

Algorithms and Datastructures

Balanced Trees (AVL-Trees, (a,b)-Trees, Red-Black-Trees)

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Algorithms and Datastructures, January 2017

Balanced Trees

- Motivation

- AVL-Trees

- (a,b)-Trees

 - Introduction

 - Runtime Complexity

- Red-Black Trees

Binary search tree:

- With `BinarySearchTree` we could perform an `lookup` or `insert` in $O(d)$, with d being the `depth` of the tree
- Best case: $d \in O(\log n)$, keys are inserted randomly
- Worst case: $d \in O(n)$, keys are inserted in ascending / descending order (20, 19, 18, ...)



Gnarley trees:

■ <http://people.ksp.sk/~kuko/bak>



Figure: Binary search tree with random insert [Gna]



Figure: Binary search tree with descending insert [Gna]

Balanced trees:

- We do not want to rely on certain properties of our **key set**
- We explicitly want a depth of $O(\log n)$
- We **rebalance** the tree from time to time

How do we get a depth of $O(\log n)$?

■ AVL-Tree:

- Binary tree with 2 children per node
- Balancing via “rotation”

■ (a,b)-Tree or B-Tree:

- Node has between a and b children
- Balancing through **splitting** and **merging** nodes
- Used in databases and file systems

■ Red-Black-Tree:

- Binary tree with “black” and “red” nodes
- Balancing through “rotation” and “recoloring”
- Can be interpreted as (2, 4)-tree
- Used in C++ `std::map` and Java `SortedMap`

AVL-Tree:

- Gregory Maximovich **Adelson-Velskii**, Yevgeniy Mikhailovlovich **Landis** (1963)
- Search tree with modified **insert** and **remove** operations while satisfying a **depth** condition
- Prevents degeneration of the search tree
- Height difference of left and right subtree is at maximum one
- With that the height of the search tree is always $O(\log n)$
- We can perform all basic operations in $O(\log n)$



Figure: Example of an AVL-Tree



Figure: **Not** an AVL-Tree



Figure: Another example of an AVL-Tree

Rotation:



Figure: Before rotating

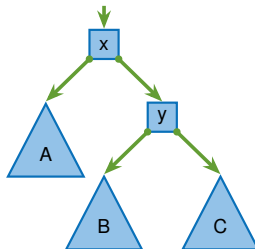


Figure: After rotating

- Central operation of **rebalancing**
- After rotation to the right:
 - Subtree **A** is a layer higher and subtree **C** a layer lower
 - The parent child relations between nodes **x** and **y** have been swapped

AVL-Tree:

- If a height difference of ± 2 occurs on an **insert** or **remove** operation the tree is rebalanced
- Many different cases of rebalancing
- **Example:** **insert** of 1,2,3,...



Figure: Inserting 1,...,10 into an AVL-tree [Gna]

Summary:

- Historical the first search tree providing guaranteed `insert`, `remove` and `lookup` in $O(\log n)$
- However not amortized update costs of $O(1)$
- Additional memory costs: We have to save a height difference for every node
- Better (and easier) to implement are (a,b) -trees

(a,b)-Tree:

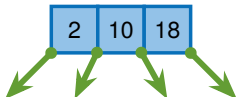
- Also known as **b-tree** (b for “balanced”)
- Used in databases and file systems

Idea:

- Save a varying number of elements per node
- So we have space for elements on an **insert** and balance operation

(a,b)-Tree:

- All leaves have the same depth
- Each inner node has $\geq a$ and $\leq b$ nodes
(Only the root node may have less nodes)



- Each node with n children is called “node of degree n ” and holds $n - 1$ sorted elements
- Subtrees are located “between” the elements
- We require: $a \geq 2$ and $b \geq 2a - 1$

(2,4)-Tree:

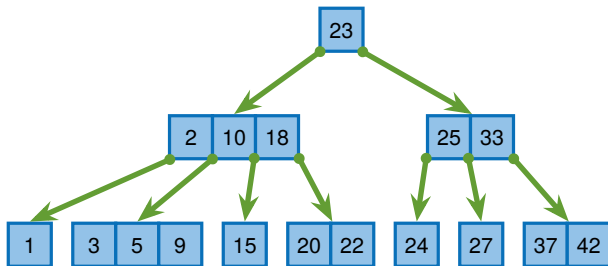


Figure: Example of an (2,4)-tree

- (2,4)-tree with depth of 3
- Each node has between 2 and 4 children (1 to 3 elements)

Not an (2,4)-Tree:



Figure: **Not** an (2,4)-tree

- Invalid sorting
- Degree of node too large / too small
- Leaves on different levels

Searching an element: (lookup)

- The same algorithm as in [BinarySearchTree](#)
- Searching from the root downwards
- The keys at each node set the path



Figure: (3,5)-Tree [Gna]

Inserting an element: (`insert`)

- Search the position to insert the key into
- This position will always be an leaf
- Insert the element into the tree
- **Attention:** As a result node can overflow by one element (Degree $b+1$)
- Then we **split** the node

Inserting an element: (`insert`)



Figure: Splitting a node

- If the degree is higher than $b + 1$ we split the node
- This results in a node with $\text{ceil}\left(\frac{b-1}{2}\right)$ elements, a node with $\text{floor}\left(\frac{b-1}{2}\right)$ elements and one element for the parent node
- That's why we have the limit $b \geq 2a - 1$

Inserting an element: (`insert`)

- If the degree is higher than $b+1$ we split the node
- Now the parent node can be of a higher degree than $b+1$
- We `split` the parent nodes the same way
- If we split the root node we create a new parent root node
(The tree is now one level deeper)

Removing an element: (remove)

- Search the element in $O(\log n)$ time
- **Case 1:** The element is contained by a leaf
 - Remove element
- **Case 2:** The element is contained by an inner node
 - Search the **successor** in the right subtree
 - The **successor** is always contained by a leaf
 - Replace the element with its **successor** and delete the **successor** from the leaf
- **Attention:** The leaf might be too small (degree of $a - 1$)
⇒ We **rebalance** the tree

Removing an element: (`remove`)

- **Attention:** The leaf might be too small (degree of $a - 1$)
⇒ We **rebalance** the tree
- **Case a:** If the left or right neighbour node has a degree **greater than a** we **borrow** one element from this node



Figure: Borrow an element

Removing an element: (`remove`)

- **Attention:** The leaf might be too small (degree of $a - 1$)
⇒ We **rebalance** the tree
- **Case b:** We **merge** the node with its right or left neighbour

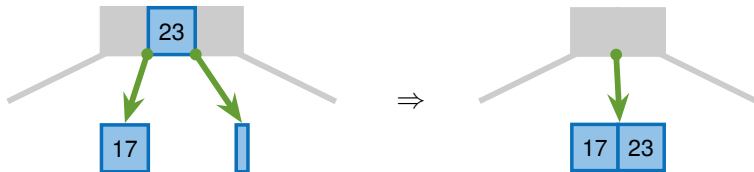


Figure: Merge two nodes

Removing an element: (remove)

- Now the parent node can be of degree $a - 1$
- We merge parent nodes the same way
- If the root has only a single child
 - Remove the root
 - Define sole child as new root
 - The tree shrinks by one level

Runtime complexity of `lookup`, `insert` and `remove`:

- All operations in $O(d)$ with d being the depth of the tree
- Each node (except the root) has **more than a children**
 $\Rightarrow n \geq a^{d-1}$ and $d \leq 1 + \log_a n = O(\log_a n)$

In detail:

- `lookup` always takes $\Theta(d)$
- `insert` and `remove` often require only $O(1)$ time
- **Worst case:** `split` or `merge` all nodes on path up to the root
- Therefore instead of $b \geq 2a - 1$ we need $b \geq 2a$

Counter example (2,3)-Tree:

- Before executing `delete(11)`

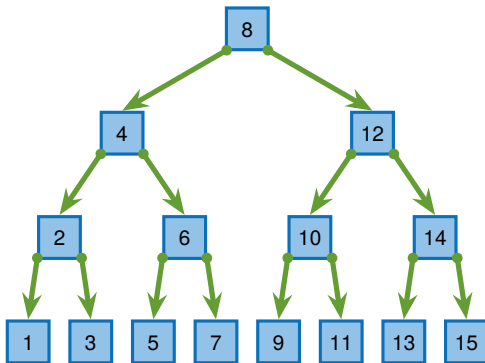


Figure: Normal (2,3)-Tree

Counter example (2,3)-Tree:

- Executing `delete(11)`



Figure: (2,3)-Tree - Delete step 1

Counter example (2,3)-Tree:

- Executing `delete(11)`



Figure: (2,3)-Tree - Delete step 2

Counter example (2,3)-Tree:

- Executing `delete(11)`



Figure: (2,3)-Tree - Delete step 3

Counter example (2,3)-Tree:

- Executed `delete(11)`



Figure: (2,3)-Tree - Delete step 4

Counter example (2,3)-Tree:

- Executing `insert(11)`

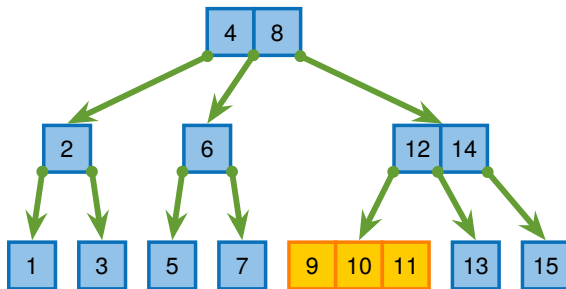


Figure: (2,3)-Tree - Insert step 1

Counter example (2,3)-Tree:

- Executing `insert(11)`



Figure: (2,3)-Tree - Insert step 2

Counter example (2,3)-Tree:

- Executing `insert(11)`



Figure: (2,3)-Tree - Insert step 3

Counter example (2,3)-Tree:

- Executed `insert(11)`



Figure: (2,3)-Tree - Insert step 4

Counter example (2,3)-Tree:

- We are exactly where we started
- If $b = 2a - 1$ then we can create a sequence of **insert** and **remove** operations where each operation costs $O(\log n)$
- We need $b \geq 2a$ instead of $b \geq 2a - 1$

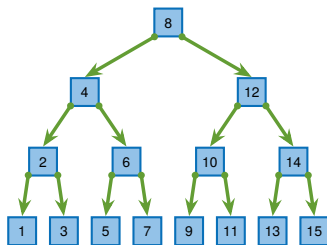


Figure: (2,3)-Tree

(2,4)-Tree:

- If all nodes have 2 children we have to merge the nodes up to the root on a remove operation
- If all nodes have 4 children we have to split the nodes up to the root on a insert operation
- If all nodes have 3 children it takes some time to reach one of the previous two states

⇒ **Nodes of degree 3 are stable**

Neither an insert nor a remove operation trigger rebalancing operations

(2,4)-Tree:

■ Idea:

- After an expensive operation the tree is in a stable state
- It takes some time until the next expensive operation occurs
- Like with dynamic arrays:
 - **Reallocation** is expensive but it takes some time until the next expensive operation occurs
 - If we **overallocate** clever we have an amortized runtime of $O(1)$

Terminology:

- We analyze a sequence of n operations
- Let ϕ_i be the potential of the tree after the i -th operation
- ϕ_i = the number of stable nodes with degree 3
- Empty tree has 0 nodes: $\phi = 0$

Example:

- Nodes of degree 3 are highlighted



Figure: Tree with potential $\phi = 4$

Terminology:

- Let c_i be the costs = runtime of the i -th operation
- We will show:
 - Each operation can at most destroy one stable node
 - For each cost incurring step the operation creates an additional stable node
- The costs for operation i are coupled to the difference of the potential levels

$$c_i \leq A \cdot (\underbrace{\phi_i - \phi_{i-1}}_{\text{difference of potential levels}}) + B, \quad A > 0 \text{ and } B > A$$

Number of gained stable nodes (degree 3) ≥ -1

- Each operation has an amortized cost of $O(1)$ summing up to $O(n)$ in total

Case 1: i -th operation is an **insert** operation on a full node



Figure: Splitting a node on **insert**

- Each splitted node creates a node of **degree 3**
- The parent node receives an element from the splitted node
- If the parent node is also full we have to split it too

Case 1: i -th operation is an **insert** operation on a full node

- Let m be the number of nodes split
- The potential rises by m
- If the “stop-node” is of **degree 3** then the potential goes down by one

$$\begin{aligned}\phi_i &\geq \phi_{i-1} + m - 1 \\ \Rightarrow m &\leq \phi_i - \phi_{i-1} + 1\end{aligned}$$

Costs: $c_i \leq A \cdot m + B$

$$\begin{aligned}\Rightarrow c_i &\leq A \cdot (\phi_i - \phi_{i-1} + 1) + B \\ c_i &\leq A \cdot (\phi_i - \phi_{i-1}) + \underbrace{A + B}_{B'}\end{aligned}$$

Case 2: *i*-th operation is an **remove** operation

■ **Case 2.1:** Inner node

- Searching the successor in a tree is $O(d) = O(\log n)$
- Normally the tree is coupled with a doubly linked list
⇒ We can find the successor in $O(1)$

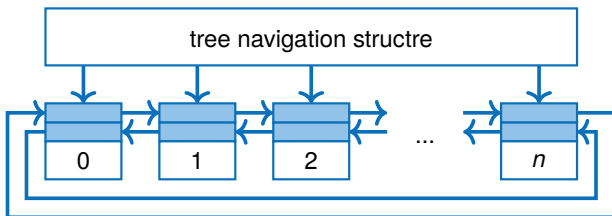


Figure: Tree with doubly linked list

Case 2: *i*-th operation is an **remove** operation

■ **Case 2.1:** Borrow a node

- Creates no additional operations
- Case 2.1.1: Potential rises by one



Figure: Case 2.1.1: Borrow an element

Case 2: *i*-th operation is an **remove** operation

■ **Case 2.1:** Borrow a node

- Creates no additional operations
- Case 2.1.2: Potential is lowered by one



Figure: Case 2.1.2: Borrow an element

Case 2: i -th operation is an **remove** operation

■ **Case 2.2:** Merging two nodes



Figure: Merging two nodes

- Potential rises by one
- Parent node has one element less after the operation
- This operation propagates upwards until a node of degree > 2 or a node of degree 2, which can borrow from a neighbour

Case 2: i -th operation is an **remove** operation

■ **Case 2.2:** Merging two nodes

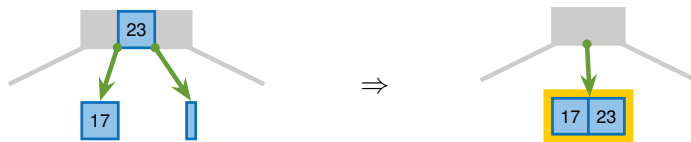


Figure: Merging two nodes

- The potential rises by m
- If the “stop-node” is of **degree 2** then the potential eventually goes down by one
- Same costs as **insert**

Lemma:

- We know:

$$c_i \leq A \cdot (\phi_i - \phi_{i-1}) + B, \quad A > 0 \text{ and } B > A$$

- With that we can conclude:

$$\sum_{i=0}^n c_i \in O(n)$$

Proof:

$$\begin{aligned}\sum_{i=0}^n c_i &\leq \underbrace{A \cdot (\phi_1 - \phi_0) + B}_{\leq c_1} + \underbrace{A \cdot (\phi_2 - \phi_1) + B}_{\leq c_2} + \dots + \underbrace{A \cdot (\phi_n - \phi_{n-1}) + B}_{\leq c_n} \\ &= A \cdot (\phi_n - \phi_0) + B \cdot n && | \text{ telescope sum} \\ &= A \cdot \phi_n + B \cdot n && | \text{ we start with an empty tree} \\ &< A \cdot n + B \cdot n \in O(n) && | \text{ number of degree 3 nodes} \\ &&& < \text{ number of nodes}\end{aligned}$$

Red-Black Tree:

- Binary tree with **red** and **black** nodes
- Number of **black** nodes on path to leaves is equal
- Can be interpreted as **(2,4)-tree** (also named 2-3-4-tree)
- Each **(2,4)-tree**-node is a small red-black-tree with a **black** root node

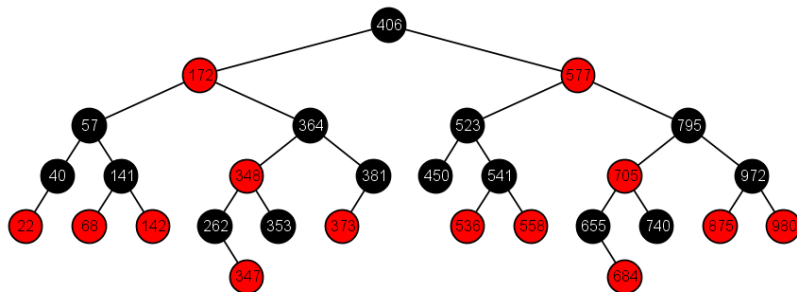


Figure: Example of an red-black-tree [Gna]

■ General

[CRL01] Thomas H. Cormen, Ronald L. Rivest, and Charles E. Leiserson.

Introduction to Algorithms.

MIT Press, Cambridge, Mass, 2001.

[MS08] Kurt Mehlhorn and Peter Sanders.

Algorithms and data structures, 2008.

<https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf>.

■ Gnarley Trees

[Gna] **Gnarley Trees**

<https://people.ksp.sk/~kuko/gnarley-trees/>

■ AVL-Tree

[Wik] [AVL tree](#)

`https://en.wikipedia.org/wiki/AVL_tree`

■ (a,b)-Tree

[Wika] [2-3-4 tree](#)

`https://en.wikipedia.org/wiki/2%E2%80%933%E2%80%934_tree`

[Wikb] [\(a,b\)-tree](#)

`https://en.wikipedia.org/wiki/\(a,b\)-tree`

■ Red-Black-Tree

[Wik] [Red-black tree](https://en.wikipedia.org/wiki/Red%E2%80%93black_tree)

`https://en.wikipedia.org/wiki/Red%E2%80%93black_tree`