

Algorithms and Datastructures

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

Albert-Ludwigs-Universität Freiburg



**UNI
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Bioinformatics Group / Department of Computer Science
Algorithms and Datastructures, January 2017

Balanced Trees

- Motivation

- AVL-Trees

- (a,b)-Trees

 - Introduction

 - Runtime Complexity

- Red-Black Trees

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Motivation

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



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- <http://people.ksp.sk/~kuko/bak>



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Abbildung: Binary search tree with random insert [Gna]



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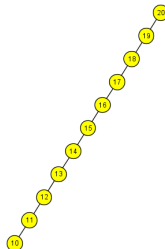
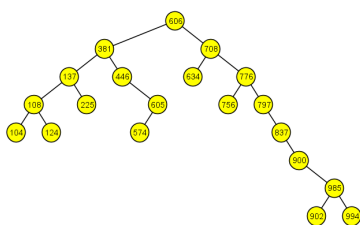


Abbildung: Binary search tree with random insert [Gna]

Abbildung: Binary search tree with descending insert [Gna]



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

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- With that the height of the search tree is always $O(\log n)$
- We can perform all basic operations in $O(\log n)$



Abbildung: Example of an AVL-Tree

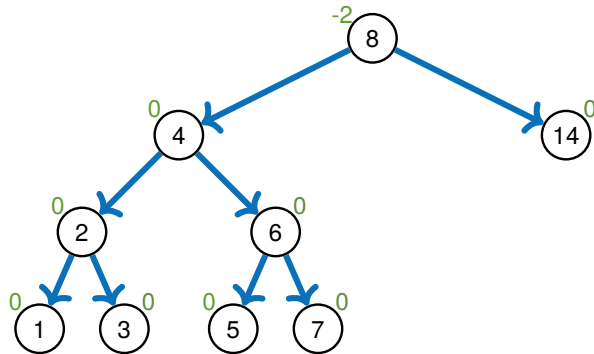


Abbildung: **Not** an AVL-Tree



Abbildung: Another example of an AVL-Tree

Rotation:

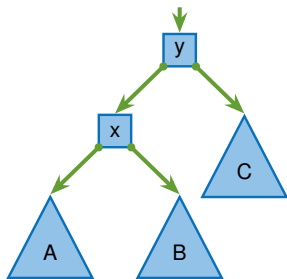


Abbildung: Before rotating

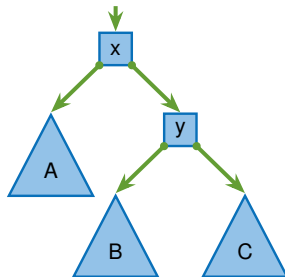


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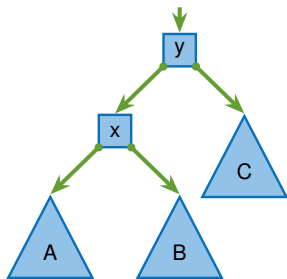


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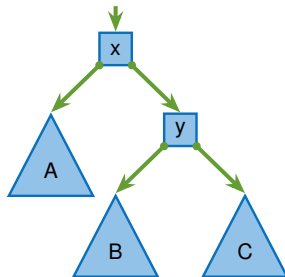


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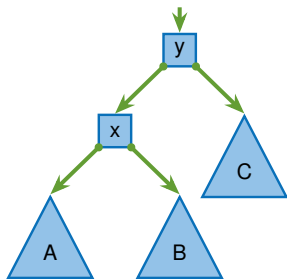


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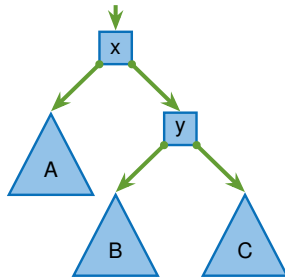


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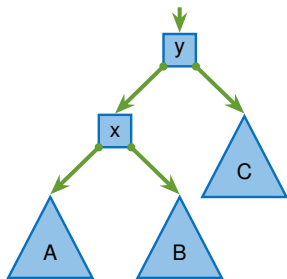


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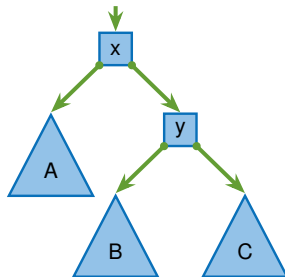


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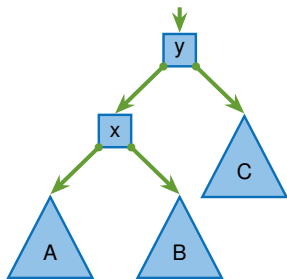


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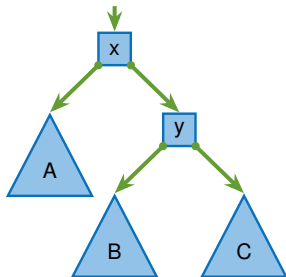


Abbildung: After rotating

- Central operation of **rebalancing**
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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 swanned



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



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- 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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(a,b) -Tree:

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



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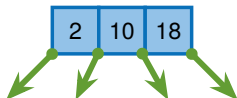
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- We require: $a \geq 2$ and $b \geq 2a - 1$

(2,4)-Tree:



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

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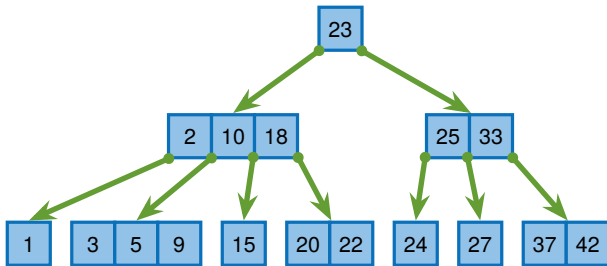


Abbildung: Example of an (2,4)-tree

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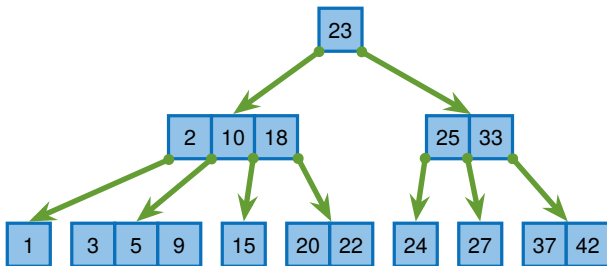


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- (2,4)-tree with depth of 3
- Each node has between 2 and 4 children (1 to 3 elements)

Not an (2,4)-Tree:

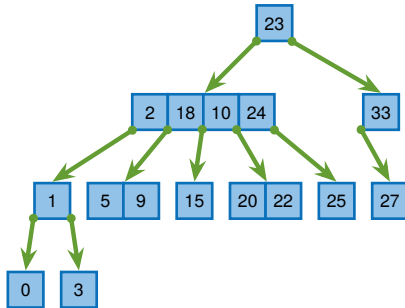


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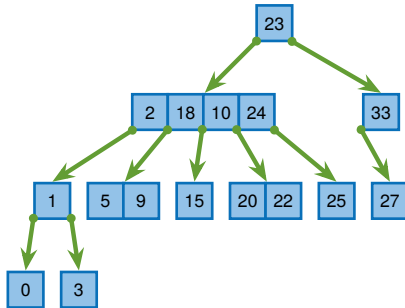


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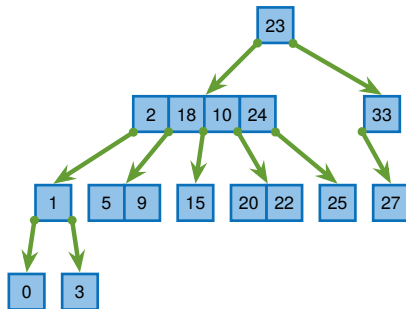


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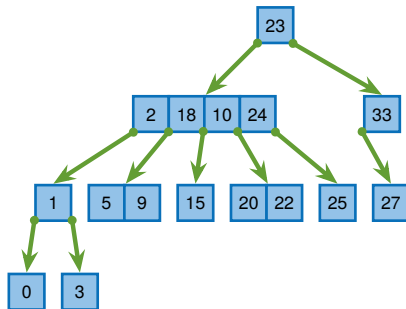


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- Invalid sorting
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- Leaves on different levels



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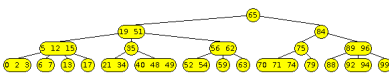
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BST AVL tree B tree Red-black tree AA tree Skiplist Max Heap Min Heap Treap Scapegoat tree Splay tree

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

Inserting an element: (`insert`)



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- If the degree is higher than $b + 1$ we split the node

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

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 - 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
 - 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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 - Search the **successor** in the right subtree
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⇒ We **rebalance** the tree



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Abbildung: Borrowing an element



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Removing an element: (remove)

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 - **Case b:** We **combine** the node with its right or left neighbour

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Abbildung: Combining two nodes

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- Now the parent node can be of degree $a - 1$

Removing an element: (remove)

- Now the parent node can be of degree $a - 1$
- We combine parent nodes the same way

Removing an element: (remove)

- Now the parent node can be of degree $a - 1$
- We combine parent nodes the same way
- If the root has only one child left we take the child as new root
(The tree shrinks one level)



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

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- All operations in $O(d)$ with d being the depth of the tree

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 $d \leq 1 + \log_a n = O(\log_a n)$

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 - 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)`

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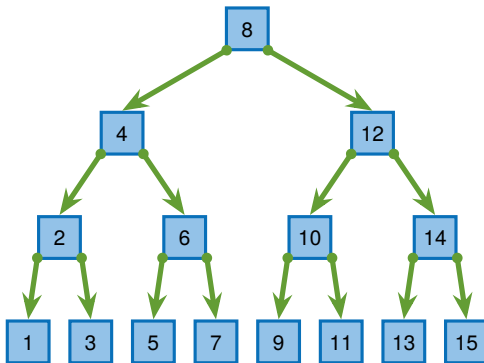


Abbildung: Normal (2,3)-Tree

(2,3)-Tree:

- Executing `delete(11)`

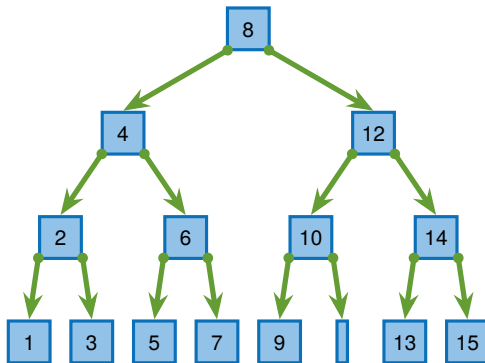


Abbildung: (2,3)-Tree - Delete step 1

(2,3)-Tree:

- Executing `delete(11)`

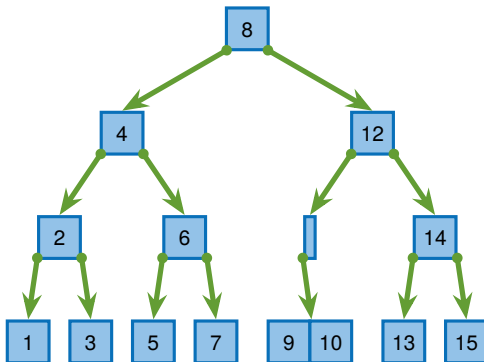


Abbildung: (2,3)-Tree - Delete step 2

(2,3)-Tree:

- Executing `delete(11)`

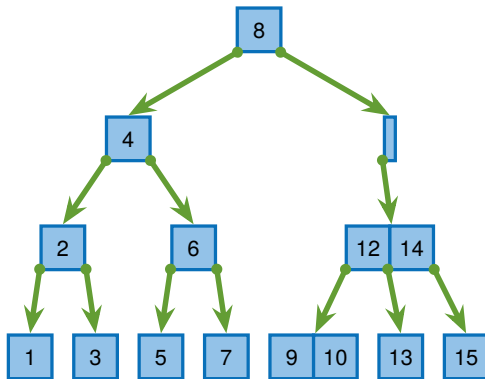


Abbildung: (2,3)-Tree - Delete step 3

(2,3)-Tree:

- Executed `delete(11)`

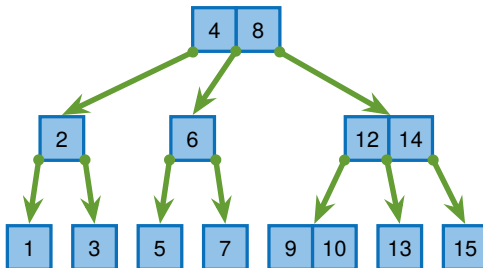


Abbildung: (2,3)-Tree - Delete step 4

(a,b) -Trees

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



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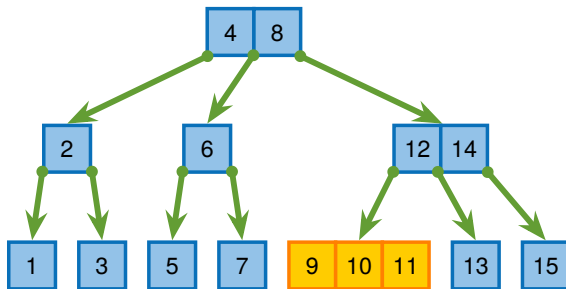


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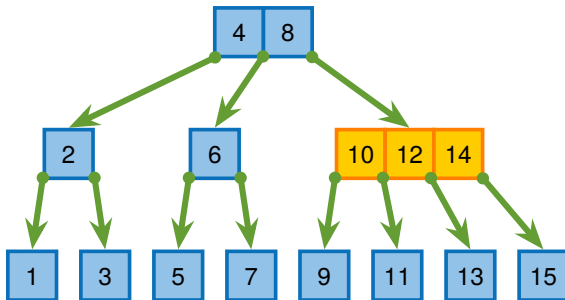


Abbildung: (2,3)-Tree - Insert step 2

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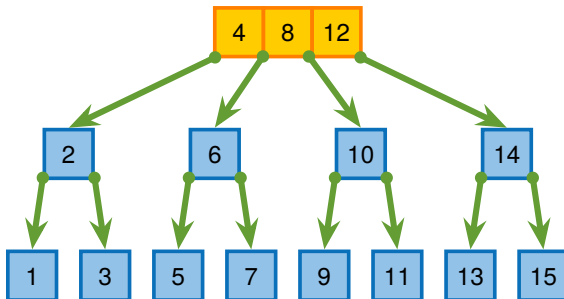


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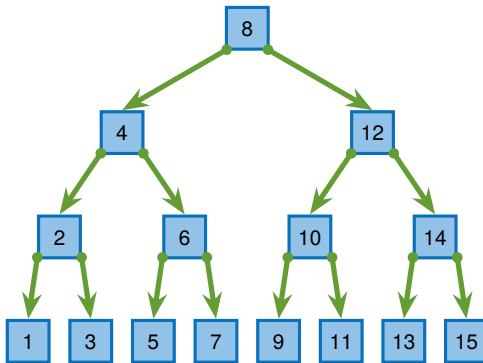


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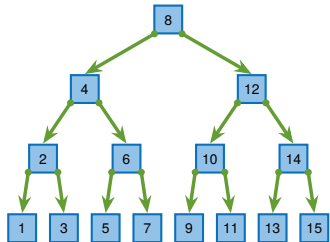


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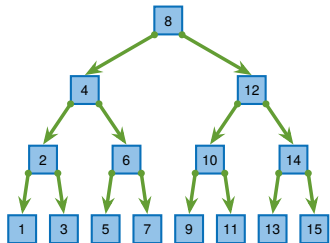


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(2,3)-Tree:

- 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 $b \geq 2a - 1$

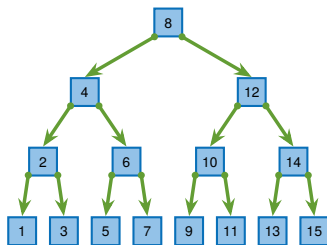


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(2,4)-Tree:

- If all nodes have **2 children** we have to **combine** 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 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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- After an expensive operation the tree is in a stable state
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- Like with dynamic arrays:
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 - If we **overallocate** clever we have an amortized runtime of $O(1)$



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Example:



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Abbildung: Tree with potential $\Phi = 4$



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

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 $O(1)$

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Abbildung: Splitting a node on `insert`

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Abbildung: Splitting a node on **insert**

- Each splitted node creates a node of **degree 3**
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- 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



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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



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

■ **Case 2.1:** Inner node

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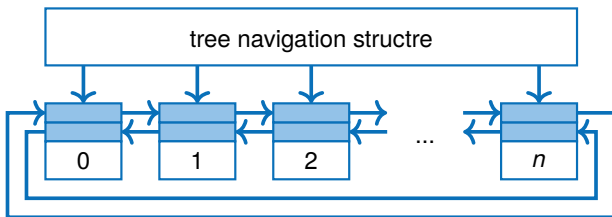


Abbildung: Tree with doubly linked list



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



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- **Case 2.1:** Borrowing a node

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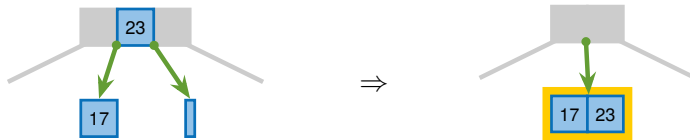


Abbildung: Merging two nodes

■ Potential rises by one

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

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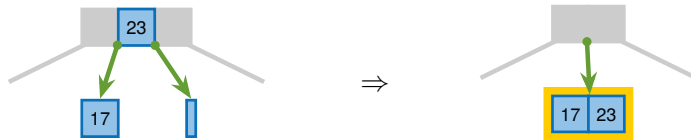


Abbildung: Merging two nodes

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

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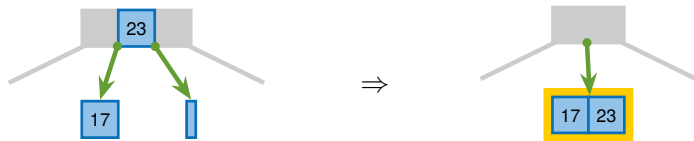


Abbildung: Merging two nodes

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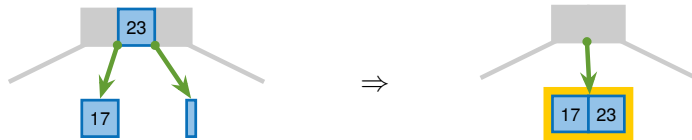


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- Same costs as **insert**



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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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- 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



Abbildung: 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)

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