

Algorithms and Datastructures

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

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Structure

Balanced Trees

- Motivation

- AVL-Trees

- (a,b)-Trees

 - Introduction

 - Runtime Complexity

- Red-Black Trees

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Motivation

Binary search tree:

Balanced Trees

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Binary search tree:

- ▶ With `BinarySearchTree` we could perform an `lookup` or `insert` in $O(d)$, with d being the `depth` of the tree

Balanced Trees

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- ▶ Best case: $d \in O(\log n)$, keys are inserted randomly

Balanced Trees

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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 $(20, 19, 18, \dots)$

Balanced Trees

Motivation

Gnarley trees:

Balanced Trees

Motivation

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- ▶ <http://people.ksp.sk/~kuko/bak>



Balanced Trees

Motivation



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Figure: Binary search tree with random insert [Gna]

Balanced Trees

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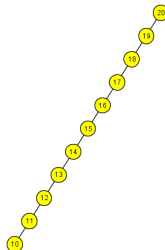


Figure: Binary search tree with descending insert [Gna]

Balanced Trees

Motivation

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- ▶ We do not want to rely on certain properties of our **key set**

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Balanced Trees

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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

Balanced Trees

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

Balanced Trees

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- ▶ **AVL-Tree:**

Balanced Trees

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- ▶ Can be interpreted as (2, 4)-tree

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- ▶ Can be interpreted as (2, 4)-tree
- ▶ Used in C++ `std::map` and Java `SortedMap`

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AVL-Trees

(a,b)-Trees

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AVL-Tree

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Balanced Trees

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- ▶ Gregory Maximovich **A**delson-**V**elskii, Yevgeniy Mikhailovlovich **L**andis (1963)

Balanced Trees

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Balanced Trees

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- ▶ With that the height of the search tree is always $O(\log n)$

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- ▶ 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 $O(\log n)$

Balanced Trees

AVL-Tree



Figure: Example of an AVL-Tree

Balanced Trees

AVL-Tree

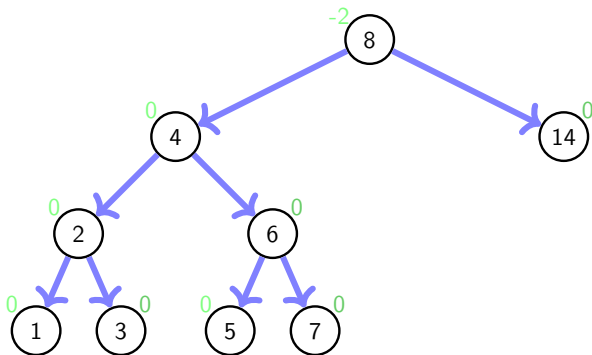


Figure: **Not** an AVL-Tree

Balanced Trees

AVL-Tree



Figure: Another example of an AVL-Tree

Balanced Trees

AVL-Tree - Rebalancing

Rotation:



Figure: Before rotating



Figure: After rotating

Balanced Trees

AVL-Tree - Rebalancing

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- Central operation of **rebalancing**

Balanced Trees

AVL-Tree - Rebalancing

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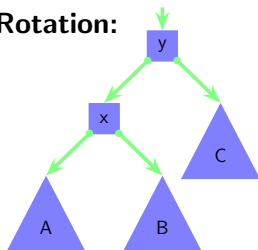


Figure: Before rotating



Figure: After rotating

- ▶ Central operation of **rebalancing**
- ▶ After rotation to the right:

Balanced Trees

AVL-Tree - Rebalancing

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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

Balanced Trees

AVL-Tree - Rebalancing

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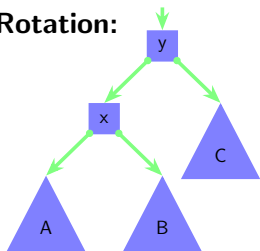


Figure: Before rotating

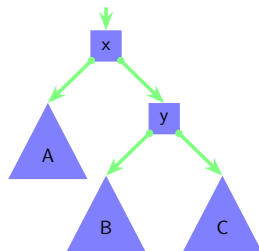


Figure: After rotating

- ▶ 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

Balanced Trees

AVL-Tree - Rebalancing

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- ▶ If a height difference of ± 2 occurs on an `insert` or `remove` operation the tree is rebalanced

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- ▶ Many different cases of rebalancing

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- ▶ **Example:** `insert` of 1, 2, 3, ...

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- ▶ 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]

Balanced Trees

AVL-Tree - Summary

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- ▶ Historical the first search tree providing guaranteed `insert`, `remove` and `lookup` in $O(\log n)$

Balanced Trees

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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 $O(1)$

Balanced Trees

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Summary:

- ▶ Historical the first search tree providing guaranteed **insert**, **remove** and **lookup** in $O(\log n)$
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- ▶ Additional memory costs: We have to save a height difference for every node

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Summary:

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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

Structure

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(a,b)-Trees

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(a,b) -Trees

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(a,b) -Tree:

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(a,b)-Tree:

- ▶ Also known as **b-tree** (b for “balanced”)

(a,b)-Trees

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(a,b)-Trees

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Idea:

(a,b)-Trees

Introduction

(a,b)-Tree:

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Idea:

- ▶ Save a varying number of elements per node

(a,b)-Trees

Introduction

(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) -Trees

Introduction

(a,b) -Tree:

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(a,b) -Tree:

- ▶ All leaves have the same depth

(a,b)-Trees

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(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)

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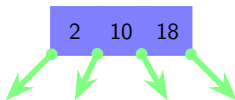


(a,b)-Trees

Introduction

(a,b)-Tree:

- ▶ All leaves have the same depth
- ▶ Each inner node has $\geq a$ and $\leq b$ nodes
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- ▶ Each node with n children is called “node of degree n ” and holds $n - 1$ sorted elements

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- ▶ Subtrees are located “between” the elements

(a,b)-Trees

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- ▶ All leaves have the same depth
- ▶ Each inner node has $\geq a$ and $\leq b$ nodes
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- ▶ 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 $b \geq 2a - 1$

(a,b)-Trees

Introduction

(2,4)-Tree:

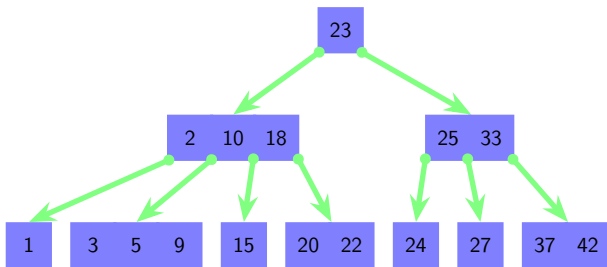


Figure: Example of an (2,4)-tree

(a,b)-Trees

Introduction

(2,4)-Tree:

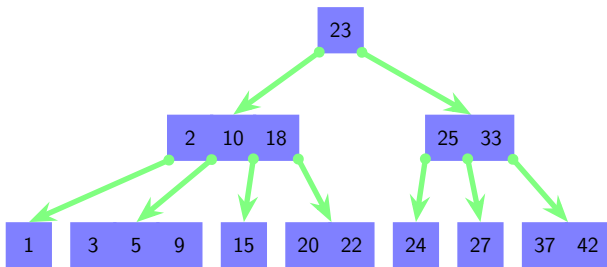


Figure: Example of an (2,4)-tree

- (2,4)-tree with depth of 3

(a,b)-Trees

Introduction

(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)

(a,b)-Trees

Introduction

Not an (2,4)-Tree:

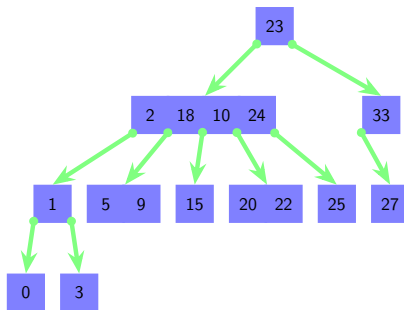


Figure: **Not** an (2,4)-tree

(a,b)-Trees

Introduction

Not an (2,4)-Tree:



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

- Invalid sorting

(a,b)-Trees

Introduction

Not an (2,4)-Tree:



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

- ▶ Invalid sorting
- ▶ Degree of node too large / too small

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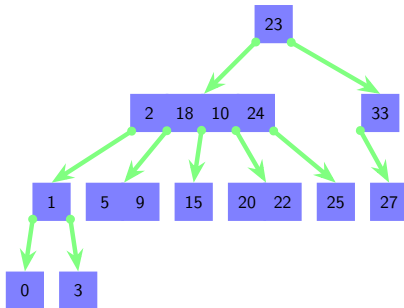


Figure: **Not** an (2,4)-tree

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

(a,b)-Trees

Implementation - Lookup

Searching an element: (lookup)

(a,b)-Trees

Implementation - Lookup

Searching an element: (`lookup`)

- ▶ The same algorithm as in `BinarySearchTree`

(a,b)-Trees

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- ▶ The keys at each node set the path

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Searching an element: (lookup)

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- ▶ Searching from the root downwards
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Figure: (3,5)-Tree [Gna]

(a,b)-Trees

Implementation - Insert

Inserting an element: (`insert`)

(a,b)-Trees

Implementation - Insert

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- ▶ Search the position to insert the key into

(a,b)-Trees

Implementation - Insert

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- ▶ Search the position to insert the key into
- ▶ This position will always be an leaf

(a,b)-Trees

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- ▶ Search the position to insert the key into
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- ▶ Insert the element into the tree

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- ▶ **Attention:** As a result node can overflow by one element (Degree $b + 1$)

(a,b)-Trees

Implementation - Insert

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

(a,b)-Trees

Implementation - Insert

Inserting an element: (`insert`)



Figure: Splitting a node

(a,b)-Trees

Implementation - Insert

Inserting an element: (`insert`)



Figure: Splitting a node

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

(a,b)-Trees

Implementation - Insert

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

(a,b)-Trees

Implementation - Insert

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 $\text{ceil}(\frac{b-1}{2})$ elements, a node with $\text{floor}(\frac{b-1}{2})$ elements and one element for the parent node
- ▶ That's why we have the limit $b \geq 2a - 1$

(a,b)-Trees

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(a,b)-Trees

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Inserting an element: (`insert`)

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(a,b)-Trees

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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 $b + 1$

(a,b)-Trees

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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

(a,b)-Trees

Implementation - Insert

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)

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

- ▶ Search the element in $O(\log n)$ time

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

- ▶ Search the element in $O(\log n)$ time
- ▶ **Case 1:** The element is contained by a leaf
 - ▶ Remove element

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

- ▶ Search the element in $O(\log n)$ time
- ▶ **Case 1:** The element is contained by a leaf
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 - ▶ Search the `successor` in the right subtree
 - ▶ The `successor` is always contained by a leaf

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

(a,b) -Trees

Implementation - Remove

Removing an element: (remove)

- ▶ **Attention:** The leaf might be too small (degree of $a - 1$)
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(a,b) -Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

(a,b) -Trees

Implementation - Remove

Removing an element: (remove)

- ▶ **Attention:** The leaf might be too small (degree of $a - 1$)
⇒ We **rebalance** the tree

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

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

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

(a,b)-Trees

Implementation - Remove

Removing an element: (`remove`)

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

(a,b)-Trees

Implementation - Remove

Removing an element: (remove)

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

(a,b)-Trees

Implementation - Remove

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

(a,b) -Trees

Runtime Complexity

Runtime complexity of lookup, insert and remove:

(a,b)-Trees

Runtime Complexity

Runtime complexity of lookup, insert and remove:

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

(a,b)-Trees

Runtime Complexity

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

(a,b)-Trees

Runtime Complexity

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:

(a,b)-Trees

Runtime Complexity

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 $\Theta(d)$

(a,b)-Trees

Runtime Complexity

Runtime complexity of lookup, insert and remove:

- ▶ All operations in $O(d)$ with d being the depth of the tree
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In detail:

- ▶ lookup always takes $\Theta(d)$
- ▶ insert and remove often require only $O(1)$ time

(a,b)-Trees

Runtime Complexity

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
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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

(a,b)-Trees

Runtime Complexity

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 $b \geq 2a$

(a,b) -Trees

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

Counter example $(2,3)$ -Tree:

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Before executing `delete(11)`

(a,b)-Trees

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

Counter example (2,3)-Tree:

- Before executing `delete(11)`

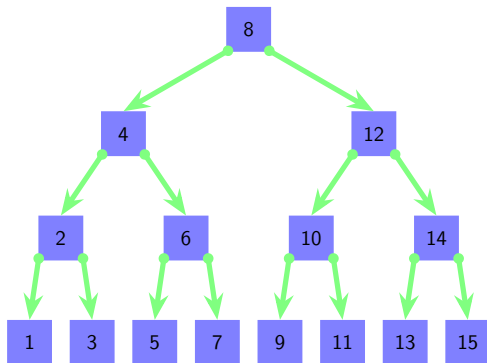


Figure: Normal (2,3)-Tree

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executing `delete(11)`



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

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executing `delete(11)`

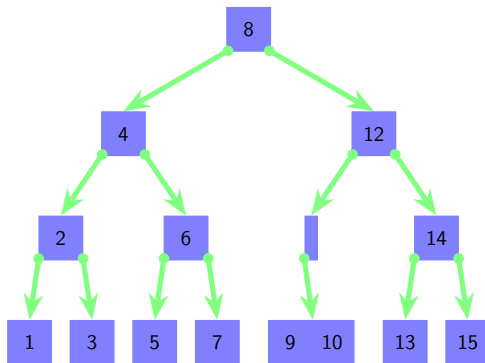


Figure: (2,3)-Tree - Delete step 2

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executing `delete(11)`



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

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executed `delete(11)`



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

(a,b) -Trees

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

Counter example $(2,3)$ -Tree:

- ▶ Executing `insert(11)`

(a,b) -Trees

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

Counter example $(2,3)$ -Tree:

- ▶ Executing `insert(11)`

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executing `insert(11)`



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

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executing `insert(11)`

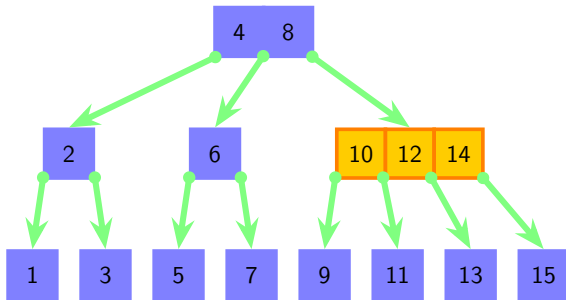


Figure: (2,3)-Tree - Insert step 2

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executing `insert(11)`



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

(a,b)-Trees

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

Counter example (2,3)-Tree:

- ▶ Executed `insert(11)`

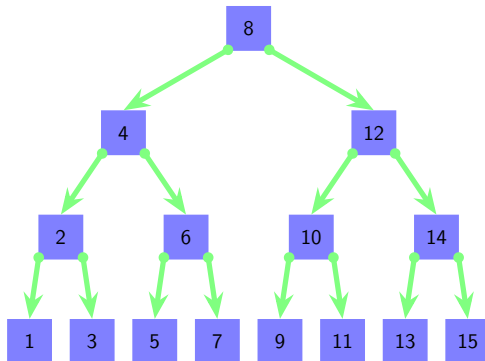


Figure: (2,3)-Tree - Insert step 4

(a,b)-Trees

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

Counter example (2,3)-Tree:

- We are exactly where we started



Figure: (2,3)-Tree

(a,b)-Trees

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

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 $O(\log n)$

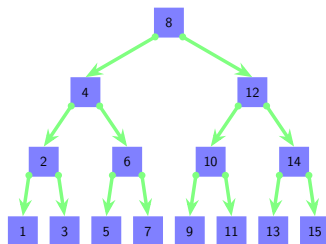


Figure: (2,3)-Tree

(a,b)-Trees

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

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 $b \geq 2a - 1$

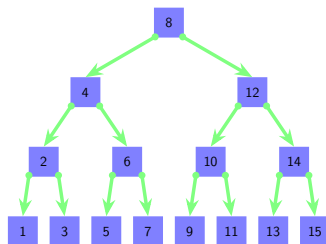


Figure: (2,3)-Tree

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

$(2,4)$ -Tree:

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

(2,4)-Tree:

- ▶ If all nodes have 2 children we have to merge the nodes up to the root on a remove operation

(a,b)-Trees

Runtime Complexity - (2,4)-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

(a,b)-Trees

Runtime Complexity - (2,4)-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

(a,b)-Trees

Runtime Complexity - (2,4)-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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

$(2,4)$ -Tree:

► **Idea:**

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

$(2,4)$ -Tree:

- ▶ **Idea:**

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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

$(2,4)$ -Tree:

- ▶ **Idea:**

- ▶ After an expensive operation the tree is in a stable state
- ▶ It takes some time until the next expensive operation occurs

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

$(2,4)$ -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:

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

(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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

(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 $O(1)$

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

Terminology:

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

Terminology:

- ▶ We analyze a sequence of n operations

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

Terminology:

- ▶ We analyze a sequence of n operations
- ▶ Let Φ_i be the potential of the tree after the i -th operation

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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: $\Phi = 0$

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

Example:

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

Example:

- ▶ Nodes of degree 3 are highlighted

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

Example:

- Nodes of degree 3 are highlighted



Figure: Tree with potential $\phi = 4$

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

Terminology:

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

Terminology:

- ▶ Let c_i be the costs = runtime of the i -th operation

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

Terminology:

- ▶ Let c_i be the costs = runtime of the i -th operation
- ▶ We will show:

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

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

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

$$c_i \leq A \cdot (\underbrace{\Phi_i - \Phi_{i-1}}_{\text{degree 3}}) + B, \quad A > 0 \text{ and } B > A$$

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

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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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



Figure: Splitting a node on **insert**

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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**

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

- ▶ Let m be the number of nodes split

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

▶ **Case 2.1:** Inner node

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

- ▶ **Case 2.1:** Inner node

- ▶ Searching the successor in a tree is $O(d) = O(\log n)$

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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 $O(1)$

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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 $O(1)$

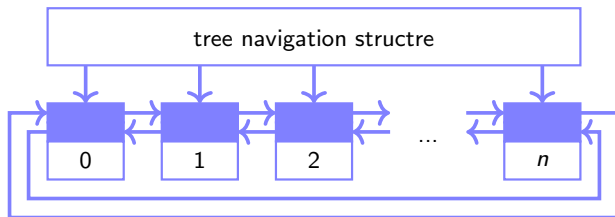


Figure: Tree with doubly linked list

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

- ▶ **Case 2.1:** Borrow a node

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

- ▶ **Case 2.1:** Borrow a node
 - ▶ Creates no additional operations

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

- ▶ **Case 2.1:** Borrow a node

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

- ▶ **Case 2.1:** Borrow a node
 - ▶ Creates no additional operations

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

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

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree

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

- ▶ **Case 2.2:** Merging two node

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two node



Figure: Merging two nodes

► Potential rises by one

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two node



Figure: Merging two nodes

- Potential rises by one
- Parent node has one element less after the operation

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two nodes

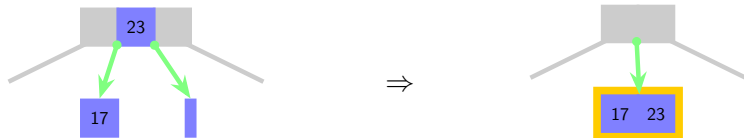


Figure: Merging two nodes

- 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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two node

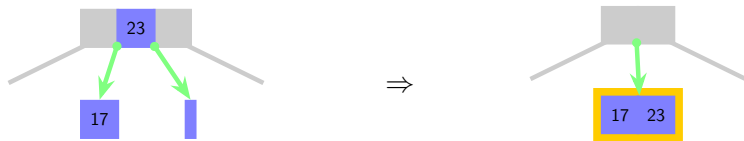


Figure: Merging two nodes

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two node

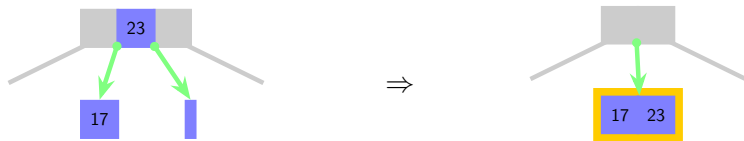


Figure: Merging two nodes

► The potential rises by m

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two node

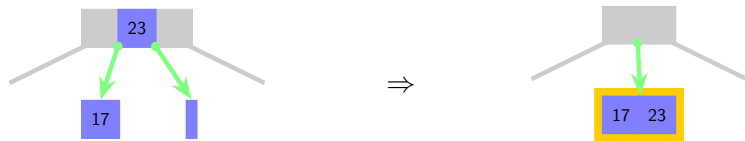


Figure: Merging two nodes

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree

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

► **Case 2.2:** Merging two node



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**

(a,b) -Trees

Runtime Complexity - $(2,4)$ -Tree - Lemma

Lemma:

(a,b)-Trees

Runtime Complexity - (2,4)-Tree - Lemma

Lemma:

- We know:

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree - Lemma

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:

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

(a,b)-Trees

Runtime Complexity - (2,4)-Tree - Lemma - Proof

Proof:

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

Structure

Balanced Trees

Motivation

AVL-Trees

(a,b)-Trees

Introduction

Runtime Complexity

Red-Black Trees

Red-Black-Trees

Introduction

Red-Black Tree:

Red-Black-Trees

Introduction

Red-Black Tree:

- ▶ Binary tree with red and black nodes

Red-Black-Trees

Introduction

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- ▶ Number of black nodes on path to leaves is equal

Red-Black-Trees

Introduction

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- ▶ Can be interpreted as (2,4)-tree (also named 2-3-4-tree)

Red-Black-Trees

Introduction

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

Red-Black-Trees

Introduction

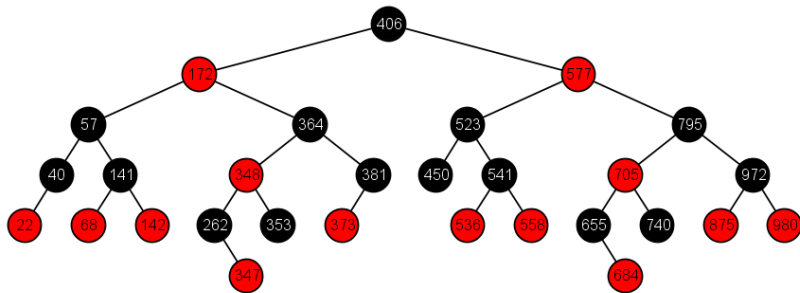


Figure: Example of an red-black-tree [Gna]

► 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](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`