Balanced Trees
Part One
Balanced Trees

• Balanced search trees are among the most useful and versatile data structures.

• Many programming languages ship with a balanced tree library.
  • C++: std::map / std::set
  • Java: TreeMap / TreeSet
  • Python: OrderedDict

• Many advanced data structures are layered on top of balanced trees.
  • We'll see them used to build y-Fast Tries later in the quarter. (They’re really cool, trust me!)
Where We're Going

- **B-Trees (Today)**
  - A simple type of balanced tree developed for block storage.

- **Red/Black Trees (Today)**
  - The canonical balanced binary search tree.

- **Augmented Search Trees (Tuesday)**
  - Adding extra information to balanced trees to supercharge the data structure.

- **Two Advanced Operations (Tuesday)**
  - Splitting and joining BSTs.
Outline for Today

- **BST Review**
  - Refresher on basic BST concepts and runtimes.

- **Overview of Red/Black Trees**
  - What we're building toward.

- **B-Trees and 2-3-4 Trees**
  - A simple balanced tree in depth.

- **Intuiting Red/Black Trees**
  - A much better feel for red/black trees.
A Quick BST Review
Binary Search Trees

- A **binary search tree** is a binary tree with the following properties:
  - Each node in the BST stores a **key**, and optionally, some auxiliary information.
  - The key of every node in a BST is strictly greater than all keys to its left and strictly smaller than all keys to its right.
  - The **height** of a binary search tree is the length of the longest path from the root to a leaf, measured in the number of **edges**.
    - A tree with one node has height 0.
    - A tree with no nodes has height -1, by convention.
Searching a BST
Inserting into a BST
Inserting into a BST
Deleting from a BST

Case 1: If the node has just no children, just remove it.
Deleting from a BST

**Case 2:** If the node has just one child, remove it and replace it with its child.
Deleting from a BST

**Case 3:** If the node has two children, find its inorder successor (which has zero or one child), replace the node's key with its successor's key, then delete its successor.
Runtime Analysis

• The time complexity of all these operations is $O(h)$, where $h$ is the height of the tree.
  • That’s the longest path we can take.
• In the best case, $h = O(\log n)$ and all operations take time $O(\log n)$.
• In the worst case, $h = \Theta(n)$ and some operations will take time $\Theta(n)$.

**Challenge:** How do you efficiently keep the height of a tree low?
A Glimpse of Red/Black Trees
Red/Black Trees

- A **red/black tree** is a BST with the following properties:
  - Every node is either red or black.
  - The root is black.
  - No red node has a red child.
  - Every root-null path in the tree passes through the same number of black nodes.
Red/Black Trees

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  • Every node is either red or black.
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Red/Black Trees

• **Theorem**: Any red/black tree with $n$ nodes has height $O(\log n)$.
  - We could prove this now, but there's a much simpler proof of this we'll see later on.
  - Given a fixed red/black tree, lookups can be done in time $O(\log n)$. 
What are we supposed to do with this new node?
How do we fix up the black-height property?
Fixing Up Red/Black Trees

- **The Good News:** After doing an insertion or deletion, can locally modify a red/black tree in time $O(\log n)$ to fix up the red/black properties.

- **The Bad News:** There are a lot of cases to consider and they're not trivial.

- Some questions:
  - How do you memorize / remember all the different types of rotations?
  - How on earth did anyone come up with red/black trees in the first place?
B-Trees
Generalizing BSTs

• In a binary search tree, each node stores a single key.
• That key splits the “key space” into two pieces, and each subtree stores the keys in those halves.
Generalizing BSTs

- In a **multiway search tree**, each node stores an arbitrary number of keys in sorted order.
- A node with \( k \) keys splits the key space into \( k + 1 \) regions, with subtrees for keys in each region.
Generalizing BSTs

- In a **multiway search tree**, each node stores an arbitrary number of keys in sorted order.

- Surprisingly, it’s a bit easier to build a balanced multiway tree than it is to build a balanced BST. Let’s see how.
Balanced Multiway Trees

- In some sense, building a balanced multiway tree isn’t all that hard.
- We can always just cram more keys into a single node!

At a certain point, this stops being a good idea – it’s basically just a sorted array.
Balanced Multiway Trees

- What could we do if our nodes get too big?
  - **Option 1:** Push keys down into new nodes.
  - **Option 2:** Split big nodes, kicking keys higher up.

- What are some advantages of each approach?
- What are some disadvantages?
Balanced Multiway Trees

- **Option 1:** Push keys down into new nodes.
  - Simple to implement.
  - Can lead to tree imbalances.

```
10 50 99
20 30 40
31 35 39
32 33 34
```
Balanced Multiway Trees

- **Option 1:** Push keys down into new nodes.
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- **Option 2:** Split big nodes, kicking keys higher up.
  - Keeps the tree balanced.
  - Slightly trickier to implement.
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Each existing node’s depth just increased by one.
Balanced Multiway Trees

- **General idea:** Keep nodes holding roughly between $b$ and $2b$ keys, for some parameter $b$.
  - (Exception: the root node can have fewer keys.)
- If a node gets too big, split it and kick a key higher up.

- **Advantage 1:** The tree is always balanced.
- **Advantage 2:** Insertions and lookups are pretty fast.
Balanced Multiway Trees

• We currently have a *mechanical definition* of how these balanced multiway trees work:
  • Nodes should have between roughly $b$ and $2b$ keys in them.
  • Split nodes when they get too big and propagate the splits upward.

• We currently don’t have an *operational definition* of how these balanced multiway trees work.
  • e.g. “A Cartesian tree for an array is a binary tree that’s a min-heap and whose inorder traversal gives back the original array.”
  • e.g. “A suffix tree is a Patricia trie with one node for each suffix and branching word of $T$."

B-Trees

- A **B-tree of order** \(b\) is a multiway search tree where
  - each node has (roughly) between \(b\) and \(2b\) keys, except the root, which may only have one key;
  - each node is either a leaf or has one more child than key; and
  - all leaves are at the same depth.

- Different authors give different bounds on how many keys can be in each node. The ranges are often \([b-1, 2b-1]\) or \([b, 2b]\). For the purposes of today’s lecture, we’ll use the range \([b-1, 2b-1]\) for the key limits, just for simplicity.
Analyzing Multiway Trees
The Height of a B-Tree

- What is the maximum possible height of a B-tree of order \( b \)?
The Height of a B-Tree

- **Theorem:** The maximum height of a B-tree of order $b$ containing $n$ keys is $\log_b \left( \frac{(n + 1)}{2} \right)$.

- **Proof:** Number of keys $n$ in a B-tree of height $h$ is guaranteed to be at least

$$1 + 2(b - 1) + 2b(b - 1) + 2b^2(b - 1) + \ldots + 2b^{h-1}(b - 1)$$

$$= 1 + 2(b - 1)(1 + b + b^2 + \ldots + b^{h-1})$$

$$= 1 + 2(b - 1)((b^h - 1) / (b - 1))$$

$$= 1 + 2(b^h - 1) = 2b^h - 1.$$  

Solving $n = 2b^h - 1$ yields $h = \log_b \left( \frac{(n + 1)}{2} \right)$.

- **Corollary:** B-trees of order $b$ have height $\Theta(\log_b n)$. 
Analyzing Efficiency

• Suppose we have a B-tree of order \( b \).

• What is the worst-case runtime of looking up a key in the B-tree?

• \textbf{Answer:} It depends on how we do the search!
Analyzing Efficiency

- To do a lookup in a B-tree, we need to determine which child tree to descend into.
- This means we need to compare our query key against the keys in the node.
- **Question:** How should we do this?
Analyzing Efficiency

- **Option 1**: Use a linear search!
- Cost per node: $O(b)$. 
- Nodes visited: $O(\log_b n)$.
- Total cost:
  \[
  O(b) \cdot O(\log_b n) = O(b \log_b n)
  \]
Analyzing Efficiency

- **Option 2:** Use a binary search!
- Cost per node: $O(\log b)$.
- Nodes visited: $O(\log_b n)$.
- Total cost:
  \[
  O(\log b) \cdot O(\log_b n) = O(\log b \cdot \log_b n) = O(\log b \cdot (\log n) / (\log b)) = O(\log n). 
  \]

**Intuition:** We can’t do better than $O(\log n)$ for arbitrary data, because it’s the information-theoretic minimum number of comparisons needed to find something in a sorted collection!
Analyzing Efficiency

- Suppose we have a B-tree of order $b$.
- What is the worst-case runtime of inserting a key into the B-tree?
- Each insertion visits $O(\log_b n)$ nodes, and in the worst case we have to split every node we see.
- **Answer:** $O(b \log_b n)$.
Analyzing Efficiency

• The cost of an insertion in a B-tree of order $b$ is $O(b \log_b n)$.

• What’s the best choice of $b$ to use here?

• Note that

$$b \log_b n = b \left(\log n / \log b\right) = \left(b / \log b\right) \log n.$$ 

• What choice of $b$ minimizes $b / \log b$?

• **Answer:** Pick $b = e$.
2-3-4 Trees

- A **2-3-4 tree** is a B-tree of order 2. Specifically:
  - each node has between 1 and 3 keys;
  - each node is either a leaf or has one more child than key; and
  - all leaves are at the same depth.
- You actually saw this B-tree earlier! It’s the type of tree from our insertion example.
The Story So Far

• A B-tree supports
  • lookups in time $O(\log n)$, and
  • insertions in time $O(b \log_b n)$.
• Picking $b$ to be around 2 or 3 makes this optimal in Theoryland.
  • The 2-3-4 tree is great for that reason.
• Plot Twist: In practice, you most often see choices of $b$ like 1,024 or 4,096.
• Question: Why would anyone do that?
The Memory Hierarchy
Memory Tradeoffs

- There is an enormous tradeoff between speed and size in memory.
- SRAM (the stuff registers are made of) is fast but very expensive:
  - Can keep up with processor speeds in the GHz.
  - As of 2010, cost is $5/MB. (Anyone know a good source for a more recent price?)
  - Good luck buying 1TB of the stuff!
- Hard disks are cheap but very slow:
  - As of 2019, you can buy a 4TB hard drive for about $70.
  - As of 2019, good disk seek times for magnetic drives are measured in ms (about two to four million times slower than a processor cycle!)
The Memory Hierarchy

- **Idea:** Try to get the best of all worlds by using multiple types of memory.

```
<table>
<thead>
<tr>
<th>Level</th>
<th>Capacity</th>
<th>Access Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Registers</td>
<td>256B - 8KB</td>
<td>0.25 – 1ns</td>
</tr>
<tr>
<td>L1 Cache</td>
<td>16KB – 64KB</td>
<td>1ns – 5ns</td>
</tr>
<tr>
<td>L2 Cache</td>
<td>1MB – 4MB</td>
<td>5ns – 25ns</td>
</tr>
<tr>
<td>Main Memory</td>
<td>4GB – 256GB</td>
<td>25ns – 100ns</td>
</tr>
<tr>
<td>Hard Disk</td>
<td>1TB+</td>
<td>3 – 10ms</td>
</tr>
<tr>
<td>Network (The Cloud)</td>
<td><em>Lots</em></td>
<td>10 – 2000ms</td>
</tr>
</tbody>
</table>
```
External Data Structures

- Suppose you have a data set that’s way too big to fit in RAM.
- The data structure is on disk and read into RAM as needed.
- Data from disk doesn’t come back one byte at a time, but rather one page at a time.
- **Goal:** Minimize the number of disk reads and writes, not the number of instructions executed.
External Data Structures

• Because B-trees have a huge branching factor, they're great for on-disk storage.
  • Disk block reads/writes are glacially slow.
  • The high branching factor minimizes the number of blocks to read during a lookup.
  • Extra work scanning inside a block offset by these savings.

• Major use cases for B-trees and their variants (B+-trees, H-trees, etc.) include
  • databases (huge amount of data stored on disk);
  • file systems (ext4, NTFS, ReFS); and, recently,
  • in-memory data structures (due to cache effects).
Analyzing B-Trees

• Suppose we tune $b$ so that each node in the B-tree fits inside a single disk page.

• *We only* care about the number of disk pages read or written.
  
  • It’s so much slower than RAM that it’ll dominate the runtime.

• *Question:* What is the cost of a lookup in a B-tree in this model?
  
  • Answer: The height of the tree, $O(\log_b n)$.

• *Question:* What is the cost of inserting into a B-tree in this model?
  
  • Answer: The height of the tree, $O(\log_b n)$. 
Analyzing B-Trees

• The cost model we use will change our overall analysis.

• Cost is number of operations:
  \[ O(\log n) / \text{lookup}, \ O(b \log_b n) / \text{insertion}. \]

• Cost is number of blocks accessed:
  \[ O(\log_b n) / \text{lookup}, \ O(\log_b n) / \text{insertion}. \]

• Going forward, we’ll use operation counts as our cost model, though looking at caching effects of data structures would make for an awesome final project!
The Story So Far

• We’ve just built a simple, elegant, balanced multiway tree structure.
• We can use them as balanced trees in main memory (2-3-4 trees).
• We can use them to store huge quantities of information on disk (B-trees).
• We’ve seen that different cost models are appropriate in different situations.
Time-Out for Announcements!
CS Townhall

• John Mitchell (CS Department Chair) and Mehran Sahami (CS Associate Chair for Education) are holding a CS townhall event next month.

• What are we doing well? What can we improve on? This is your chance to provide input!

• Held in Gates 104 from 4:30PM – 6:00PM on Tuesday, May 14th.
Problem Sets

- Problem Set One solutions are now available up on the course website.
  - We’re working on getting them graded – stay tuned!
- Problem Set Two is due next Thursday.
  - Have questions? Ask them on Piazza or stop by our office hours!
Back to CS166!
So... red/black trees?
A **red/black tree** is a BST with the following properties:

- Every node is either red or black.
- The root is black.
- No red node has a red child.
- Every root-null path in the tree passes through the same number of black nodes.
Red/Black Trees

- A **red/black tree** is a BST with the following properties:
  - Every node is either red or black.
  - The root is black.
  - No red node has a red child.
  - Every root-null path in the tree passes through the same number of black nodes.
- After we hoist red nodes into their parents:
  - Each “meta node” has 1, 2, or 3 keys in it. (No red node has a red child.)
  - Each “meta node” is either a leaf or has one more key than node. (Root-null path property.)
  - Each “meta leaf” is at the same depth. (Root-null path property.)

This is a 2-3-4 tree!
Data Structure Isometries

- Red/black trees are an *isometry* of 2-3-4 trees; they represent the structure of 2-3-4 trees in a different way.
- Many data structures can be designed and analyzed in the same way.
- **Huge advantage:** Rather than memorizing a complex list of red/black tree rules, just think about what the equivalent operation on the corresponding 2-3-4 tree would be and simulate it with BST operations.
The Height of a Red/Black Tree

**Theorem:** Any red/black tree with \( n \) nodes has height \( O(\log n) \).

**Proof:** Contract all red nodes into their parent nodes to convert the red/black tree into a 2-3-4 tree. This decreases the height of the tree by at most a factor of two. The resulting 2-3-4 tree has height \( O(\log n) \), so the original red/black tree has height \( 2 \cdot O(\log n) = O(\log n) \). ■
Exploring the Isometry

- Nodes in a 2-3-4 tree are classified into types based on the number of children they can have.
  - **2-nodes** have one key (two children).
  - **3-nodes** have two keys (three children).
  - **4-nodes** have three keys (four children).
- How might these nodes be represented?
Exploring the Isometry
Red/Black Tree Insertion

- **Rule #1:** When inserting a node, if its parent is black, make the node red and stop.

- **Justification:** This simulates inserting a key into an existing 2-node or 3-node.
Tree Rotations

A

B

< A

> A

< B

> B

A

B

< A

> A

< B

> B

A

B

< A

> A

< B

> B
This applies any time we're inserting a new node into the middle of a “3-node.”

By making observations like these, we can determine how to update a red/black tree after an insertion.
change colors
Building Up Rules

• All of the crazy insertion rules on red/black trees make perfect sense if you connect it back to 2-3-4 trees.

• There are lots of cases to consider because there are many different ways you can insert into a red/black tree.

• **Main point:** Simulating the insertion of a key into a node takes time $O(1)$ in all cases. Therefore, since 2-3-4 trees support $O(\log n)$ insertions, red/black trees support $O(\log n)$ insertions.

• The same is true of deletions.
My Advice

- **Do** know how to do B-tree insertions and searches.
  - You can derive these easily if you remember to split nodes.
- **Do** remember the rules for red/black trees and B-trees.
  - These are useful for proving bounds and deriving results.
- **Do** remember the isometry between red/black trees and 2-3-4 trees.
  - Gives immediate intuition for all the red/black tree operations.
- **Don't** memorize the red/black rotations and color flips.
  - This is rarely useful. If you're coding up a red/black tree, just flip open CLRS and translate the pseudocode. 😊
More to Explore

- The **2-3 tree** is another simple B-tree that’s often used in place of 2-3-4 trees.
  - It gives rise to the **AA-tree**, another balanced tree data structure.
- The **left-leaning red/black tree** is a simplification of red/black trees that forces 3-nodes to be encoded in only one way.
- **Cache-oblivious data structures** get the benefit of good cache performance, but without having advance knowledge of the cache size.
- B-tree variants are used in many contexts:
  - The **B⁺-Tree** are used in databases.
  - The **R-tree** is used for spatial indexing.
- These might be interesting topics to look into for a final project!
Next Time

• **Augmented Trees**
  • Building data structures on top of balanced BSTs.

• **Splitting and Joining Trees**
  • Two powerful operations on balanced trees.