

CSC 212: Data Structures and Abstractions

Balanced trees (part 1)

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Balanced search trees

- **Balanced search trees** are a type of search trees that maintain specific structural invariants to ensure their height h remains $O(\log n)$ for n nodes

- ✓ among the most important data structures in computer science
- ✓ widely implemented in standard libraries:
 - Java: TreeSet and TreeMap,
 - C++: std::set and std::map
 - Python: no built-in implementation, but available through third-party libraries

- Examples of balanced trees:

- ✓ AVL trees, **Red-Black trees**, B-trees, Treaps, etc.

Practice

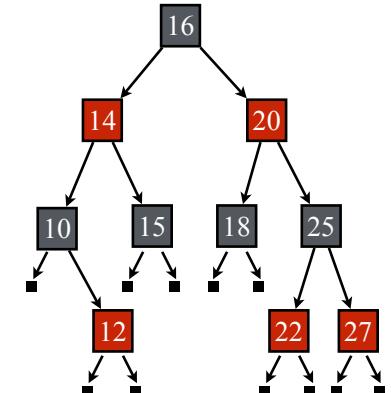
- Assume a dictionary has n keys, and a book has m words
 - ✓ What is the time complexity of identifying which words from the book do NOT appear in the dictionary?
 - dictionary is represented as a BST and assume that $h = O(\log n)$
 - book is represented as an array (vector) of strings, where each string is a word

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Red-black trees

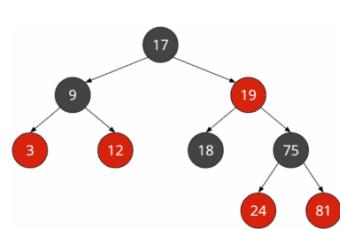
- Red-black trees are BSTs that maintain near-perfect balance by enforcing the following properties on the nodes:

- ✓ every node is colored **red** or **black**
- ✓ the root is always **black**
- ✓ **red** nodes cannot have **red** children (no two consecutive red nodes)
- ✓ null nodes are considered **black**
- ✓ every root-to-null path must have the same number of **black** nodes

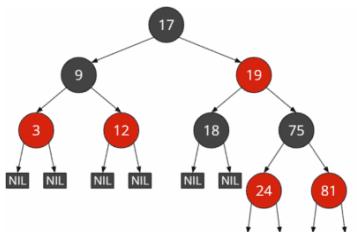


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Examples



Red-black tree with implicit NIL leaves



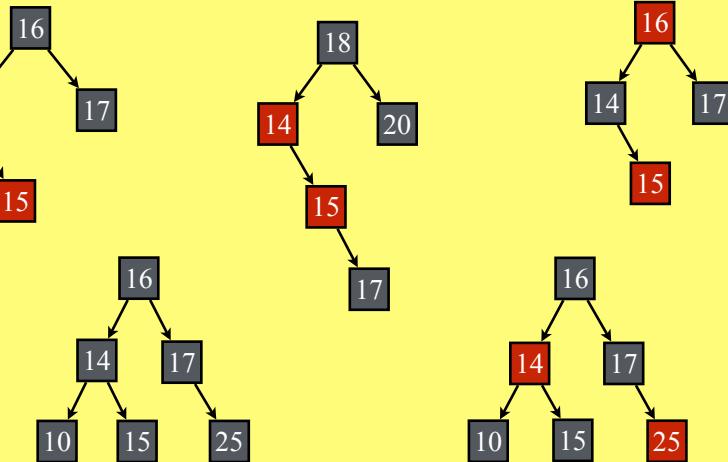
Red-black tree with explicit NIL leaves

<https://www.happycoders.eu/algorithms/red-black-tree-java/>

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Practice

- Are these valid red-black trees? — (null nodes not shown)



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Height of red-black trees

- A red-black tree with n nodes has height $h = O(\log n)$
 - after an insertion or deletion, the tree may temporarily violate one or more red-black properties
 - these violations are efficiently corrected through:
 - rotations (left or right) and recoloring of nodes
- Equivalence to **2-3-4 Trees**
 - red-black trees are conceptually equivalent to 2-3-4 trees ([B-trees of order 4](#))
 - this correspondence provides intuition for:
 - how rebalancing maintains logarithmic height
 - why red-black tree operations run in $O(\log n)$ time

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2-3-4 Trees (interlude)

Multi-way search trees

- A multi-way search tree is a generalization of a BST in which:

- ✓ each node can store multiple keys (instead of just one)
- ✓ each node can have more than two children

Properties

- ✓ the keys within each node are stored in **sorted** (increasing) order
- ✓ for a node containing keys $[k_1, k_2, \dots, k_m]$ and child subtrees $[T_0, T_1, \dots, T_m]$:
 - all keys in T_0 are less than k_1
 - all keys in T_i (for $0 < i < m$) are between k_i and k_{i+1}
 - all keys in T_m are greater than k_m

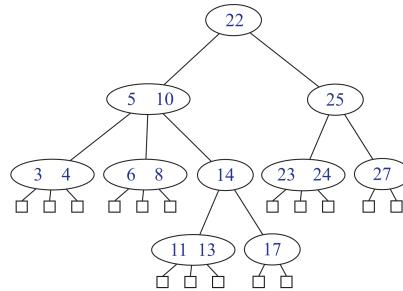


Image credit: Data Structures and Algorithms in C++ 2e

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Search on a multi-way search tree

- Perform **search** for 12, 17, 24, and 50 on the following tree

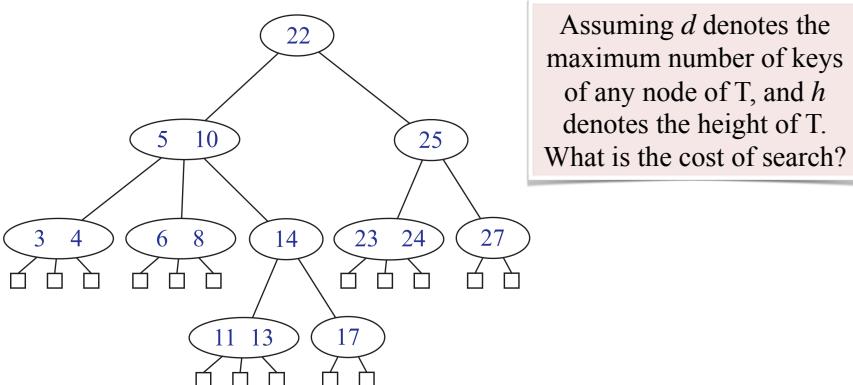


Image credit: Data Structures and Algorithms in C++ 2e

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Example of a multi-way search tree

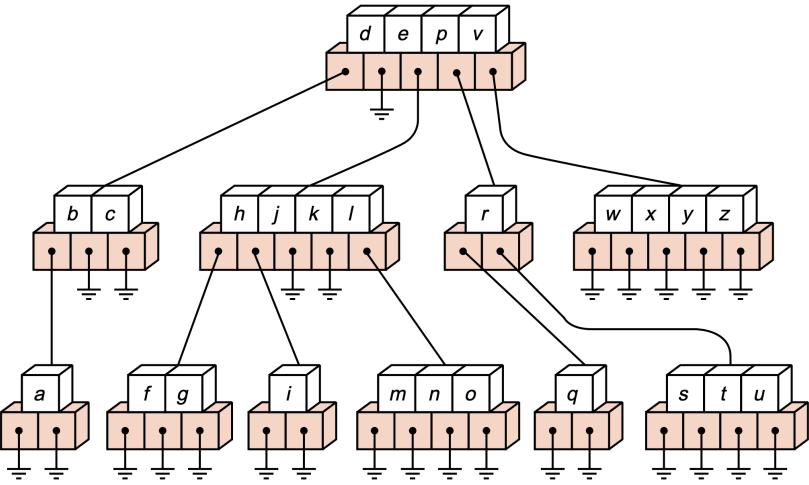


Image credit: Data Structures and Program Design In C++, Kruse and Ryba

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Balanced multi-way search trees

- A balanced multi-way search tree is a multi-way search tree that:

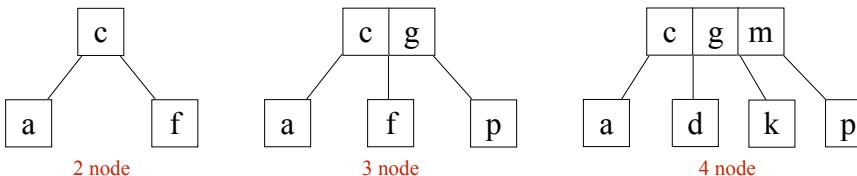
- ✓ limits each node to a fixed maximum number of children
- ✓ keeps all leaf nodes at the same depth, ensuring the tree remains perfectly balanced
- A B-tree is a specific type of balanced multi-way search tree
 - ✓ in a B-tree of **order m** (maximum number of children), every node, except the root, must have between $\lceil m/2 \rceil$ and m children
 - the term "order" can vary slightly between sources — some define it as the maximum number of keys, others as the maximum number of children
 - ✓ B-trees are heavily used in databases, filesystems, and storage systems because they minimize disk I/O by storing many keys per node (typical orders: 1024, 2048, 4096, ...)

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2-3-4 tree

- A 2-3-4 tree (also called a 2-4 tree) is a B-tree of order 4

- ✓ each node can have 2, 3, or 4 children
- ✓ all nodes (except the root, which can be empty) must have at least 1 key and at most 3 keys



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Practice

- Insert the following sequence into a 2-3-4 tree
 - ✓ 15, 10, 25, 5, 1, 30, 45, 60, 100, 70, 80, 40, 35, 90

Insertion (2-3-4 tree)

- Steps

- ✓ **start at the root** and traverse downward to find the correct leaf for insertion
- ✓ if the leaf has fewer than 3 keys
 - insert the new key into the node in sorted order
- ✓ if the leaf already has 3 keys
 - temporarily insert the new key (so it contains 4 keys)
 - split the node into two nodes by promoting the middle key to the parent node and forming two new child nodes with the remaining keys
 - if the parent now has more than 3 keys, repeat this splitting process upward until the root if necessary

- Tree remains balanced after each insertion

- ✓ all leaf nodes are at the same level

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Practice

- What is the max h of a 2-3-4 tree with n nodes?
 - ✓ to maximize the height, we want to minimize the number of keys per node (**instance of a worst-case**)
 - ✓ draw an example tree and express h in terms of n

- What is the cost of search and insert on a 2-3-4 tree?
 - ✓ worst-case scenario

Analysis

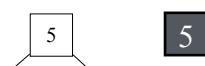
- The cost of operations in a B-tree of order b is $O(b \log_b n)$
 - ✓ insert, search, remove
 - ✓ small values of b make this cost optimal
- In practice ...
 - ✓ B-trees are widely used in databases and file systems to manage large amounts of data efficiently
 - ✓ useful for systems that read and write large blocks of data
 - B-trees can minimize the number of disk accesses required (much larger order values)

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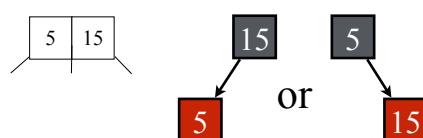
2-3-4 trees and red-black trees

Red-black trees \Leftrightarrow 2-3-4 trees

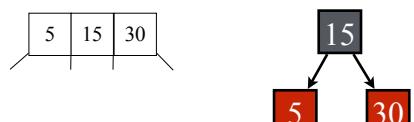
- A 2-node in a 2-3-4 tree corresponds to a **black** node in a red-black tree



- A 3-node corresponds to a **black** node with one **red** child



- A 4-node corresponds to a **black** node with two **red** children

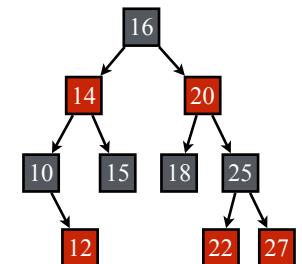


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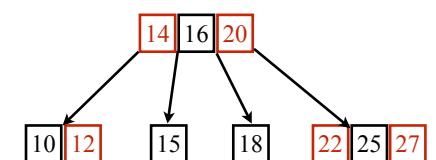
Red-black trees \Leftrightarrow 2-3-4 trees

- Red-black trees are **isomorphic** to 2-3-4 trees

- ✓ the number of black nodes on any root-to-null path corresponds to the number of levels of the 2-3-4 tree
- ✓ every red-black tree can be transformed into an equivalent 2-3-4 tree and vice versa



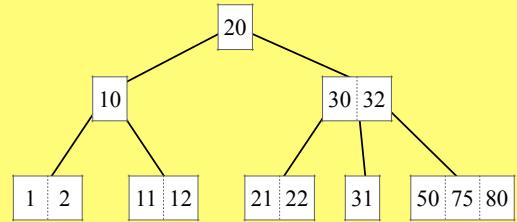
- ✓ the relationship is not bijective
 - a 3-node in a 2-3-4 tree can be represented in two ways in a red-black tree (leaning left or right)
 - each red-black tree corresponds to exactly one 2-3-4 tree (but not vice versa)



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Practice

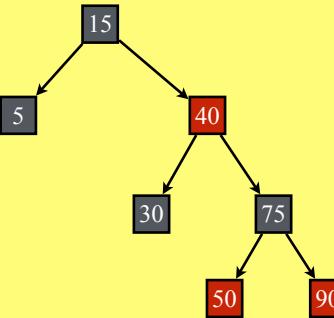
- Draw the red-black tree that corresponds to the following 2-3-4 tree



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Practice

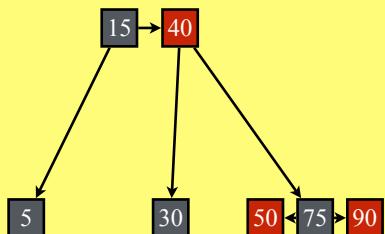
- Draw the 2-3-4 tree that corresponds to the following red-black tree



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Practice

- Draw the 2-3-4 tree that corresponds to the following red-black tree



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