

# Algorithms and Datastructures

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

Albert-Ludwigs-Universität Freiburg



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



## Gnarley trees:



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



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**Figure:** Binary search tree with random insert [Gna]



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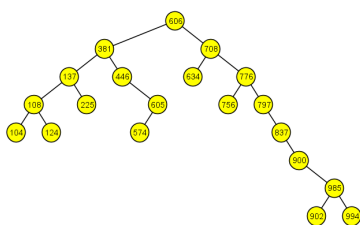


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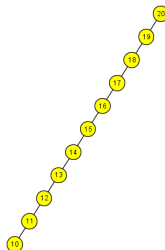


Figure: Binary search tree with descending insert [Gna]



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



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- Can be interpreted as (2, 4)-tree
- 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  $O(\log n)$



Figure: Example of an AVL-Tree



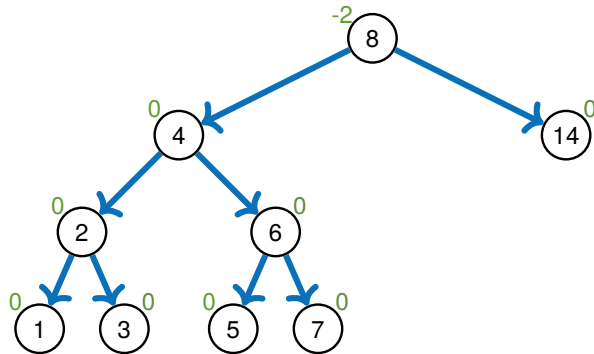


Figure: **Not** an AVL-Tree



Figure: Another example of an AVL-Tree

### Rotation:

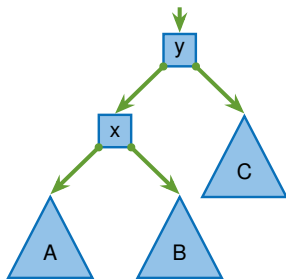


Figure: Before rotating

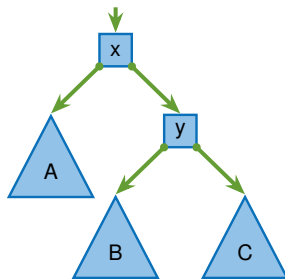


Figure: After rotating

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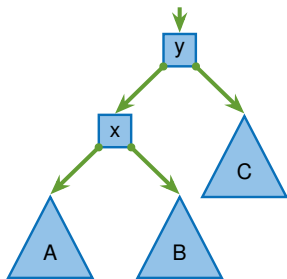


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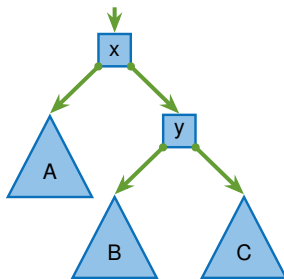


Figure: After rotating

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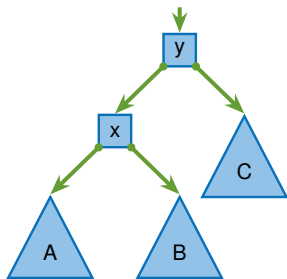


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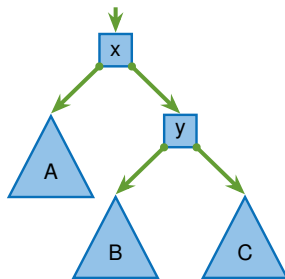


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  - Subtree **A** is a layer higher and subtree **C** a layer lower

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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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### **$(a,b)$ -Tree:**

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### Idea:

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



## $(a,b)$ -Tree:



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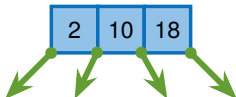
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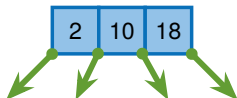
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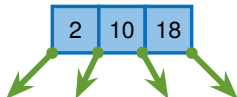
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- We require:  $a \geq 2$  and  $b \geq 2a - 1$



### (2,4)-Tree:



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

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

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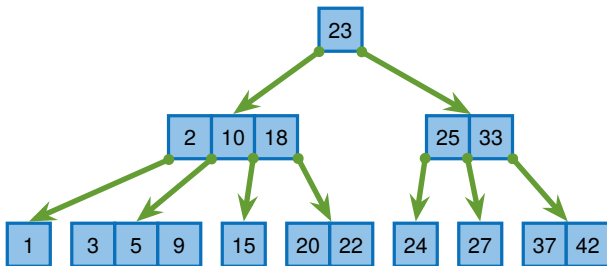


Figure: Example of an (2,4)-tree

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

### Not an (2,4)-Tree:



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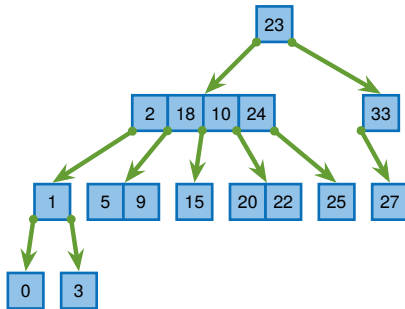


Figure: **Not** an (2,4)-tree

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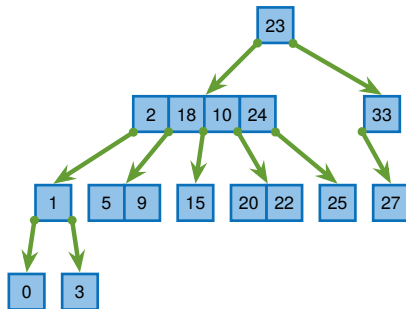


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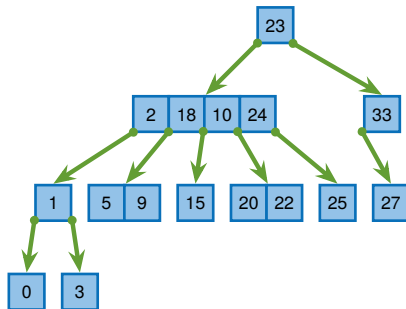


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- Degree of node too large / too small
- Leaves on different levels



**Searching an element:** (`lookup`)





### Searching an element: (lookup)

- The same algorithm as in [BinarySearchTree](#)



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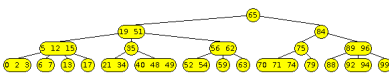
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BST AVL tree B tree Red-black tree AA tree Skiplist Max Heap Min Heap Treap Scapegoat tree Splay tree

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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- This position will always be an leaf
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- Then we **split** the node

Inserting an element: (`insert`)



Figure: Splitting a node

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### Inserting an element: (`insert`)



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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

### 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  $\lceil \frac{b-1}{2} \rceil$  elements, a element for the parent node, and a node with  $\lfloor \frac{b-1}{2} \rfloor$  elements
  - That's 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)



**Removing an element:** (`remove`)



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  - Search the `successor` in the right subtree



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  - 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`)

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- **Attention:** The leaf might be too small (degree of  $a - 1$ )  
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Figure: Borrowing an element



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

**UNI  
FREI**

- UNI  
FREI**



**UNI  
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**Removing an element:** (`remove`)

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

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  - 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



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## **$(2,3)$ -Tree:**



### (2,3)-Tree:

- Before executing `delete(11)`

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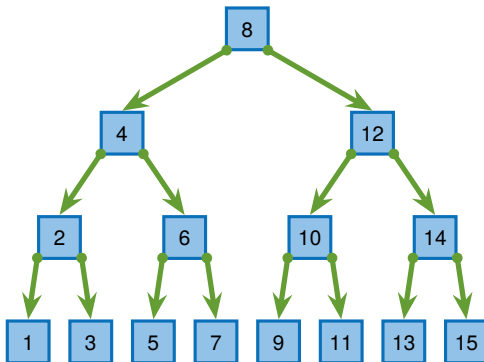


Figure: Normal (2,3)-Tree

### (2,3)-Tree:

- Executing `delete(11)`

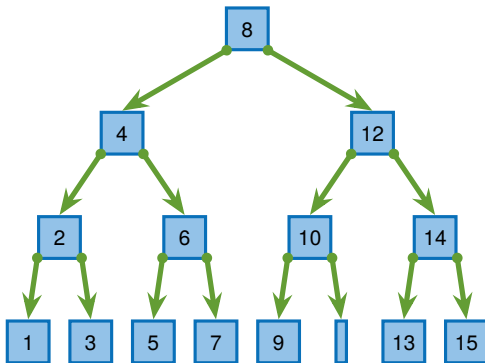


Figure: (2,3)-Tree - Delete step 1

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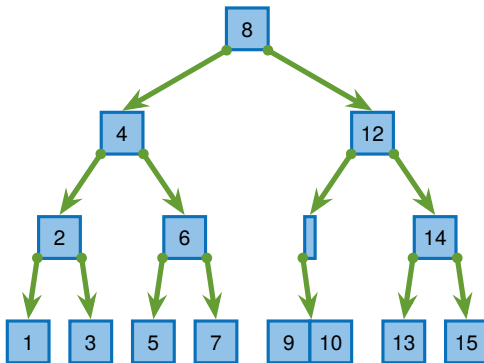


Figure: (2,3)-Tree - Delete step 2

### (2,3)-Tree:

- Executing `delete(11)`



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

### (2,3)-Tree:

- Executed `delete(11)`

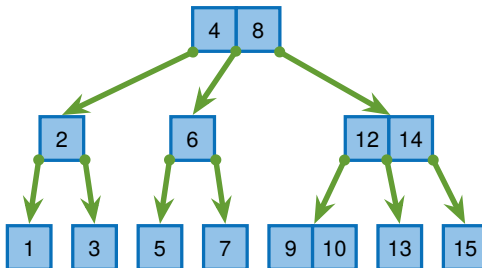


Figure: (2,3)-Tree - Delete step 4



# $(a,b)$ -Trees

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



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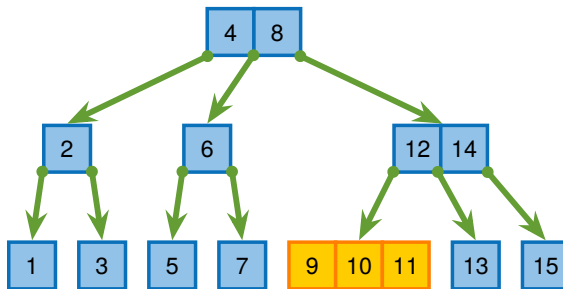


Figure: (2,3)-Tree - Insert step 1

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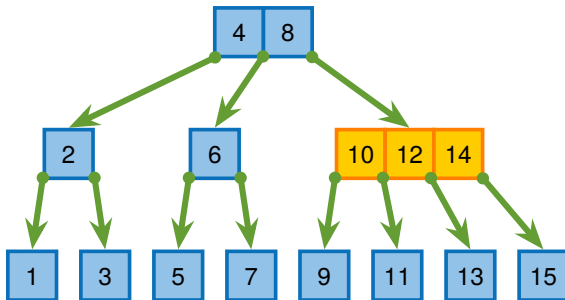


Figure: (2,3)-Tree - Insert step 2

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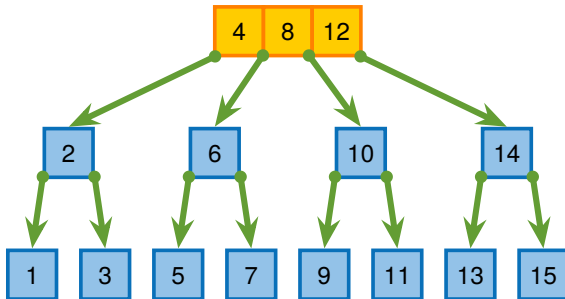


Figure: (2,3)-Tree - Insert step 3

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

### (2,3)-Tree:



Figure: (2,3)-Tree

### (2,3)-Tree:

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Figure: (2,3)-Tree



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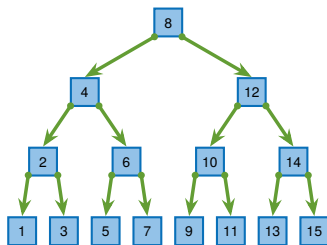


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### (2,3)-Tree:

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- 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  $b \geq 2a - 1$

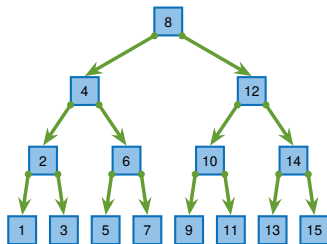


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⇒ **Nodes of degree 3 are harmless**

Neither an insert nor a remove operation trigger rebalancing operations



### **$(2,4)$ -Tree:**





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### Example:



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Figure: Tree with potential  $\Phi = 4$



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- The costs for operation  $i$  are coupled to the difference of the potential levels

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

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

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



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Figure: Tree with doubly linked list



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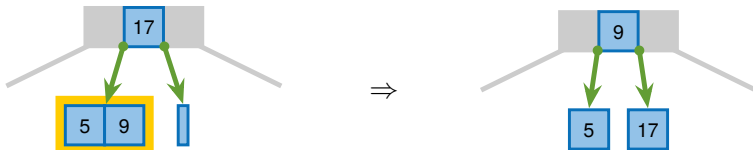


Figure: Borrowing an element case 2.1.2



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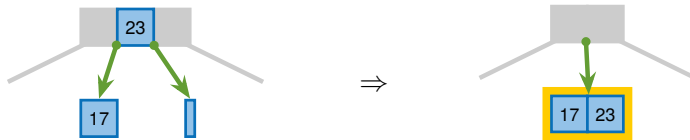


Figure: Merging two nodes

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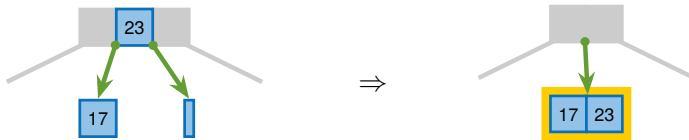


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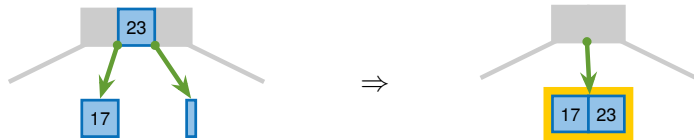


Figure: Merging two nodes

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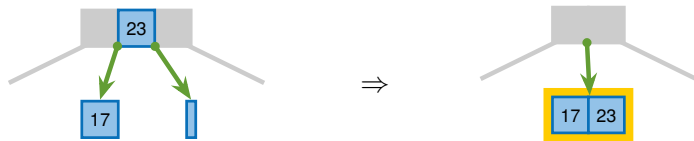


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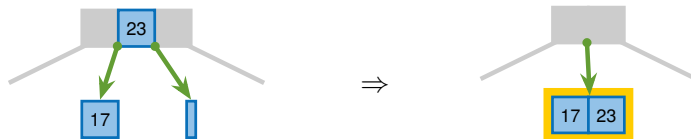


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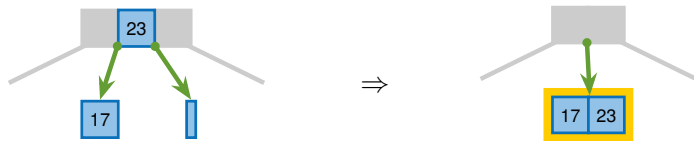


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Lemma:

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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:

### Red-Black Tree:

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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



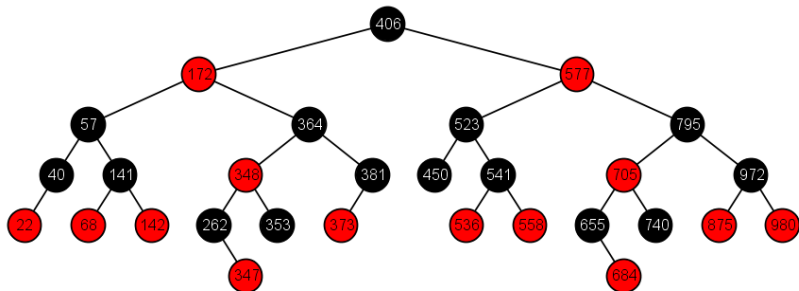


Figure: Example of an red-black-tree [Gna]

## ■ General

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

**Introduction to Algorithms.**

MIT Press, Cambridge, Mass, 2001.

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<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`