Multi-Way Search Trees

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**Motivation**

- We keep the *ordering* idea of BSTs
  - *Fast search*, by excluding whole subtrees
- And add *more than two children* for each node
  - Gives more flexibility in restructuring the tree
  - And new ways to *keep it balanced*

**Multi-way search trees**

- *d*-node: a node with *d* children
- Each *internal* *d*-node stores *d − 1 ordered* values \( k_1 < \ldots < k_{d-1} \)
  - *No duplicate* values in the whole tree
- All values in a *subtree* lie in-between the corresponding node values
  - For all values \( l \) in the \( i \)-th subtree: \( k_{i-1} < l < k_i \)
  - Convention: \( k_0 = -\infty, k_d = +\infty \)
- *m*-way search tree: all nodes have *at most* *m* children
  - A BST is a 2-way search tree

**Example multi-way search tree**

\[
\begin{array}{c}
\text{22} \\
\downarrow \\
\text{5} \quad \text{10} \\
\downarrow \\
\text{3} \quad \text{4} \\
\quad \downarrow \\
\text{6} \quad \text{8} \quad \text{14} \\
\quad \downarrow \\
\text{11} \quad \text{13} \\
\quad \downarrow \\
\text{23} \quad \text{24} \quad \text{27} \\
\quad \downarrow \\
\text{17} \\
\end{array}
\]

\[m = 3\]
Searching in a multi-way search tree

- Simple adaptation of the algorithm for BSTs
- Start from the root, traverse towards the leaves
- In each node, there is a single subtree that can possibly contain a value $l$
  - The subtree $i$ such that $k_{i-1} < l < k_i$
  - Continue in that subtree

Example multi-way search tree

Search for value 12

Unsuccessful search

Search for value 24

Successful search
Insertion in a multi-way search tree

- Again, simple adaptation of BSTs
  - But: we don’t always need to create a new node
  - We can insert in an existing one if there is space
- Start with a search for the value we want to insert
- If found, stop (no duplicates)
- If not found, insert at the leaf we reached
  - If full, create an $i$-th child, such that $k_{i-1} < l < k_i$

Value 28 inserted

Insert value 28

Insert value 32

Value 28 inserted

Insert value 32
Value 32 inserted

Insert value 12

Value 12 inserted

Deletion from a multi-way search tree

Left as an exercise.
Complexity of operations

- We need to traverse the tree from the root to a leaf
- The time spent at each node is constant
  - Eg. find $i$ such that $k_{i-1} < l < k_i$
  - Assuming $m$ is fixed!
- So as usual all complexities are $O(h)$
  - $O(n)$ in the worst-case

Balanced multi-way search trees

- Similarly to BSTs we need to keep the tree balanced
  - So that $h = O(\log n)$
- AVL where a kind of balanced BSTs
- We will study two kinds of balanced multi-way search trees:
  - 2-3 trees
  - 2-3-4 trees (also known as (2,4) trees)

2-3 trees

- A 2-3 tree is a 3-way search tree which has the following properties
  - Size property
    - Each node contains 1 or 2 values
      (so each internal node contains 2 or 3 children)
  - Depth property
    - All leaves have the same depth (lie on the same level)

Example of 2-3 tree
**Height of 2-3 trees**

- All nodes at all levels except the last one are internal
  - And each internal node has at least 2 children
  - So at level $i$ we have at least $2^i$ nodes
- Hence $n \geq 2^h$, in other words $h = O(\log n)$
- So we can search for an element in time $O(\log n)$
  - Using the standard algorithm for $m$-way trees

**Insertion in 2-3-trees**

- We can start by following the generic algorithm for $m$-way trees
- Search for the value $L$ we want to insert
  - If found, stop (no duplicates)
  - If not found, insert at the leaf we reached
Insertion in 2-3-trees

- But what if there is **no space at the leaf** (overflow)?
- The standard algorithm will insert a child at the leaf
  - But this **violates the depth property**!
  - The new leaf is not at the same level
- Different strategy
  - **split** the overflowed node into two nodes
    - pass the **middle value** to the parent (**separator** of the two nodes)
- The middle value might **overflow the parent**
  - Same procedure: split and send the middle value up
M overflows this node.

The node is split in two and L is passed to the parent node.

L overflows this node.

The node is split in two and L is passed up to the parent.
Example: result

H L
D
J
N
A B E F I K M O P

L is inserted in the root node

Example: insert Q

H L
D
J
N
A B E F I K M O P

O P

Q overflows this node

Example: insert Q

H L
D
J
N
A B E F I K M O P

Q

This node is split up and P is passed up

Example: result

H L
D
J
N
A B E F I K M O Q

This node is split up and P is passed up
Example: insert R

- The root might also overflow
- Same procedure
  - Split it
  - The middle value moves up, creating a new root
- This is the only operation that increases the tree’s height
  - It increases the depth of all nodes simultaneously
  - 2-3-trees grow at the root, not at the leaves!

Example: insert S

- S overflows this node
- S overflows this node
- This node is split and R is sent up

R is inserted in the node with Q where there is space.

S overflows this node
Example: insert S

Example: insert S

Example: insert S

Example: result
Complexity of insertion

- We traverse the tree
  - From the root to a leaf when searching
  - From the leaf back to the root while splitting
- Each split takes constant time
  - We do at most $h + 1$ of them
- So in total $O(h) = O(\log n)$ steps
  - Recall, the tree is balanced

(2,4) trees

- A (2,4) tree (or 2-3-4 tree) is a 4-way search tree with 2 extra properties
- Size property
  - Each node contains between 1 and 3 values (so each internal node contains between 2 and 4 children)
- Depth property
  - All leaves have the same depth (lie on the same level)
- Such trees are balanced
  - $h = O(\log n)$
  - Proof: exercise

Insertion in (2,4) trees

- Same as for 2-3-trees
  - Search for the value
  - Insert at a leaf
- In case of an overflow (5-node)
  - Split it into a 3-node and a 2-node
  - Move the separator value $k_3$ to the parent

Overflow at a 5-node
The separating value is sent to the parent node

Node replaced with a 3-node and a 2-node

Example: insert 4

Example: insert 6
Example: insert 12

Example: insert 15 - overflow

Creation of new root node

Split
Example: insert 3

Example: insert 5 - overflow

5 is sent to the parent node

Split
Example: insert 10

Example: insert 8

Example

Example: insert 17 - overflow

Inserted 11, 13 and 14.
Split and send 15 to the parent node

The root overflows

Creation of new root

Split
### Final tree

![Final tree diagram]

### Complexity
- Same as for 2-3-trees
  - At most $h$ splits
  - Each split is constant time
- $O(\log n)$
  - Because the tree is balanced

### Removal in (2,4) 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
  - Similar to the BST case of nodes with two children
- To remove a value from a leaf
  - We simply remove it
  - But it might violate the size property (underflow)

### Fixing underflows
Two strategies for fixing an underflow at $\nu$
- Is there an immediate sibling $\omega$ with a “spare” value? (2 or 3 values)
- If so, we do a transfer operation
  - Move a value of $\omega$ to its parent $u$
  - Move a value of the parent $u$ to $\nu$
- If not, we do a fusion operation
  - Merge $\nu$ and $\omega$, creating a new node $\nu'$
  - Move a value from the parent $u$ to $\nu'$
  - This might underflow the parent, continue the same procedure there
Initial tree

Remove 4

Transfer

After the transfer
Remove 12

Fusion of and

After the fusion
After the removal of 13

Fusion
Readings

- T. A. Standish. *Data Structures, Algorithms and Software Principles in C*. Section 9.9
- R. Sedgewick. *Αλγόριθμοι σε C*. 3η Αμερικανική Έκδοση. Εκδόσεις Κλειδάριθμος. Section 13.3