

Algorithms and Datastructures

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

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Balanced Trees

- Motivation

- AVL-Trees

- (a,b)-Trees

 - Introduction

 - Runtime Complexity

- Red-Black Trees

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Motivation

AVL-Trees

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Introduction

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Motivation

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Introduction

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 - if the keys are inserted in ascending / descending order
(20, 19, 18, ...)



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Figure: Binary search tree with random insert [Gna]



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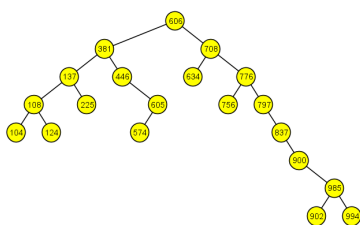


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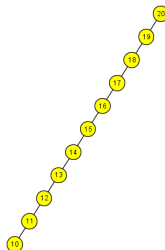


Figure: Binary search tree with descending insert [Gna]



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- We **rebalance** the tree from time to time



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- Used in C++ `std::map`, Java `SortedMap`

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Motivation

AVL-Trees

(a,b)-Trees

Introduction

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- 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:

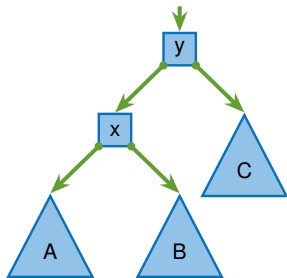


Figure: Before rotating

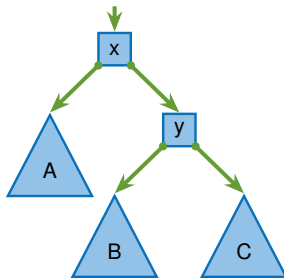


Figure: After rotating

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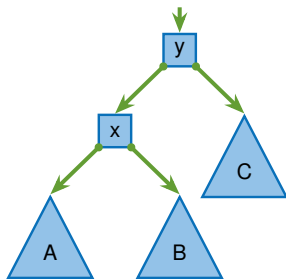


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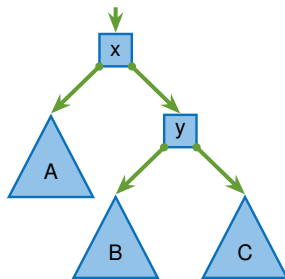


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 - Subtree **A** is a layer higher and subtree **C** a layer lower
 - The parent child relations between nodes **x** and **y** have been swapped



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



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- 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

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- So we have space for elements on an **insert** and balance operation



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- We require: $a \geq 2$ and $b \geq 2a - 1$

(2,4)-Tree:



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- (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

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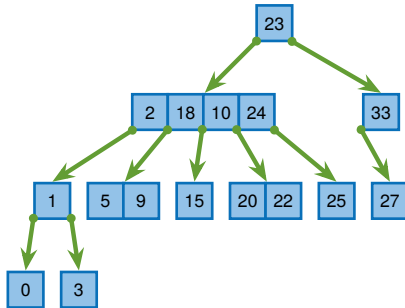


Figure: **Not** an (2,4)-tree

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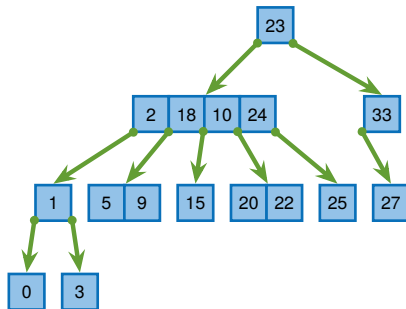


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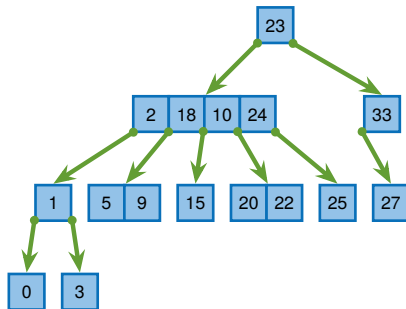


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- Invalid sorting
- Degree of node too large / too small
- Leaves on different levels



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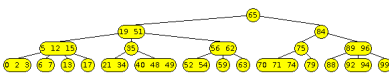
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BST AVL tree B tree Red-black tree AA tree Skiplist Max Heap Min Heap Treap Scapegoat tree Splay tree

Display



Text

Search
Found.

Control

50 Insert Find Delete Next

☐ Pause ☐ Small 4

#Nodes: 22 #Keys: 37 = 56% full Height: 3



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- Then we **split** the node

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- 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 element for the parent node, and a node with $\text{floor}\left(\frac{b-1}{2}\right)$ elements

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 - Thats why we have the limit $b \geq 2a - 1$

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- If the node to split is the root we split it and create a new root node
(The tree is now one level deeper)



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Figure: Borrowing an element



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Figure: Combining two nodes

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- If the root has only one child left we take the child as new root
(The tree shrinks one level)



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 - We want to analyse in detail
 - Therefore instead of $b \geq 2a - 1$ we need $b \geq 2a$.
 - Here is a counter-example for (2,3)-trees, analysis of (2,4)-trees

(a,b) -Trees

Runtime Complexity - Counter-example for $(2,3)$ -Tree



$(2,3)$ -Tree:



(2,3)-Tree:

- Before executing `delete(11)`

(2,3)-Tree:

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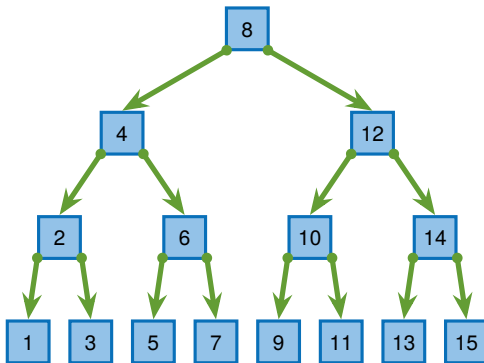


Figure: Normal (2,3)-Tree

(2,3)-Tree:

- Executing `delete(11)`



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

(2,3)-Tree:

- Executing `delete(11)`



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

(2,3)-Tree:

- Executing `delete(11)`



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

(2,3)-Tree:

- Executed `delete(11)`

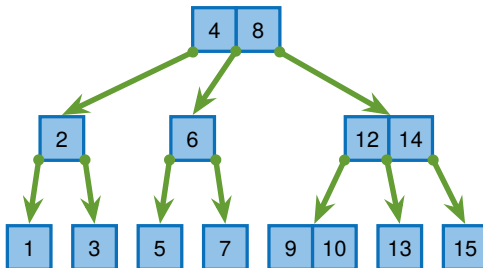


Figure: (2,3)-Tree - Delete step 4

(a,b) -Trees

Runtime Complexity - Counter example for $(2,3)$ -Tree



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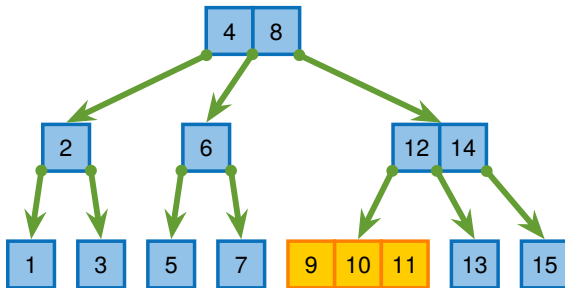


Figure: (2,3)-Tree - Insert step 1

(2,3)-Tree:

- Executing `insert(11)`

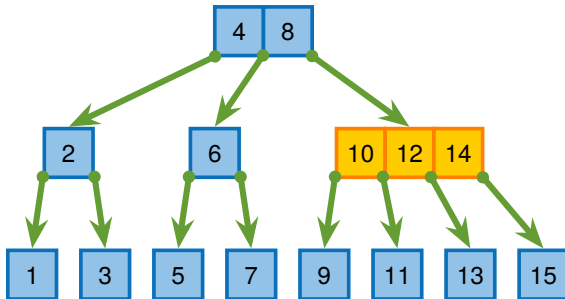


Figure: (2,3)-Tree - Insert step 2

(2,3)-Tree:

- Executing `insert(11)`

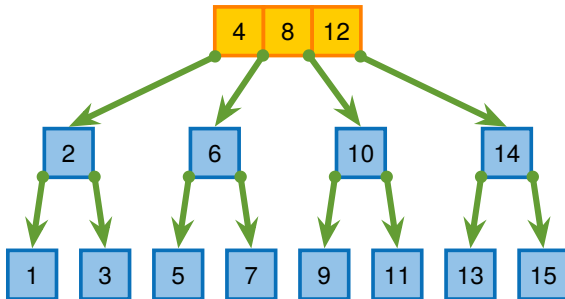


Figure: (2,3)-Tree - Insert step 3

(2,3)-Tree:

- Executed `insert(11)`



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

(2,3)-Tree:



Figure: (2,3)-Tree

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- We are exactly where we started



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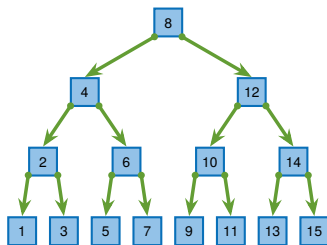


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- We are exactly where we started
- If $b = 2a - 1$ then we can create a sequence of **insert** and **remove** operations where each operation costs $O(\log n)$
- We need $b \geq 2a$ instead of $b \geq 2a - 1$

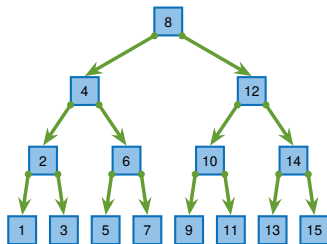


Figure: (2,3)-Tree



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- If all nodes have 3 children it takes some time to reach one of the previous two states

⇒ **Nodes of degree 3 are harmless**

Neither an insert nor a remove operation trigger rebalancing operations



$(2,4)$ -Tree:



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- Idea:

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- **Idea:**

- After an expensive operation the tree is in a stable state

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■ 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 $O(1)$



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Example:



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- Nodes of degree 3 are highlighted

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Figure: Tree with potential $\phi = 4$



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

Number of harmless (degree 3) nodes at operation i . Can be -1 , but not smaller than -1

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- With that each operation has an amortized cost of $O(1)$

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

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Figure: Splitting a node on `insert`

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



Figure: Splitting a node on **insert**

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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

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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

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⇒ We can find the successor in $O(1)$

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Figure: Tree with doubly linked list



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Figure: Borrowing an element case 2.1.2



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Figure: Merging two nodes

■ Potential rises by one

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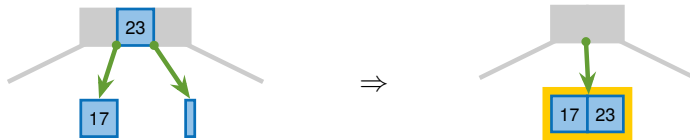


Figure: Merging two nodes

- Potential rises by one
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Case 2: i -th operation is an **remove** operation

■ **Case 2.2:** Merging a node

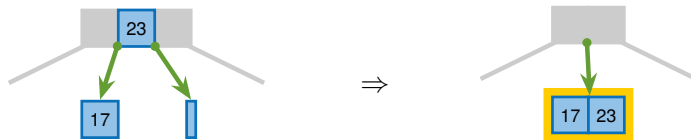


Figure: Merging two nodes

- Potential rises by one
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- This operation propagates upwards until a node of degree > 2 or a degree 2 node, which can borrow from a neighbour

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

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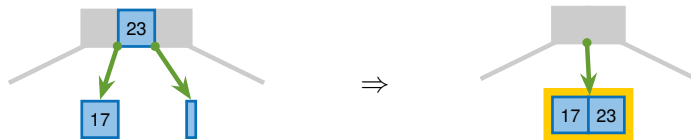


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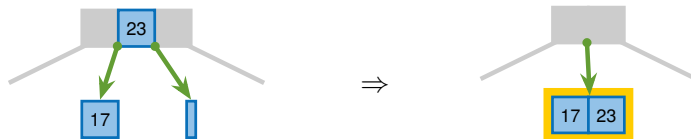


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- Potential rises by one
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- If the “stop-node” is of **degree 2** then the potential eventually goes down by one
- Same costs as **insert**



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- With that we can conclude:

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

Proof:

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

Balanced Trees

Motivation

AVL-Trees

(a,b)-Trees

Introduction

Runtime Complexity

Red-Black Trees



Red-Black Tree:

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- Binary tree with red and black nodes

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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`