Last Time

- Heap
Balanced Binary Search Trees - AVL Trees
Review Binary Search Trees

- Define Binary Search Trees
All BST operations are $O(d)$, where $d$ is the tree depth.

Minimum $d$: $d \leq \lceil \log n \rceil$ for a binary tree with $n$ nodes.
  - What is the best case tree?
  - What is the worst case tree?

Best case running time of BST operations is $O(\log n)$. 
Worst case running time is $O(n)$.

What happens when you insert elements in order (ascending or descending)?
- Insert: 1, 3, 4, 5, 7, 10, 12 into an empty BST

Lack of “balance”.

Unbalanced degenerate tree. Requires linear time access, as an unsorted array.
If we can balance a tree in $O(\log n)$ time for each operation, we can establish strict $O(\log n)$ bounds on worst-case runtimes.

**Possible Approaches**

- **Do nothing.**
  - No overhead. Relies on the randomness of data to keep depth to approximately $\log n$, but may end up with some deep nodes.

- **Strict balancing**
  - Guarantee that the tree is always balanced perfectly.

- **Moderately good balance**
  - Allow some (bound) imbalance in exchange for keeping balancing overhead low.

- **Adjust on access**
  - Self-adjusting
There are many approaches to keep BSTs balanced.

- **Today**: Adelson-Velskii and Landis (AVL) trees. Height balancing
- Next time: Red-black trees and 2-3 trees. Other self adjusting trees.
Perfect balance requires a **complete tree** after every operation.

- **Complete Trees** are full with the exception of the lower right part of the tree. I.e., at all depths $1 \leq d \leq D$ contains $2^{d-1}$ nodes, and all leaves at depth $D$ are as far left as possible.
- Heaps are Complete Trees.

Maintaining this is expensive – $O(n)$. 
AVL Trees – Good but not Perfect balance

- AVL trees are height-balanced binary search trees
- Balance factor, $\text{BalanceFactor}(T)$, of a node, $T$: $\text{height}(T.\text{left}) - \text{height}(T.\text{right})$
- AVL trees calculate a balance factor for every node.
- For each node, the height of the left and right sub trees can differ by no more than 1. I.e. $|\text{BalanceFactor}(T)| \leq 1$
- Store the height of each node.
N(h) = minimum number of nodes in an AVL tree of height h.

Bases: N(0) = 1, N(1) = 2

Induction: N(h) = N(h-1) + N(h-2) + 1.

Solution $N(h) \geq \phi^h$ (where $\phi \approx 1.62$) (cf. Fibonacci)
\[ N(h) \geq \phi^h \text{ (where } \phi \approx 1.62) \]
- So we have \( n \) nodes in an AVL tree of height \( h \).
- \( n \geq N(h) \)
- \( n \geq \phi^h \) therefore \( \log_\phi n \geq h \)
- \( h \leq 1.44 \log n \)
- Therefore operations take \( O(h) = O(1.44 \log n) = O(\log n) \)
Node Heights

Tree A (AVL)

height = 2, BF = 1 - 0 = 1

height of node = h
balance factor = h_{left} - h_{right}
empty height = -1

Tree B (AVL)
Node Heights after Insert

Tree A (AVL)

Tree B (not AVL)

height of node = \( h \)
balance factor = \( h_{\text{left}} - h_{\text{right}} \)
empty height = -1

balance factor 1-(-1) = 2
- Insert can cause the balance factor of a node to become 2 or -2
- Only nodes on the path from the insertion point to the root might have changed
- After Insert, traverse up the tree to the root, updating heights
- If a new balance factor is 2 or -2, adjust the tree by rotation around the node
Rotation in an AVL Tree
There are 4 cases that will give rise to rebalancing. (Let $T$ be the node that needs rebalancing.)

1. Insertion into the left subtree of the left child of $T$
2. Insertion into the right subtree of the right child of $T$
3. Insertion into the right subtree of the left child of $T$
4. Insertion into the left subtree of the right child of $T$

These lead to four rotation algorithms.
Consider a valid AVL subtree
Outside Rotation in an AVL Tree

Inserting into X destroys the AVL property at node j

<table>
<thead>
<tr>
<th>X</th>
<th>h+1</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>j</td>
</tr>
<tr>
<td></td>
<td></td>
<td>h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z</td>
</tr>
</tbody>
</table>
Outside Rotation in an AVL Tree

Do a "right rotation"
Outside Rotation in an AVL Tree

Do a "right rotation"
Outside Rotation in an AVL Tree

“Right rotation” done! (“Left rotation” is mirror symmetric)

AVL property has been restored!
Consider a valid AVL subtree
Inside Rotation in an AVL Tree

Inserting into Y destroys the AVL property at node j.

Does “right rotation” restore balance?
"Right rotation" does not restore balance... now k is out of balance
Consider the structure of subtree Y...
Inside Rotation in an AVL Tree

Y = node i and subtrees V and W
Inside Rotation in an AVL Tree

We will do a left-right "double rotation"...
Inside Rotation in an AVL Tree

left rotation complete
Inside Rotation in an AVL Tree

Now do a right rotation
Inside Rotation in an AVL Tree

Right rotation complete

Balance has been restored
No need to store the height. Just the balance factor.

I.e. the difference in height.

Must be maintained even if rotations are not performed.
Single Rotation

**RotateFromRight**\( (T) \)

\[
\begin{align*}
p & \leftarrow T.\text{right} \\
T.\text{right} & \leftarrow p.\text{left} \\
p.\text{left} & \leftarrow T \\
T & \leftarrow p
\end{align*}
\]

Also need to modify the heights or balance factors of \( T \) and \( p \).
Double Rotation can be implemented in 2 lines.

\textbf{DOUBLE\textsc{RO}TA\textsc{TE}\textsc{FROM}\textsc{RI}GHT}(T)

??????
??????
Insertion in AVL Trees

- Insert at the leaf.
- Note: Only nodes in the path from the insertion point to the root node might have changed in height.
- After `INSERT()` traverse up the tree to the root, updating heights (or balance factors).
- If a new balance factor is 2 or -2, adjust by rotation around the node.
Recall \texttt{INSERT} algorithm.

\begin{algorithm}
\caption{\texttt{INSERT}(T,x)}
\begin{algorithmic}
\STATE \textbf{if} $T = \text{null}$ \textbf{then}
\STATE \hspace{1em} $T = \text{new Tree}(x)$
\ELSE
\STATE \hspace{1em} \textbf{if} $x \leq T.data$ \textbf{then}
\STATE \hspace{2em} \texttt{INSERT}(T.left, x)
\ELSE
\STATE \hspace{2em} \texttt{INSERT}(T.right, x)
\ENDIF
\ENDIF
\end{algorithmic}
\end{algorithm}
Insertion in AVL Trees

\[ \text{Insert}(T, x) \]

\[
\text{if } T = \text{null} \text{ then} \\
\quad T = \text{new Tree}(x) \\
\text{else} \\
\quad \text{if } x \leq T\text{.data} \text{ then} \\
\quad \quad \text{Insert}(T\text{.left, } x) \\
\quad \quad \text{if } \text{height}(T\text{.left}) - \text{height}(T\text{.right}) = 2 \text{ then} \\
\quad \quad \quad \text{if } T\text{.left\text{.data} } \geq x \text{ then} \\
\quad \quad \quad \quad \text{RotateFromLeft}(T) \\
\quad \quad \quad \quad \text{else} \\
\quad \quad \quad \quad \quad \text{DoubleRotateFromLeft}(T) \\
\quad \quad \quad \text{end if} \\
\quad \quad \text{end if} \\
\quad \text{end if} \\
\text{else} \\
\quad \text{Insert}(T\text{.right, } x) \\
\quad Similar \text{ code as above} \\
\quad \text{end if} \\
\text{end if} \\
T\text{.height} = \max(\text{height}(T\text{.left}), \text{height}(T\text{.right}) + 1)\]
Inside Rotation in an AVL Tree

Insert 5, 40
Inside Rotation in an AVL Tree

Now Insert 45
Inside Rotation in an AVL Tree

[Diagram showing an AVL tree with nodes labeled 5, 10, 20, 30, 35, 40, and 45. An arrow indicates an imbalance, and another arrow shows the tree after inserting 34.]
Inside Rotation in an AVL Tree

Insertion of 34

Imbalance
AVL Tree Deletion

- Delete is more complex than insertion.
- Imbalances can propagate upwards.
- Multiple (though no more than \( \log n \)) rotations may be needed.)
Pros and Cons of AVL Trees

- Arguments for AVL Trees
  1. Find is guaranteed to be $O(\log n)$ for all AVL trees.
  2. Insert and Delete are also $O(\log n)$
  3. Height balancing adds only a constant factor to the speed of Insert and Delete

- Arguments against AVL Trees
  1. While asymptotically faster, rebalancing takes time.
  2. Can be difficult to program and debug.
  3. Additional space is required for balancing.
  4. There are other more commonly used balanced trees optimized for disk accesses. We’ll see at least one of them tomorrow.
Double Rotation Solution

- Double Rotation can be implemented in 2 lines.

\[
\text{DoubleRotateFromRight}(T)
\]

\[
\text{RotateFromLeft}(T.\text{right})
\]

\[
\text{RotateFromRight}(T)
\]
Bye

- HW-5 is up on the website.
- Next time
  - More Balanced Binary Search Trees.
    - Red-Black Trees
    - 2-3 Trees (B-Trees)
- For Next Class
  - Read 13.1, 13.2, 13.3, 13.4