Module 4: Dictionaries and Balanced Search Trees

CS 240 - Data Structures and Data Management

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Based on lecture notes by many previous cs240 instructors

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Spring 2017

Dictionary ADT

A *dictionary* is a collection of *items*, each of which contains

- a *key*
- some *data*,

and is called a *key-value pair* (KVP). Keys can be compared and are (typically) unique.

Operations:

- *search*(k)
- *insert*(k, v)
- *delete*(k)
- optional: *join*, *isEmpty*, *size*, *etc.*

Elementary Implementations

Common assumptions:

- Dictionary has n KVPs
- Each KVP uses constant space
- Comparing keys takes constant time

Unordered array or linked list

search $\Theta(n)$
insert $\Theta(1)$
delete $\Theta(n)$ (need to search)

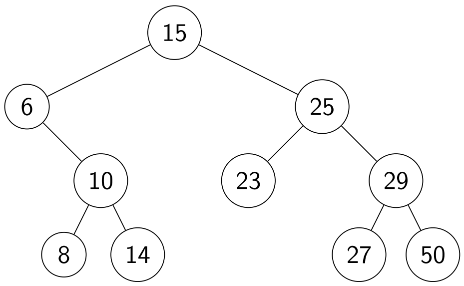
Ordered array

search $\Theta(\log n)$
insert $\Theta(n)$
delete $\Theta(n)$

Binary Search Trees (review)

Structure A BST is either empty or contains a KVP, left child BST, and right child BST.

Ordering Every key k in $T.left$ is less than the root key. Every key k in $T.right$ is greater than the root key.



BST Search and Insert

search(k) Compare k to current node, stop if found, else recurse on subtree unless it's empty

insert(k, v) Search for k, then insert (k, v) as new node

Example:

BST Delete

- If node is a leaf, just delete it.
- If node has one child, move child up
- Else, swap with *successor* or *predecessor* node and then delete

Height of a BST

search, *insert*, *delete* all have cost $\Theta(h)$, where
h = height of the tree = max. path length from root to leaf

If n items are *insert*ed one-at-a-time, how big is h?

- Worst-case:
- Best-case:
- Average-case:

AVL Trees

Introduced by Adel'son-Vel'skiĭ and Landis in 1962, an *AVL Tree* is a BST with an additional structural property:
The heights of the left and right subtree differ by at most 1.

(The height of an empty tree is defined to be -1.)

At each non-empty node, we store $height(R) - height(L) \in \{-1, 0, 1\}$:

-1 means the tree is *left-heavy*
0 means the tree is *balanced*
1 means the tree is *right-heavy*

- We could store the actual height, but storing balances is simpler and more convenient.

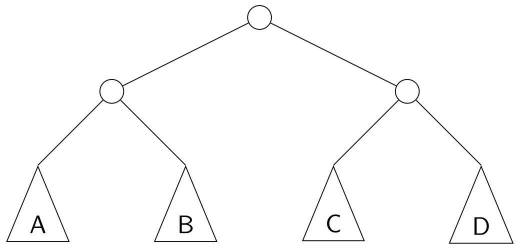
AVL insertion

To perform *insert*(T, k, v):

- First, insert (k, v) into T using usual BST insertion
- Then, move up the tree from the new leaf, updating balance factors.
- If the balance factor is -1, 0, or 1, then keep going.
- If the balance factor is ± 2, then call the *fix* algorithm to "rebalance" at that node. We are done.

How to "fix" an unbalanced AVL tree

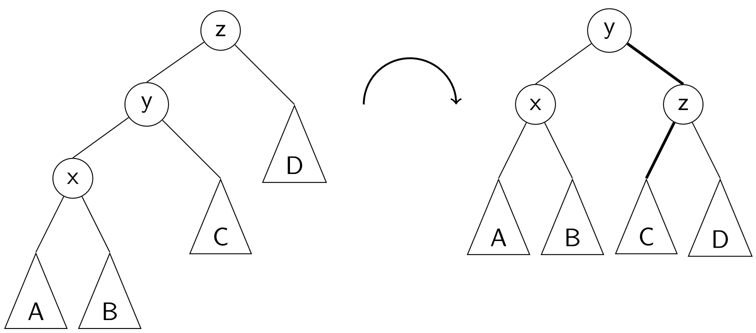
Goal: change the *structure* without changing the *order*



Notice that if heights of A, B, C, D differ by at most 1, then the tree is a proper AVL tree.

Right Rotation

This is a *right rotation* on node z:

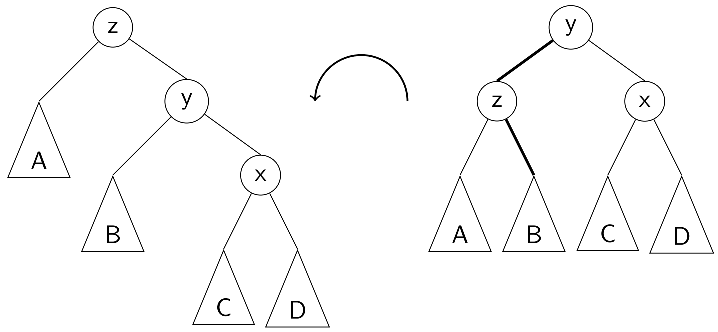


Note: Only two edges need to be moved, and two balances updated. Useful to fix left-left imbalance.

Again . . .

Left Rotation

This is a *left rotation* on node z:



Again, only two edges need to be moved and two balances updated.
Useful to fix right-right imbalance.

Again . . .

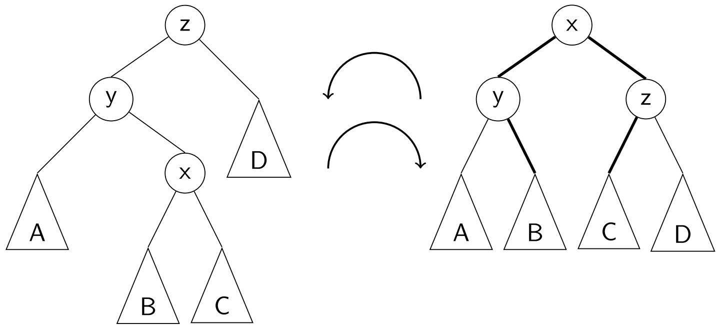
Pseudocode for rotations

rotate-right(T)
T: AVL tree
returns rotated AVL tree
1. *newroot* ← T.*left*
2. T.*left* ← *newroot*.*right*
3. *newroot*.*right* ← T
4. **return** *newroot*

rotate-left(T)
T: AVL tree
returns rotated AVL tree
1. *newroot* ← T.*right*
2. T.*right* ← *newroot*.*left*
3. *newroot*.*left* ← T
4. **return** *newroot*

Double Right Rotation

This is a *double right rotation* on node z:

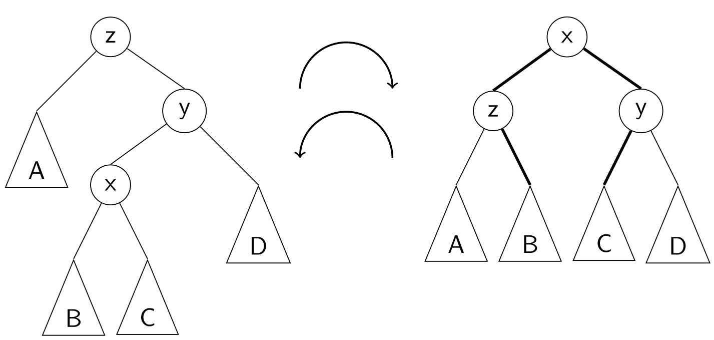


First, a left rotation on the left subtree (y). Second, a right rotation on the whole tree (z).
Useful for left-right imbalance.

Again . . .

Double Left Rotation

This is a *double left rotation* on node z:



Right rotation on right subtree (y), followed by left rotation on the whole tree (z).
Useful for right-left imbalance.

Fixing a slightly-unbalanced AVL tree

Idea: Identify one of the previous 4 situations, apply rotations

fix(T)
T: AVL tree with $T.balance = \pm 2$
returns a balanced AVL tree

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if T.balance = −2 then
    if T.left.balance = 1 then
        T.left ← rotate-left(T.left)
    return rotate-right(T)
else if T.balance = 2 then
    if T.right.balance = −1 then
        T.right ← rotate-right(T.right)
    return rotate-left(T)
```


AVL Tree Operations

search: Just like in BSTs, costs $\Theta(height)$

insert: Shown already, total cost $\Theta(height)$

- *fix* restores the height of the tree it fixes to what it was,
- so *fix* will be called *at most once*.

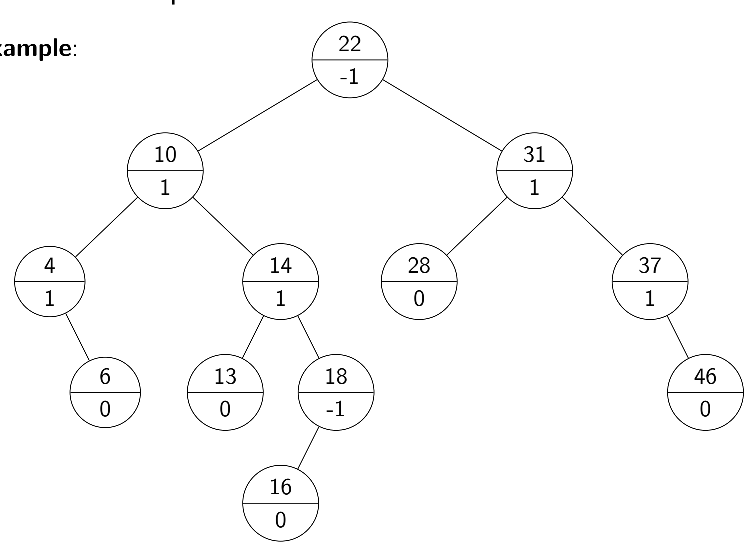
delete: First search, then swap with successor (as with BSTs), then move up the tree and apply *fix* (as with *insert*).

- *fix* may be called $\Theta(height)$ times.

Total cost is $\Theta(height)$.

AVL tree examples

Example:



Height of an AVL tree

Define $N(h)$ to be the *least* number of nodes in a height-h AVL tree.

One subtree must have height at least $h-1$, the other at least $h-2$:

$$N(h) = \begin{cases} 1 + N(h-1) + N(h-2), & h \geq 1 \\ 1, & h = 0 \\ 0, & h = -1 \end{cases}$$

What sequence does this look like?

AVL Tree Analysis

Easier lower bound on $N(h)$:

$$N(h) > 2N(h-2) > 4N(h-4) > 8N(h-6) > \cdots > 2^i N(h-2i) \geq 2^{\lfloor h/2 \rfloor}$$

Since $n > 2^{\lfloor h/2 \rfloor}$, $h \leq 2 \lg n$,
and thus an AVL tree with n nodes has height $O(\log n)$.
Also, $n \leq 2^{h+1} - 1$, so the height is $\Theta(\log n)$.

$\Rightarrow$ *search*, *insert*, *delete* all cost $\Theta(\log n)$.