2.3 Recursion
Overview

What is recursion? When one function calls itself directly or indirectly.

Why learn recursion?
- New mode of thinking.
- Powerful programming paradigm.

Many computations are naturally self-referential.
- Mergesort, FFT, gcd, depth-first search.
- Linked data structures.
- A folder contains files and other folders.

Closely related to mathematical induction.
Greatest Common Divisor

**Gcd.** Find largest integer that evenly divides into p and q.

**Ex.** gcd(4032, 1272) = 24.

\[
\begin{align*}
4032 & = 2^6 \times 3^2 \times 7^1 \\
1272 & = 2^3 \times 3^1 \times 53^1 \\
gcd & = 2^3 \times 3^1 = 24
\end{align*}
\]

**Applications.**
- Simplify fractions: \( 1272/4032 = 53/168 \).
- RSA cryptosystem.
Greatest Common Divisor

**Gcd.** Find largest integer \( d \) that evenly divides into \( p \) and \( q \).

**Euclid's algorithm.** [Euclid 300 BCE]

\[
gcd(p, q) = \begin{cases} 
  p & \text{if } q = 0 \\
  \gcd(q, p \% q) & \text{otherwise}
\end{cases}
\]

\[
gcd(4032, 1272) = \gcd(1272, 216) = \gcd(216, 192) = \gcd(192, 24) = \gcd(24, 0) = 24.
\]

\[
4032 = 3 \times 1272 + 216
\]
Greatest Common Divisor

Gcd. Find largest integer d that evenly divides into p and q.

\[
gcd(p, q) = \begin{cases} 
  p & \text{if } q = 0 \\
  \gcd(q, p \% q) & \text{otherwise}
\end{cases}
\]

- base case
- reduction step, converges to base case

\(p = 8x\)
\(q = 3x\)
\(\gcd(p, q) = x\)
Greatest Common Divisor

**Gcd.** Find largest integer d that evenly divides into p and q.

\[
gcd(p, q) = \begin{cases} 
  p & \text{if } q = 0 \\
  gcd(q, p \% q) & \text{otherwise}
\end{cases}
\]

Java implementation.

```java
public static int gcd(int p, int q) {
    if (q == 0) return p;
    else return gcd(q, p % q);
}
```
H-tree of order n.

- Draw an H.
- Recursively draw 4 H-trees of order n-1, one connected to each tip.

Htree
public class Htree {
    public static void draw(int n, double sz, double x, double y) {
        if (n == 0) return;
        double x0 = x - sz/2, x1 = x + sz/2;
        double y0 = y - sz/2, y1 = y + sz/2;
        StdDraw.line(x0, y, x1, y);
        StdDraw.line(x0, y0, x0, y1);
        StdDraw.line(x1, y0, x1, y1);
        draw(n-1, sz/2, x0, y0);
        draw(n-1, sz/2, x0, y1);
        draw(n-1, sz/2, x1, y0);
        draw(n-1, sz/2, x1, y1);
    }
    public static void main(String[] args) {
        int n = Integer.parseInt(args[0]);
        draw(n, .5, .5, .5);
    }
}
Animated H-tree

Animated H-tree. Pause for 1 second after drawing each H.
Towers of Hanoi

Towers of Hanoi

Move all the discs from the leftmost peg to the rightmost one.
- Only one disc may be moved at a time.
- A disc can be placed either on empty peg or on top of a larger disc.

Towers of Hanoi demo

Edouard Lucas (1883)
Towers of Hanoi Legend

Q. Is world going to end (according to legend)?
- 64 golden discs on 3 diamond pegs.
- World ends when certain group of monks accomplish task.

Q. Will computer algorithms help?
Towers of Hanoi: Recursive Solution

Move n-1 smallest discs right.

Move largest disc left.

Move n-1 smallest discs right.
Towers of Hanoi: Recursive Solution

public class TowersOfHanoi {

    public static void moves(int n, boolean left) {
        if (n == 0) return;
        moves(n-1, !left);
        if (left) System.out.println(n + " left");
        else System.out.println(n + " right");
        moves(n-1, !left);
    }

    public static void main(String[] args) {
        int N = Integer.parseInt(args[0]);
        moves(N, true);
    }
}

moves(n, true) : move discs 1 to n one pole to the left
moves(n, false): move discs 1 to n one pole to the right
### Towers of Hanoi: Recursive Solution

<table>
<thead>
<tr>
<th>% java TowersOfHanoi 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 left</td>
</tr>
<tr>
<td>2 right</td>
</tr>
<tr>
<td>1 left</td>
</tr>
<tr>
<td>3 left</td>
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<tr>
<td>1 left</td>
</tr>
<tr>
<td>2 right</td>
</tr>
<tr>
<td>1 left</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% java TowersOfHanoi 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 right</td>
</tr>
<tr>
<td>2 left</td>
</tr>
<tr>
<td>1 right</td>
</tr>
<tr>
<td>3 right</td>
</tr>
<tr>
<td>1 right</td>
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<tr>
<td>2 left</td>
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<tr>
<td>1 right</td>
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<tr>
<td>4 left</td>
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<tr>
<td>1 right</td>
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<tr>
<td>2 left</td>
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<tr>
<td>1 right</td>
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<tr>
<td>3 right</td>
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<tr>
<td>1 right</td>
</tr>
<tr>
<td>2 left</td>
</tr>
<tr>
<td>1 right</td>
</tr>
</tbody>
</table>

*every other move is smallest disc*

*subdivisions of ruler*
Towers of Hanoi: Recursion Tree
Towers of Hanoi: Properties of Solution

Remarkable properties of recursive solution.
- Takes \(2^n - 1\) moves to solve \(n\) disc problem.
- Sequence of discs is same as subdivisions of ruler.
- Every other move involves smallest disc.

Recursive algorithm yields non-recursive solution!
- Alternate between two moves:
  - move smallest disc to right if \(n\) is even
  - make only legal move not involving smallest disc

Recursive algorithm may reveal fate of world.
- Takes 585 billion years for \(n = 64\) (at rate of 1 disc per second).
- Reassuring fact: any solution takes at least this long!
Divide-and-Conquer

Divide-and-conquer paradigm.
- Break up problem into smaller subproblems of same structure.
- Solve subproblems recursively using same method.
- Combine results to produce solution to original problem.

Many important problems succumb to divide-and-conquer.
- FFT for signal processing.
- Parsers for programming languages.
- Multigrid methods for solving PDEs.
- Quicksort and mergesort for sorting.
- Hilbert curve for domain decomposition.
- Quad-tree for efficient N-body simulation.
- Midpoint displacement method for fractional Brownian motion.
Fibonacci Numbers
Fibonacci Numbers

Fibonacci numbers. 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, ...

\[ F(n) = \begin{cases} 
0 & \text{if } n = 0 \\
1 & \text{if } n = 1 \\
F(n-1) + F(n-2) & \text{otherwise} 
\end{cases} \]

L. P. Fibonacci (1170 - 1250)
**Fibonacci Numbers and Nature**

**Fibonacci numbers.** 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, ...

\[
F(n) = \begin{cases} 
0 & \text{if } n = 0 \\
1 & \text{if } n = 1 \\
F(n-1) + F(n-2) & \text{otherwise} 
\end{cases}
\]

- **Pinecone**
- **Cauliflower**
A Possible Pitfall With Recursion

Fibonacci numbers. 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, ...

\[
F(n) = \begin{cases} 
0 & \text{if } n = 0 \\
1 & \text{if } n = 1 \\
F(n-1) + F(n-2) & \text{otherwise}
\end{cases}
\]

A natural for recursion?

```java
public static long F(int n) {
    if (n == 0) return 0;
    if (n == 1) return 1;
    return F(n-1) + F(n-2);
}
```
Recursion Challenge 1 (difficult but important)

Q. Is this an efficient way to compute F(50)?

public static long F(int n) {
    if (n == 0) return 0;
    if (n == 1) return 1;
    return F(n-1) + F(n-2);
}

A. No, no, no! This code is spectacularly inefficient.

F(50) is called once.
F(49) is called once.
F(48) is called 2 times.
F(47) is called 3 times.
F(46) is called 5 times.
F(45) is called 8 times.
...
F(1) is called 12,586,269,025 times.

recursion tree for naïve Fibonacci function
Recursion Challenge 2 (easy and also important)

Q. Is this a more efficient way to compute $F(50)$?

A. Yes. This code does it with 50 additions.

Lesson. Don’t use recursion to engage in exponential waste.

Context. This is a special case of an important programming technique known as dynamic programming (stay tuned).

FYI: classic math

$$F(n) = \frac{\phi^n - (1 - \phi)^n}{\sqrt{5}}$$

$$= \left\lfloor \frac{\phi^n}{\sqrt{5}} \right\rfloor$$

$\phi$ = golden ratio $\approx 1.618$
Summary

How to write simple recursive programs?
- Base case, reduction step.
- Trace the execution of a recursive program.
- Use pictures.

Why learn recursion?
- New mode of thinking.
- Powerful programming tool.

Divide-and-conquer. Elegant solution to many important problems.