6. Recursion
6. Recursion

- Foundations
- A classic example
- Recursive graphics
- Avoiding exponential waste
- Dynamic programming
Overview

Q. What is recursion?

A. When something is specified in terms of itself.

Why learn recursion?

- Represents a new mode of thinking.
- Provides a powerful programming paradigm.
- Enables reasoning about correctness.
- Gives insight into the nature of computation.

Many computational artifacts are naturally self-referential.

- File system with folders containing folders.
- Fractal graphical patterns.
- Divide-and-conquer algorithms (stay tuned).
Example: Convert an integer to binary

Recursive program

To compute a function of a positive integer \( N \)

- **Base case.** Return a value for small \( N \).
- **Reduction step.** Assuming that it works for smaller values of its argument, use the function to compute a return value for \( N \).

```java
public class Binary {
    public static String convert(int N) {
        if (N == 1) return "1";
        return convert(N/2) + (N % 2);
    }
    public static void main(String[] args) {
        int N = Integer.parseInt(args[0]);
        StdOut.println(convert(N));
    }
}
```

Q. How can we be convinced that this method is correct?

A. Use **mathematical induction**.
Mathematical induction (quick review)

To prove a statement involving a positive integer $N$

- **Base case.** Prove it for some specific values of $N$.
- **Induction step.** Assuming that the statement is true for all positive integers less than $N$, use that fact to prove it for $N$.

Example

The sum of the first $N$ odd integers is $N^2$.

**Base case.** True for $N = 1$.

**Induction step.** The $N$th odd integer is $2N - 1$.
Let $T_N = 1 + 3 + 5 + ... + (2N - 1)$ be the sum of the first $N$ odd integers.

- Assume that $T_{N-1} = (N - 1)^2$.
- Then $T_N = (N - 1)^2 + (2N - 1) = N^2$.
Proving a recursive program correct

**Recursion**

To compute a function of \( N \)

- **Base case.** Return a value for small \( N \).
- **Reduction step.** Assuming that it works for smaller values of its argument, use the function to compute a return value for \( N \).

**Mathematical induction**

To prove a statement involving \( N \)

- **Base case.** Prove it for small \( N \).
- **Induction step.** Assuming that the statement is true for all positive integers less than \( N \), use that fact to prove it for \( N \).

**Recursive program**

```java
public static String convert(int N) {
    if (N == 1) return "1";
    return convert(N/2) + (N % 2);
}
```

**Correctness proof, by induction**

\( \text{convert()} \) computes the binary representation of \( N \)

- **Base case.** Returns "1" for \( N = 1 \).
- **Induction step.** Assume that \( \text{convert()} \) works for \( N/2 \)

  1. Correct to append "0" if \( N \) is even, since \( N = 2(N/2) \).

  \[
  \begin{array}{c|c}
  N/2 & N \\
  \hline
  & 0 \\
  \end{array}
  \]

  2. Correct to append "1" if \( N \) is odd since \( N = 2(N/2) + 1 \).

  \[
  \begin{array}{c|c}
  N/2 & N \\
  \hline
  & 1 \\
  \end{array}
  \]
Mechanics of a function call

System actions when any function is called

- **Save environment** (values of all variables and call location).
- **Initialize values** of argument variables.
- **Transfer control** to the function.
- **Restore environment** (and assign return value)
- **Transfer control** back to the calling code.

```java
public class Binary {
    public static String convert(int N) {
        if (N == 1) return "1";
        return convert(N/2) + (N % 2);
    }
    public static void main(String[] args) {
        int N = Integer.parseInt(args[0]);
        System.out.println(convert(N));
    }
}
```

```java
convert(26)
if (N == 1) return "1";
return "1101" + "0";
```

```java
convert(13)
if (N == 1) return "1";
return "110" + "1";
```

```java
convert(6)
if (N == 1) return "1";
return "11" + "0";
```

```java
convert(3)
if (N == 1) return "1";
return "1" + "1";
```

```java
convert(1)
if (N == 1) return "1";
return convert(0) + "1";
```

% java Convert 26
11010
Programming with recursion: typical bugs

**Missing base case**

```java
public static double bad(int N)
{
    return bad(N-1) + 1.0/N;
}
```

**No convergence guarantee**

```java
public static double bad(int N)
{
    if (N == 1) return 1.0;
    return bad(1 + N/2) + 1.0/N;
}
```

Both lead to *infinite recursive loops* (bad news).

Try \( N = 2 \)

*need to know how to stop them on your computer*
Collatz Sequence

Collatz function of $N$.
- If $N$ is 1, stop.
- If $N$ is even, divide by 2.
- If $N$ is odd, multiply by 3 and add 1.

```
public static void collatz(int N)
{
    StdOut.print(N + " ");
    if (N == 1) return;
    if (N % 2 == 0) collatz(N / 2);
    collatz(3*N + 1);
}
```

Amazing fact. No one knows whether or not this function terminates for all $N$ (!)

Note. We usually ensure termination by only making recursive calls for smaller $N$. 

Collatz sequence: 7 22 11 34 17 52 26 13 49 20 ...

% java Collatz 7
7 22 11 34 17 52 26 13 40 20 10 5 16 8 4 2 1
THE COLLATZ CONJECTURE STATES THAT IF YOU PICK A NUMBER, AND IF IT'S EVEN DIVIDE IT BY TWO AND IF IT'S ODD MULTIPLY IT BY THREE AND ADD ONE, AND YOU REPEAT THIS PROCEDURE LONG ENOUGH, EVENTUALLY YOUR FRIENDS WILL STOP CALLING TO SEE IF YOU WANT TO HANG OUT.
Image sources

http://xkcd.com/710/
6. Recursion

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Warmup: subdivisions of a ruler (revisited)

ruler(n): create subdivisions of a ruler to \(1/2^n\) inches.
- Return one space for \(n = 0\).
- Otherwise, sandwich \(n\) between two copies of ruler(n-1).

```java
public class Ruler {
    public static String ruler(int n) {
        if (n == 0) return " ";
        return ruler(n-1) + n + ruler(n-1);
    }
    public static void main(String[] args) {
        int n = Integer.parseInt(args[0]);
        StdOut.println(ruler(n));
    }
}
```

% java Ruler 1
  1
% java Ruler 2
  1 2 1
% java Ruler 3
  1 2 1 3 1 2 1
% java Ruler 4
  1 2 1 3 1 2 1 4 1 2 1 3 1 2 1
% java Ruler 50
Exception in thread "main"
java.lang.OutOfMemoryError:
Java heap space

\(2^{50} - 1\) integers in output.
Tracing a recursive program

Use a *recursive call tree*

- One node for each recursive call.
- Label node with return value after children are labeled.

```
  ruler(0)  1  1  1  1
    |      |      |      |
  ruler(1)  1  1  1  1
    |      |      |      |
  ruler(2)  1  1  1  1
    |      |      |      |
  ruler(3)  1  1  1  1
    |      |      |      |
  ruler(4)  1  2  1  3  1  2  1  4  1  2  1  3  1  2  1
```
Towers of Hanoi puzzle

A legend of uncertain origin
- $n = 64$ discs of differing size; 3 posts; discs on one of the posts from largest to smallest.
- An ancient prophecy has commanded monks to move the discs to another post.
- When the task is completed, \textit{the world will end.}

Rules
- Move discs one at a time.
- Never put a larger disc on a smaller disc.

Q. Generate list of instruction for monks?

Q. When might the world end?
Towers of Hanoi

For simple instructions, use cyclic wraparound

• Move right means 1 to 2, 2 to 3, or 3 to 1.
• Move left means 1 to 3, 3 to 2, or 2 to 1.

A recursive solution

• Move $n - 1$ discs to the left (recursively).
• Move largest disc to the right.
• Move $n - 1$ discs to the left (recursively).
Towers of Hanoi solution (n = 3)

1R 2L 1R 3R 1R 2L 1R
Towers of Hanoi: recursive solution

hanoi(n): Print moves for $n$ discs.
- Return one space for $n = 0$.
- Otherwise, set move to the specified move for disc $n$.
- Then sandwich move between two copies of hanoi(n-1).

```java
public class Hanoi {
    public static String hanoi(int n, boolean left) {
        if (n == 0) return " ";
        String move;
        if (left) move = n + "L";
        else move = n + "R";
        return hanoi(n-1, !left) + move + hanoi(n-1, !left);
    }

    public static void main(String[] args) {
        int n = Integer.parseInt(args[0]);
        StdOut.println(hanoi(n, false));
    }
}

% java Hanoi 3
1R 2L 1R 3R 1R 2L 1R
Recursive call tree for towers of Hanoi

Structure is the same as for the ruler function and suggests 3 useful and easy-to-prove facts.
- Each disc always moves in the same direction.
- Moving smaller disc always alternates with a unique legal move.
- Moving $n$ discs requires $2^n - 1$ moves.
Answers for towers of Hanoi

Q. Generate list of instructions for monks?

A. (Long form). 1L 2R 1L 3L 1L 2R 1L 4R 1L 2R 1L 3L 1L 2R 1L 5L 1L 2R 1L 3L 1L 2R 1L 4R ...

A. (Short form). Alternate "1L" with the only legal move not involving the disc 1.

"L" or "R" depends on whether \( n \) is odd or even.

Q. When might the world end?

A. Not soon: need \( 2^{64} - 1 \) moves.

Note: Recursive solution has been proven optimal.

<table>
<thead>
<tr>
<th>moves per second</th>
<th>end of world</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.84 billion centuries</td>
</tr>
<tr>
<td>1 billion</td>
<td>5.84 centuries</td>
</tr>
</tbody>
</table>

---

[Diagram of towers of Hanoi]

[Diagram of towers of Hanoi]
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Recursive graphics in the wild
"Hello, World" of recursive graphics: H-trees

H-tree of order $n$
- If $n$ is 0, do nothing.
- Draw an H, centered.
- Draw four H-trees of order $n-1$ and half the size, centered at the tips of the H.
H-trees

**Application.** Connect a large set of regularly spaced sites to a single source.
Recursive H-tree implementation

```java
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);
    }
}
```
Deluxe H-tree implementation

```java
class HtreeDeluxe {
  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);
    StdAudio.play(PlayThatNote.note(n, .25*n));
    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);
  }
}
```
Fractional Brownian motion

A process that models many phenomenon.
• Price of stocks.
• Dispersion of fluids.
• Rugged shapes of mountains and clouds.
• Shape of nerve membranes.

Brownian bridge model

An actual mountain

Price of an actual stock

Black–Scholes model (two different parameters)
Fractional Brownian motion simulation

Midpoint displacement method

- Consider a line segment from \((x_0, y_0)\) to \((x_1, y_1)\).
- If sufficiently short draw it \textit{and return}
- Divide the line segment in half, at \((x_m, y_m)\).
- Choose \(\delta\) at random \textit{from Gaussian distribution}.
- Add \(\delta\) to \(y_m\).
- Recur on the left and right line segments.
public class Brownian
{
    public static void
    curve(double x0, double y0, double x1, double y1,
            double var, double s)
    {
        if (x1 - x0 < .01)
            {StdDraw.line(x0, y0, x1, y1); return; }
        double xm = (x0 + x1) / 2;
        double ym = (y0 + y1) / 2;
        double stddev = Math.sqrt(var);
        double delta = StdRandom.gaussian(0, stddev);
        curve(x0, y0, xm, ym+delta, var/s, s);
        curve(xm, ym+delta, x1, y1, var/s, s);
    }

    public static void main(String[] args)
    {
        double hurst = Double.parseDouble(args[0]);
        double s = Math.pow(2, 2*hurst);
        curve(0, .5, 1.0, .5, .01, s);
    }
}
A 2D Brownian model: plasma clouds

Midpoint displacement method
- Consider a rectangle centered at \((x, y)\) with pixels at the four corners.
- If the rectangle is small, do nothing.
- Color the midpoints of each side the average of the endpoint colors.
- Choose \(\delta\) at random from Gaussian distribution.
- Color the center pixel the average of the four corner colors plus \(\delta\)
- Recurse on the four quadrants.

Booksite code actually draws a rectangle to avoid artifacts
A Brownian cloud
A Brownian landscape
Image sources

http://www.mcescher.com/gallery/most-popular/circle-limit-iv/
http://www.megamonalisa.com/recursion/
http://fractalfoundation.org/OFC/FractalGiraffe.png
http://www.nytimes.com/2006/12/15/arts/design/15serk.html?pagewanted=all&r=0
http://www.geocities.com/aaron_torpy/gallery.htm
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Fibonacci numbers

Let $F_n = F_{n-1} + F_{n-2}$ for $n > 1$ with $F_0 = 0$ and $F_1 = 1$.

<table>
<thead>
<tr>
<th>$n$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_n$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>13</td>
<td>21</td>
<td>34</td>
<td>55</td>
<td>89</td>
<td>144</td>
<td>233</td>
<td>...</td>
</tr>
</tbody>
</table>

Models many natural phenomena and is widely found in art and architecture.

Examples.
- Model for reproducing rabbits.
- Nautilus shell.
- Mona Lisa.
- ...

Facts (known for centuries).
- $F_n / F_{n-1} \to \phi = 1.618...$ as $n \to \infty$
- $F_n$ is the closest integer to $\phi^n / \sqrt{5}$

Leonardo Fibonacci

C. 1170 – C. 1250
Fibonacci numbers and the golden ratio in the wild

- Mona Lisa
- Galaxy
- Sunflower
- Parthenon
- Darth Vader

Fibonacci sequence:

1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, ...
Computing Fibonacci numbers

Q. [Curious individual.] What is the exact value of $F_{60}$?

A. [Novice programmer.] Just a second. I'll write a recursive program to compute it.

```java
public class FibonacciR {
    public static long F(int n) {
        if (n == 0) return 0;
        if (n == 1) return 1;
        return F(n-1) + F(n-2);
    }
    public static void main(String[] args) {
        int n = Integer.parseInt(args[0]);
        StdOut.println(F(n));
    }
}
```

```
% java FibonacciR 5
5
% java FibonacciR 6
8
% java FibonacciR 10
55
% java FibonacciR 12
144
% java FibonacciR 50
12586269025
% java FibonacciR 60
```

Is something wrong with my computer?

takes a few minutes
Hmm. Why is that?
Recursive call tree for Fibonacci numbers
Exponential waste

Let $C_n$ be the number of times $F(n)$ is called when computing $F(60)$.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$C_n$</th>
<th>$F_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1</td>
<td>$F_1$</td>
</tr>
<tr>
<td>59</td>
<td>1</td>
<td>$F_2$</td>
</tr>
<tr>
<td>58</td>
<td>2</td>
<td>$F_3$</td>
</tr>
<tr>
<td>57</td>
<td>3</td>
<td>$F_4$</td>
</tr>
<tr>
<td>56</td>
<td>5</td>
<td>$F_5$</td>
</tr>
<tr>
<td>55</td>
<td>8</td>
<td>$F_6$</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0</td>
<td>$&gt;2.5\times10^{12}$</td>
<td>$F_{61}$</td>
</tr>
</tbody>
</table>

Exponentially wasteful to recompute all these values. (trillions of calls on $F(0)$, not to mention calls on $F(1)$, $F(2)$,...)
Exponential waste dwarfs progress in technology

If you engage in exponential waste, you will not be able to solve a large problem.

### 1970s

<table>
<thead>
<tr>
<th>$n$</th>
<th>time to compute $F_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>minutes</td>
</tr>
<tr>
<td>40</td>
<td>hours</td>
</tr>
<tr>
<td>50</td>
<td>weeks</td>
</tr>
<tr>
<td>60</td>
<td>years</td>
</tr>
<tr>
<td>70</td>
<td>centuries</td>
</tr>
<tr>
<td>80</td>
<td>millenia</td>
</tr>
</tbody>
</table>

### 2010s: 10,000+ times faster

<table>
<thead>
<tr>
<th>$n$</th>
<th>time to compute $F_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>minutes</td>
</tr>
<tr>
<td>60</td>
<td>hours</td>
</tr>
<tr>
<td>70</td>
<td>weeks</td>
</tr>
<tr>
<td>80</td>
<td>years</td>
</tr>
<tr>
<td>90</td>
<td>centuries</td>
</tr>
<tr>
<td>100</td>
<td>millenia</td>
</tr>
</tbody>
</table>

1970s: "That program won't compute $F_{60}$ before you graduate!"

2010s: "That program won't compute $F_{80}$ before you graduate!"
Avoiding exponential waste

**Memoization**

- Maintain an array memo[] to remember all computed values.
- If value known, just return it.
- Otherwise, compute it, remember it, and then return it.

```java
public class FibonacciM {
    static long[] memo = new long[100];
    public static long F(int n) {
        if (n == 0) return 0;
        if (n == 1) return 1;
        if (memo[n] == 0) {
            memo[n] = F(n-1) + F(n-2);
            return memo[n];
        }
        return memo[n];
    }
    public static void main(String[] args) {
        int n = Integer.parseInt(args[0]);
        StdOut.println(F(n));
    }
}
```

Simple example of *dynamic programming* (next).
Image sources

http://en.wikipedia.org/wiki/Fibonacci
http://en.wikipedia.org/wiki/Ancient_Greek_architecture#mediaviewer/
  File:Parthenon-uncorrected.jpg
http://openclipart.org/detail/184691/teaching-by-ousia-184691
7. Recursion

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An alternative to recursion that avoids recomputation

Dynamic programming.
- Build computation from the "bottom up".
- Solve small subproblems and save solutions.
- Use those solutions to build bigger solutions.

Fibonacci numbers

```java
public class Fibonacci
{
    public static void main(String[] args)
    {
        int n = Integer.parseInt(args[0]);
        long[] F = new long[n+1];
        F[0] = 0; F[1] = 1;
        for (int i = 2; i <= n; i++)
            F[i] = F[i-1] + F[i-2];
        StdOut.println(F[n]);
    }
}
```

Key advantage over recursive solution. Each subproblem is addressed only once.
**DP example: Longest common subsequence**

**Def.** A *subsequence* of a string $s$ is any string formed by deleting characters from $s$.

**Ex 1.**

\[
\begin{align*}
\text{s} &= \text{ggcaccacg} \\
   &\quad \text{cac ggcaccacg} \\
   &\quad \text{gcaacg ggcaccacg} \\
   &\quad \text{**ggcaacg** ggcaccacg} \\
   &\quad \text{ggcaccacg ggcaccacg} \\
   &\quad \ldots
\end{align*}
\]

[2\(^n\) subsequences in a string of length $n$]

**Ex 2.**

\[
\begin{align*}
\text{t} &= \text{acggcgataacg} \\
   &\quad \text{gacg acggcgataacg} \\
   &\quad \text{ggggg ac gg ggataacg} \\
   &\quad \text{cggcgg acggcgataacg} \\
   &\quad \text{**ggcaacg** acggcgataacg} \\
   &\quad \text{ggggaacg acggcgataacg} \\
   &\quad \ldots
\end{align*}
\]

**Def.** The *LCS* of $s$ and $t$ is the longest string that is a subsequence of both.

**Goal.** Efficient algorithm to compute the LCS and/or its length

numerous scientific applications
Longest common subsequence

**Goal.** Efficient algorithm to compute the *length* of the LCS of two strings \( s \) and \( t \).

**Approach.** Keep track of the length of the LCS of \( s[i..M] \) and \( t[j..N] \) in \( \text{opt}[i, j] \)

Three cases:
- \( i = M \) or \( j = N \)
  \[ \text{opt}[i][j] = 0 \]
- \( s[i] = t[j] \)
  \[ \text{opt}[i][j] = \text{opt}[i+1, j+1] + 1 \]
- otherwise
  \[ \text{opt}[i][j] = \max(\text{opt}[i, j+1], \text{opt}[i+1][j]) \]

Ex: \( i = 6, j = 7 \)
- \( s[6..9] = \text{acg} \)
- \( t[7..12] = \text{atacg} \)
- \( \text{LCS}(\text{cg}, \text{tacg}) = \text{cg} \)
- \( \text{LCS}(\text{acg}, \text{atacg}) = \text{acg} \)

Ex: \( i = 6, j = 4 \)
- \( s[6..9] = \text{acg} \)
- \( t[4..12] = \text{cggatacg} \)
- \( \text{LCS}(\text{acg}, \text{gatacg}) = \text{acg} \)
- \( \text{LCS}(\text{cg}, \text{cggatacg}) = \text{cg} \)
- \( \text{LCS}(\text{acg}, \text{cggatacg}) = \text{acg} \)
LCS example

<table>
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opt[i][j] = max(opt[i, j+1], opt[i+1][j])

opt[i][j] = opt[i+1, j+1] + 1
LCS length implementation

```java
public class LCS {
    public static void main(String[] args) {
        String s = args[0];
        String t = args[1];
        int M = s.length();
        int N = t.length();
        int[][] opt = new int[M+1][N+1];
        for (int i = M-1; i >= 0; i--)
            for (int j = N-1; j >= 0; j--)
                if (s.charAt(i) == t.charAt(j))
                    opt[i][j] = opt[i+1][j+1] + 1;
                else
                    opt[i][j] = Math.max(opt[i+1][j], opt[i][j+1]);
        System.out.println(opt[0][0]);
    }
}
```

**Exercise.** Add code to print LCS itself (see `LCS.java` on book site for solution).
Dynamic programming and recursion

_Broadly useful_ approaches to solving problems by combining solutions to smaller subproblems.

Why learn DP and recursion?
- Represent a new mode of thinking.
- Provide powerful programming paradigms.
- Give insight into the nature of computation.
- Successfully used for decades.

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<td>advantages</td>
<td>Decomposition often obvious. Easy to reason about correctness.</td>
<td>Avoids exponential waste. Often simpler than memoization.</td>
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<tr>
<td>pitfalls</td>
<td>Potential for exponential waste. Decomposition may not be simple.</td>
<td>Uses significant space. Not suited for real-valued arguments. Challenging to determine order of computation</td>
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Image sources

http://upload.wikimedia.org/wikipedia/en/7/7a/Richard_Ernest_Bellman.jpg
http://apprendre-math.info/history/photos/Polya_4.jpeg
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6. Recursion