // Χωρίζουμε τον κόμβο node σε 2 κόμβους
    BTreeNode right = node_create();
    right->parent = node->parent; // Οι 2 κόμβοι έχουν τον ίδιο π

    // Μετακίνησε τις μισές τιμές και παιδιά από τον αριστερό κόμβο ο
    int half = node->count/2;
    if (!is_leaf(node))
        for (int i = 0; i <= half; i++)
            node_add_child(right, node->children[i + half + 1], i);

    for (int i = 0; i < half; i++) {
        node_add_value(right, node->set_nodes[i + half + 1], i);
        node->count--;
    }

    // Αφαίρεση μεσαίας τιμής
    SetNode median = node->set_nodes[node->count-1];
    node->count--;

    ...
}
```

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Code, split

```
// Προσθέτουμε το median στον πατέρα του κόμβου node.
BTreeNode parent = node->parent;
if (parent == NULL) { // Ο node είναι η ρίζ
    BTreeNode new_root = node_create(); // Δημιούργησε καινού

    node_add_value(new_root, median, 0);

    right->parent = node->parent = new_root;
    new_root->children[0] = node;
    new_root->children[1] = right;
} else {
    int index; // Βρες τη θέση εισαγωγής της τιμής στον πατέρα.
    for (index = 0; index < parent->count; index++)
        if (compare(median->value, parent->set_nodes[index]->valu
            break;

    // Πρόσθεσε τον right ως δεξιό παιδί της (νέας) διαχωριστικής
    node_add_child(parent, right, index+1);
    node_add_value(parent, median, index);

    if (parent->count > MAX_VALUES) // parent overflows
        split(parent, compare);
}
}
```

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Removal from B-trees

- Same as for 2-3 and 2-3-4-trees
- To remove a value k_i from an **internal** node
 - Replace with its **predecessor** (or its **successor**)
 - Right-most value in the i -th subtree
- To remove a value from a **leaf**
 - We simply remove it
 - But it might violate the **size** property (**underflow**)

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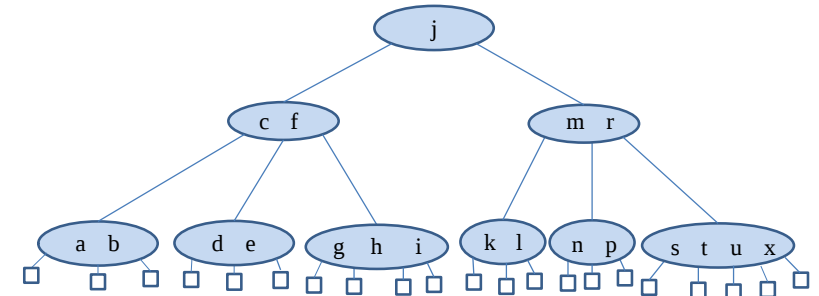
Fixing underflows

Two strategies for fixing an underflow at ν

- Is there an **immediate sibling** w with a “spare” value?
 - If so, we do a **transfer** operation
 - Move a value of w to its parent u
 - Move a value of the parent u to ν
- If not, we do a **fusion** operation
 - Merge ν and w , creating a new node ν'
 - Move a value from the parent u to ν'
 - This might **underflow the parent**, continue the same procedure there

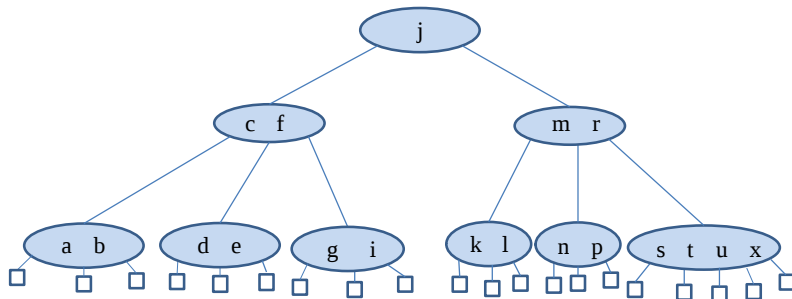
13

Example



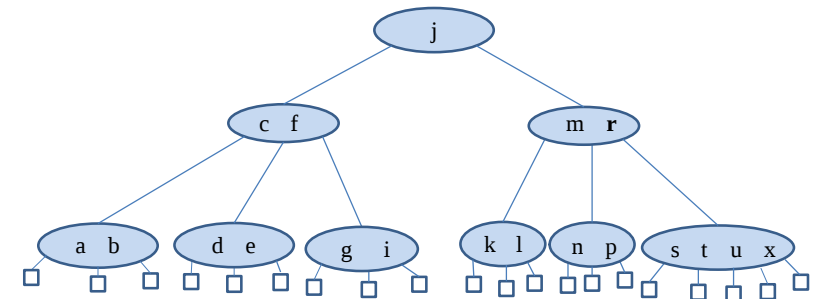
14

Delete h



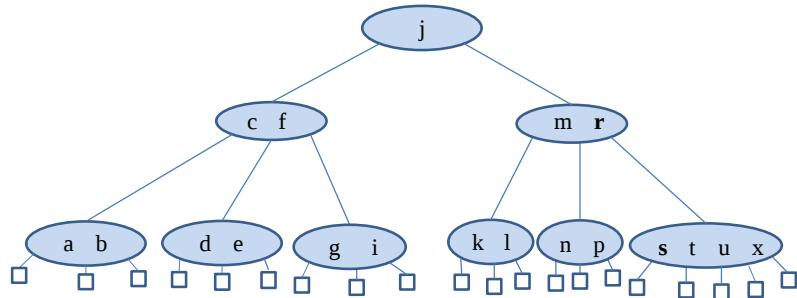
15

Delete r



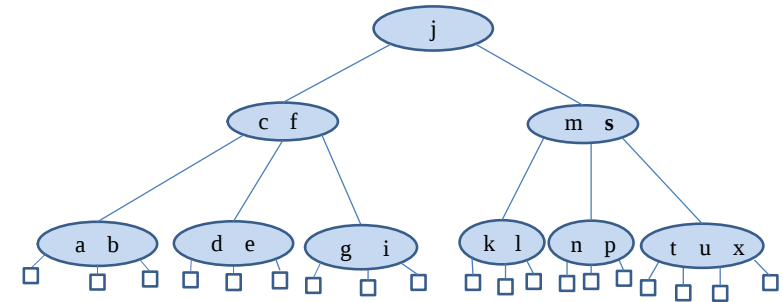
16

Find the Successor of r



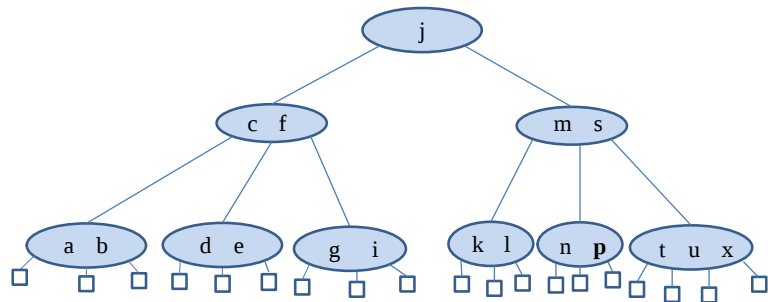
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Promote the Successor of r – Delete the Successor from its Place



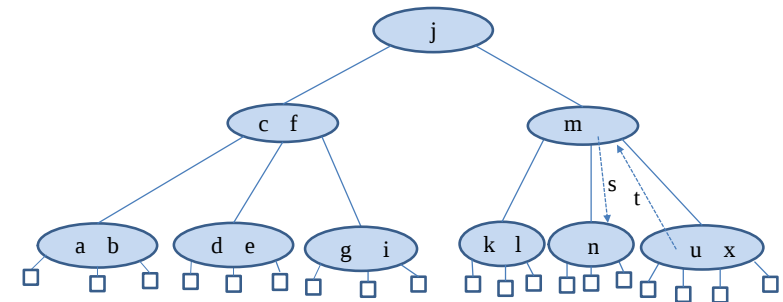
18

Delete p



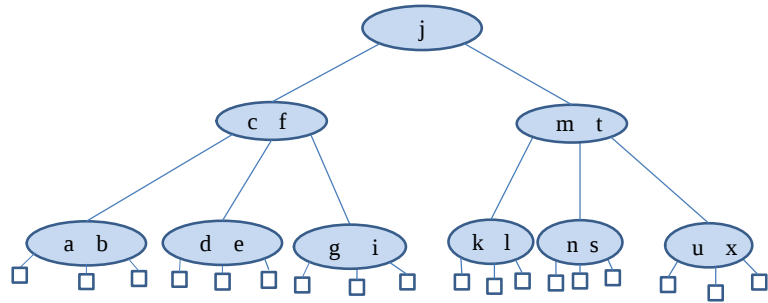
19

Transfer



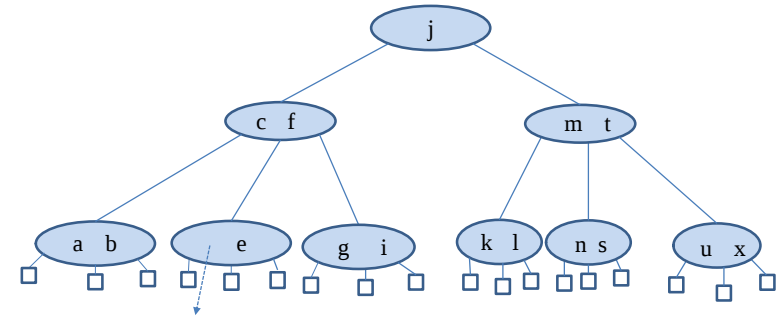
20

After the Transfer



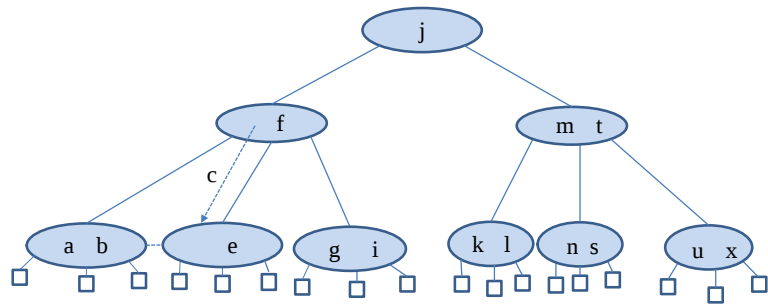
21

Delete d



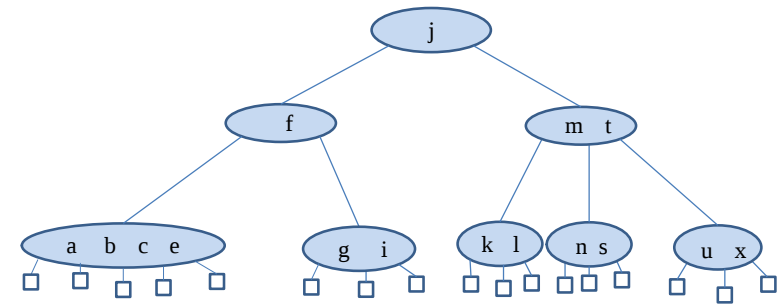
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Fusion



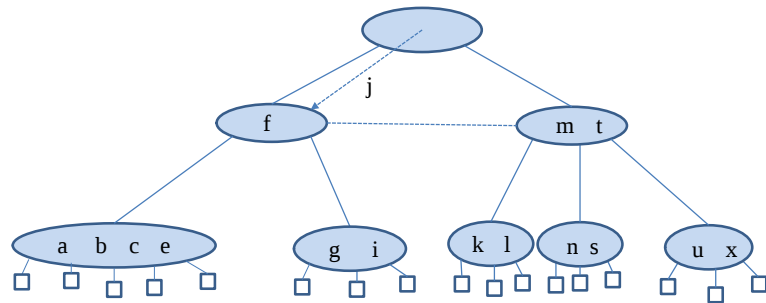
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After the Fusion – Underflow at f



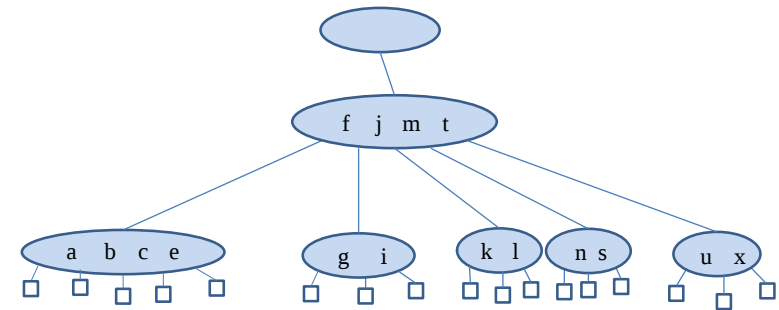
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Fusion



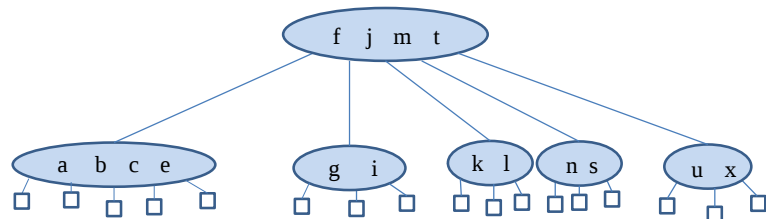
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After the Fusion – Delete Root



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Final Tree



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Code, node_remove

```
BTreeNode node_remove(BTreeNode root, CompareFunc compare, Pointer va
// Βρες τον κόμβο που περιέχει την τιμή.
int index;
BTreeNode node = node_find(root, compare, value, &index);

if (index == -1) // Η τιμή δεν υπάρχει στο δέντρο.
    return root;

// Βρέθηκε ισοδύναμη τιμή στον node, οπότε τον διαγράφουμε
// Το πώς θα γίνει αυτό εξαρτάται από το αν έχει παιδιά.

if (is_leaf(node)) {
    // Φύλλο: διάγραψε την τιμή, αναδιατάξε τα δεδομένα, repair
    // Ολίσθησε όλα τα δεδομένα 1 θέση αριστερά.
    for (int i = index; i < node->count-1; i++)
        node->set_nodes[i] = node->set_nodes[i + 1];

    node->count--; // Αφαίρεσε το δεδομένο.

    repair_underflow(node); // Αναδιαμόρφωσε το δένδρο.
```

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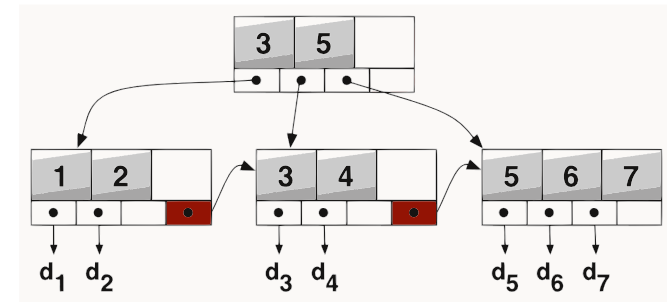
Code, node_remove

```
} else {  
    // Αν είναι εσωτερικός κόμβος αντικατάσταση με την next τιμή  
    // και remove της τιμής αυτής  
    SetNode max = node_find_max(node->children[index]);  
  
    BTreeNode max_node = max->owner;  
    max_node->count--;    // Αφαίρεσε το δεδομένο.  
  
    node->set_nodes[index] = max;  
    max->owner = node;  
  
    repair_underflow(max_node);    // Αναδιαμόρφωσε το δέντρο.  
}  
  
// Αν η ρίζα αδειάσει, ρίζα γίνεται το (μοναδικό, αν έχει) παιδί  
if (root->count == 0) {  
    BTreeNode first_child = root->children[0];  
    if (first_child != NULL)  
        first_child->parent = NULL;  
    root = first_child;  
}  
return root;  
}
```

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B+-trees

A variant of B-trees, important in today's **file systems** and **databases**.



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Readings

- M. T. Goodrich, R. Tamassia and D. Mount. Data Structures and Algorithms in C++. 2nd edition. John Wiley.
- Sartaj Sahni. Δομές Δεδομένων, Αλγόριθμοι και Εφαρμογές στη C++. Εκδόσεις Τζιόλα.
- R. Sedgewick. Αλγόριθμοι σε C. Κεφ. 16.3

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