Q is for …

- **Queue**
  - First-in-first-out, FIFO
- **Quicksort**
  - So very fast. Not stable

**Announcements**

- **Assignment P4 DNA-Link**
  - Part 2 due March 26 – Code and more Analysis
- **Assignment P5 will be out Friday?**
  - Then P6 will be last assignment
- **APT-5 is now out and due Tuesday, March 31**

**Plan for WASB**

- **Binary Trees**
  - Review, Recursion, Solving Problems
- **Runtime analysis of recursive algorithms**
  - Recurrence relations to aid analysis
  - From intuition to understanding
- **Recursion and Invariants with List Reverse**
  - Thinking about recursion and iteration
- **Work in 201**
**Syllabus Changes**

- Please see: https://www2.cs.duke.edu/courses/spring20/compsci201/infonew.php
- Grading of exams and apt quiz – max counts more
- Participation not required for Discussions, but strongly recommended
- Lecture now taped and recorded before lecture time, includes WOTOs
  - Lecture now for questions and go over WOTOs,
  - Participation for WOTOs has been cut back, 65%
- Try to turn things in on time
  - Need a few more days, fill out the extension form

**Motivation for Trees**

- **HashSet** and **HashMap** are **O(1) average**
- Astonishing! Search, insert, delete
  - No order for keys, sometimes order matters
- **Worst-case?** Everything in same locker/bucket
  - Just in case? Use a tree in that locker/bucket

- **Search Trees:** **TreeSet** and **TreeMap**
  - \( O(\log N) \) no matter what, average and worst
  - Alphabetical or other order and range queries
    - Find all keys in range \([low, high]\) efficiently

**Why Trees are \( O(\log N) \)**

- With each query: eliminate half of tree
  - 1024, 512, 256, 128, 64, 32, 16, 8, 4, 2, 1
- Can ensure trees are balanced: **TreeSet**/**TreeMap**
  - Re-balance on add or delete

**Review: Inorder Traversal**

- Think of search trees as recursive/hierarchical
  - Empty OR Root/Node with two subtrees
  - Root, leaves, paths, oh my!

```java
public void print(TreeNode root) {
    if (root != null) {
        print(root.left);
        System.out.println(root.info);
        print(root.right);
    }
}
```
Constructing and Printing Tree

• Code and visualize: constructor has 3 parameters

```
public static void main(String[] args) {
    TreeNode root =
        new TreeNode("mango",
                    new TreeNode("durian",
                                    new TreeNode("apple",null,null),
                                    new TreeNode("grapefruit",null,null)),
                    new TreeNode("pear",
                                    new TreeNode("orange",null,null),
                                    new TreeNode("tangerine",null,null)));

    print(root);
}
```

Review: Java Comparable Interface

Java-isms for comparing

• We can compare int, double, char
  • Using ==, and !-=, and <, <=, >, >=
  • Primitives use conventional symbols

• Cannot write "apple" < "zebra"
  • Must compare objects using specific method
  • Objects must be comparable, that is they must implement the Comparable interface

Strings are Comparable

• Compare strings lexicographically, natural ordering, dictionary order
  • "zebra" > "aardvark" but "Zebra" < "aardvark"
  • Conceptual, cannot use < or > or ==
    • We had to use s.equals(t) for strings/objects

• "yak".compareTo(s) returns < 0, == 0, > 0
  • s is “zebra”, “yak”, and “toad”, respectively

• The int convention also used in C++, C, others
Comparable Elements

- TreeSet<String>, TreeMap<String, Anything>
  - Tree elements must be comparable
    - Must implement Comparable<..>
  - It's possible to supply a Comparator, later

- Arrays.sort, Collections.sort 🍓 🍊
  - What algorithm is used in sorting?
  - Can change order of sort: Comparator, later

From Recursion to Recurrence

- How do we analyze runtime: recursive algorithms
  - Difficult to see how many recursive calls made sometimes
  - Difficult to account for diminishing size in recursion using intuition

- Concepts grounded in mathematical induction
  - Analysis of algorithms matches structure of recursive methods

Determine height of a tree

- Longest root-to-leaf path (# nodes):
  - Balanced trees can use height to re-balance

Determine height of a tree

- Longest root-to-leaf path (# nodes):
  - Balanced trees can use height to re-balance
Tree function: Tree height in TreeDemo.java

- Compute tree height (longest root-to-leaf path)
  
  public int height(TreeNode root) {
    if (root == null) return 0;
    return 1 + Math.max(height(root.left), height(root.right));
  }

- Find height of left subtree, height of right subtree
  - Combine results to determine height of tree
  - Always use results of recursive calls

Complexity/Efficiency

Tree has n nodes

- Intuitively: visit every node once for height: \( O(n) \)
  - How can we analyze this mathematically?

- Write a recurrence relation describing runtime
  - Eventually we will solve, but for now? Just write

  Let \( T(n) \) be time for height to run on n-node tree
  - \( T(0) = O(1) \)
  - Then \( T(n) = O(1) + 2*T(n/2) \) balanced tree

Annotated Tree height

- Compute tree height (longest root-to-leaf path)
  
  public int height(TreeNode root) {
    if (root == null) return 0;
    return 1 + Math.max(height(root.left), height(root.right));
  }

- Base case? \( O(1) \) – Recursive? \( 2T(n/2) \), why?
  - Work to combine results? \( O(1) \)
  - \( T(n) = 2T(n/2) + O(1) \)
  - Unbalanced? \( T(n) = T(n-1) + O(1) \)

Recurrence Relations

No need to derive, remember or look up. Derive?
Once here, more in 230 and 330

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Balanced Trees and Complexity

- A tree is height-balanced if
  - Left and right subtrees are height-balanced
  - Left and right heights differ by at most one
- Which trees are balanced?

![Balanced Trees Diagram]

Complexity of isBalanced

- We know that height(root) is $O(N)$ for N-node tree
  - Recurrence was $T(N) = 2T(N/2) + O(1)$

- Recurrence for isBalanced (average case)
  - $T(N)$ is time for isBalanced on N-node tree
  - Call height twice: $O(N)$, each tree N/2 nodes
  - Make two recursive calls $2T(N/2)$
  - Recurrence: $T(N) = 2T(N/2) + O(N)$

Annotating every line

- Let $T(n)$ be run time for isBalanced for roughly-balanced N-node tree: $2T(n/2) + O(n)$
  - Why roughly balanced?
    - Recurrence for unbalanced? All but one node in right subtree: $T(n) = O(n) + T(n-1)$

```java
public boolean isBalanced(Tree root) {
    if (root == null) return true;
    int lh = height(root.left);
    int rh = height(root.right);
    return isBalanced(root.left) &&
           isBalanced(root.right) &&
           Math.abs(lh - rh) <= 1;
}
```
Recurrence Relations

No need to derive, remember or look up. Derive?
Once here, more in 230 and 330

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Solve recurrence

• T(n) is time for isBalanced to run on n-node tree
  • T(n) = 2T(n/2) + n

Recurrence relations

• You will solve recurrence relations if you take CompSci 230 or 330
• After solving you would use proof by induction to prove the recurrence relation you came up with is correct.
  • In this class just solved one so you could see.
• We will not solve or prove by induction
• We will just form recurrence relations and look up!

Recurrence Relations

No need to derive, remember or look up

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Must use TreeNode class for Tree APTs
Not nested in file!
Must be a class in your folder of APTs

```
public class HeightLabel {
    public TreeNode rewire(TreeNode t) {
        // replace with working code
        return null;
    }
}
```

• Create a new tree from a tree parameter
  • [https://www2.cs.duke.edu/csed/newapt/heightlabel.html](https://www2.cs.duke.edu/csed/newapt/heightlabel.html)
• Same shape, but nodes labeled with tree-size
  • Must call `new TreeNode`. With what values …

Creating a New Tree Recursively

• `root == null`: Not interesting, but necessary
  • Easy to make a copy of nothing?

• Create one new node, recursion creates all others
  • Constructor: value, left subtree, right subtree
  • What value stored in node? Call height
  • What values stored in subtrees? Recurse

```
public TreeNode rewire(TreeNode t) {
    if (t == null) return null;
    return new TreeNode(height(t),
                        rewire(t.left),
                        rewire(t.right));
}

private int height(TreeNode t) {
    if (t == null) return 0;
    return 1 + Math.max(height(t.left),
                         height(t.right));
}
```
Tree APTs

- Must include TreeNode class in project src
  - Similar to ListNode, not submitted as code

- Helper method often useful: add a parameter
  - Can be ArrayList<> or String or …
  - Also useful to add instance variables

- For running/testing outside of APT system?
  - Create tree in main to test (see prev slide)

Height Label - Analyze

```java
public TreeNode rewire(TreeNode t) {
    if (t == null) return null;
    return new TreeNode(height(t),
                         rewire(t.left),
                         rewire(t.right));
}

private int height(TreeNode t) {
    if (t == null) return 0;
    return 1 + Math.max(height(t.left),
                         height(t.right));
}
```

When balanced: $T(n) = 2T(n/2) + O(n)$

When not balanced?

WOTO


Turing Award 2017:
John Hennessy and David Patterson


Patterson: “Computer science is becoming an extraordinarily popular major,” Patterson said. “Berkeley is a diverse campus, and what’s happening with popularity is that the field is getting more diverse. All of us in the field who have been here a long time think that’s just wonderful.”

In response to James Damore memo

Computer Architecture
RISC processors
Is Recursion Important?

• Solving problems is important
• Scaling solutions is important
• Knowledge of tools to solve and scale are important
• You'll be expected to understand recursion!
  • Interviews, later courses, fundamental Compsci
  • You can always solve a problem iteratively
    • May be less elegant, may be harder to code

• But, the tool itself? ….

LeafSum APT

• [https://www2.cs.duke.edu/csed/newapt/leafsum.html](https://www2.cs.duke.edu/csed/newapt/leafsum.html)
• Sum all the values in leaves of tree
  • Base cases?
  • Recursive calls?

• What should big-Oh be?
  • N-node tree?
  • Visit each node ….
  • Balanced or stringy ….
  • Similar to tree height

LeafSum correct?

• What do we do with null tree? Why?
  • From base-case to combining recursive calls
  • Recurrence expression?

public class LeafSum {
    public int sum(TreeNode t) {
        if (t == null) return 0;
        // something is missing here!
        return sum(t.left) + sum(t.right);
    }
}

Susan Rodger
March 25, 2020
Now solve APT Leaf Sum

- What is the Big-Oh of Leaf sum?

Recurrence Relations

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I’ve just done 2 APTs for you

- You should try to do them without looking at the notes!
Sometimes Recursion Isn't Simple

- How do we reverse nodes in a linked list?
  - Similar to DNA Reverse, but different
  - Iterative and Recursive Solutions

Thinking with Invariants: Reverse

- We want to turn list = ['A', 'B', 'C'] into
  - rev = ['C', 'B', 'A']
- We will move one node at a time, no new nodes!
  - Iteratively and recursively

Iteration Step One A

- We moved ['A'] from list to the front of rev
  - rev = ['A'] and list = ['B', 'C']
  - Invariant: rev points to front of reversed so far
    - What was rev before this step? null
Iteration Step One B

- How to make progress and maintain invariant?
  - Invariant: \( \text{rev} \) points to front reversed-so-far
  - What should ['B'] or \( \text{list.next} \) point to?
    - What happens if we write \( \text{list.next} = \text{rev} \)
  - What should \( \text{rev} \) point to? And \( \text{list} \) point to?

\[
\text{rev} \rightarrow A \rightarrow \mid \mid \mid \text{list} \rightarrow B \rightarrow C \rightarrow \mid \mid \mid
\]

Iteration Step One C

- Making progress and maintain invariant?
  - \( \text{temp} = \text{list.next} \) (so we don't lose ['C'])
  - \( \text{list.next} = \text{rev} \) (add to front point to ['A'])
  - \( \text{rev} = \text{list} \) (rev points to front, ['B'])
  - \( \text{list} = \text{temp} \) (list updated)

\[
\text{rev} \rightarrow A \rightarrow \mid \mid \mid \text{list} \rightarrow B \rightarrow C \rightarrow \mid \mid \mid
\]

Loop and method finished

- Establish invariant: \( \text{rev} \) is reversed-so-far (null)
- Update and re-establish within loop

\[
\text{public void reverse(ListNode front)\{}
\]
\[
\text{ListNode rev = null;}
\]
\[
\text{ListNode list = front;}
\]
\[
\text{while (list != null) \{}
\]
\[
\text{ListNode temp = list.next;}
\]
\[
\text{rev = list;}
\]
\[
\text{list.next = rev;}
\]
\[
\text{list = temp;}
\]
\[
\text{\}}
\]
\[
\text{front = rev; // update state!}
\]

Look at reverse2 - ListReverse.java

https://coursework.cs.duke.edu/201spring20/classcode/-/blob/master/src/ListReverse.java

```java
50 @
51 private Node reverse2(Node list) {
52     Node rev = null;
53     while (list != null) {
54         Node temp = list.next;
55         rev = new Node(list.info, rev);
56         list = temp;
57     }
58     return rev;
59 }
```
Reverse Recursively

- This is harder to visualize, shorter to write
  - Which method is preferred? Decide yourself

- Base case: zero or one node list, nothing to do
  - Reversing a one node list: done

- *Believe in the recursion*
  - Reverse all nodes after first, reconnect
  - Pictures are important!

Are you kidding? What? Dissect

- This method returns the list passed, reversed

```java
private ListNode doRev(ListNode list) {
    if (list == null || list.next == null) {
        return list;
    }
    ListNode after = doRev(list.next);
    list.next.next = list;
    list.next = null;
    return after;
}
```
Establishing the base case

- Does the base case do the right thing?
  - What if first == null? Or a one node list?

```java
private ListNode doRev(ListNode list){
    if (list == null || list.next == null)
        return list;
    ListNode after = doRev(list.next);
    list.next.next = list;
    list.next = null;
    return after;
}
```

```java
public void reverse(){
    front = doRev(front);
}
```

This code really does reverse the list!

- This method returns the list passed, reversed

```java
private ListNode doRev(ListNode list){
    if (list == null || list.next == null)
        return list;
    ListNode after = doRev(list.next);
    list.next.next = list;
    list.next = null;
    return after;
}
```

Runtime of Reverse?

- We are reversing an n-node list, likely O(n)?
  - Iterative version visits every node and does O(1) work each time loop iterates
  - Recursive version: T(n) = T(n-1) + O(1)

- Define T and define n. Or use another letter
  - Let R(n) be the time for reverse to execute with an n-node list: R(n) = R(n-1) + O(1)
Recurrence Relations

No need to derive, remember or look up

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Edsger Dijkstra

- Goto considered Harmful
- Shortest Path algorithm
- Turing Award

For me, the first challenge for computing science is to discover how to maintain order in a finite, but very large, discrete universe that is intricately intertwined. And a second, but not less important challenge is how to mold what you have achieved in solving the first problem, into a teachable discipline: it does not suffice to hone your own intellect ... you must teach others how to hone theirs. The more you concentrate on these two challenges, the clearer you will see that they are only two sides of the same coin: teaching yourself is discovering what is teachable EWD 709

WOTO – Correctness counts